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LIQUID FLOW THROUGH WIRE SCREENS

A THESIS

Presented to
the Faculty of the Graduate Division

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by

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Georgia Institute of Technology
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LIQUID FLOW THROUGH WIRE SCREENS

Approved:

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I wish to thank Aircraft Porous Media, Inc. for furnishing the screen specimens which were used in the test and Lockheed Nuclear Products Division of the Lockheed Aircraft Corporation for the loan of equipment.

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LIST OF ILLUSTRATIONS

Figures 5 through 15 are graphical representations of test results.

LIST OF SYMBOLS

P_t - differential pressure across the screen as measured in the test if corrections were required.

P - differential pressure across the screen after corrections for the effectof the oil on top of the mercury in the manometer.

V_t - volume of oil collected as indicated by the scale on a graduate.

V_a - volume of oil after corrections if required.

t - time.

t - screen thickness.

T - temperature °F.

Q_t - flow rate as determined from test data or as measured prior to corrections.

Q_a - flow rate adjusted for the effect of tubes submerged in the oil

Q'_r - reference flow rate at a reference pressure generally the flow first recorded.

Q_r - average of the two reference flow rates at the reference pressure, measured before and after each test run.

Q_c - flow rate based on the reference viscosity, 1.8×10^2 lb/ft sec, and adjusted for a change in net open area of the screen due to contamination. Considered to be the final or correct flow rate - one which can be used for correlating the results.

Q'_c - the flow rate Q_t after adjustment for an area change due to contamination.

ρ - density.

μ - viscosity

ν - kinematic viscosity

A - total area of the screen specimen exposed to the oil (inside area of the 1/2 inch O.D. tube).

A_o - net open area per mesh.

A_t - total area per mesh $(\frac{\text{in.}}{\text{mesh}} \times \frac{\text{in.}}{\text{mesh}})$.

A_{no} - net open area of that part of the screen wetted by the oil, during a test run.

A'_{no} - net open area of that part of the screen wetted by the oil, during the initial reference run.

SUMMARY

Eight type screens, four of a Dutch Twill weave and four of a plain weave, rolled to the thickness of the wires and sintered in an oven to weld the wires together at the point of contact, were used in the tests. A screen specimen was placed in a screen holding device which facilitated the forcing of oil through the screen and the measurement of the pressure on each side of the screen. Apparatus was assembled to force the oil through the screen and to measure the flow rate through the screen and the pressure differential across the screen.

The flow rate through the screen was measured for various pressure differentials from about four inches of mercury to 1500 psi. It was found impractical to control the temperature accurately so methods for correcting the data for changes in viscosity were developed. It was also found that the screens became contaminated during the tests. A method was developed to correct the data so that the results would be based on the same net open area of the screen.

The flow rate versus pressure differential relationship for the four Dutch Twill screens which reportedly had open areas of the order of two microns, five microns, ten microns, and twenty microns respectively, was found to be linear for pressure differentials up to approximately 25 psi. All except the twenty micron screen demonstrated linearity up to a pressure differential of 100 psi, and the two micron screen demonstrated substantial linearity up to 1500 psi - its structural limit in the particular application.

It was found that the flow rate pressure differential relationship is non-linear for screens with holes of the order of twenty microns or larger.

The data for the four plain weave screens was correlated using dimensionless parameters.

CHAPTER I

INTRODUCTION

The problem developed as a result of discussions with representatives of Aircraft Porous Media, Inc., manufacturers of filters for aircraft hydraulic, fuel and pneumatic systems.

Problem.--Hydraulic and pneumatic engineers usually assume that the flow rate-pressure differential characteristic of a wire mesh screen is equivalent to that of an assemblage of orifices.[1] Accepted equations for expressing the pressure differential across an orifice as a function of the flow rate through the orifice for turbulent flow show the pressure differential to be essentially proportional to the square of the flow rate. It is reported, however, that for wire mesh screens with hole sizes below 25 microns the relationship is linear[1] for practical values of pressure differential.

Purpose.--The purpose of this investigation was to experimentally determine the flow rate versus differential pressure relationship for viscous liquid flow through the finer type wire mesh screens which are used in the manufacture of filters for hydraulic systems.

Use.--The use of extremely fine filter screens for filtering hydraulic fluid has in recent years become of great importance due to the

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[1] Letter, Dr. David B. Pall, Pall Filtration Companies, June 11, 1958.

relatively recent development and extensive use of electro-hydraulic servo systems in aircraft flight controls and industrial machine controls. Most servo valves incorporate small orifices and close fits around sliding spools. The small orifices become clogged and the spools jammed by contamination unless good oil filtration is provided.

The fine screen mesh has become one of the better means of providing reliable oil filtration. It does not itself offer loose material which can contaminate the system. Such filters as sintered metal powders, paper, and aggregates do not positively contain their own material so that some particles which were a part of the filter itself may migrate into the fluid and contaminate the system.

The development of the extremely fine wire mesh has suggested studies which were not previously of practical interest. That is, the wire mesh provides an abundance of extremely small holes of relative uniformity as compared with holes of filtering systems commonly used in the past.

CHAPTER II

DESCRIPTION OF THE TEST SYSTEMS

System A.--A reservoir pressurized by air from an air compressor was used as the means for forcing the oil through the screen mesh. A filter was installed upstream of the screen holder to clean the oil before it entered the screen. A micrometer needle valve provided a means for adjusting the flow rate. One-eighth inch OD copper tubing was used to provide a passageway from each side of the screen to a 50-inch mercury manometer. The head of the manometer was located above the screen holder (not as shown in Figure 1) to facilitate bleeding air from the manometer-to-holder tubes. The 1000 milliliter graduate was used to measure the volume flow rate of the oil. A return hand pump was provided to transfer the oil from the graduate back to the reservoir so that the system was closed and free from external contamination. A cover was provided over the graduate to prevent dust or other contaminants from falling into the graduate. Check valves and shut-off valves were provided to facilitate operation of the apparatus. Copper tubing, one quarter of an inch OD, was used between the reservoir and the filter and from the graduate through the hand pump back to the reservoir. Copper tubing, one half of an inch OD, was used from the micrometer needle valve through the screen holder to the graduate. System A was used to obtain the data for screen Types B, K-2, J, and M for pressure differentials to approximately 50 in. of

Hg. The data procured using System A is presented in Tables 2, 5, 7, and 9 and in Figures 5, 8, 10, and 12.

System B.--In the system shown in Figure 2 the fluid supply was furnished by a hydraulic test bench. A filter reportedly capable of removing all particles larger than three microns was installed in the line upstream of the screen holder. The downstream tube was cut off close to the screen holder, and a pressure gauge was connected to the upstream pressure "take-off" tube only. A graduate was used to collect the oil and a stop watch used to measure the time to collect a specific volume. To measure the oil temperature a thermometer was held in the oil as it discharged from the tube into the graduate. System B was used to obtain the data for screen Types B and K-2 for pressure differentials to approximately 200 psi for Type B and 100 psi for Type K-2. The data is presented in Tables 3 and 5 and Figures 6 and 8.

System C.--To provide the system shown in Figure 3 the tubing on each side of the screen holder and the pressure "take-off" tubing was replaced with stainless steel tubing brazed in place. The modified screen holder assembly was connected to a hydraulic test bench with the return line passing through a variable area flow meter. Three flow meters were used to cover the range of flow rates. The flow rate capabilities were 0.30 to 1.60 gpm, 1.3 to 6.9 gpm, and 6.0 to 31.0 gpm. The meters were Fischer and Porter variable area tube-float type, calibrated for a liquid with a viscosity of 35 centistokes and a specific gravity of 0.92. The accuracy of the flow meters is one per cent when the calibration fluid is used and probably less than 3% over the range of viscosities encountered in the tests. The three micron filter was installed in the line upstream of the screen holder. A dial type thermometer was installed in the downstream tube to measure the oil temperature.

System C was used to obtain the data for screen Types B, J, and M, and all the plain weave screens for pressure differentials to approximately 1500 psi for Type B, 130 psi for Types J and M, and 100 psi for the plain weave types. Data is presented in Tables 4, 8, 10, 11, 12, 13, 14 and in Figures 11, 13, and 14.

Screen Holder.--The screen holder is shown in detail in Figure 4.

Screen Specimen.--The screen specimens were furnished by Aircraft Porous Media, Inc., Glen Cove, New York, a Pall Filtration Company. The grades used and other information concerning the specimen screens are shown in Table 1.

Oil.--A light mineral oil was used in the test system shown in Figure 1 and ORONITE 8515, a high temperature hydraulic fluid, was used in the systems shown in Figures 2 and 3. The relationships of viscosity and density as functions of temperature for the two oils are shown in Figures 16 and 17.

CHAPTER III

PROCEDURES

Preparation for a Test, System A.--A square section of screen large enough to overlap the hole of the holder an eighth of an inch or more was installed in the holder and the holder halves securely bolted together. The tube connection at the manometer head, upstream side, was disconnected. With air pressure in the reservoir and valve A open, the needle valve was opened slowly and left open until a stream of oil free of air flowed from the pressure "take-off" tube. The tube was then reconnected to the manometer head. The manometer had been previously filled with the test oil on top of the mercury. The needle valve was then opened further until a full scale reading of the manometer was obtained. This setting was maintained until no air bubbled from the tube outlet in the graduate. This operation removed air from the main tube downstream of the screen holder and also from the manometer-to-holder downstream connecting tube. The oil from the graduate was returned to the reservoir by closing Valve C, opening valves B and D and operating the return hand pump until all but approximately one inch of oil was removed from the graduate. Valve B was then closed to prevent any reverse leakage through the check valves and hand pump back into the graduate. Valve D was closed and valve C opened to again pressurize the reservoir. The system was then ready for recording runs.

Prior to the first test run and prior to installation of the test screen the oil in the system was circulated a number of times through the system in a manner similar to that described above in order to clean the oil with the system filter.

Test Procedure, System A.--With the reservoir pressurized, the needle valve was adjusted to obtain approximately a 4 inch reading on the manometer. The time required for a certain volume of oil to flow into the graduate was measured with a stop watch. That is, the time required for the level of the oil in the graduate to rise from one level to another level was measured. The needle valve was then adjusted to obtain approximately an 8 inch reading on the manometer and the flow rate measured as described above. The needle valve was then again adjusted to obtain a 4 inch manometer reading and the flow rate measured. The needle valve was then adjusted to a new differential pressure and the flow rate measured. Each new differential pressure was approximately 4 inches greater than the previous. After each measurement at a new pressure differential the measurement at a 4 inch differential was performed. This procedure was followed in order to secure data which could be used to compute a correction to compensate for contamination of the screen. The method for computing the correction is discussed in Appendix D.

Measurements of flow rates for various pressure differentials up to approximately 50 inches manometer reading were performed using Types B, K-2, J and M screens.

Test Procedure for System B.--The needle valve was adjusted to obtain the desired upstream pressure. The graduate was placed under the discharge and a stop watch started. When the desired quantity of oil had been collected the watch was stopped. Oil temperature was measured by holding a thermometer in the oil discharge. Reference measurements as described previously were performed after each recording run in order to provide data which could be used to compute a correction to compensate for contamination of the screen.

Test Run Procedure for System C.--The needle valve was adjusted to obtain the desired upstream pressure. When the pressure gauges had stabilized the flow rate as indicated by the flow meter, the pressure of both the upstream and downstream gauges, and the temperature were recorded. Reference runs after each recording run were performed as in the previous tests.

CHAPTER IV

DISCUSSION OF RESULTS

Linearity.--The flow rate versus pressure differential relationship for the Dutch Twill screens, Figures 5 through 13, was found to be linear over the range of pressure differentials, 0 to 100 psi. The relationship for the type B screens, Figure 7, is at least substantially linear up to a differential of 1600 psi. A slightly bowed line could be drawn that would give a somewhat better fit than the straight line for the last three data points. However, with only four points available it was not possible to make a definite conclusion.

The flow rate versus differential pressure relationship for the type K-2 screen, Figure 9, indicates the possibility of a slight variation from linearity. However, for the type J screen, Figure 11, which has larger openings the relationship is apparently linear except for one isolated point. Since the relationship for the type B and type J screens is linear and the openings in the type K-2 screen are larger than those in the type B and smaller than those in type J it appears reasonable to conclude that the relationship for the K-2 screen is also linear and that the data points of Figure 9 are erroneous. The relationship for the type M screen, Figure 13 does not appear to be completely linear. The type M screen has the largest openings of the four Dutch Twill screens used. As shown in Table 1 the type M screen is rated at 20 microns, a rating based on the screens reported capability of removing 98 per cent of all incident particles larger than 20 microns. As mentioned in the introduction, the relationship for screens with openings smaller than 25 microns was reported to be completely linear. The results of the tests of the type M screen indicate that the range of linearity is substantially as reported.

It was to be expected that the relationship would be similar to the orifice relationship for the larger hole sizes, and that the curve would tend to drop at the higher pressure differentials. The relationship for the plain weave screens, Figure 14 and the correlation curve of Figure 15 indicate this to be the case.

The flow rate versus pressure differential relationship for the plain weave screens, Figure 14, is conclusively non-linear.

Correlation of the Data for Plain Screens.--The data for the four plain weave screens was correlated using the two dimensionless parameters in Figure 15. Very good correlation is indicated in this figure.

No attempt was made to correlate the data for the Dutch Twill screens as no method for determining the net open area was available.

Results of Tests Using the Same Type Screen.--More than one test was performed with each of the Dutch Twill screens. To compare the results of the tests in which the same type screen was used the graphical representation of the results of each test is shown on the same set of axes. Figures 7, 9, 11, and 13 indicate the comparison. These comparisons generally do not coincide. The slope of the lines is a function of the total net open area of the screen at the time of the initial reference test, and the net area may be inherently different in two specimens of the same type screen. Also the degree of clogging which had occurred before the first reference test may also have been different. The comparisons indicate that the oil was cleaner in Systems B and C than it was in System A. The results of the tests using System B and C are believed to represent substantially clean screens.

Viscosity and Area Corrections.--The viscosity and area corrections which are described in Appendix D improved the comparisons between the data which was obtained for two or more of the same type screens. The area correction improved the linearity of the data for the Dutch Twill screens.

Screen Stretching.--During the test with the type B screen at high pressure differentials the last reference test produced a considerably larger flow rate than the previous reference tests. Probably the screen had stretched, and the screen openings had become enlarged.

CHAPTER V

CONCLUSIONS

Flow Rate Versus Pressure Differential.--The pressure differential across woven wire screens when viscous liquid is flowing through the mesh is not the same type of function of the flow rate for all sizes of screen mesh. It is apparent that the flow rate is a linear function of the pressure differential when the holes in the screen are smaller than 10 microns and the pressure differentials are less than 100 psi. The relationship between the pressure differential and flow rate becomes non-linear for holes larger than some value in the range of 10 to 25 microns. For screens woven in a Dutch Twill type weave and with hole sizes of the order of 2 microns the flow rate versus pressure differential relationship is substantially linear over the range of pressure differentials less than 1500 psi.

CHAPTER VI

RECOMMENDATIONS

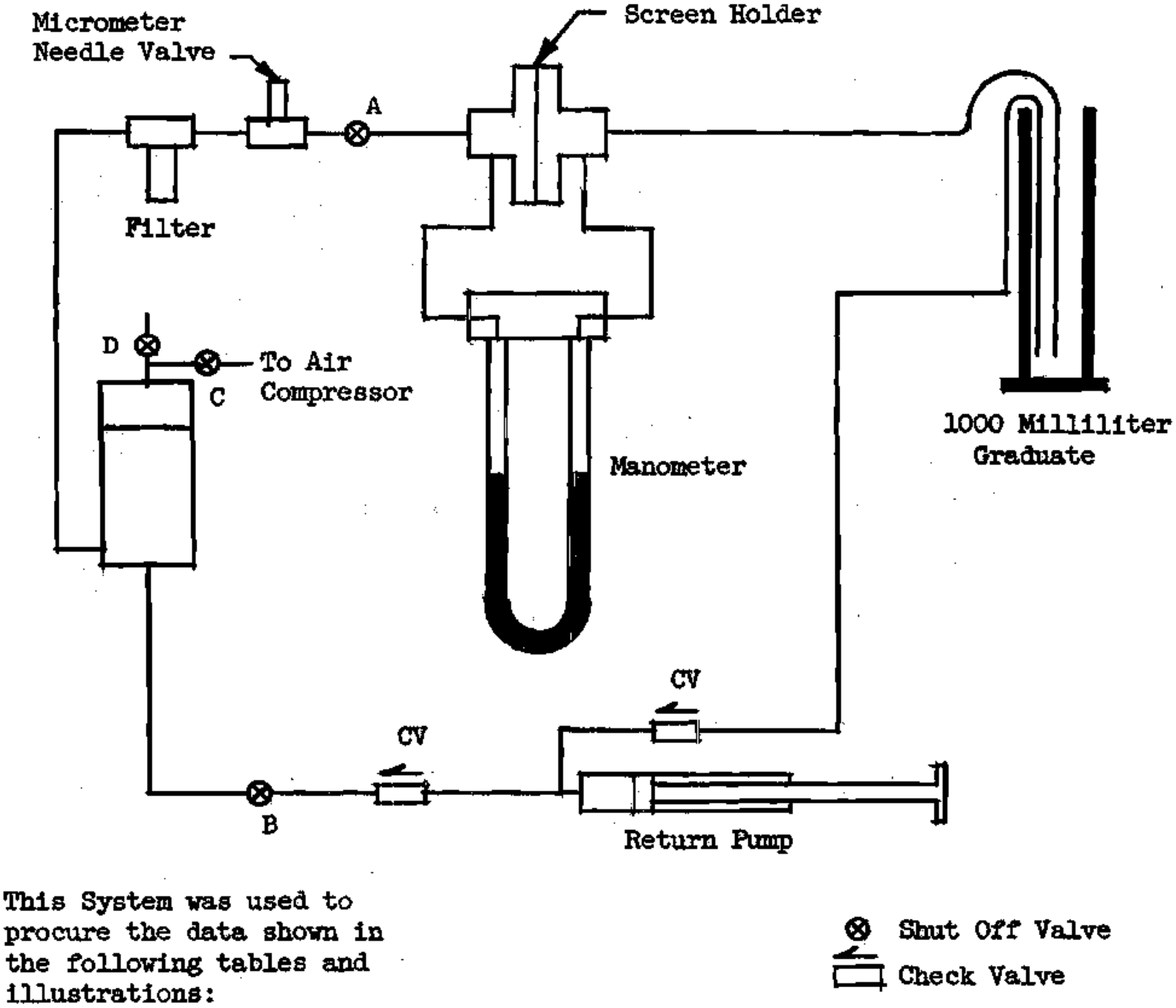
Further Analysis of the Data Herein.--Efforts should be made to determine an average opening size for the Dutch Twill screens, and the data obtained for these screens should be correlated in a manner similar to that explained in Appendix D.

Future Investigations.--Experiments using other fluids including air should be performed to substantiate the correlation curve, Figure 15, applicable to the plain weave screens.

Investigations performed at higher pressure differentials should be of interest especially with screen types B, K-2, J, and M.

APPENDIX A

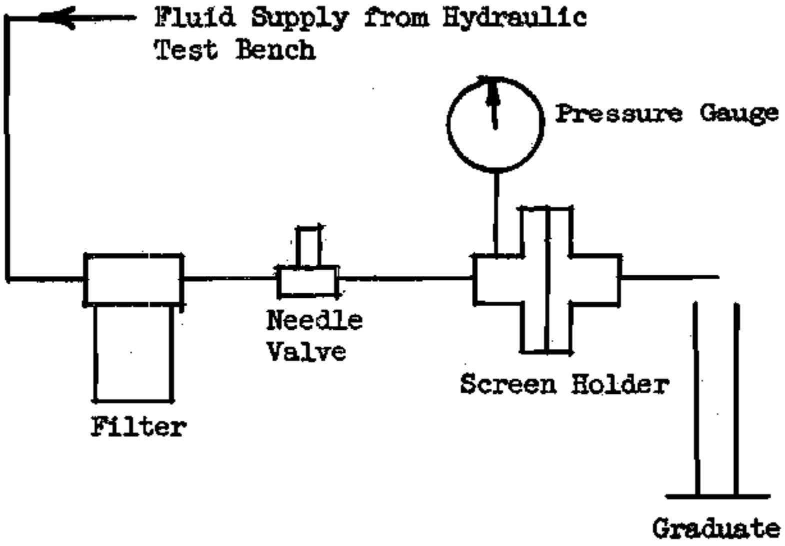
APPARATUS



This System was used to
procure the data shown in
the following tables and
illustrations:

Tables - 2, 5, 7 and 9
Figures - 5, 8, 10, and 12

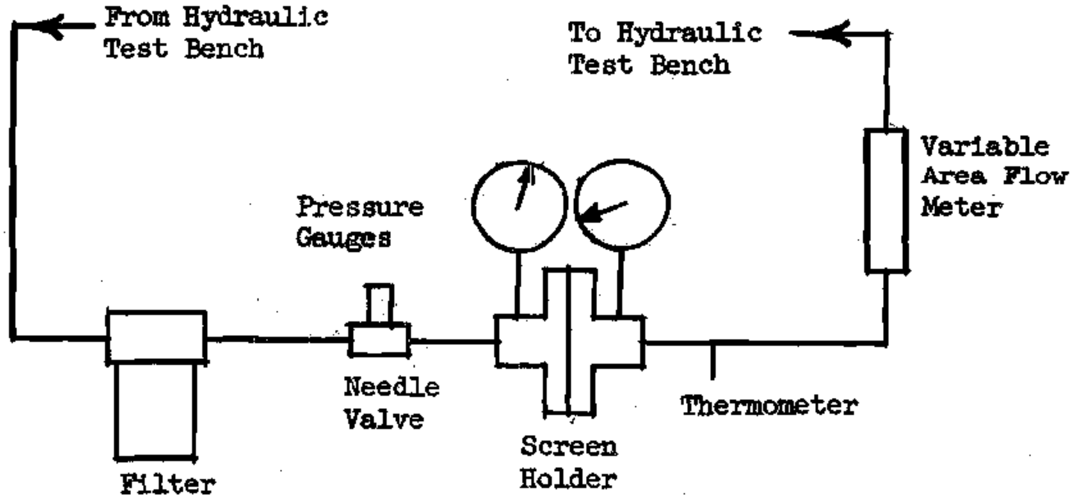
Figure 1. Schematic Diagram of Test System A



This System was used to procure the data shown in the following tables and illustrations:

Tables - 3 and 5
Figures - 6 and 8

Figure 2. Schematic Diagram of Test System B



This System was used to procure
the data shown in the following
tables and illustrations:

Tables - 4, 8, 10, 11, 12, 13 and 14
Figures - 7, 11 and 14

Figure 3. Schematic Diagram of Test System C

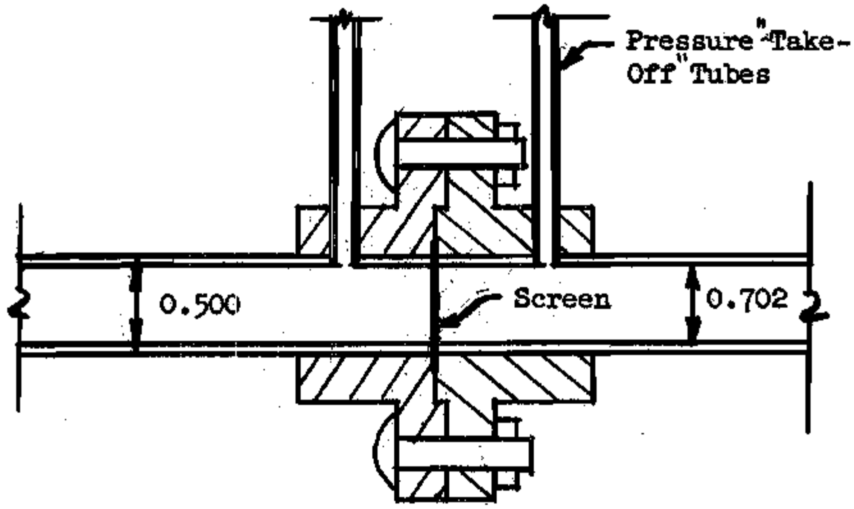


Figure 4. Cross Sectional View of Screen Holder

APPENDIX B

GRAPHICAL REPRESENTATION OF RESULTS

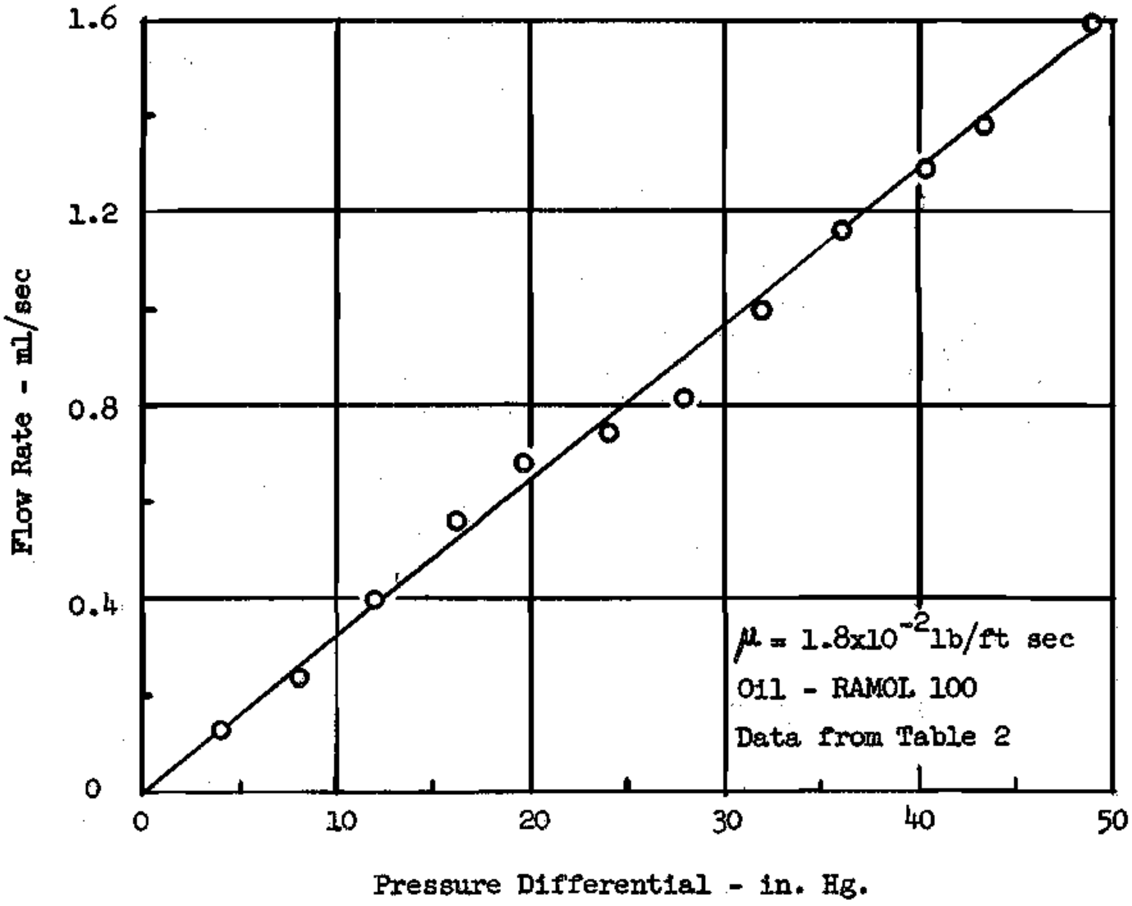


Figure 5. Type B Screen, 0 - 50 in. Hg.

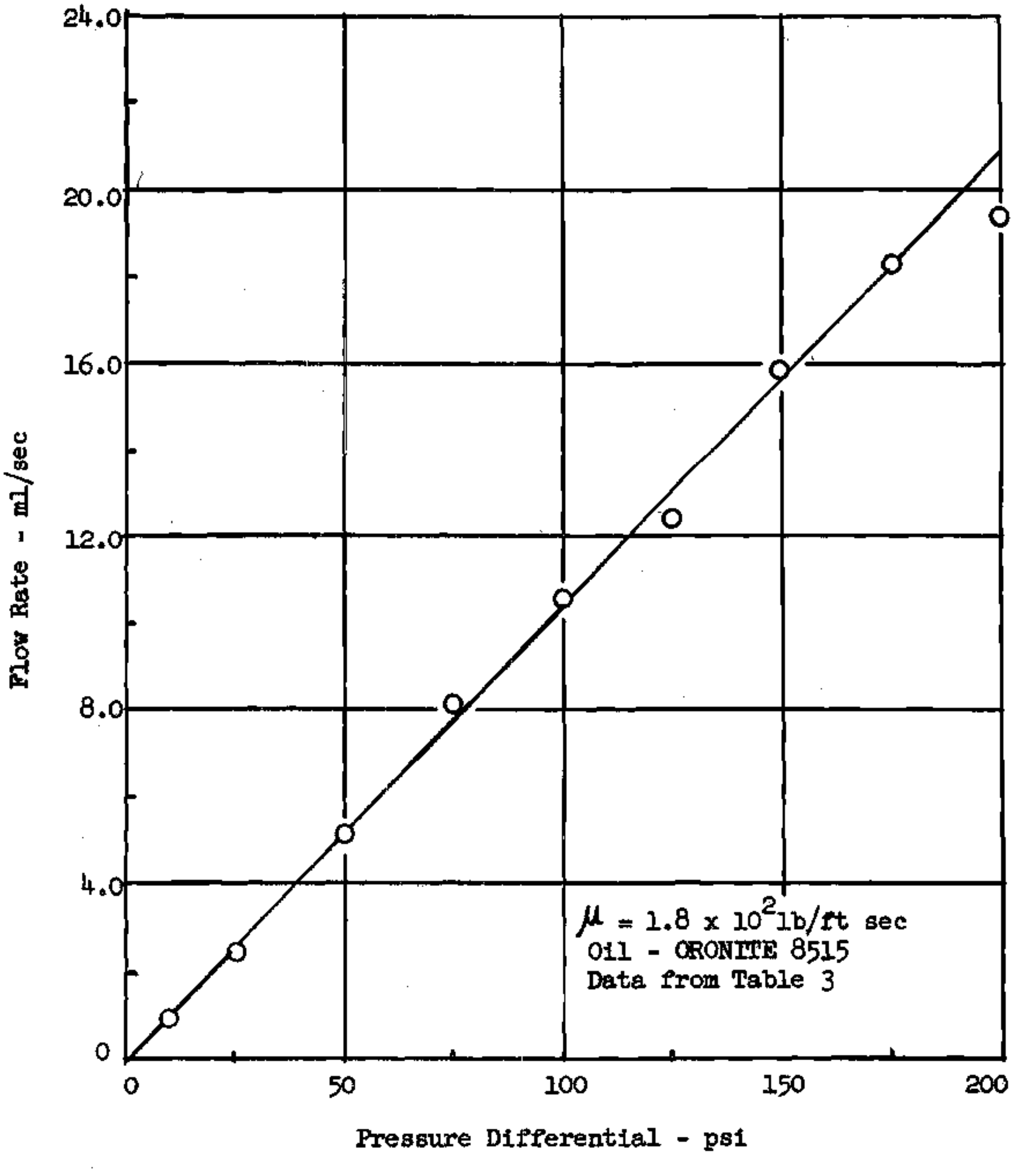


Figure 6. Type B Screen, 0 - 200 psi

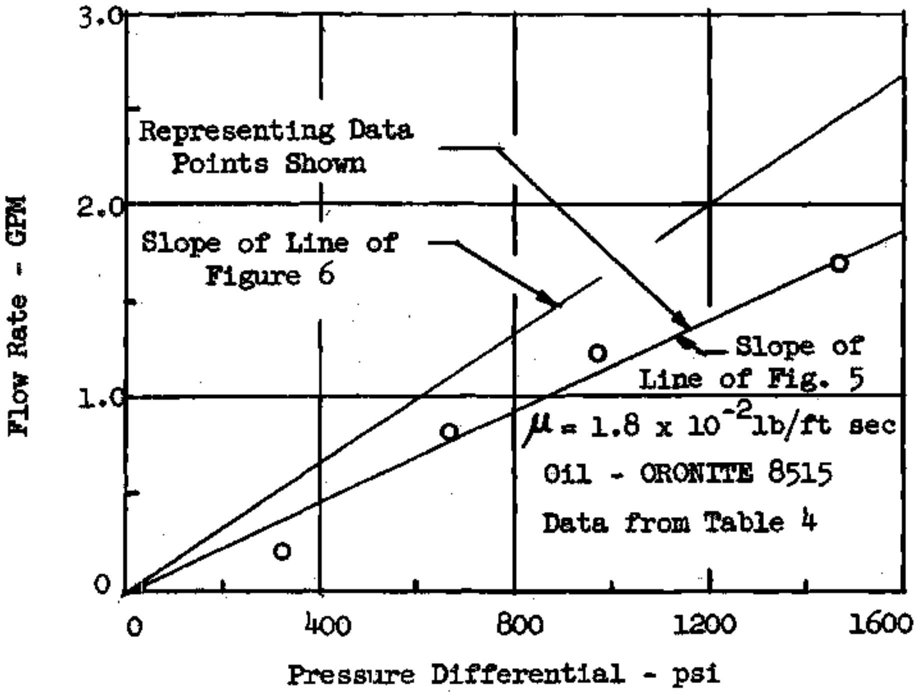


Figure 7. Type B Screen, 0 - 1500 psi

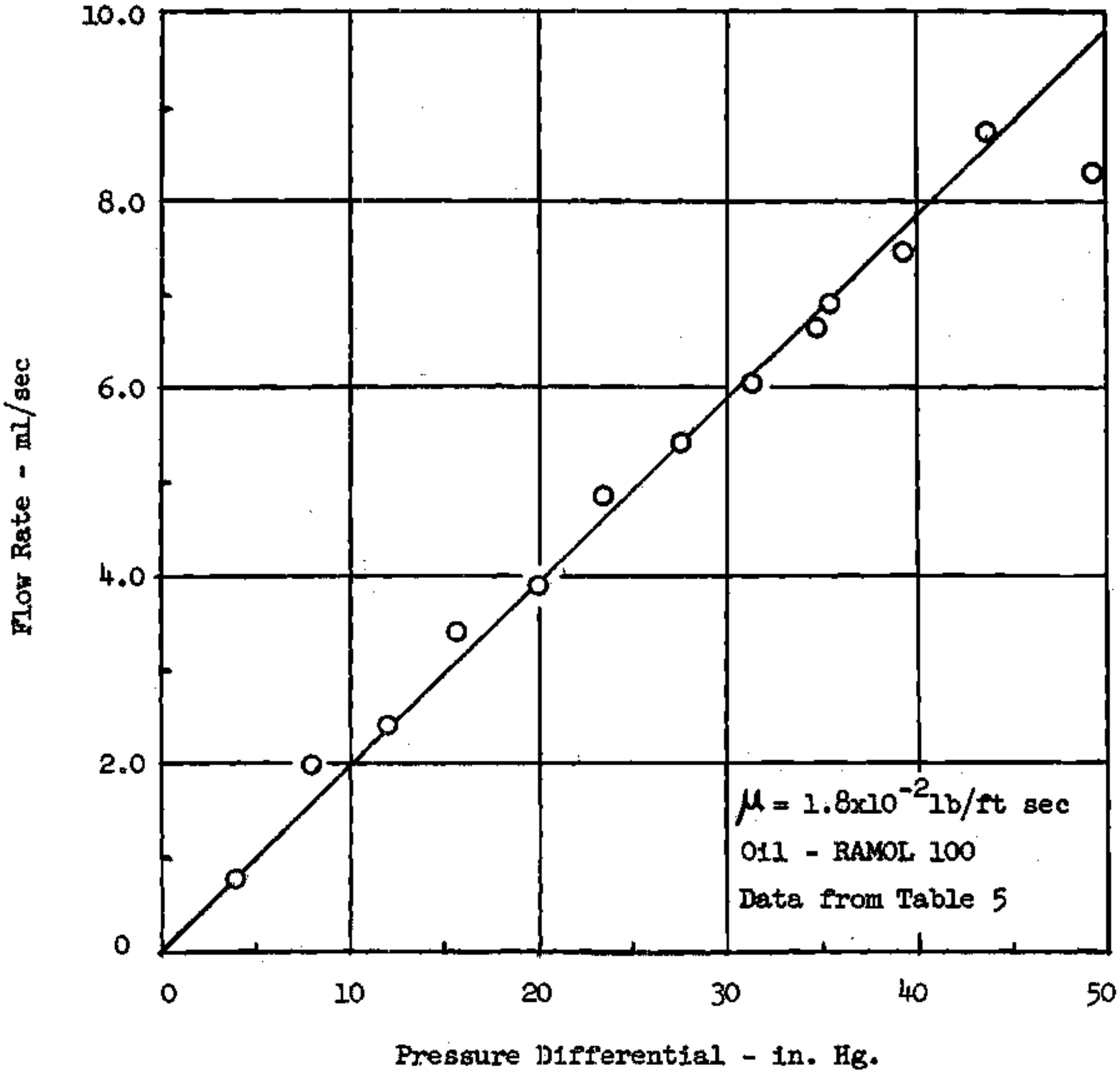


Figure 8. Type K-2 Screen, 0 - 50 in. Hg.

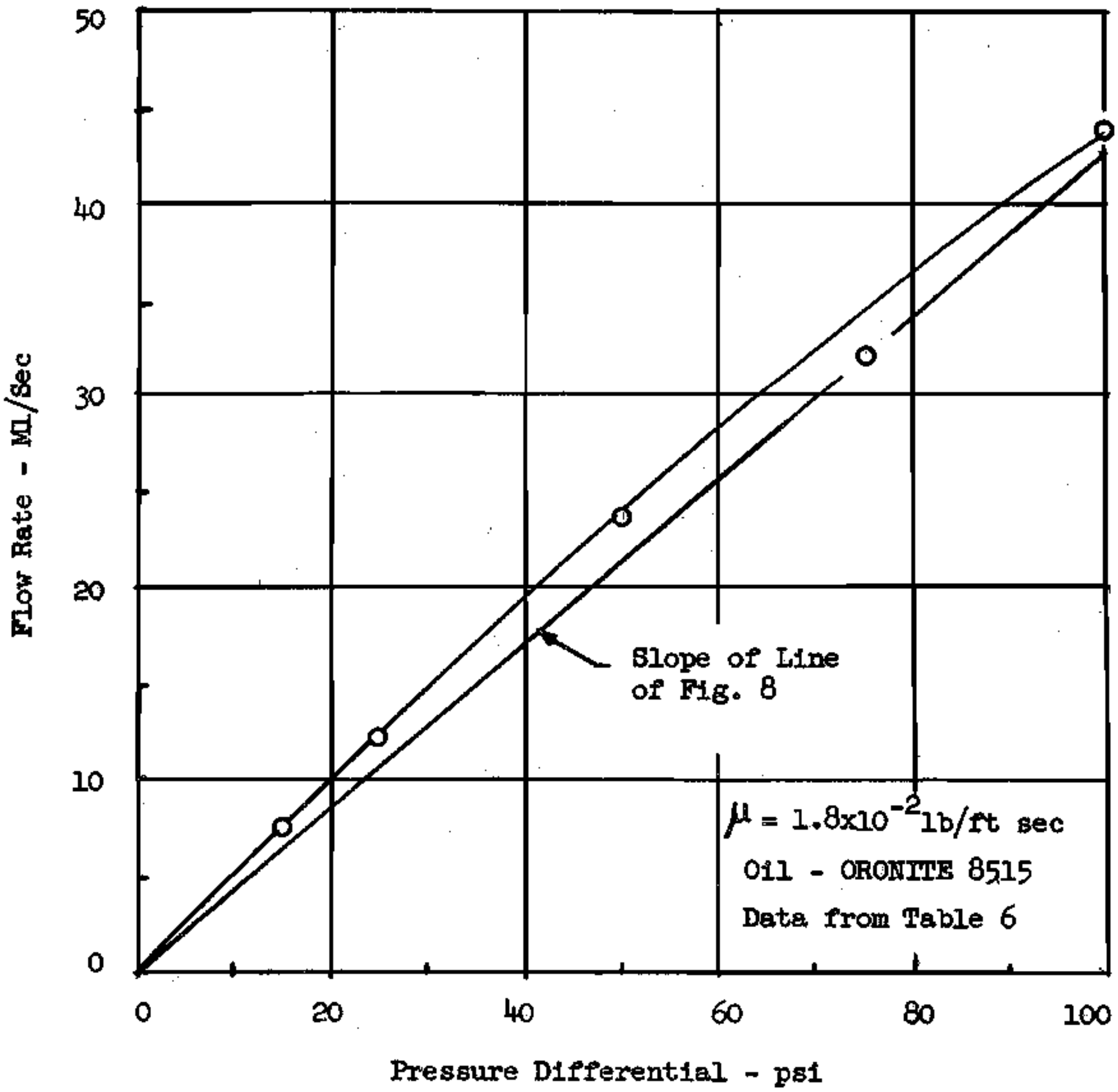


Figure 9. Type K-2 Screen, 0 - 100 psi

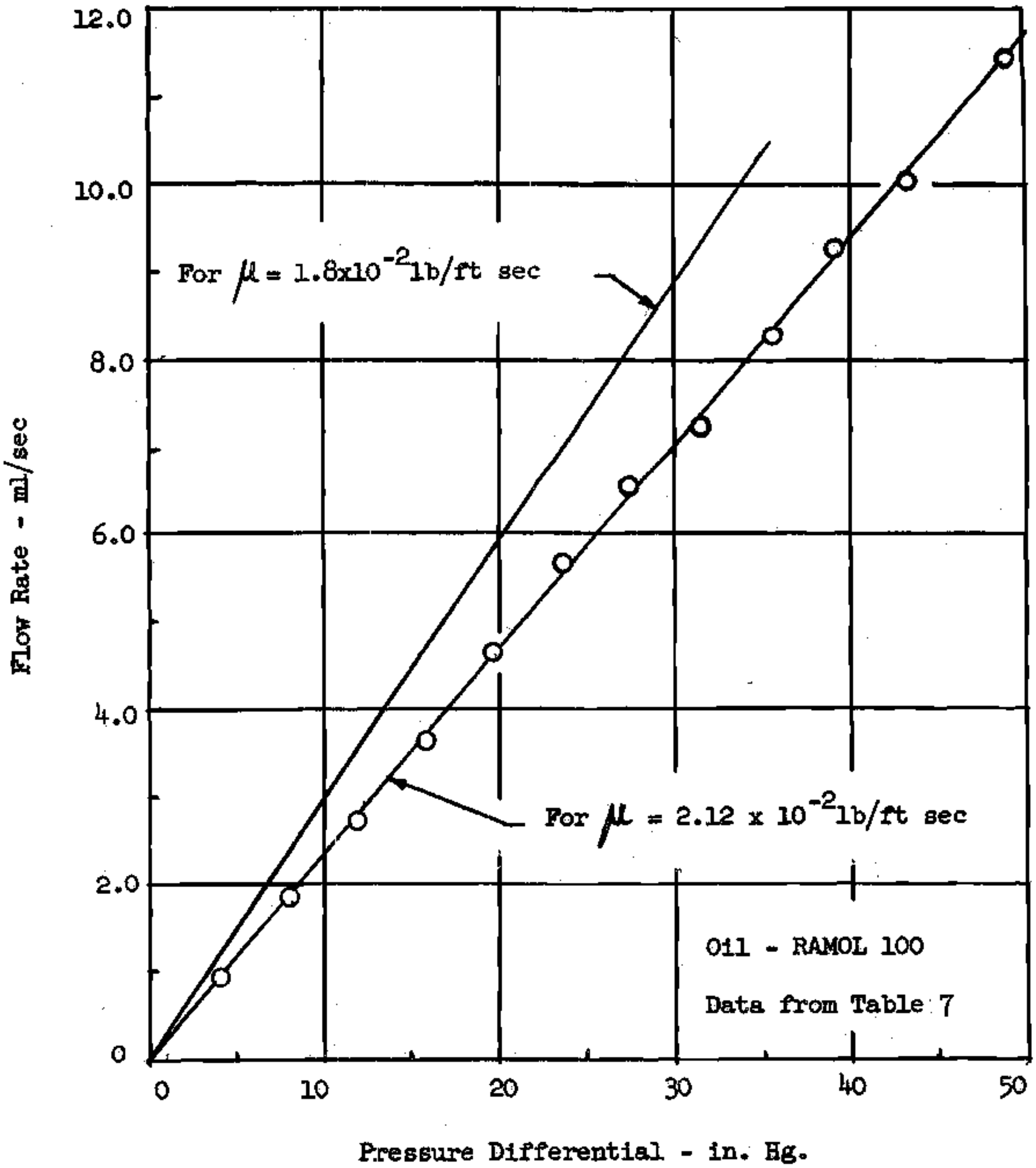


Figure 10. Type J Screen, 0 - 50 in. Hg.

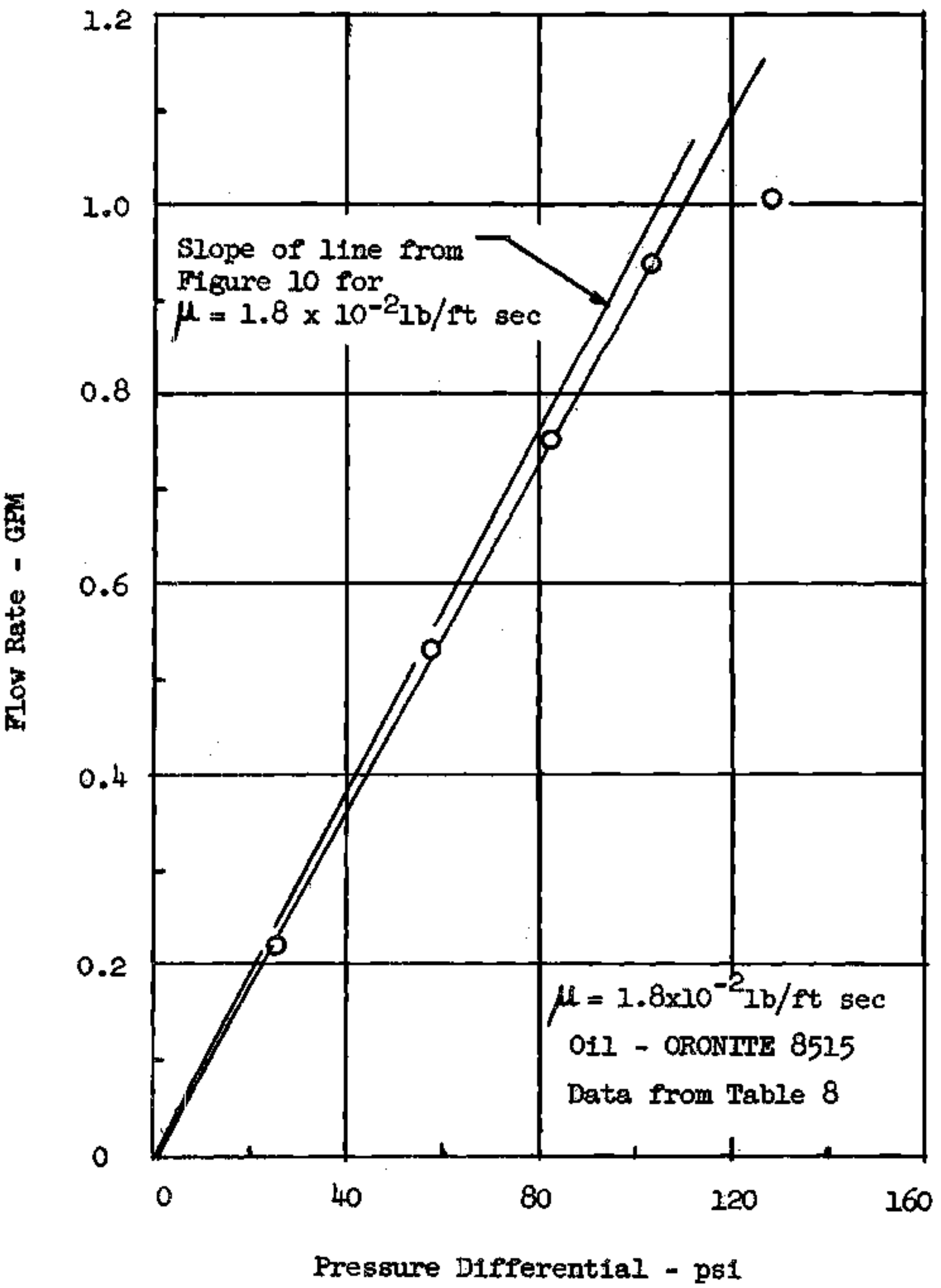


Figure 11. Type J Screen, 0 - 130 psi

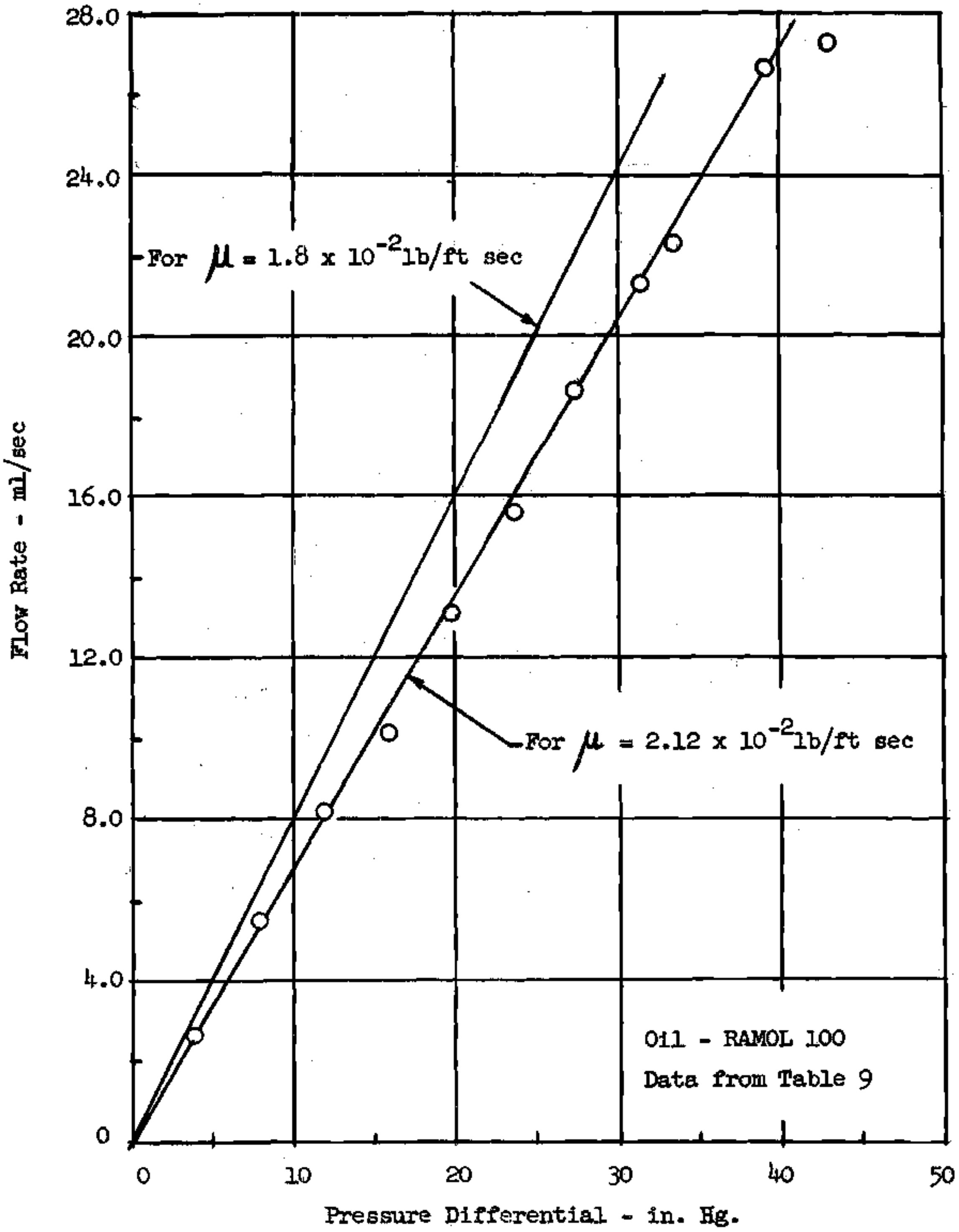


Figure 12. Type M Screen, 0 - 50 in. Hg.

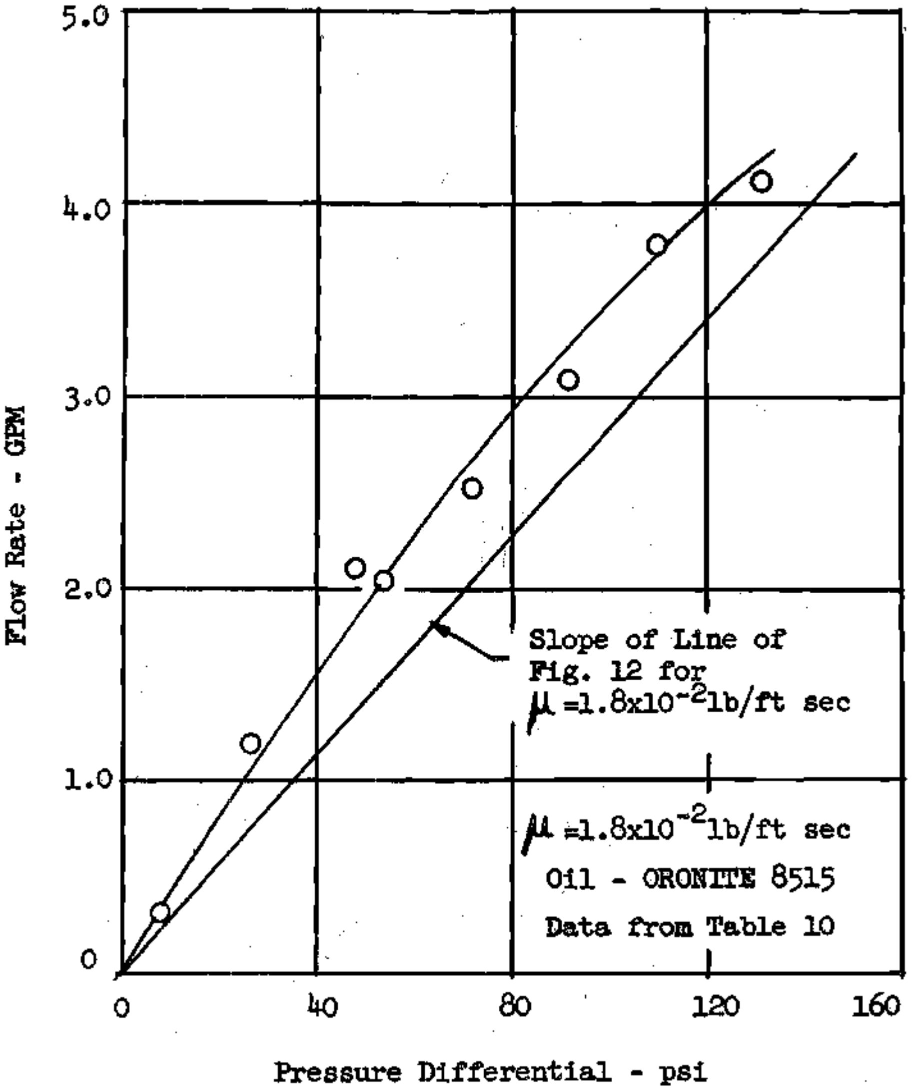


Figure 13. Type M Screen, 0 - 130 psi

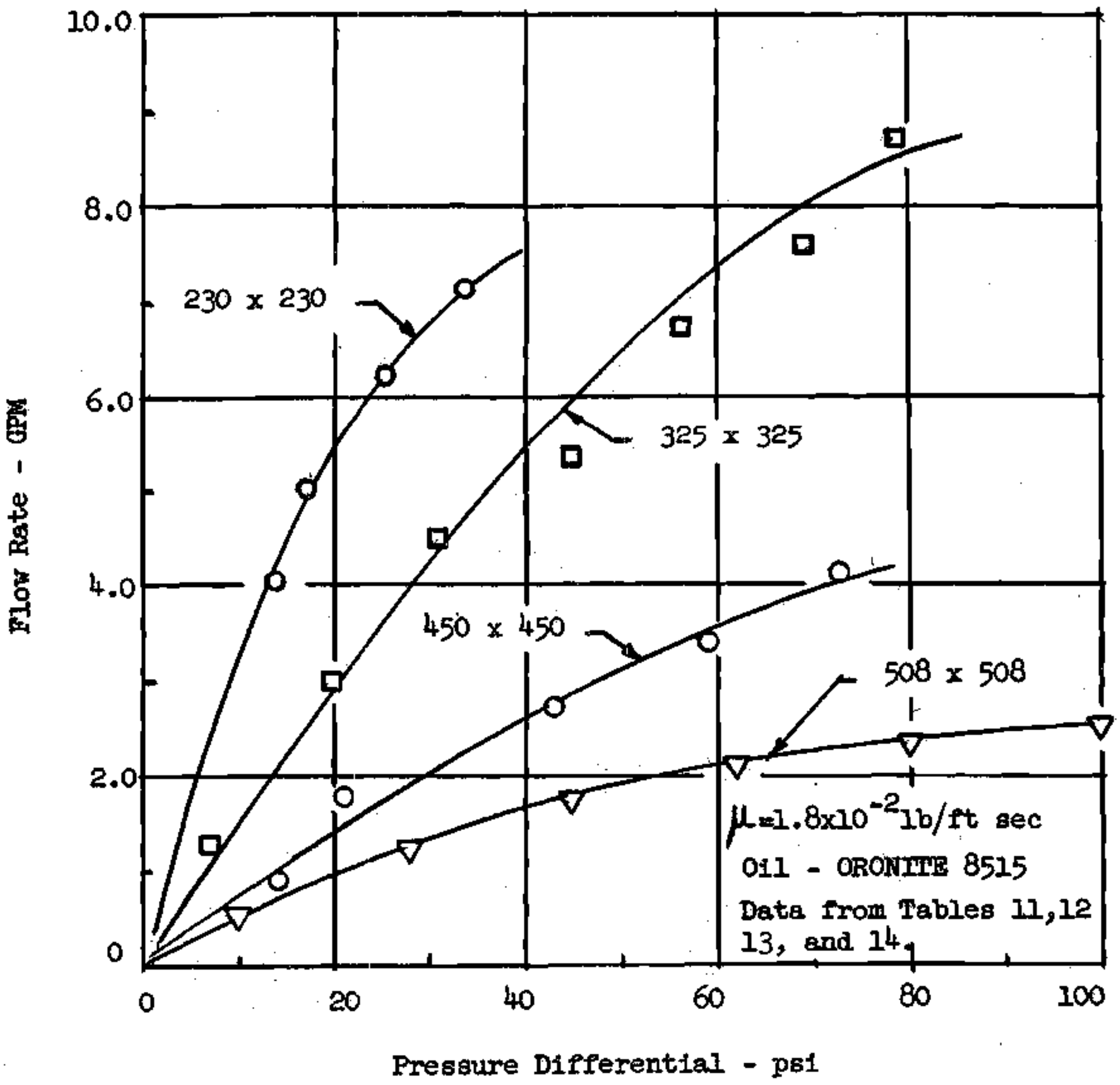


Figure 14. Plain Weave Screens, 0 - 100 psi

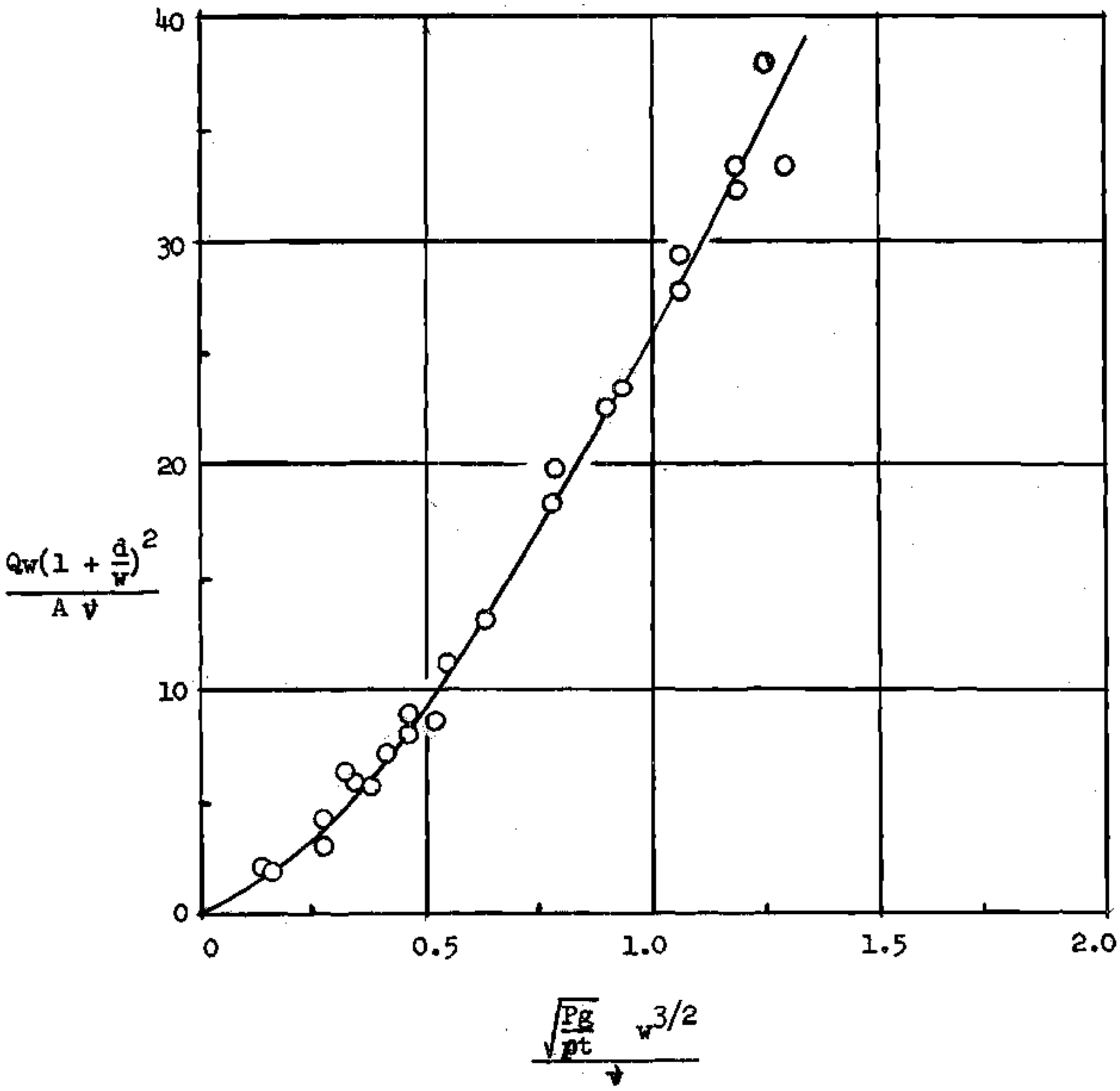


Figure 15. Dimensionless Parameter Correlation for the Plain Weave Screens

APPENDIX C

OIL AND SCREEN DATA

Table 1. List of Screen Specimens with Descriptive Information

(1) Grade	(2) Wire Diam.	(3) Thickness	(4) No. of Mesh Per Inch	(5) No. of Mesh Per Inch	(1) Filter Rating (microns)	(6) Type Weave	(7) Opening Size (length of one side of a square) (inches)
B	0.0014	0.0045	346	196	2	Dutch Twill	
K-2	0.0014	0.006	345	200	5	Dutch Twill	
J	0.0018	0.006	339	160	10	Dutch Twill	
M	0.0020	0.007	196	161	20	Dutch Twill	
508x508	0.0012	0.001	478	475	--	Plain Weave	0.008
450x450	0.0012	0.001	435	442	--	Plain Weave	0.0010
325x325	0.0016	0.0015	313	334	--	Plain Weave	0.0018
230x230	0.0016	0.0015	261	262	--	Plain Weave	0.0023

(1) Code, designating grade and filter rating as indicated in a pamphlet entitled RIGIMESH, Release No. 215, of The Pall Filtration Companies, Glen Cove, New York.

(2) The wire diameter is the diameter of the curved wires in the case of the Dutch Twill weave and of all wires of the plain weave. The straight wire diameter of the Dutch Twill screens can be estimated using the following equation:

$$d_s = t - 2d$$

where: d_s = diameter of the straight wire
d = diameter of the curved wire from column (2)
t = screen thickness

(3) The thickness of the screen was obtained by measurement with a micrometer.

(4) Number of mesh per inch in a direction measured parallel to the straight wires.

(5) Number of mesh per inch in a direction measured perpendicular to the straight wires. The inverse of this number is the distance between the centers of the straight wires.

(7) The openings in the Dutch Twill screens were not straight through so could not be measured. The holes in the plain weave screens were generally square with radius corners.

The information in columns (2), (4), (5), and (7) was obtained by examination of the screen under a microscope which was provided with a movable specimen table having micrometer position control in two directions. A cross hair in the scope furnished a reference line.

There was a variation in wire diameter and opening size from one place on the screen to the next. The dimensions shown were selected as average. The accuracy of the measurements was estimated to be of the order of plus or minus 0.0002 of an inch.

The last four screens were rolled to the thickness shown which probably accounts at least in part for the discrepancy between columns (4) and (5) and between the wire diameter information furnished with the screens (which was 0.001, 0.001, 0.0014, 0.0014, for screens 508x508, 450x450, 325x325, and 230x230 respectively) and column (2).

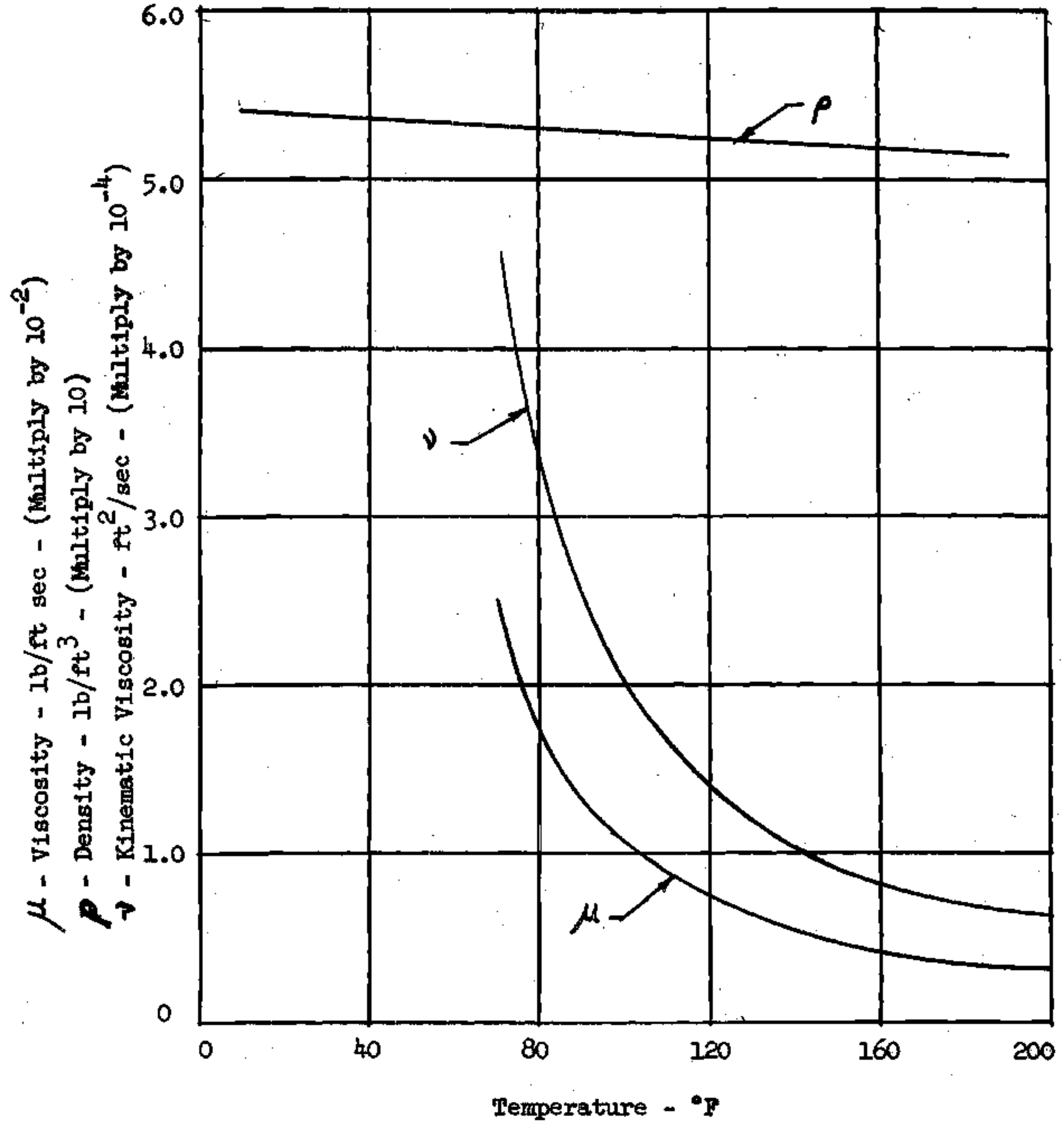


Figure 16. Viscosity - Density - vs - Temperature
For RAMOL 100

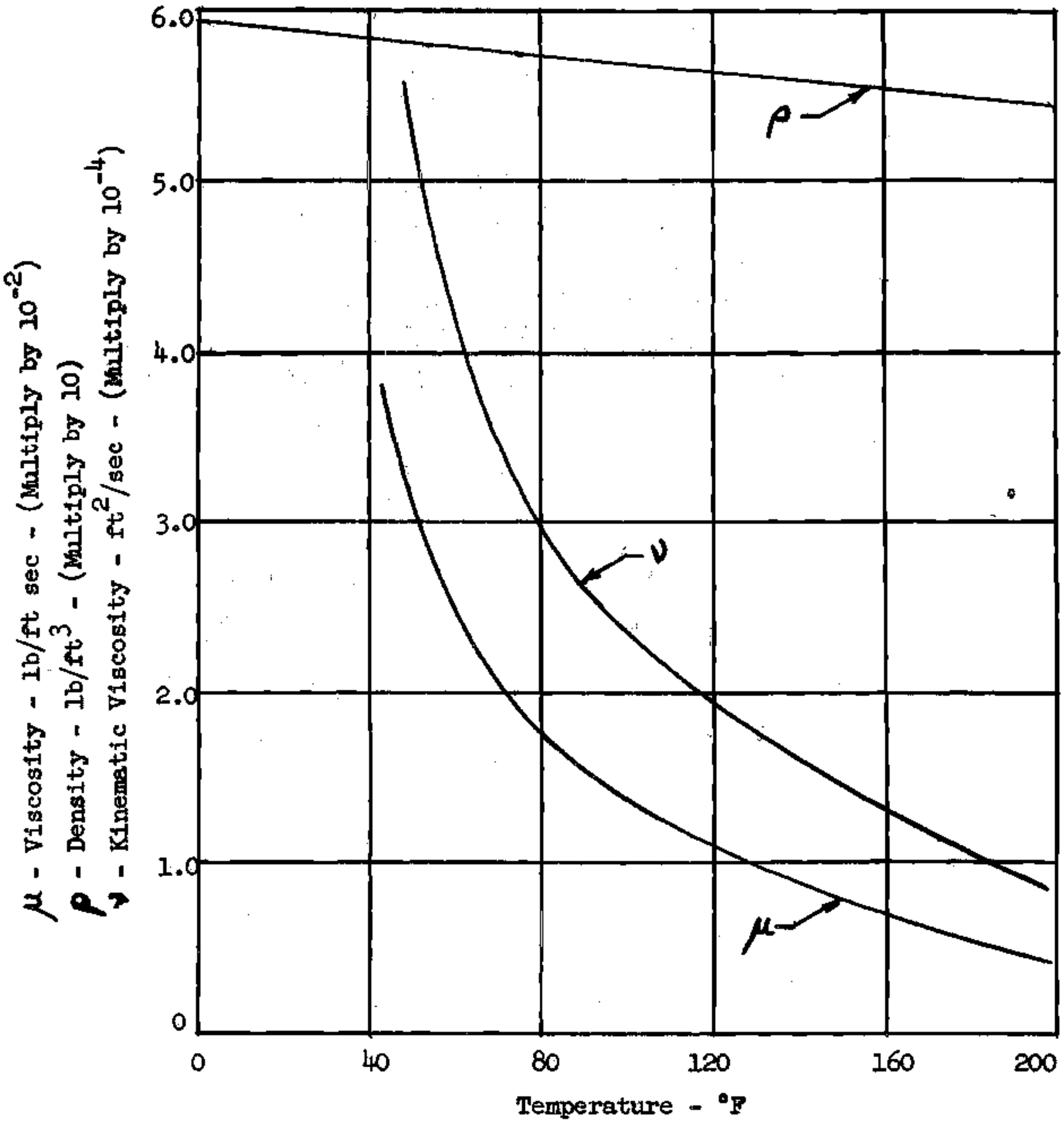


Figure 17. Viscosity - Density - vs - Temperature
For ORONITE 8515

APPENDIX D

TYPICAL COMPUTATIONS

Method for Correcting the Data for Viscosity Variations

Since it was impractical to accurately control the temperature of the oil in the test systems shown in Figures 2 and 3 and since in some of the tests there was an appreciable effect on the flow rate due to variations in the viscosity, a correction to the flow rate was made so that all flow rates would be based on a reference viscosity of 1.8×10^{-2} lb/ft sec. The following method was used:

Assumed: $$Q = \frac{C}{\mu} f(p)$$

Note that a relation of this type holds for laminar pipe flow and is substantially applicable for small changes for flow through short capillary tubes at low Reynolds numbers, (2).

where:	C	represents all parameters not otherwise represented. These parameters are assumed invariant.
	μ	viscosity
	$f(P)$	some function of the pressure differential. It is assumed that the form of $f(P)$ does not change within the range of the correction.

Then:

$$\frac{Q}{Q'} = \frac{\mu_t}{\mu_r}$$

$$Q = Q' \frac{\mu_t}{\mu_r}$$

where:

Q = flow rate which would have been attained if the viscosity at the time of the test had been μ_r

Q' = flow rate obtained when the viscosity was μ_t

μ_t = oil viscosity at the time the flow rate Q' was measured

μ_r = reference viscosity to which all data of the tests was adjusted

Substantiations of the Method.--Two tests using the same type screen were performed with different fluid viscosities. When the data of one of the tests was converted to the viscosity of the others good correlation was obtained. Refer to Figures 7, 9 and 11.

Due to the fact that a one-half inch outside diameter tube and a one quarter inch outside diameter tube were installed in the graduate the quantity markings on the graduate did not indicate the actual volume of liquid in the graduate. That is, the tubes decreased the cross-sectional area of the graduate.

The following equation was developed to obtain the actual volume:

$$V_a = V_t - V_t \, C_g \frac{\pi}{4} (d_1^2 + d_2^2) C_c$$

where:

V_a = corrected volume

V_t = recorded volume

C_g = graduate constant, inches of height per milliliter = $\frac{11.125}{800}$

C_c = conversion constant, 16.39 ml/in^3

d_1 = tube outside diameter, 0.25 inch

d_2 = tube outside diameter, 0.50 inch

or

$$V_a = .944\ V_t$$

and since:

$$V = Q\ t$$

where:

Q = volume flow rate

t = time to collect volume, V

then

$$Q_a = .944\ Q_t$$

Method Used to Adjust the Recorded Data in Order to Compensate for Screen Clogging

In preliminary tests it was found that due to the screen becoming contaminated the flow rate for a given pressure differential decreased as the total quantity of oil which had passed through the screen increased. The following method was used to correct the recorded data so that a flow rate based on the net open area of the screen at the time of the initial reference run would be available:

Assumed:

$$Q = CA_{no}\ f(P)$$

where:

Q = flow rate

C = a constant

A_{no} = net open area of the screen

$f(P)$ = a function of the pressure differential. It is is assumed that the form of $f(P)$ does not change with a change in A_{no}. For the purpose of this correction it is not necessary that $f(P)$ have the same form for every value of Q

Then:

$$\frac{Q'_r}{Q_r} = \frac{A'_{no}}{A_{no}}$$

where:

Q'_r = flow rate at a reference pressure for the initial run

Q_r = flow rate at the reference pressure, average of that obtained before and that obtained after each test run.

A'_{no} = net open area of the screen during the initial reference run at the start of the test before an appreciable quantity of oil had passed through the screen.

A_{no} = net open area during the test run for which the correction is being made.

and:

$$\frac{Q_1}{Q_2} = \frac{A'_{no}}{A_{no}}$$

where:

Q_1 = flow rate which would have been obtained in the test if the screen had not become partially clogged

Q_2 = flow rate measured in the test -- the flow rate through area A_{no}

Then

$$Q_1 = \frac{A'_{no}}{A_{no}} \qquad Q_2 = \frac{Q'_r}{Q_r} \cdot Q_2$$

Note: In Tables 2 through 14: Q'_n was generally the top figure in the Flow Rate Column before the reference flow rate column, Q_r; Q_2 was the figure in the flow rate column before the Q_r column on the same line as Q_r; and Q_1 was the figure in the flow rate column after the Q_r column on the same line as Q_r.

Method for Correlating the Results

The following dimensionless numbers were selected to determine if any correlation would develop for the flow rate and pressure differential relationship of the four plain weave screens:

$$\frac{Q(w)\left(1 + \frac{d}{w}\right)^2}{A\nu}$$

$$\sqrt{\frac{Pg}{\rho\, t}} \quad \frac{w^{3/2}}{\nu}$$

where:

w = width of the openings in the screen

d = diameter of the wire

A = total screen area or pipe area

t = screen thickness

The first expression is a Reynolds number based on the total open area of the screen and the equivalent diameter of the openings.

It was derived as follows:

$$R = \frac{VD}{\nu} = \frac{Q}{A_o} \frac{D_e}{\nu} = \frac{Q\, D_e}{A\, \frac{A_o}{A_t} \nu} = \frac{Q\, \frac{w}{4}}{A \left(\frac{w}{w + d}\right)^2 \nu}$$

$$R = \frac{Qw}{4A\nu} \left(1 + \frac{d}{w}\right)^2$$

where:

A_o = open area of each mesh

A_t = total area of each mesh between the centerlines of the wires.

For the purpose of correlating the data the "4" in the denominator was dropped.

The second expression is a dimensionless parameter involving the pressure differential and is comparable to the following parameter which is shown in Figure 8.3 of Hunsaker and Rightmire, (1).

$$\left(\frac{\tau_o}{\rho}\right)^{1/2} \frac{D}{\nu}$$

where:

τ_o = shear stress at the wall

D = pipe diameter

From the balance of wall shear force and differential pressure force on an increment of fluid:

$$\tau_o = \frac{\pi}{8} \frac{D_e}{t} P$$

Substituting this expression, dropping the constants, and letting $D_e = w$ the dimensionless parameter involving pressure becomes:

$$\sqrt{\frac{Pg}{\rho t}} \cdot \frac{w^{3/2}}{\nu}$$

The values of each of the two parameters were determined for each data point of the four plain weave screens. The relationship of these values is shown in Figure 15.

APPENDIX E

TABULATED TEST DATA
RECORDED AND COMPUTED

Table 2. Data for Type B Screens, 0-50 in. Hg.

Press. Diff. P_t	Volume (ml) V_t	Time (sec) t	Press. Diff. (in. Hg) P	Flow Rate (ml/sec) Q_t	Flow Rate (ml/sec) Q_a	Flow Rate (ml/sec) Q_r	Flow Rate (ml/sec) Q_c[1]
4.0	30	227.0	3.8	0.13	0.13		0.13
8.1	30	124.5	7.6	0.24	0.23	0.12	0.24
4.0	30	249.6	3.8	0.12	0.11		
12.0	30	84.3	11.3	0.36	0.34	0.11	0.40
4.0	10	98.9	3.8	0.10	0.10		
16.2	30	65.9	15.2	0.46	0.43	0.09	0.56
4.0	10	101.3	3.8	0.10	0.09		
19.8	30	52.3	18.5	0.57	0.54	0.10	0.68
4.2	10	92.9	3.9	0.11	0.10		
24.2	30	46.0	22.7	0.62	0.62	0.10	0.74
4.0	10	89.2	3.8	0.11	0.11		
28.0	30	42.8	26.3	0.70	0.66	0.10	0.81
4.2	10	93.6	3.9	0.11	0.10		
31.9	50	63.2	30.0	0.79	0.75	0.10	0.99
4.0	10	101.4	3.8	0.10	0.09		
36.1	50	57.9	33.8	0.87	0.82	0.09	1.16
4.0	10	114.8	3.8	0.09	0.08		
40.4	50	54.8	37.9	0.91	0.86	0.08	1.29
4.0	10	114.2	3.8	0.09	0.08		
43.5	50	52.5	40.8	0.95	0.90	0.08	1.38
4.0	10	118.3	3.8	0.09	0.08		
49.0	50	47.3	46.0	1.06	1.00	0.08	1.59

[1] Oil temperature was 80°F and viscosity was 1.8×10^{-2} lb/ft sec
OIL: RAMOL 100

Table 3. Data for Type B Screens, 0-200 psi

Press. Diff. (psi) P	Volume (ml) V_t	Time (sec) t	Temp. (°F) T	Flow Rate (ml/sec) Q_t	Flow Rate (ml/sec) Q_r	Flow Rate (ml/sec) Q'_c	Visc. $(\frac{lb \times 10^{-2}}{ft\ sec})$ μ	Flow Rate (ml/sec) Q_c^1
10	100	103.0	78	0.97		0.97	1.8	0.97
25	100	38.8	82	2.58		2.58	1.7	2.44
50	200	41.4	82	4.84	2.33	5.36	1.7	5.07
25	100	48.0	82	2.09				
75	200	30.8	82	6.50	1.96	8.56	1.7	8.10
25	100	54.4	82	1.84				
100	200	25.4	82	7.87	1.82	11.16	1.7	10.55
25	100	55.2	83	1.81				
125	400	42.4	85	9.43	1.74	13.95	1.6	12.40
25	100	60.0	85	1.67				
150	400	36.4	85	11.00	1.59	17.85	1.6	15.88
25	100	65.8	86	1.52				
175	400	33.4	86	12.00	1.50	20.64	1.6	18.37
25	100	68.0	86	1.47				
25	100	61.6	87	1.62				
200	400	30.0	90	13.30	1.57	21.85	1.5	19.40
25	100	66.0	88	1.52				

[1] The Q_c Flow Rate is based on a viscosity of 1.8×10^{-2} lb/ft sec
OIL: ORONITE 8515

Table 4. Data for Type B Screen, 0-1472 psi

Press. Diff. (psi) P	Flow Rate (gpm) Q_t	Temp. (°F) T	Flow Rate (gpm) Q_r	Flow Rate (gpm) Q'_c	Viscosity $\left(\frac{\text{lbx}10^{-2}}{\text{ft sec}}\right)$ μ	Flow Rate (gpm) Q_c[1]
325	0.30	105		0.30	1.25	0.21
668	1.54	126	0.32	1.45	1.0	0.81
325	0.35	127				
969	2.41	127	0.37	1.95	1.0	1.09
326	0.39	128				
1471.8	4.31	128	0.41	3.15	0.97	1.70
326	1.50[2]	129				

[1] The Q_c flow rate is based on a viscosity of 1.8×10^{-2} lb/ft sec.

[2] Fracture of the screen or stretch of the screen due to the force of pressure must have occurred. The screen failed during an attempt to obtain data for a higher pressure differential.

OIL: ORONITE 8515.

Table 5. Data for Type K-2 Screens, 0-50 in. Hg.

Press. Diff. (psi) P	Volume (ml) V_t	Time (sec) t	Press. Diff. (in.Hg.) P	Flow Rate (ml/sec) Q_t	Flow Rate (ml/sec) Q_a	Flow Rate (ml/sec) Q_r	Flow Rate (ml/sec) Q_c'[1]
4.0	50	60.4	3.8	0.83	0.78		0.78
8.0	50	31.3	7.5	1.60	1.51	0.76	1.97
4.0	50	63.6	3.8	0.79	0.74		
11.9	100	42.8	11.2	2.34	2.21	0.72	2.40
4.0	50	67.0	3.8	0.75	0.70		
15.8	100	34.4	14.8	2.91	2.75	0.71	3.04
4.0	50	65.4	3.8	0.77	0.72		
20.0	100	27.3	18.8	3.67	3.47	0.70	3.88
4.0	20	27.8	3.8	0.72	0.68		
23.4	100	21.9	22.0	4.56	4.31	0.69	4.85
4.0	20	27.2	3.8	0.74	0.70		
27.6	100	19.8	25.9	5.05	4.77	0.69	5.41
4.0	20	27.9	3.8	0.72	0.68		
31.4	100	18.0	29.4	5.57	5.26	0.68	6.07
4.0	20	27.6	3.8	0.73	0.69		
35.4	100	15.8	33.2	6.35	6.00	0.68	6.91
4.0	20	27.6	3.8	0.73	0.69		
39.3	100	14.8	36.9	6.76	6.38	0.67	7.49
4.0	20	28.6	3.8	0.70	0.66		
43.8	100	13.4	41.1	7.46	7.05	0.63	8.72
4.0	20	30.8	3.8	0.65	0.61		
49.3	100	12.0	46.2	6.80	6.42	0.63	8.30
4.0	20	29.5	3.8	0.68	0.64		
34.8	100	12.1	32.6	5.65	5.34	0.63	6.67

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[1] Oil temperature was 80°F and viscosity was 1.8×10^{-2} lb/ft sec.

OIL: RAMOL 100

Table 6. Data for Type K-2 Screen, 0-100 psi

Press. Diff. (psi) P	Volume (ml) V_t	Time (sec) t	Temp. (°F) T	Flow Rate (ml/sec) Q_t	Flow Rate (ml/sec) Q_r	Flow Rate (ml/sec) Q'_c	Viscosity $(\frac{lb x 10^{-2}}{ft\ sec})$ μ	Flow Rate (ml/sec) Q'_c
15	200	23.2	82	8.6		8.6	1.65	7.88
25	300	21.0	87	14.3	8.58	14.4	1.55	12.40
15	200	23.4	87	8.5				
50	500	18.8	90	26.7	8.12	28.3	1.50	23.60
15	200	26.0	90	7.7				
75	500	15.4	96	32.5	6.78	41.4	1.40	32.30
15	200	34.2	96	5.9				
100	500	13.0	100	38.5	5.56	59.7	1.33	44.10
15	200	38.0	100	5.3				

[1] The Q_c flow rate is based on a viscosity of 1.8×10^{-2} lb/ft sec.

OIL: ORONITE 8515

Table 7. Data for Type J Screen, 0-50 in. Hg.

Press. Diff. (psi)	Volume (ml)	Time (sec)	Press. Diff. (in.Hg.)	Flow Rate (ml/sec)	Flow Rate (ml/sec)	Flow Rate (ml/sec)	Flow Rate (ml/sec)
P	V_t	t	P	Q_t	Q_a	Q_r	Q'_c[1]
4.1	50	50.0	3.8	1.00	0.94		0.94
8.1	100	51.5	7.6	1.94	1.84	0.94	1.84
4.2	50	50.0	3.9	1.00	0.94		
11.9	100	34.6	11.2	2.89	2.73	0.93	2.76
4.0	50	51.2	3.8	0.98	0.92		
15.8	200	54.0	14.8	3.71	3.50	0.90	3.66
4.0	50	53.5	3.8	0.94	0.88		
19.8	100	21.8	18.6	4.58	4.33	0.88	4.62
4.0	50	53.8	3.8	0.93	0.88		
23.7	300	55.0	22.2	5.46	5.16	0.85	5.69
4.0	50	56.5	3.8	0.89	0.84		
27.5	200	32.0	25.8	6.25	5.90	0.84	6.59
3.9	50	56.0	3.7	0.89	0.84		
31.5	200	29.4	29.5	6.80	6.42	0.83	7.28
4.0	50	58.2	3.8	0.86	0.81		
35.6	200	26.4	33.4	7.57	7.15	0.81	8.30
4.0	50	58.6	3.8	0.86	0.81		
39.3	300	37.0	36.8	8.11	7.66	0.78	9.23
4.0	50	62.6	3.8	0.80	0.76		
43.3	400	46.6	40.6	8.58	8.10	0.76	10.04
4.0	50	61.3	3.8	0.82	0.77		
49.1	300	31.5	46.0	9.55	9.02	0.74	11.47
4.0	50	66.0	3.8	0.76	0.72		

[1] Q'_c was based on the viscosity of RAMOL 100 at 75°F (2.12×10^{-2} lb/ft sec). The slope of the line representing these values of Q'_c was adjusted to a viscosity of 1.8×10^{-2} lb/ft sec and shown in Figure 10.

Table 8. Data for Type J Screen, 0-130 psi

Press. Diff. (psi) P	Temp. (°F) T	Flow Rate (gpm) Q_t	Flow Rate (gpm) Q	Flow Rate (gpm) Q_c[1]	Viscosity $\left(\frac{\text{lbx}10^{-2}}{\text{ft sec}}\right)$ μ	Flow Rate (gpm) Q_c[1]
25.8	100	0.30		0.3	1.3	0.22
57.2	100	0.73	0.30	0.73	1.3	0.53
25.4	100	0.30				
82.2	100	1.00	0.29	1.04	1.3	0.75
25.4	100	0.29				
103.8	100	1.24	0.70	1.30	1.3	0.94
56.8	100	0.68				
129.0	105	1.45	0.68	1.55	1.25	1.08
56.2	105	0.70				

[1] Q_c was based on a viscosity of 1.8 x 10^2 lb/ft sec

OIL: ORONITE 8515

Table 9. Data for Type M Screens, 0-50 in. Hg.

Press. Diff. P	Volume (ml) V_t	Time (sec) t	Press. Diff. (in.Hg.) P	Flow Rate (ml/sec) Q_t	Flow Rate (ml/sec) Q_a	Flow Rate (ml/sec) Q_r	Flow Rate (ml/sec) Q'_c[1]
3.9	100	35.2	3.7	2.84	2.68		2.68
7.9	100	18.2	7.4	5.49	5.18	2.50	5.54
3.9	100	38.2	3.7	2.62	2.48		
11.9	100	12.4	11.2	8.07	7.62	2.48	8.23
3.9	100	38.3	3.7	2.63	2.48		
15.8	200	19.7	14.8	10.15	9.58	2.46	10.16
3.9	100	38.7	3.7	2.58	2.44		
19.8	200	15.8	18.5	12.65	11.95	2.44	13.17
3.9	100	38.5	3.7	2.60	2.45		
23.7	200	13.5	22.2	14.82	14.00	2.41	15.64
3.9	100	39.8	3.7	2.51	2.37		
27.5	200	11.5	25.8	17.39	16.40	2.35	18.73
3.9	100	42.0	3.7	2.48	2.34		
31.5	300	16.0	29.5	18.75	17.70	2.23	21.33
3.9	100	44.5	3.7	2.25	2.13		
33.5	300	17.0	31.4	17.65	16.65	2.02	22.31
3.9	100	49.0	3.7	2.04	1.93		
39.3	300	15.0	36.9	20.00	18.90	1.91	26.65
3.9	100	50.0	3.7	2.00	1.89		
43.3	400	20.5	40.6	19.52	18.43	1.88	27.31

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[1] Q'_c was based on the viscosity of RAMOL 100 at 75°F (2.12×10^{-2} lb/ft sec). The slope of the line representing these values of Q'_c was adjusted to a viscosity of 1.8×10^{-2} lb/ft sec and shown in Figure 12.

Table 10. Data for Type M Screen, 0-131 psi

Press. Diff. (psi) P	Flow Rate (gpm) Q_t	Temp. (°F) T	Viscosity $(\frac{lb \times 10^{-2}}{ft\ sec})$ μ	Flow Rate (ml/sec) $Q_c'^{1}$	Flow Rate (ml/sec) Q_r	Flow Rate (ml/sec) $Q_c{}^{1}$
7.8	0.42	98	1.35	0.32		0.32
26.6	1.55	100	1.3	1.20		1.20
8.2	0.45	100	1.3	0.33		
53.9	2.83	104	1.3	2.05		2.05
16.8	1.30	105	1.3	0.94		
23.0	1.30	104	1.3	0.94		
48.0	2.90	105	1.3	2.10	0.95	2.12
23.0	1.33	105	1.3	0.96		
72.0	3.72	106	1.2	2.48	0.95	2.51
23.0	1.41	107	1.2	0.94		
92.0	4.60	109	1.2	3.07	0.95	3.10
23.0	1.43	110	1.2	0.95		
110.0	5.40	111	1.2	3.60	0.99	3.80
23.0	1.55	111	1.2	1.03		
131.0	5.90	111	1.2	3.94	0.98	4.11
23.0	1.53	112	1.1	0.94		

[1] Q_c' and Q_c are based on a viscosity of 1.8×10^{-2} lb/ft sec

OIL: ORONITE 8515

Table 11. Data for Type 508 x 508 Screen, 0-100 psi

Press. Diff. (psi) P	Flow Rate (gpm) Q_t	Temp. (°F) T	Viscosity $(\frac{lb \times 10^{-2}}{ft\ sec})$ μ	Flow Rate (gpm) $Q'_c{}^1$	Flow Rate (gpm) Q_r	Flow Rate (gpm) $Q_c{}^1$	$\frac{Q_c w(1+\frac{d}{w})^2}{A\nu}$ $(3.41\ Q_c)$	$\frac{\sqrt{\frac{Pg}{\rho t}}\ w^{3/2}}{\nu}$ $(0.0415\ \sqrt{P})$
10	1.32	150	0.75	0.55		0.55	1.88	0.130
28	3.13	155	0.70	1.22	0.55	1.22	4.18	0.220
10	1.42	155	0.70	0.55				
45	4.50	158	0.70	1.75	0.55	1.75	5.96	0.279
10	1.42	159	0.70	0.55				
62	5.50	160	0.68	2.08	0.52	2.11	7.18	0.327
10	1.41	160	0.68	0.53				
80	6.30	163	0.65	2.28	0.53	2.32	7.90	0.372
10	1.50	165	0.65	0.54				
98	6.90	165	0.65	2.49	0.54	2.54	8.65	0.410

[1] Q_c and Q'_c are based on a viscosity of 1.8×10^{-2} lb/ft sec

OIL: ORONITE 8515

Table 12. Data for Type 450 x 450 Screen, 0-73 psi

Press. Diff. (psi) P	Flow Rate (gpm) Q_t	Temp. (°F) T	Viscosity $(\frac{lb x 10^{-2}}{ft\ sec})$ μ	Flow Rate (gpm) $Q_c'^{\,1}$	Flow Rate (gpm) Q_r	Flow Rate (gpm) $Q_c{}^1$	$\frac{Q_c w(1+\frac{d}{w})^2}{A \nu}$ $(3.285Q_c)$	$\frac{\sqrt{\frac{Pg}{\rho t}}\ w^{3/2}}{\nu}$ $(0.058\sqrt{P})$
14.0	1.30	100	1.32	0.95		0.95	3.12	0.217
21.0	2.82	110	1.20	1.88	0.92	1.94	6.37	0.266
13.5	1.43	114	1.12	0.89				
43.0	4.32	119	1.08	2.58	0.89	2.76	9.06	0.381
13.0	1.52	120	1.05	0.89				
58.5	5.60	121	1.02	3.18	0.88	3.44	11.30	0.444
13.0	1.53	122	1.02	0.87				
72.5	6.80	125	1.00	3.78	0.87	4.13	13.55	0.494
13.0	1.60	127	0.98	0.87				

[1] Q_c and Q_c' are based on a viscosity of 1.8×10^{-2} lb/ft sec

OIL: ORONITE 8515

Table 13. Data for Type 325 x 325 Screen, 0.80 psi

Press. Diff. (psi) P	Flow Rate (gpm) Q_t	Temp. (°F) T	Viscosity $(\frac{lb x 10^{-2}}{ft\ sec})$ μ	Flow Rate (gpm) Q'_c [1]	Flow Rate (gpm) Q_r	Flow Rate (gpm) Q_c [1]	$\frac{Q_c w(1+\frac{d}{w})^2}{A \nu}$ $(4.36\ Q_c)$	$\frac{\sqrt{\frac{Pg}{\rho t}}\ w^{3/2}}{\nu}$ $(0.115\sqrt{P})$
7.0	1.70	95	1.40	1.32		1.32	5.76	0.303
20.0	3.70	96	1.40	2.88	1.26	3.02	13.17	0.512
6.8	1.53	96	1.40	1.19				
31.1	5.50	99	1.35	4.14	1.20	4.56	19.90	0.638
7.0	1.60	99	1.35	1.20				
44.5	6.73	100	1.32	4.93	1.21	5.38	23.50	0.765
56.0	8.50	100	1.32	6.22	1.21	6.78	29.55	0.859
6.5	1.70	101	1.30	1.23				
69.0	10.0	105	1.25	6.95	1.20	7.65	33.40	0.954
6.5	1.70	105	1.25	1.18				
79.0	11.40	105	1.25	7.92	1.20	8.72	38.00	1.020

[1] Q_c and Q'_c are based on a viscosity of 1.8×10^{-2} lb/ft sec

OIL: ORONITE 8515

Table 14. Data for Type 230 x 230 Screen, 0-60 psi

Press. Diff. (psi) P	Flow Rate (gpm) Q_t	Temp. (°F) T	Viscosity $(\frac{lb x 10^{-2}}{ft\ sec})$ μ	Flow Rate (gpm) $Q_c'^{1}$	Flow Rate (gpm) Q_r	Flow Rate (gpm) Q_c^{1}	$\frac{Q_c w(1+\frac{d}{w})^2}{A \nu}$ $(4.49\ Q_c)$	$\frac{\sqrt{\frac{Pg}{\rho t}}\ w^{3/2}}{\nu}$ $(0.169 \sqrt{P})$
13.5	6.10	107	1.20	4.07		4.07	18.28	0.621
17.8	7.60	110	1.20	5.07	4.10	5.02	22.55	0.713
13.0	6.20	110	1.20	4.14				
25.8	9.50	111	1.18	6.22	4.07	6.22	27.80	0.860
12.8	6.25	112	1.15	4.00				
34.0	11.30	115	1.12	7.04	3.99	7.18	32.27	0.965
12.5	6.40	115	1.12	3.98				
60.5	12.10	118	1.08	7.26	3.97	7.43	33.40	1.315

[1] Q_c and Q_c' are based on a viscosity of 1.8×10^{-2} lb/ft sec

OIL: ORONITE 8515

APPENDIX F

ESTIMATED ERRORS

Estimated Errors in the Measurements

System A

Time or Volume.--In estimating the probable errors when Systems A and B were used it was found that when the rate of rise of the fluid in the graduate was very slow as was the case with the type B screen, it was easier to estimate the error in time, while when the rate of rise was rapid it was easier to estimate the error in volume.

Type B Screens.--It was estimated that the maximum error in starting and stopping the stop watch at the correct moment was plus or minus four seconds. Then the probable maximum error in the flow measurement for a run of 40 sec was of the order of 4/40 or ten per cent. Most of the runs exceeded fifty seconds duration, and the error should be of the order of eight per cent. In Figure 5 the data point which is the greatest distance away from the best line is about 0.08 ml/sec away from that line and the flow rate at the line is 0.88 or an error of 8/88 or about nine per cent. It so happens that this point represents the shortest test run mentioned above where the greatest probable error was estimated to be of the order of ten per cent. In the longer runs the probable error was less, estimated to be of the order of five per cent. In Figure 5 with few exceptions the test points are within five per cent of the line.

Type K-2 Screens.--It was estimated that the error in starting and stopping the watch when the type K-2 screen was installed was equivalent to an error of plus or minus three milliliters. The smallest quantity measured was fifty milliliters, so the estimated greatest possible error would be of the order of 3/50 or about six per cent. In Figure 8 with the exception of two points all data points are within a six per cent error of the best line. The two points which are away from the line by a greater error should be regarded as faulty data due to an incorrect procedure in measurement.

Type J and Type M Screens.--The maximum probable error in the flow measurements for the type J and type M screens was estimated to be of the order of plus or minus three milliliters, and the usual quantity measured was 100 milliliters or more so that the probable error was of the order of three per cent or less. For many of the points the quantity collected was 200 milliliters and the probable error was 1.5 per cent. Comparison of Figure 5, 8, 10, and 12 indicate the greater accuracy obtained in the measurements for the type J and type M screens.

System B.--The probable error when System B was used would have been comparable to that of System A except for the fact that the temperature of the oil did not remain constant throughout the test. It is estimated that the probable error in temperature was of the order of 2°F. The viscosity was such that the ratio of the change in viscosity due to a two degree change in temperature, to the viscosity is of the order of $\frac{.05}{1.5}$; then the error due to viscosity error was of the order of 3 per cent.

System C.--The probable error when System C was used becomes considerably more difficult to estimate due to a flow meter being used for measuring the flow rate. The flow meter was a Fischer and Porter variable area tube - float type which is affected by viscosity and density changes. However, the temperature measurements for System C were more accurate than for System B and it was estimated that the order of magnitude of the probable error in flow measurement for System C was not appreciably greater than that for System B.

Total Error in Flow Rate.--To estimate the total error in the flow rate due to errors in viscosity and to the error in measuring the flow rate the following method was used:

$$Q = Q' \frac{\mu_t}{\mu_r} \quad \text{(see Appendix D)}$$

Considering μ_r constant, taking the logarithm of both sides, and differentiating:

$$\left|\frac{dQ}{Q}\right| = \left|\frac{dQ'}{Q'}\right| + \left|\frac{d\mu_t}{\mu_t}\right|$$

For Systems B and C then the maximum probable error was of the order of 8 per cent.

Errors in the Pressure Measurements.--It was estimated that the maximum probable error in measuring the pressure differentials was as follows:

For measurements made with the manometer

$$\text{Max. Error} = \frac{.08}{8} = .01$$

or about one per cent.

For measurements made with pressure gauges

$$\text{Max. Error} = \frac{.2}{10} = .02$$

or about two per cent.

APPENDIX G

BIBLIOGRAPHY

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