PRESSURE DROP ACROSS FINNED-TUBES

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By

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SUMMARY

This investigation was conducted with the objective of finding the effect of varying the flow rate, the fin spacing, and the tube spacing upon the pressure drop of a fluid in crossflow across a rectangular bar finned-tube apparatus. Air was used as the fluid and the flow rates were varied so that Reynolds Numbers of 3,000 and 35,000 were obtained. These Reynolds Numbers were based on the finned section without tubes.

The specific type of apparatus under study was a rectangular plate fin two inches long and twelve inches wide with a row of one inch diameter tubes of varying length and spacing located across the flow of air. The pressure drop data across the apparatus was divided into three portions which corresponded to three separate sections of the apparatus. The first section was that part of the finned space between the leading edge of the fin and the plane of the front of the tube row. The second section was the space from the front plane of the tube row to the plane of the rear edge of the tube row. The third section was the portion of the finned space behind the tube row.

The effect of the operating variables upon the individual pressure losses across the sections are approximated by the following formulae:

$$\Delta P_1 = \frac{0.830 \times 10^{-7} Re^{2.1}}{k_1^{1.92} m^{0.38}}$$

$$\Delta P_2 = \frac{6.91 \times 10^{-7} Re^{1.9}}{k_2^{1.83} m^{2.2}}$$

$$\Delta P_3 = \frac{0.00349 \times 10^{-7} Re^{2.4} m^{0.6}}{k^{1.90}}$$

Where

Re is the Reynolds Number of the fluid flowing through the front fin section.

k_1, k_2, k_3 are the ratios of the fin spacing to the flow distance through the individual sections of the apparatus.

m is the ratio of the tube center-to-center spacing to the tube diameter.

The pressure drops computed by the three equations differ on the average of 2.9, 1.3, and 5.1% respectively for the three sections involved.

INTRODUCTION

The flow of fluids through various types of heat exchangers is an integral part of the functioning of many processes. The major portion of the previous research over heat exchangers has been devoted to the older types, consisting of bare tubes across or along the flow path. The application of extended surfaces for more efficient heat transfer in exchange equipment has become important more recently. As yet the data available to correlate pressure losses in these types of equipment are very meager.

LITERATURE SURVEY. Pressure differences across bare tubes and bundles have been consolidated in a recent paper by D. F. Boucher and C. E. Lapple (4). Using data of other investigators they have presented a great deal of information as to the results of the previous work. They state that more data are needed to determine the effect of a variation in tube spacing upon the pressure drop and also state that the previous work on finned-tubes is too meager for inclusion in their paper. A. E. Bierman and B. Pinkel (3) present data for heat transfer coefficients from a finned metal cylinder at right angles to an air stream. A paper by R. M. Armstrong (1) gives pressure drop data and heat transfer coefficients across small commercial finned-tube heat exchangers. C. S. Sage (9) presents a paper of merit wherein is outlined the value of extended surface for more efficient heat transfer. D. L. Katz, K. O. Beatty, and A. S. Faust (7) present heat transfer data obtained with tubes having integral spiral fins. A. Y. Gunter and W. A. Shaw (5) present a general correlation of friction factors for various types of surfaces in crossflow. E. A. Schryber (10), G. E. Tate and J. Cartenhour (11), R. H. Norris and W. A. Spofford (8), and S. L.

Jameson (6) present papers containing heat transfer and pressure drop data for different types of finned-tube apparatus.

The objections to those data available in the literature at the present time are twofold: (1) pressure drop data are lacking since the emphasis of nearly all of the papers is on the improved heat transfer efficiency of extended surface; (2) those data that are available in the literature give an insufficient presentation of the operating variables.

OBJECTIVES OF THIS WORK. Due to the lack of previous data for the pressure drop across finned-tubes the research necessary as a basis for this paper was initiated. An exhaustive study of all of the operating variables present in the problem would present an extensive long range solution and for this reason the effect of only a few of the important variables was chosen as the object of this investigation.

The object of the work was to find the effect of the flow rate of the fluid, fin spacing, and tube spacing on the pressure drop through the apparatus. It was desired to present those data in a manner that might be used in further work on the problem and in predicting pressure losses in similar commercial finned-tube heat exchangers.

THEORETICAL CONSIDERATIONS. An attempt was made to apply the Fanning equation for turbulent flow through ducts of constant cross section and the Poiseuille equation for laminar flow to the problem of varying cross section considered in a finned-tube apparatus. For the section occupied by the tube banks differential equations were obtained which were extremely tedious and difficult to integrate. It is very probable that because of this mathematical difficulty the pressure drop data which have been correlated in the literature are presented as empirical relations.

They are presented as a function of the mass velocity of the fluid flowing through the apparatus or as a function of the Reynolds Number. The data used in this present work are correlated as a function of the Reynolds Number of the fluid flowing through the front finned section approaching the tube row. The reasons for this type of presentation are twofold: (1) it was discovered in trying to correlate the pressure drop with the mass velocity of the fluid that the relationship of the mass velocity and the pressure drop changed when there was a change in the dimensions of the system; (2) the relation of the pressure drop to Reynolds Number remained essentially constant for changes in apparatus dimensions and the absolute size of the apparatus was incorporated in the relationship. It appeared as the equivalent diameter of the flow channel. The variation of the fin spacing and tube spacing are expressed as dimensionless ratios of tube diameter and length of flow path in the direction of flow.

PROPOSED CORRELATION. In this work it is proposed that the data be correlated in the following manner:

$$\Delta P_1 = A \, Re^r \, k_1^s \, m^t \qquad (1)$$

$$\Delta P_2 = B \, Re^u \, k_2^v \, m^w \qquad (2)$$

$$\Delta P_3 = C \, Re^x \, k_3^y \, m^z \qquad (3)$$

Where

$\Delta P_1, \Delta P_2, \Delta P_3$ are the pressure drops of the fluid in passing from the atmosphere to the tube row, across the tube row, and across a section of the rear fin.

Re is the Reynolds Number of the fluid across the front fins approaching the tube row.

k_1, k_2, k_3 are the ratios found by dividing the fin spacing by the length of the fin previous to the tube row, the tube diameter and the increment of rear fin length for which the pressure drop was obtained.

A, B, C are constants to be determined by calculations from experimental data.

DESCRIPTION OF APPARATUS

The apparatus consisted of three primary portions: the power portion; the metering portion; and the test portion.

The power portion consisted of a Spencer Turbo-Compressor with a rated output of 100 cubic feet per minute at 32 ounces per sq. in. of pressure. The flow rate was controlled by a hand regulated butterfly valve on the exit side of the blower.

The metering portion consisted of an orifice installed in 2 inch standard pipe with sufficient lengths both upstream and downstream of the orifice. Two orifices were drilled in a rotable orifice plate to provide the metering of the air through the system. Pipe taps located upstream and downstream of the orifice were connected to the orifice manometers. The metering portion was connected to the suction side of the blower by a duct as is shown in Figure 1. Also visible in the photograph are the turbo-compressor, rotable orifice plate, pressure tap connections, test section, and the rear of the manometer board. The manometer board consisted of a row of static pressure tubes connected to a common fluid reservoir for reading the static pressures along the flow path in the test portion. Manometers for reading the static pressure upstream of the orifice and for reading the pressure drop across the orifice were also mounted on the board.

The test portion consisted of two steel plates which represented the fins of a finned-tube section. The plates were separated by discs which were representative of the tubes. The assembled unit was bolted together through holes in the plates and discs. The fin spacing could be changed by varying the number of discs between the plates. To provide different

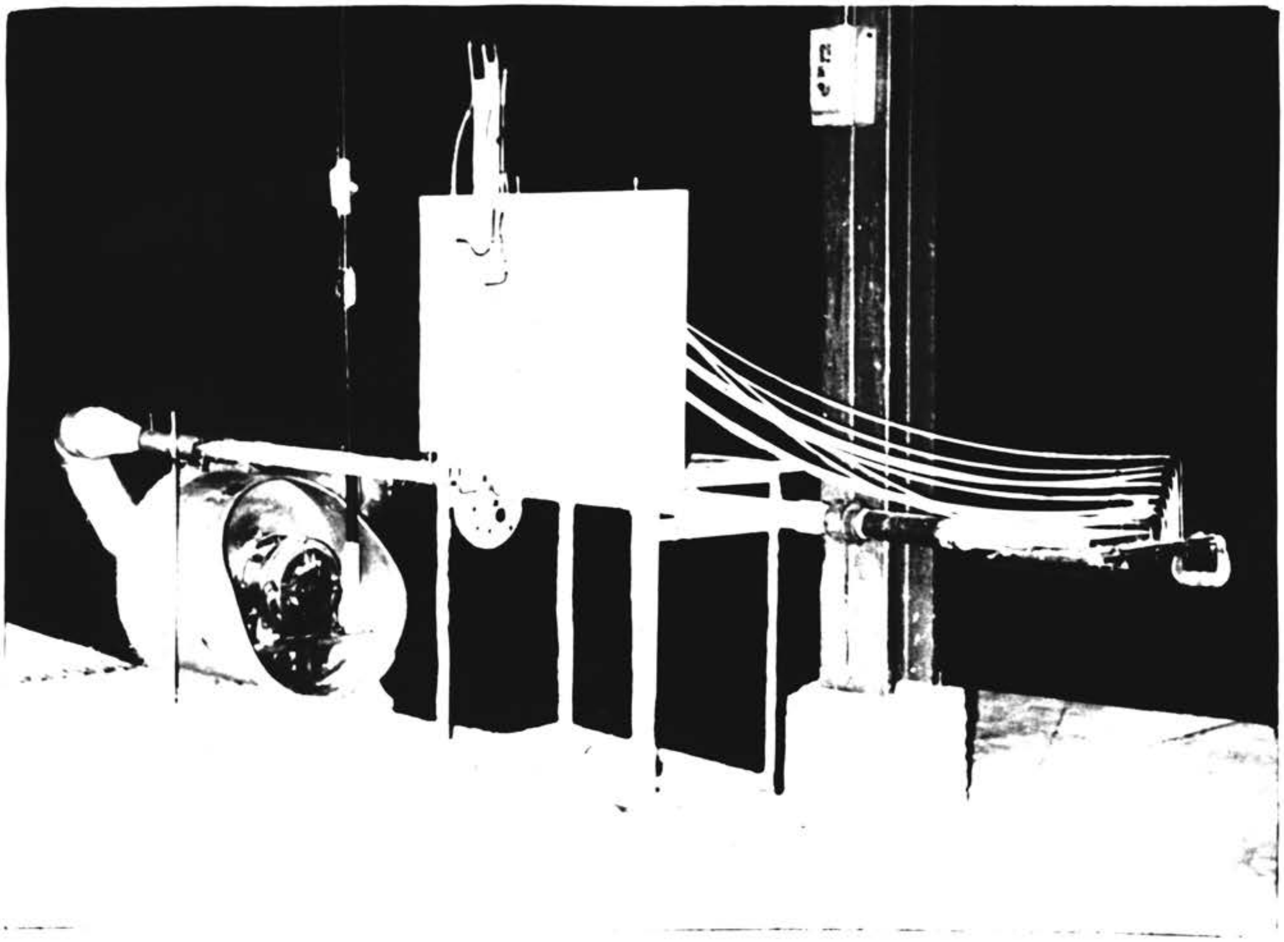


Figure 1. Rear view of apparatus.

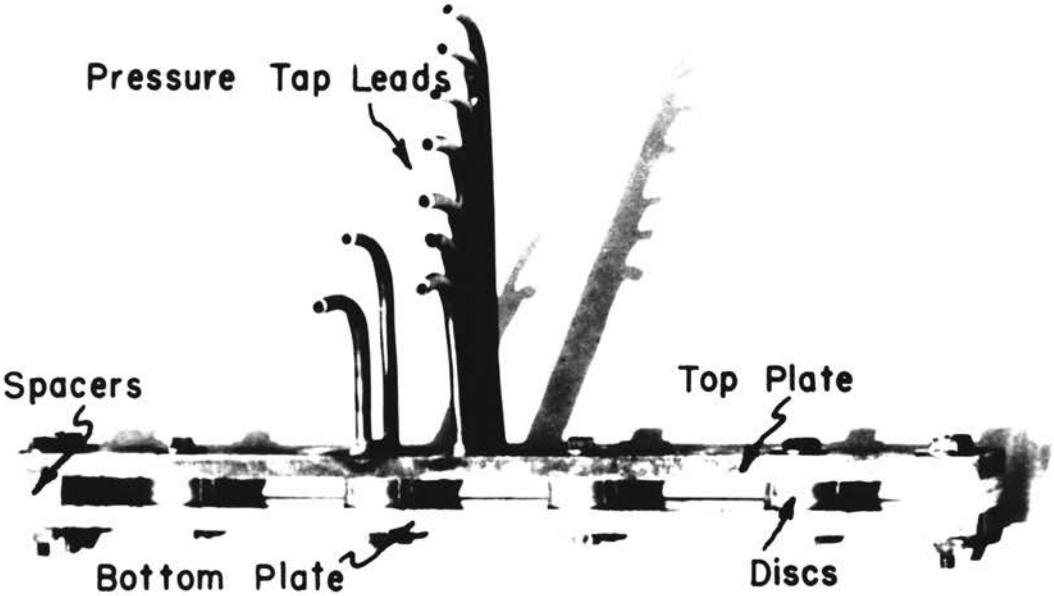


Figure 2. Test section.

tube spacings three different sets of plates were made. The plates were drilled with 3/64 inch diameter holes for pressure taps along the flow path of the fluid.

Working drawings of the apparatus with their dimensions and tolerances are in Section 1 of the Appendix.

EXPERIMENTAL PROCEDURE

The procedure followed in each series of runs with the test apparatus followed a consistent stepwise routine in order that consistent results would be attained with a minimum of errors. The first step in each case was to assemble the desired test section with the proper number of end and disc spacers. The plate separation was checked with a feeler gauge after the assembly bolts had been tightened uniformly. The assembled test section was then clamped to the duct face plate and inspected carefully for unobstructed flow passageway. A gasket was installed between the test section and the face plate to eliminate leakage.

The manometer panel was then leveled by means of adjustable lock bolts on each leg of the manometer table.

The rubber leads from the u-tubes were connected to the pressure taps and the blower started. Sufficient time was allowed for equilibrium to be attained. At the beginning of the "warm up" period the apparatus was checked for leakage. The flow rate was then adjusted to the maximum and held constant until the temperature of the air at the exit side of the metering section reached a constant value. This usually required from fifteen to thirty minutes depending on the flow rate. During this period the barometric pressure was read from a mercury barometer and recorded in laboratory notebook.

In each series of runs the maximum flow rates were used first and the flow rates were made successively smaller until the readings of either the orifice manometer or of the static pressure u-tubes were no longer significant.

The readings recorded in the laboratory notebook were the ten u-tube readings and the orifice manometer readings. The temperature of the air and the barometric pressure were recorded for each series of runs. Also recorded were the fin spacing and the tube spacing in the test section at the time of the run. Complete experimental data are tabulated in Section 4 of the Appendix.

RESULTS AND DISCUSSION

The method used in determining the effect of the variables and correlating the data was the same for the individual sections of the apparatus.

In the Introduction it was proposed that the pressure drop data be correlated in the following manner:

$$\Delta P_1 = A\ Re^r\ k_1^s\ m^t$$

$$\Delta P_2 = B\ Re^u\ k_2^v\ m^w$$

$$\Delta P_3 = C\ Re^x\ k_3^y\ m^z$$

Where

$\Delta P_1, \Delta P_2, \Delta P_3$ are the pressure drops of the fluid in passing from the atmosphere to the tube row, across the tube row, and across a section of the rear fin.

Re is the Reynolds Number of the fluid across the front fins approaching the tube row.

k_1, k_2, k_3 are the ratios found by dividing the fin spacing by the length of the fin previous to the tube row, the tube diameter, and the increment of rear fin length for which the pressure drop was obtained.

A, B, C are constants to be determined by calculations from experimental data.

The following range of variables were investigated in this work. The Reynolds Number was varied from 3,000 to 35,000. The fin spacing was varied from 0.04 inches to 0.4 inches. Three tube spacings of 2 inches, 3 inches and 4 inches were used.

The Reynolds Number was calculated using the average velocity across the front fins, the average air density across the fins and the equivalent diameter of the front fin section, based upon 4 times the hydraulic radius of the section.

In this particular correlation the pressure drop will be expressed in ft. lb./lb. After converting the pressure drops to feet of fluid head and calculating the Reynolds Number of the fluid flowing through the front fin section in each run, the exponents, r, u, and x were obtained. They were obtained by plotting ΔP_1, ΔP_2, and ΔP_3 versus the Reynolds Number on logarithmic coordinate paper at constant fin and tube spacing. These plots appear in Figures 2a, 3a, 4a, 7a, 8a, 12a, 13a, 14a, in Section 2 of the Appendix. The slope of the lines through the points of constant fin and tube spacing was determined and from the slope the values of the exponents on the Reynolds Numbers determined. It was found that the values of r, u, and x were independent of the fin and tube spacing and were determined to be 2.1, 1.9, and 2.4 respectively.

The effect of the fin spacing was obtained by plotting the values of head loss divided by the Reynolds Numbers to the power determined for the particular section versus "k", the ratio of the fin spacing to the length of the section parallel in the direction of flow. This was done for each series of runs for constant tube spacing. A line was drawn through the points for constant values of tube spacing. These plots appear in Figures 5a, 10a, and 15a in the Appendix. The slope of the lines were determined and the exponents of k_1, k_2, k_3 were found to be -1.95, -1.84, and -1.9.

The effect of a change in the tube spacing was found by plotting the average values obtained by dividing the pressure drop by the Reynolds Number and k to their respective powers versus "m" the ratio of the tube center-to-center spacing to the tube diameter. The values of t, w, and z were found to be -0.38, -2.2, and 0.6.

After the exponents were obtained values of A, B, and C were computed by dividing the pressure drop by the variables to their respective powers. The average value of A was 0.830×10^{-7}, B was 6.91×10^{-7}, and C was 0.00349×10^{-7}.

The average percentage deviation of the average values computed for the pressure drop across the front fin section was found to be 2.94%. This seems to be a good correlation and the percent deviation can be attributed to the limits of accuracy in the experimental method. The approach edge was abrupt and no attempt was made to smooth the flow entrance. It was considered that the conditions under which an actual apparatus operates would be of a similiar nature. The lower velocities of the fluid were also approximately those recommended by manufacturers of finned-tube heat exchangers. Yet to be determined is the applicability of the relations found for fins of different widths and the effect of the number and thickness of the fins. Future determinations should also include the effect of the types of fins.

The average deviation of the pressure drop across the tube row was found to be 1.3% which is as accurate as the experimental method would probably warrent. More work on this part of the problem is needed to find the effect of the tube diameter.

The average deviation of the pressure drops which could be correlated across the rear fin section was 5.1%. It was found that at the narrow tube spacing and at fin spacings of less than 0.2 inches for the case where $m = 3$ there was no correlation possible. This would indicate that the pressure distribution behind the tubes change quite radically at the narrow tube and fin spacings. The solution of the problem would be an experimental extension of the problem to find the pressure distribution in the apparatus.

This work is a part of a large problem. The results of the experiment indicate that the relations found could be used in further work of a similiar nature and could be applied to the flow apparatus of comparative dimensions. The definite nature of the plots indicate that extrapolated values could be used. As has been pointed out more work is needed to completely solve the problem.

The effect of the variables would indicate that the pressure drop varies as the square of the Reynolds Number and the -1.9 power of the fin spacing. No definite over-all correlation between the tube spacing and the pressure drop was indicated.

CONCLUSIONS

1. The experimental results indicate that the pressure drop is proportional to approximately the square of the Reynolds Number. The relation is similiar to the Fanning and equations for contraction and other losses with turbulent flow.
2. The experimental results indicate that the pressure drop is proportional to the -2 power of the fin spacing. This is contrary to the Fanning equation where the diameter appears as the -3 power indicating that the type of flow present depends upon the cross section of the flow passage.
3. No definite correlation was obtained for the over-all effect of the tube spacing.

RECOMMENDATIONS

It is recommended that the following investigations be initiated in future work on the problem.

1. Extend this type of experiment to apparatus of the same design but of other size.
2. Study the effect of a change in the physical properties of the fluid.
3. Study the effect of more than one tube row upon the pressure drop.
4. Study the effect of the surface arrangement upon the pressure drop.
5. Investigate in a more detailed manner the pressure distribution under varying flow.

NOMENCLATURE

A, B, C = Constants.

D = Diameter, in., or ft.

De = Equivalent diameter, ft.

H_L = Venturi reading, ft. of water.

P = Average static pressure across sections, mm. of mercury.

P_B = Barometric pressure, mm. of mercury.

ΔP = Pressure drop, ft. lb./lb.

R_1, R_2, R_3, ... R_{10} = U-tube static pressure readings, in. H_2O.

Re = Reynolds Number of air across front fin section.

S = Fin spacing, in.

T = Temperature, $^{\circ}R$.

U = Average velocity across sections, ft./sec.

W = Weight rate of flow of air, lb./sec.

k = Ratio of fin spacing to flow path length.

m = Ratio of tube center-to-center spacing.

p_1 = Upstream static pressure difference of orifice, mm. Hg.

p_v = Downstream static pressure difference of venturi, in. H_2O.

ρ = Density, lb./cu. ft.

μ = Viscosity, English units.

Subscripts

1 refers to front fin section.

2 refers to tube row section.

3 refers to rear fin section.

o refers to orifice.

v refers to venturi.

APPENDIX 1

Table Ia is a tabulated list of dimensions which appear in Drawings No. 1-5.

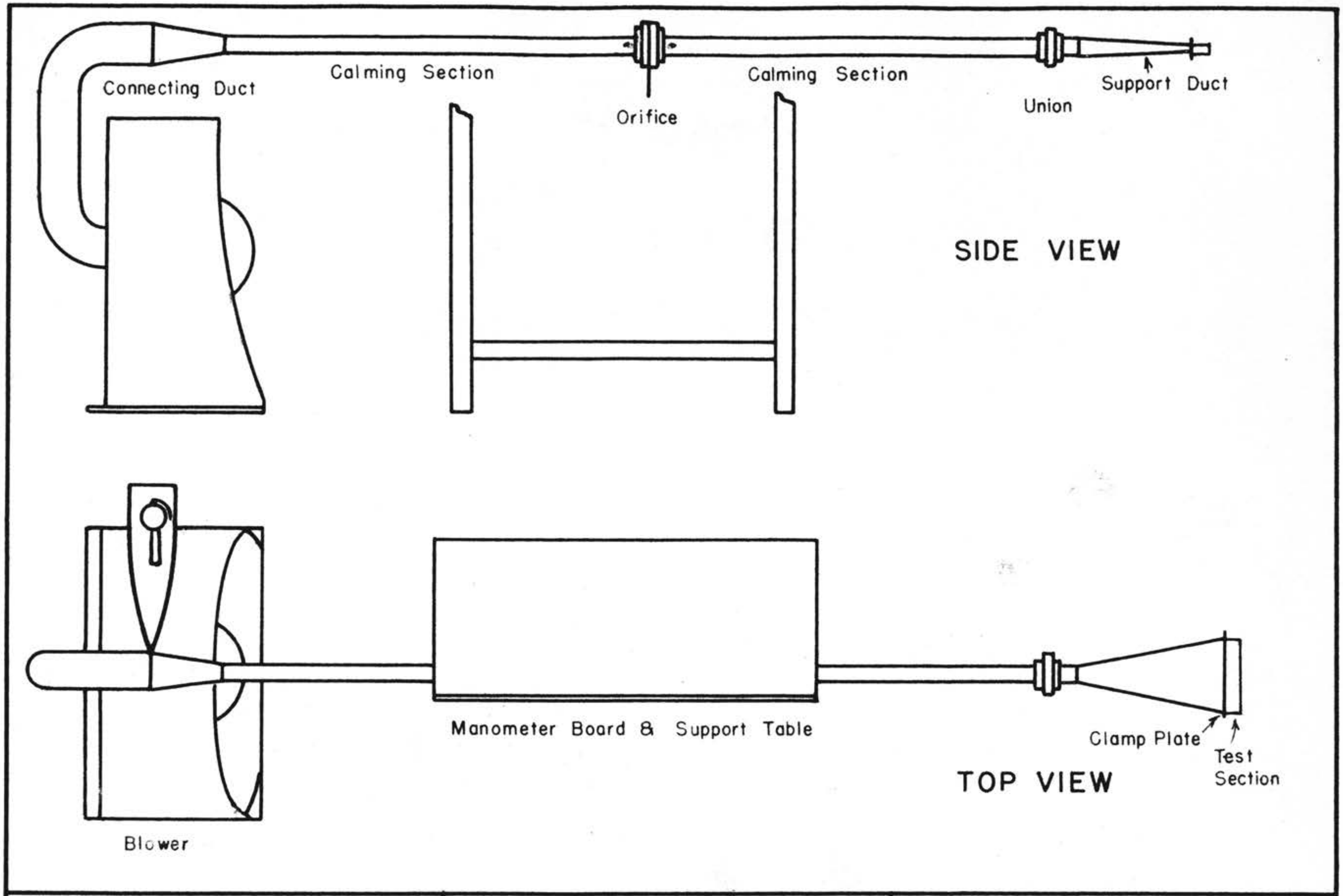
TABLE Ia

DIMENSIONS TO ACCOMPANY DRAWING NO. 4

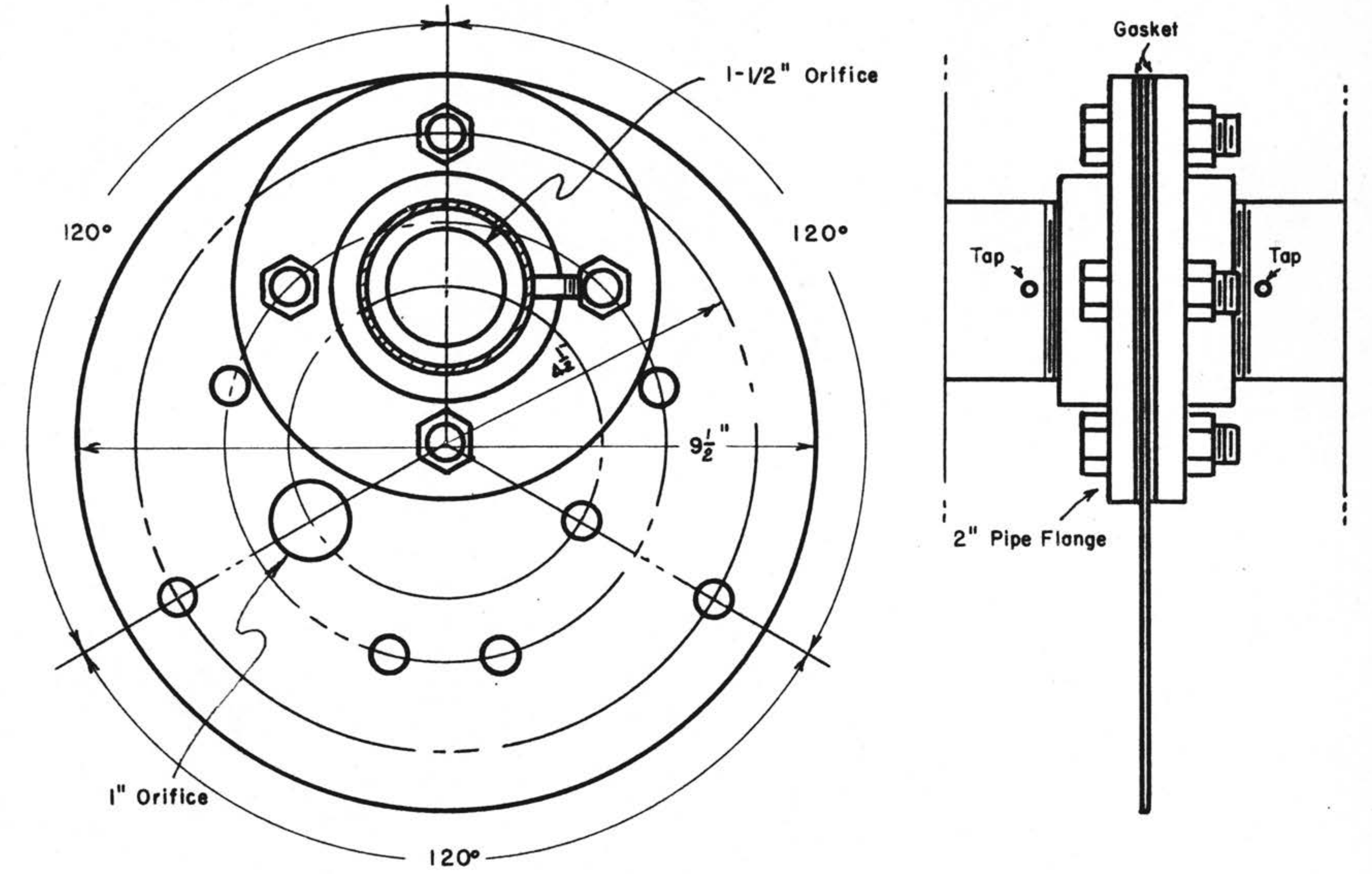
Dimension Symbol	Name of Apparatus Part	Number Required	Dimension Value	Tolerance
A	Top & Bottom Plate No. 1	2	1.50 inches	0.005 inches
B	" " " "		2.00 "	0.005 "
C	" " " "		0.50 "	- - - -
D	" " " "		14.00 "	- - - -
E	" " " "		1.00 "	0.002 inches
F	" " " "		0.50 "	0.002 "
G	" " " "		2.00 "	0.002 "
H	" " " "		0.25 "	- - - -
A	Top & Bottom Plate No. 2	2	2.00 inches	0.005 inches
B	" " " "		3.00 "	0.005 "
C	" " " "		0.50 "	- - - -
D	" " " "		14.00 "	- - - -
E	" " " "		1.00 "	0.002 "
F	" " " "		0.50 "	0.002 "
G	" " " "		2.00 "	0.002 "
H	" " " "		0.25 "	- - - -
A	Top & Bottom Plate No. 3	2	2.50 inches	0.005 inches
B	" " " "		4.00 "	0.005 "
C	" " " "		0.50 "	- - - -
D	" " " "		14.00 "	- - - -
E	" " " "		1.00 "	0.002 "
F	" " " "		0.50 "	0.002 "
G	" " " "		2.00 "	0.002 "
H	" " " "		0.25 "	--- - -
J	Spacer	20	0.50 inches	0.001 inches
K	"		0.50 "	0.002 "
G	"		2.00 "	0.002 "
L	Disc	60	1.00 inches	0.001 inches
M	"		0.25 "	+ 0.001 "
N	Pressure tap lead	3	4.0 inches	- - - -
O	" " "		1.0 "	- - - -

TABLE Ia (CONTINUED)

Dimension Symbol	Name of Apparatus Part	Number Required	Dimension Value	Tolerance
N	Pressure tap lead	3	3.5 inches	- - - -
O	" " "		1.0 "	- - - -
N	Pressure tap lead	3	3.0 inches	- - - -
O	" " "		1.0 "	- - - -
N	Pressure tap lead	5	2.5 inches	- - - -
O	" " "		1.0 "	- - - -
N	Pressure tap lead	6	2.0 inches	- - - -
O	" " "		1.0 "	- - - -
N	Pressure tap lead	6	1.5 inches	- - - -
O	" " "		1.0 "	- - - -
N	Pressure tap lead	3	1.0 inches	- - - -
O	" " "		1.0 "	- - - -
Not Drawn	Assembly bolts	10		
	diameter		0.25 inches	- 0.001 inches
	length		1.50 inches	- - - -
	length of thread		1.00 inches	- - - -



DRAWING NO. 1	EQUIPMENT SET-UP	OCP-12-22-49



DRAWING NO. 2

ORIFICE PLATE & FLANGE

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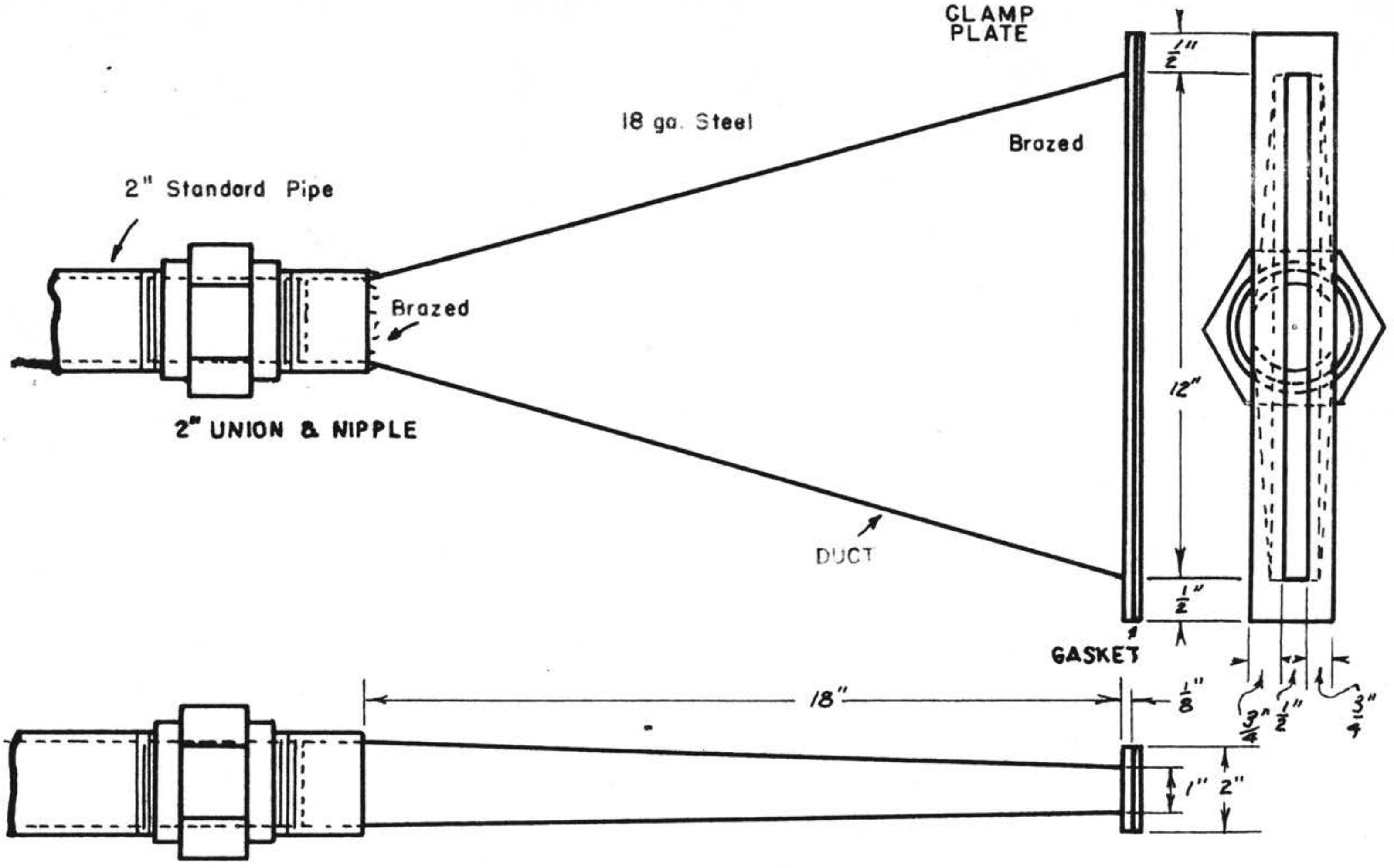
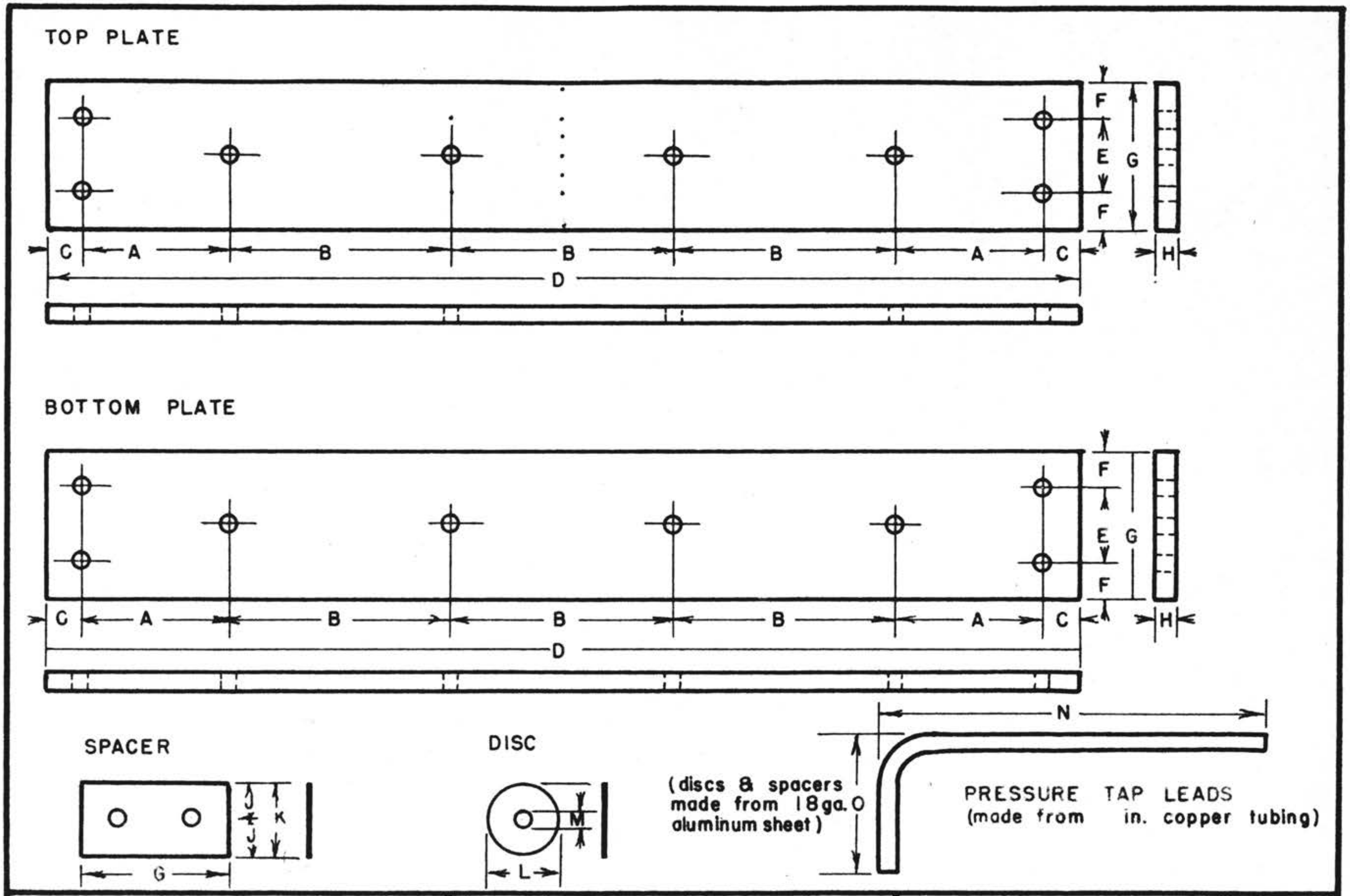
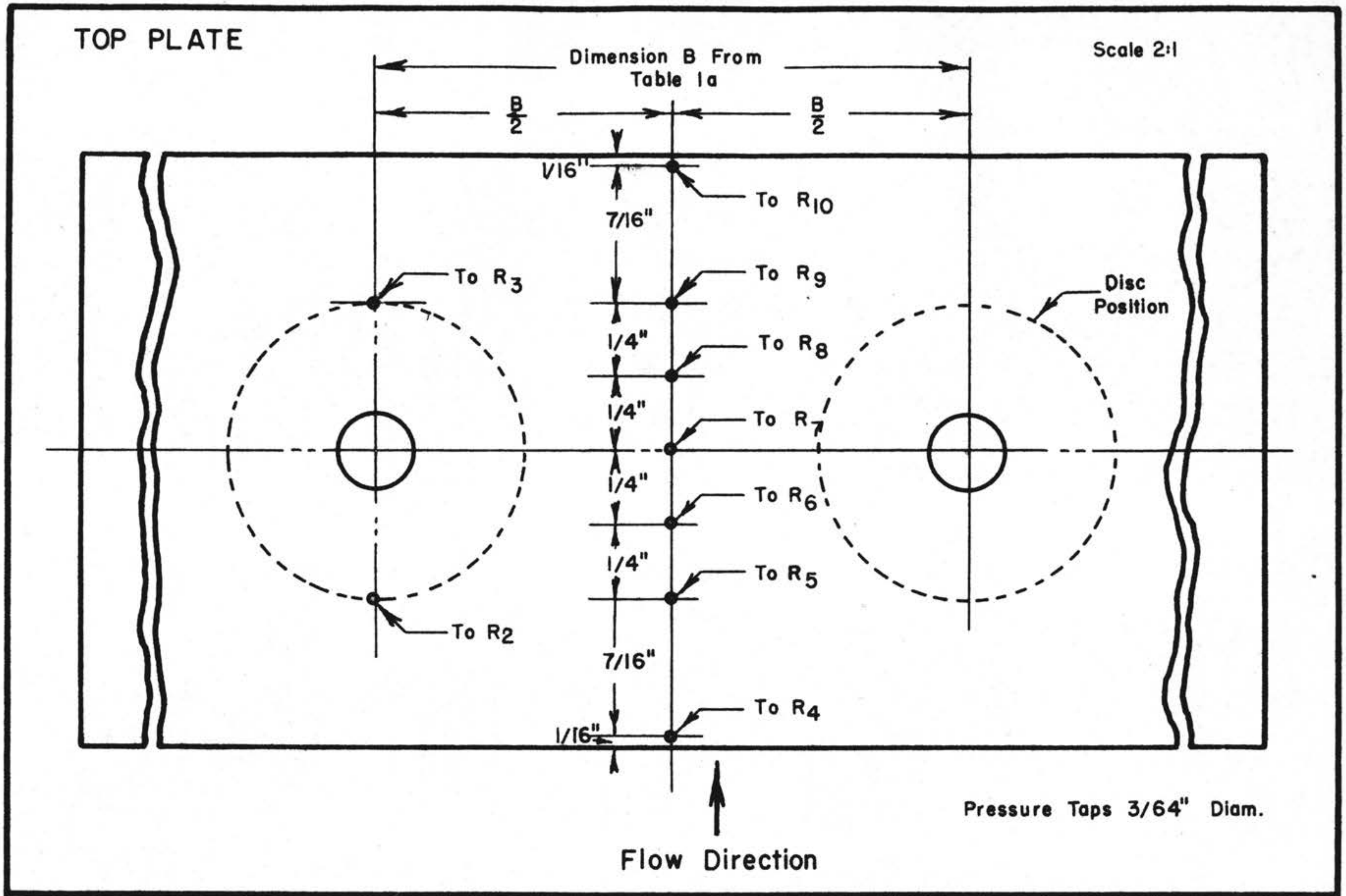


DRAWING NO. 3	DUCT & PLATE	OCP-12-21-49



DRAWING NO. 4	TEST SECTION PARTS	OCP-12-21-49



DRAWING NO. 5 | PRESSURE TAP DETAILS | OCP-12-21-49

APPENDIX 2

SAMPLE CALCULATION

Experimental Data:

Run	85	
Barometric Pressure		743.1 mm. Hg.
Temperature	88°F.	548°R.

U-Tube Readings

R_1	2.15 atm. leg, in. H_2O
R_5	7.72 in. H_2O.
R_9	10.22 in. H_2O.
R_{10}	11.30 in. H_2O.

Orifice Manometer Readings

P_1	24 mm. mercury
R_o	476 mm. water

Calculations:

(a) Pressure drop across apparatus sections.

1. Across front fin section.

$$\Delta P_1 = R_5 - R_1, \text{ inches of water}$$
$$= 7.72 - 2.15$$
$$= 5.57 \text{ inches of water}$$

2. Across tube row.

$$\Delta P_2 = R_9 - R_5, \text{ inches of water}$$
$$= 10.22 - 7.72$$
$$= 2.50 \text{ inches of water}$$

3. Across rear fin section.

$$\Delta P_3 = R_{10} - R_9, \text{ inches of water}$$
$$= 11.30 - 10.22$$
$$= 1.08 \text{ inches of water}$$

(b) Average static pressure of fluid across apparatus sections.

$$1.869 \text{ mm. Hg} = 1 \text{ inch of water}$$

1. Across front fin section.

$$P_1 = \text{Barometric pressure} - 1.869\left(\frac{R_5 - R_1}{2}\right)$$
$$= 743.1 - 4.82$$
$$= 738.3 \text{ mm. Hg.}$$

2. Across tube row.

$$P_2 = \text{Barometric pressure} - 1.869\left(\frac{R_9 - R_5}{2}\right)$$
$$= 743.1 - 12.05$$
$$= 731.0 \text{ mm. Hg.}$$

3. Across rear fin section.

$$P_3 = \text{Barometric pressure} - 1.869\left(\frac{R_{10} - R_9}{2}\right)$$
$$= 743.1 - 15.12$$
$$= 728.0 \text{ mm. Hg.}$$

(c) Average density of fluid through apparatus sections.

$$\rho = \frac{29 \text{ lb./lb.mol.}}{359 \text{ cu.ft./lb.mol.}} \quad \text{at S.C.}$$
$$= 0.08075 \text{ lb./cu.ft. at S.C.}$$
$$= 0.08075 \left(\frac{P}{760}\right)\left(\frac{492}{T}\right)$$
$$= 0.05225 \frac{P}{T}$$

1. Across front fin section.

$$\rho_1 = 0.05225 \frac{P_1}{T}$$
$$= \frac{0.05225\ (738.3)}{548}$$
$$= 0.0704 \text{ lb./cu.ft.}$$

2. Across tube row.

$$\rho_2 = 0.05225 \frac{P_2}{T}$$
$$= \frac{0.05225\ (731.0)}{548}$$
$$= 0.0696 \text{ lb./cu.ft.}$$

3. Across rear fin section.

$$\rho_3 = 0.05225 \frac{P_3}{T}$$
$$= \frac{0.05225\ (728.0)}{548}$$
$$= 0.0693 \text{ lb./cu.ft.}$$

(d) Pressure drop in feet of fluid head across the apparatus sections.

$$P = \text{U-tube reading difference} \frac{(\rho \text{ water})}{(\rho \text{ air})}$$
$$= \Delta R \frac{(62.4 \text{ lb./ft}^3)}{(12 \text{ inches})}$$
$$= \frac{\Delta R\ (5.2)}{\text{air}}$$

1. Across front fin section.

$$\Delta P_1 = 5.2(5.57)/0.0704$$
$$= 412 \text{ feet of fluid}$$

2. Across tube row.

$$\Delta P_2 = 5.2(2.50)/0.0696$$
$$= 186.9 \text{ feet of fluid}$$

3. Across rear fin section.

$$\Delta P_3 = 5.2(1.08)/0.0693$$
$$= 81.2 \text{ feet of fluid}$$

(e) Weight rate of fluid flowing across the apparatus

Orifice upstream static pressure

$$P_o = \text{Barometric pressure} - p_1$$
$$= 743.1 - 24$$
$$= 719.1 \text{ mm. Hg}$$

Orifice upstream density.

$$\rho_o = 0.05225 \frac{P}{T}o$$
$$= 0.05225 \left(\frac{719.1}{548}\right)$$
$$= 0.0685 \text{ lb./cu.ft.}$$

$$\text{Reading x Density} = 476(0.0685)$$
$$= 32.6$$

From the orifice calibration chart (Figure 1a)

$$W = 0.210 \text{ lb./sec.}$$

(f) Velocity of fluid across front fin section.

$$U_1 = \frac{(W, \text{ lb./sec.})}{(\rho_1 \text{ lb./cu.ft.})(\text{Area, sq.ft.})}$$
$$= \frac{(0.210)}{(0.0704)(0.02666)}$$
$$= 111.7 \text{ ft./sec.}$$

(g) Reynolds Number of the fluid across the front fin section.

Viscosity of air at 88°F. = 0.018 cp.

$$Re = \frac{(\text{Diam.}_{eq}, \text{ft.})(U, \text{ft./sec.})(\rho_1, \text{lb./cu.ft.})}{(\text{viscosity, English units})}$$

$$= \frac{(4 \times \frac{0.02666}{2.0533})(111.7)(0.0704)}{(0.018 \times 0.000672)}$$

$$= 34,800$$

SAMPLE CALCULATIONS FOR FIGURES

$m = 3$
$\Delta P_1 = 412$
$\Delta P_2 = 186.9$
$\Delta P_3 = 81.2$
$Re = 34,000$

$$k_1 = \frac{S}{\text{flow path length}_1}$$

$$= \frac{0.32}{0.50}$$

$$= 0.64$$

$$k_2 = \frac{S}{\text{flow path length}_2}$$

$$= \frac{0.32}{1.00}$$

$$= 0.32$$

$$k_3 = \frac{S}{\text{flow path length}_3}$$

$$= \frac{0.32}{4.37}$$

$$= 0.731$$

Across front fin section

1. From Figure 3a, slope = 2.1

$$Re^{2.1} = (34{,}000)^{2.1}$$
$$= 328.2 \times 10^{7}$$

Value to be averaged for Figure 5a

$$\frac{\Delta P_1}{Re^{2.1}} = \frac{412}{328.2 \times 10^{7}}$$
$$= 1.254 \times 10^{-7}$$

2. From Figure 5a, slope = -1.92

$$k_1^{-1.92} = (0.64)^{-1.92}$$
$$= 2.35$$

Value to be averaged for Figure 6a

$$\frac{\Delta P_1}{Re^{2.1}\ k^{-1.92}} = 0.528 \times 10^{-7}$$

3. From Figure 6a, slope = -0.38

$$m^{-0.38} = (3)^{-0.38}$$
$$= 0.595$$

Value to be averaged for constant A

$$\frac{\Delta P_1}{Re^{2.1}\ k^{-1.92}\ m^{-0.38}} = 0.888 \times 10^{-7}$$

Calculated value for ΔP_1 from formula

$$\Delta P_{1\ (\text{calc.})} = 0.802 \times 10^{-7}\ Re^{2.1}\ k^{-1.92}\ m^{-0.38}$$
$$= (0.802 \times 10^{-7})(328 \times 10^{7})(2.35)(0.595)$$
$$= 368$$

$$\Delta P_1 \text{ (obs.)} = 412$$

$$\% \text{ difference} = \frac{412 - 368}{368} \times 100$$

$$= 11.9\%$$

Across tube row

1. From Figure 8a, slope = 1.9

$$Re^{1.9} = (34{,}000)^{1.9}$$

$$= 40.72 \times 10^7$$

Value to be averaged for Figure 10a

$$\frac{\Delta P_2}{Re^{1.9}} = \frac{186.9}{40.72 \times 10^7}$$

$$= 4.59 \times 10^{-7}$$

2. From Figure 10a, slope = -1.83

$$k_2^{-1.83} = (0.32)^{-1.83}$$

Value to be averaged for Figure 11a

$$\frac{\Delta P_2}{Re^{1.9}\ k^{-1.83}} = 0.561 \times 10^{-7}$$

3. From Figure 11a, slope = 2.2

$$m^{-2.2} = 2^{2.2}$$

$$= 0.0892$$

Value to be averaged for constant B

$$\frac{\Delta P_2}{Re^{1.9}\ k^{-1.83}\ m^{2.2}} = 6.29 \times 10^{-7}$$

Calculated value for ΔP_2 from formula

$$\Delta P_2 \text{ (calc.)} = (6.91 \times 10^{-7})(40.72 \times 10^7)(8.20)(0.0892)$$

$$= 204$$

$$\Delta P_2 \text{ (obs.)} = 186.9$$

$$\% \text{ difference} = \frac{204 - 186.9}{204} \times 100$$

$$= 8.3\%$$

Across rear fin section

1. From Figure 13a, slope = 2.4

$$Re^{2.4} = (34{,}000)^{2.4}$$

$$= 7508 \times 10^{7}$$

Value to be averaged for Figure 15a

$$\frac{\Delta P_3}{Re^{2.4}} = \frac{81.2}{7508 \times 10^{7}}$$

$$= 0.0108 \times 10^{-7}$$

2. From Figure 15a, slope = -1.9

$$k_3^{-1.9} = (0.731)^{-1.9}$$

$$= 1.815$$

Value to be averaged for Figure 16a

$$\frac{\Delta P_3}{Re^{2.4}\, k^{-1.9}} = 0.00600 \times 10^{-7}$$

3. From Figure 16a, slope = 0.6

$$m^{0.6} = (3)^{0.6}$$

$$= 1.932$$

Value to be averaged for constant C

$$\frac{\Delta P_3}{Re^{2.4}\, k^{-1.9}\, m^{0.6}} = 0.0031 \times 10^{-7}$$

Calculated value of ΔP_3 from formula

$$\Delta P_{3\,(\text{calc.})} = (0.00349 \times 10^{-7})(7508 \times 10^{7})(1.815)(1.932)$$

$$= 91.9$$

$$\Delta P_{3\,(\text{obs.})} = 81.2$$

$$\%\ \text{difference} = \frac{91.9 - 81.2}{91.9} \times 100$$

$$= 11.6\%$$

Figure 2a

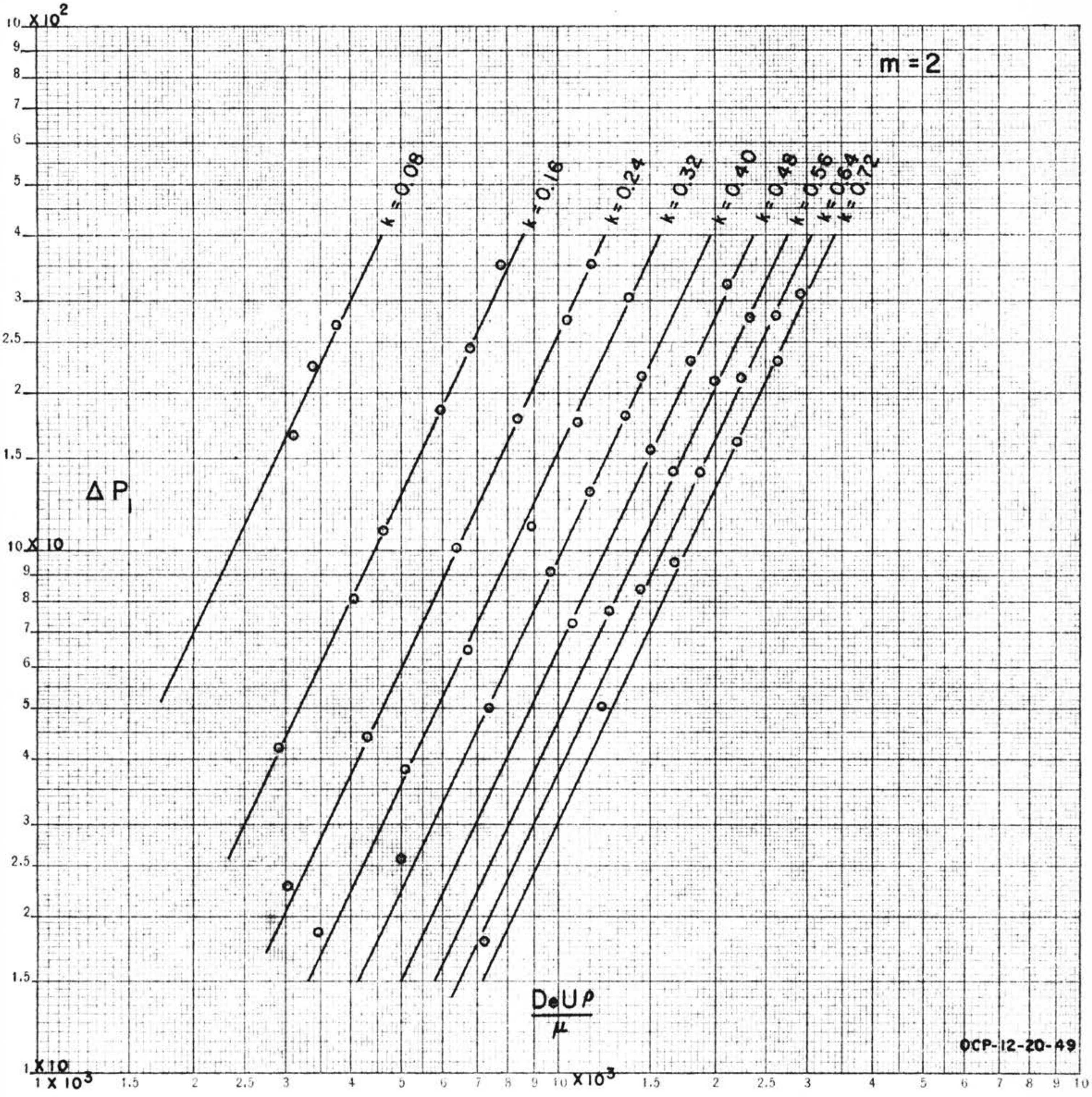

m = 2
k = 0.08
k = 0.16
k = 0.24
k = 0.32
k = 0.40
k = 0.48
k = 0.56
k = 0.64
k = 0.72
ΔP₁
DeUρ/μ
10 X 10²
9
8
7
6
5
4
3
2.5
2
1.5
10 X 10
1 X 10
1 X 10³
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10³
10
OCP-12-20-49

Figure 3a

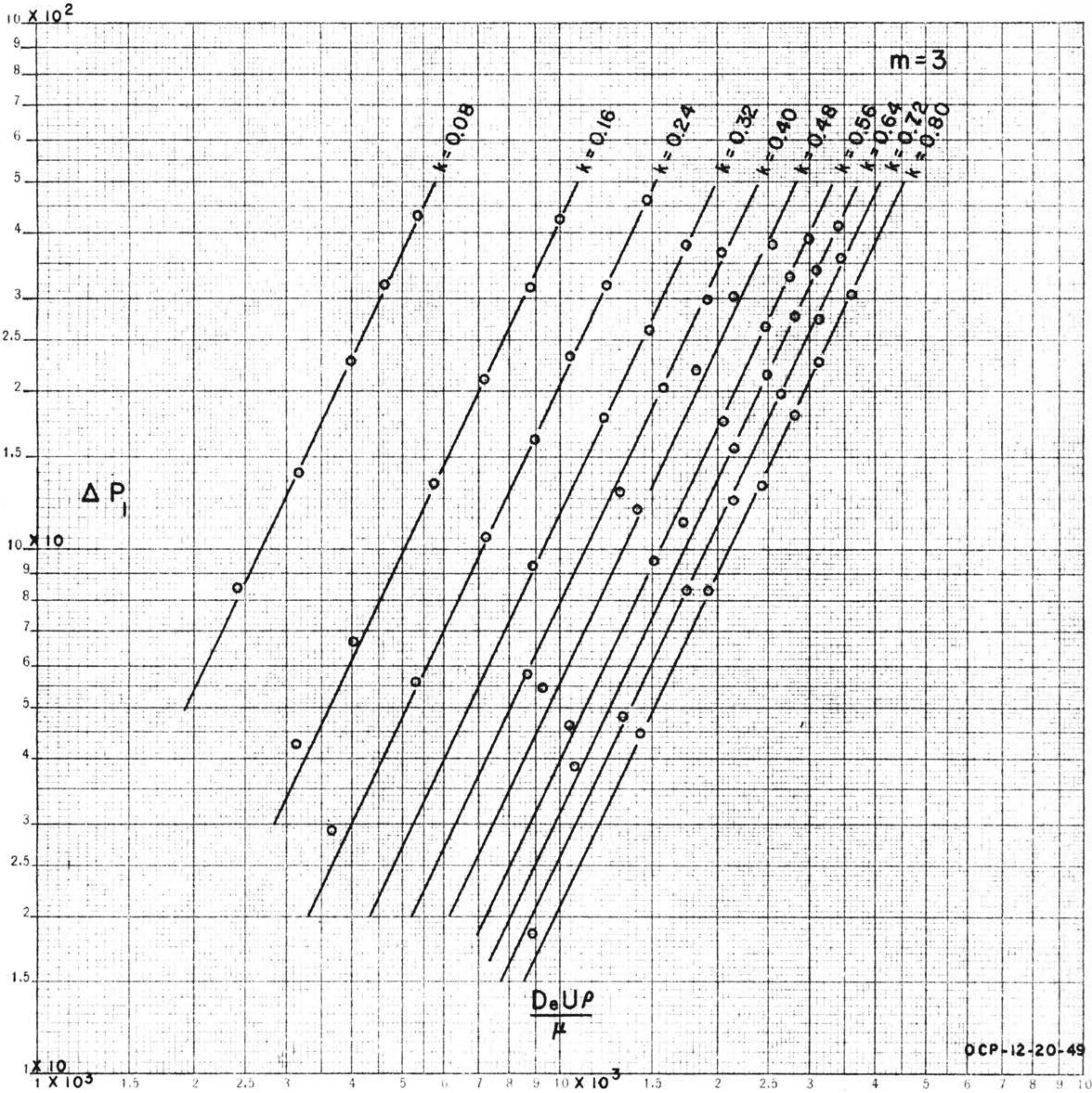

10 X 10^2
9
8
7
6
5
4
3
2.5
2
1.5
10 X 10
9
8
7
6
5
4
3
2.5
2
1.5
1 X 10
ΔP_1
m = 3
k = 0.08
k = 0.16
k = 0.24
k = 0.32
k = 0.40
k = 0.48
k = 0.56
k = 0.64
k = 0.72
k = 0.80
DeUρ/μ
1 X 10^3
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10^3
1.5
2
2.5
3
4
5
6
7
8
9
10
OCP-12-20-49

Figure 4a

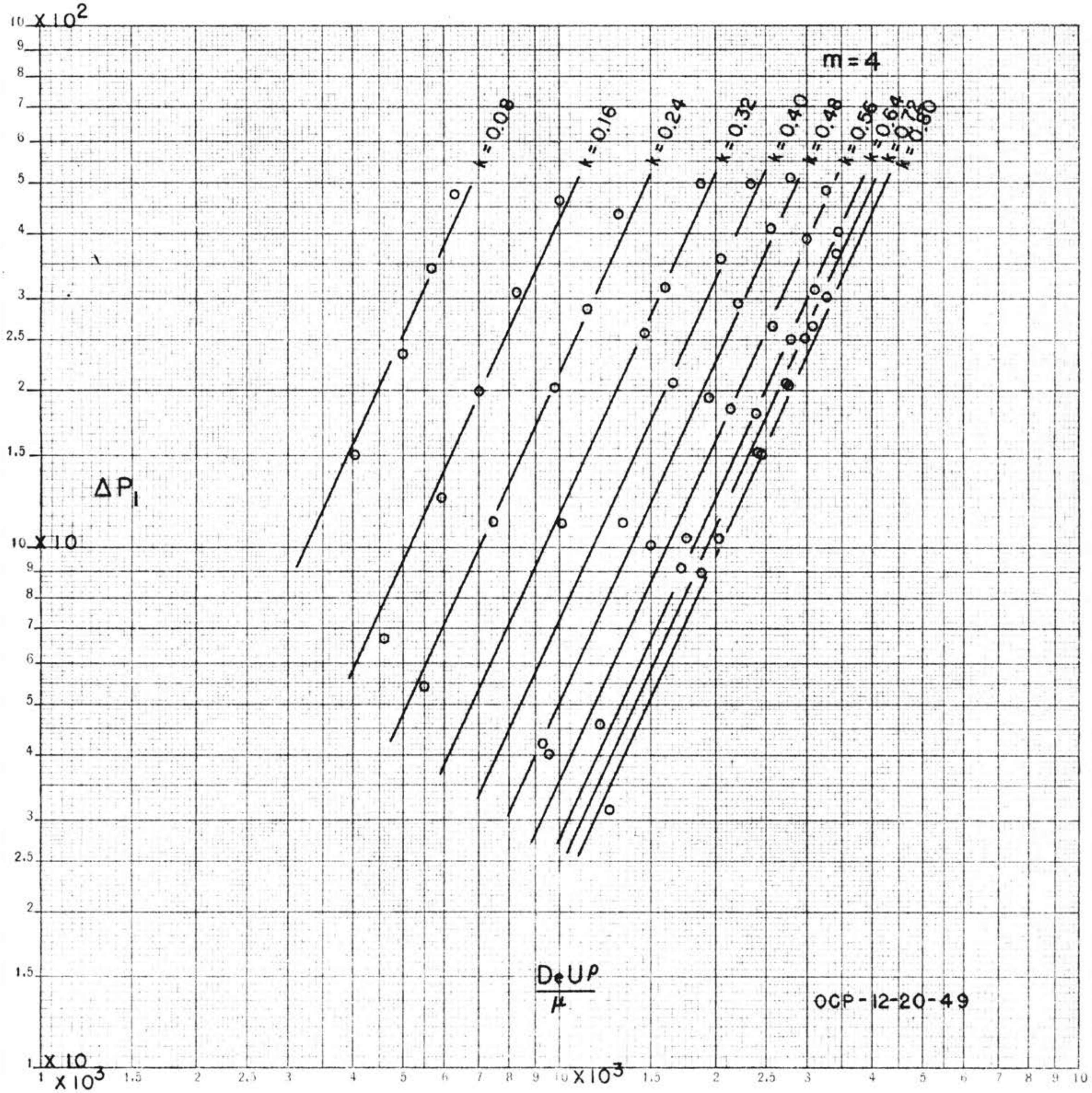

10 X 10^2
9
8
7
6
5
4
3
2.5
2
1.5
10 X 10
9
8
7
6
5
4
3
2.5
2
1.5
1 X 10
ΔP1
m = 4
k = 0.08
k = 0.16
k = 0.24
k = 0.32
k = 0.40
k = 0.48
k = 0.56
k = 0.64
k = 0.72
k = 0.80
DeUρ/μ
OCP-12-20-49
1 X 10^3
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10^3
1.5
2
2.5
3
4
5
6
7
8
9
10

Figure 5a

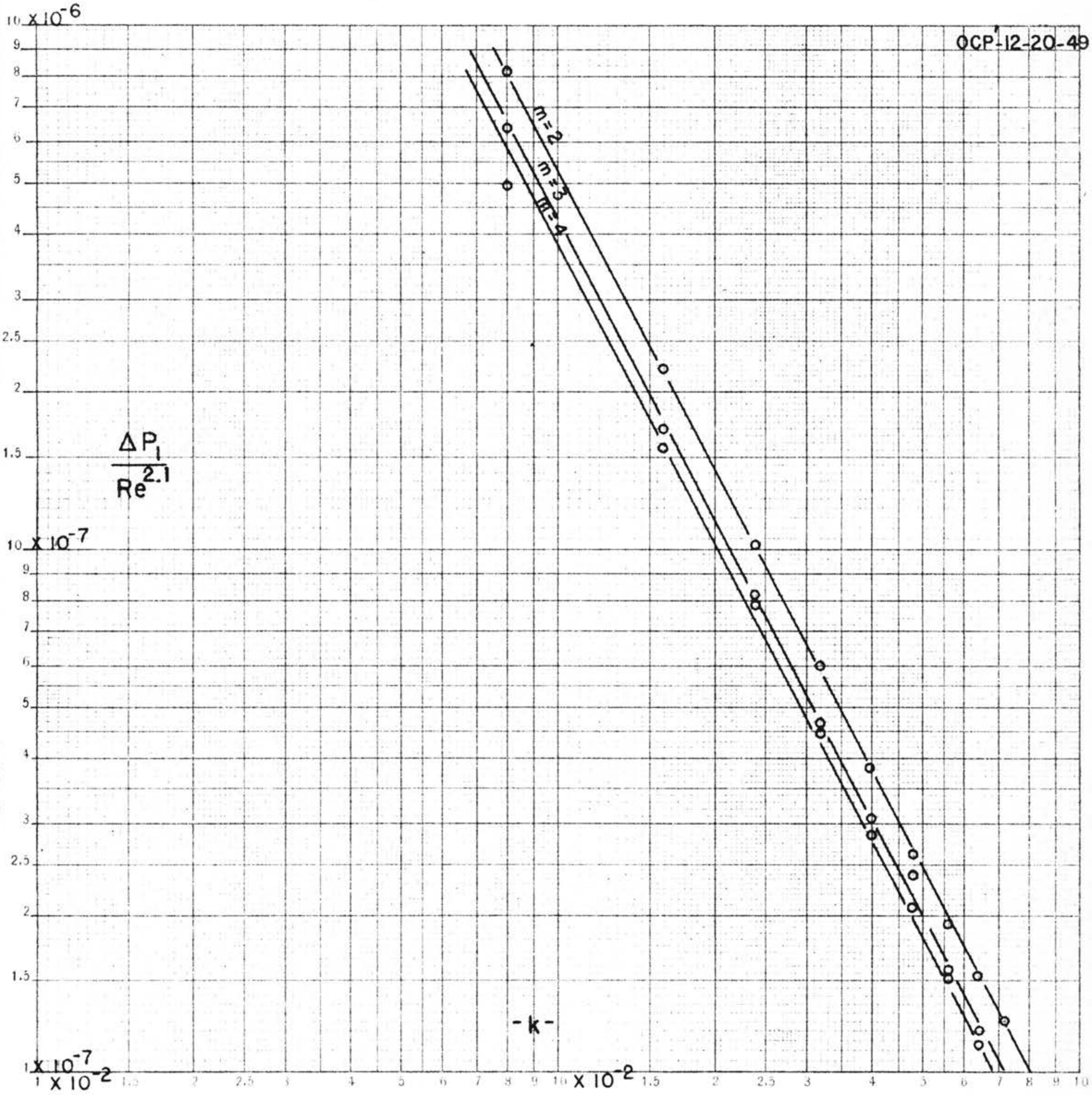

OCP-12-20-49
$\frac{\Delta P_1}{Re^{2.1}}$
10 X 10⁻⁶
9
8
7
6
5
4
3
2.5
2
1.5
10 X 10⁻⁷
9
8
7
6
5
4
3
2.5
2
1.5
1 X 10⁻⁷
1 X 10⁻²
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10⁻²
1.5
2
2.5
3
4
5
6
7
8
9
10
m = 2
m = 3
m = 4
- k -

Figure 6a

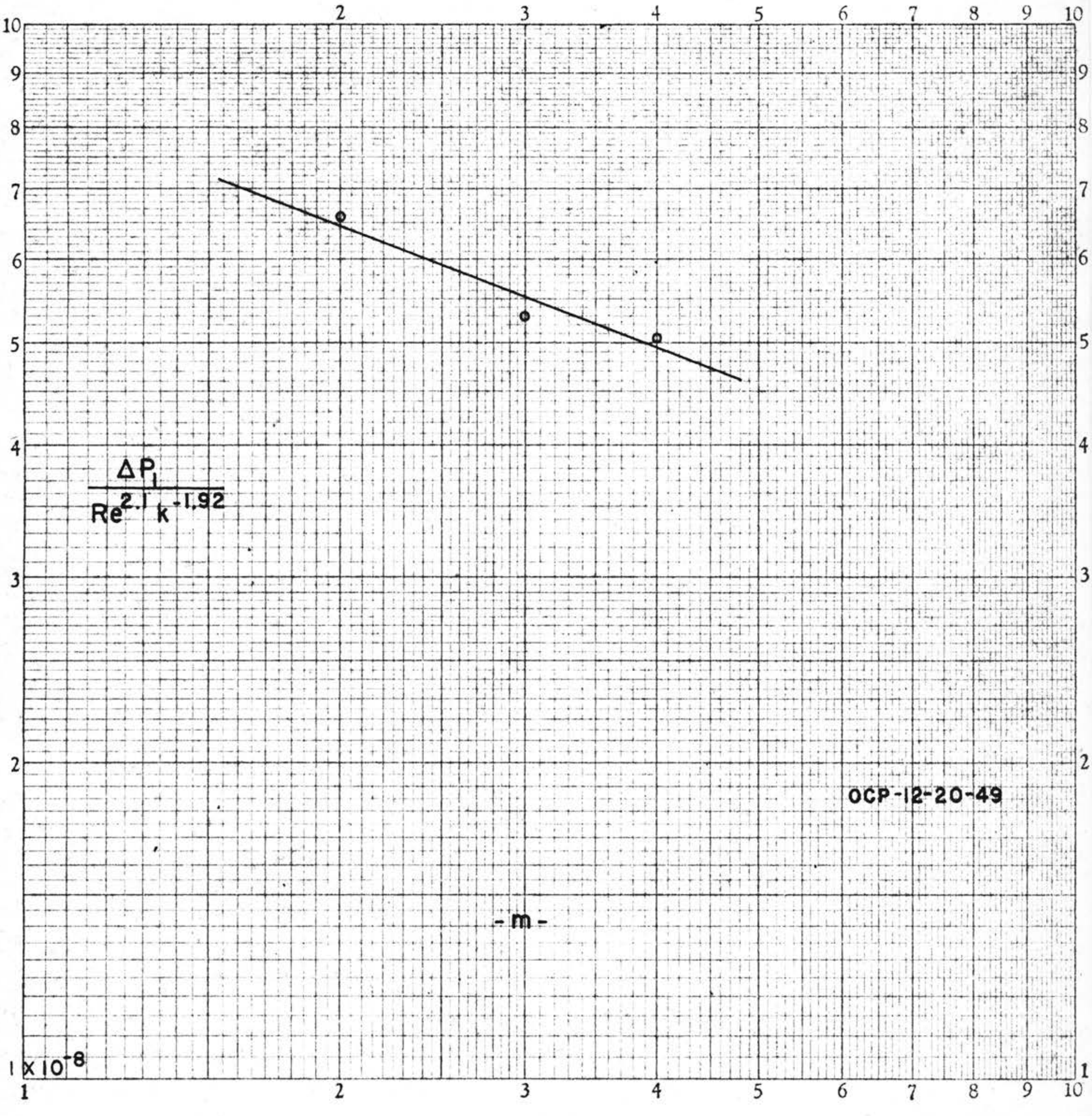

10
9
8
7
6
5
4
3
2
1 X 10^-8
1
2
3
4
5
6
7
8
9
10
$\frac{\Delta P_1}{Re^{2.1}\,k^{-1.92}}$
- m -
OCP-12-20-49

Figure 7a

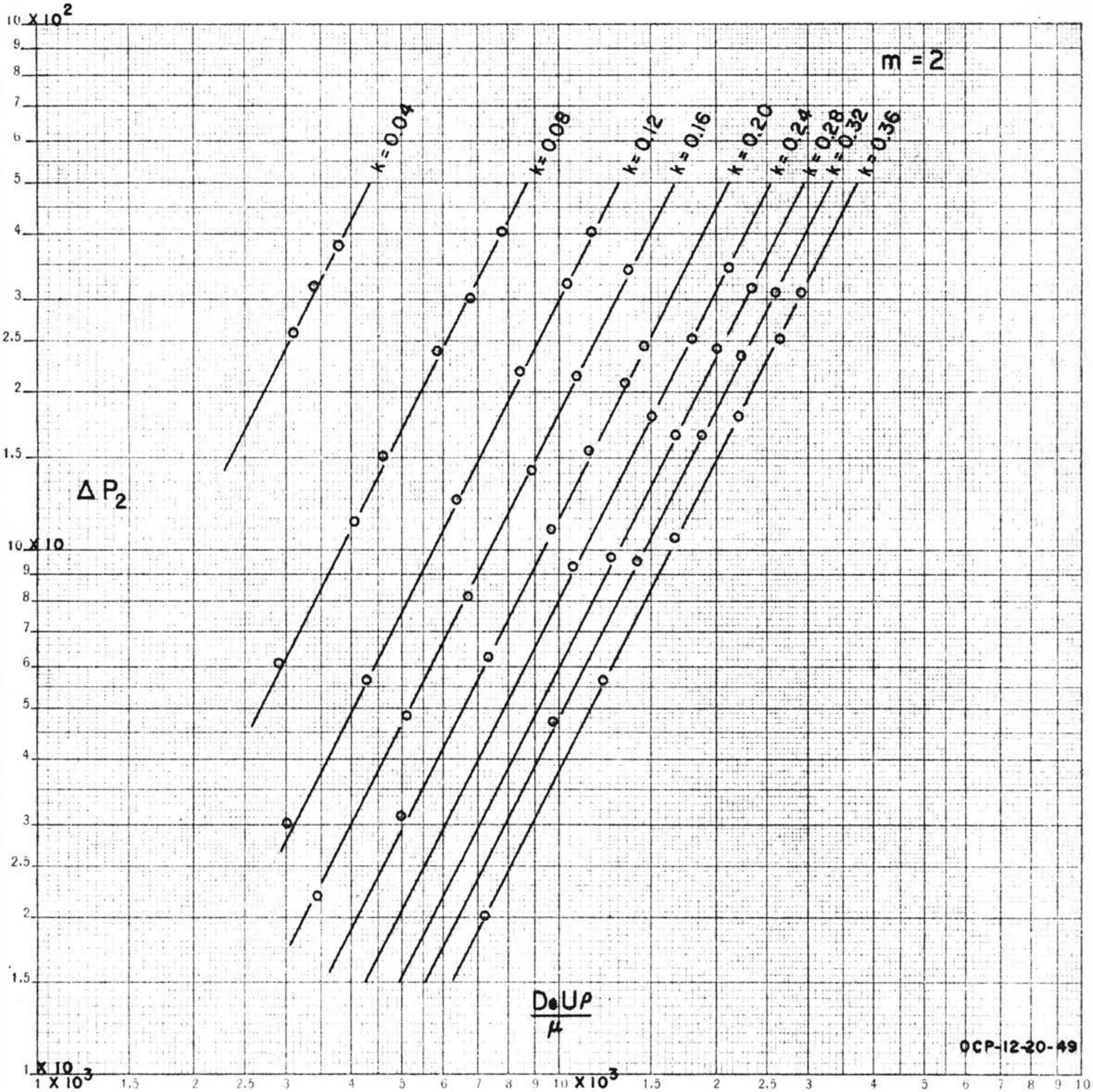

m = 2
k = 0.04
k = 0.08
k = 0.12
k = 0.16
k = 0.20
k = 0.24
k = 0.28
k = 0.32
k = 0.36
ΔP₂
De U ρ / μ
OCP-12-20-49
10 X 10²
9
8
7
6
5
4
3
2.5
2
1.5
10 X 10
1 X 10
1 X 10³
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10³
10

Figure 8a

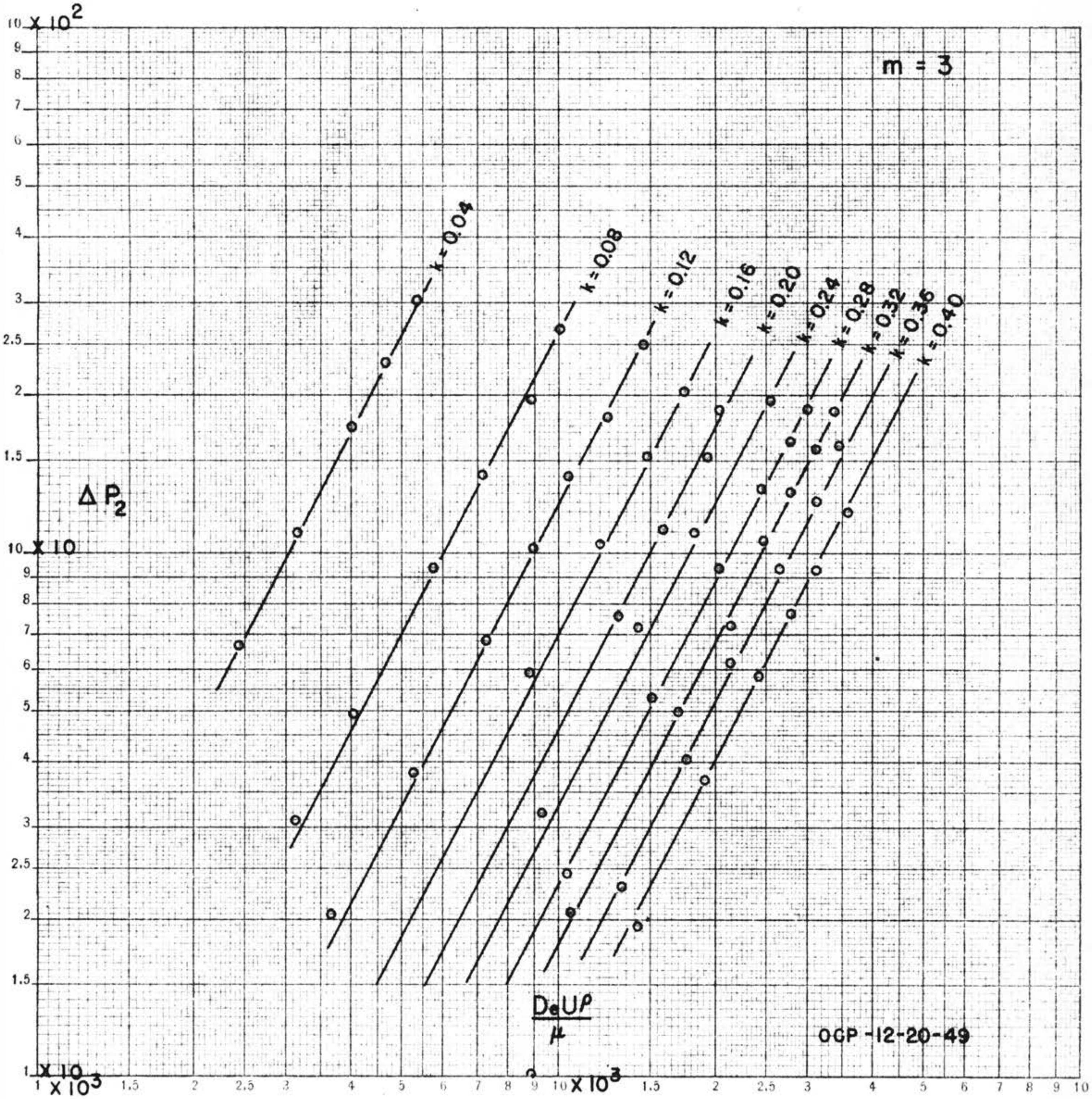

m = 3
k = 0.04
k = 0.08
k = 0.12
k = 0.16
k = 0.20
k = 0.24
k = 0.28
k = 0.32
k = 0.36
k = 0.40
ΔP₂
$\frac{D_e U \rho}{\mu}$
OCP-12-20-49
10 X 10²
9
8
7
6
5
4
3
2.5
2
1.5
10 X 10
1 X 10
1 X 10³
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10³
1.5
2
2.5
3
4
5
6
7
8
9
10

Figure 9a

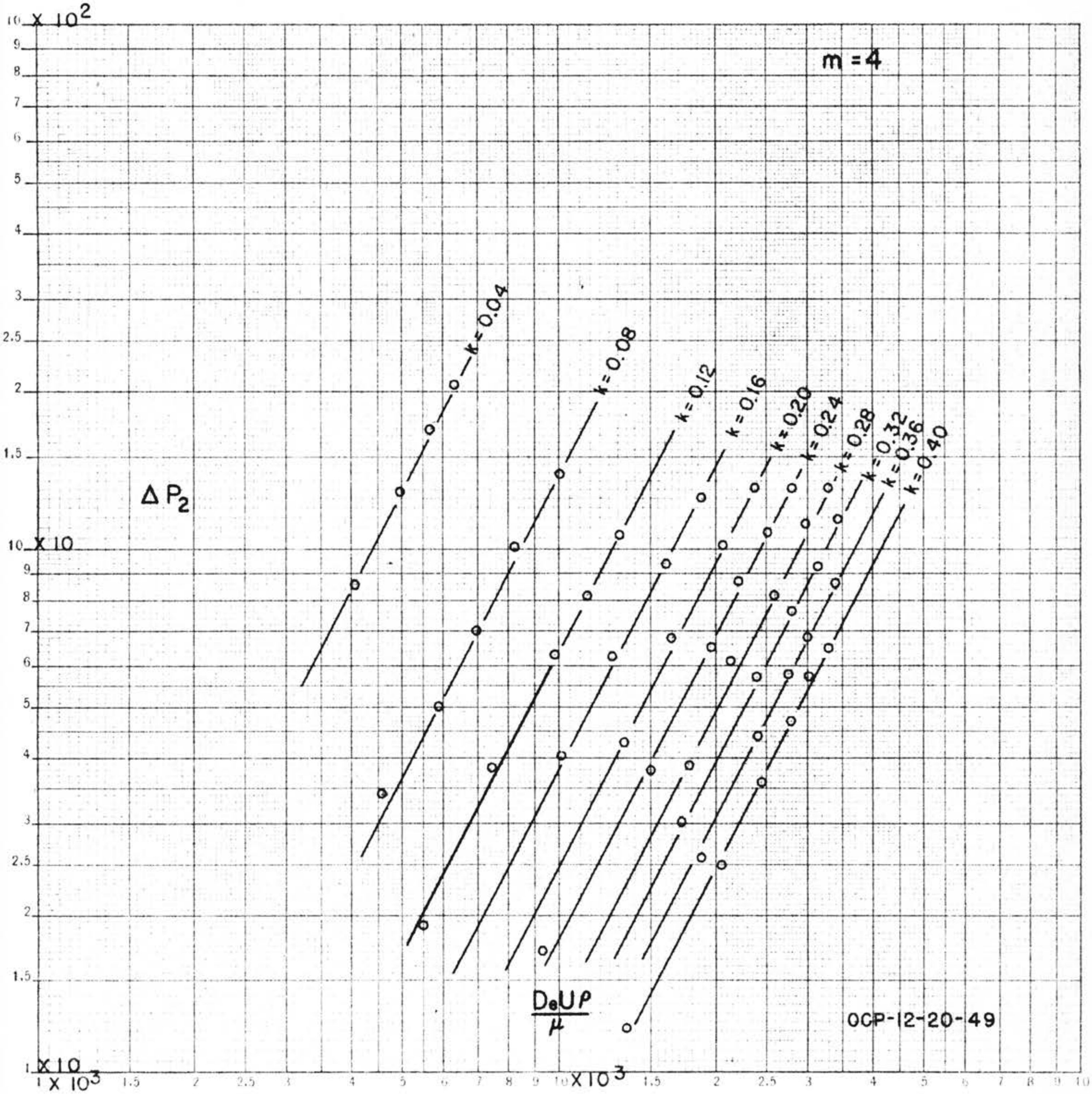
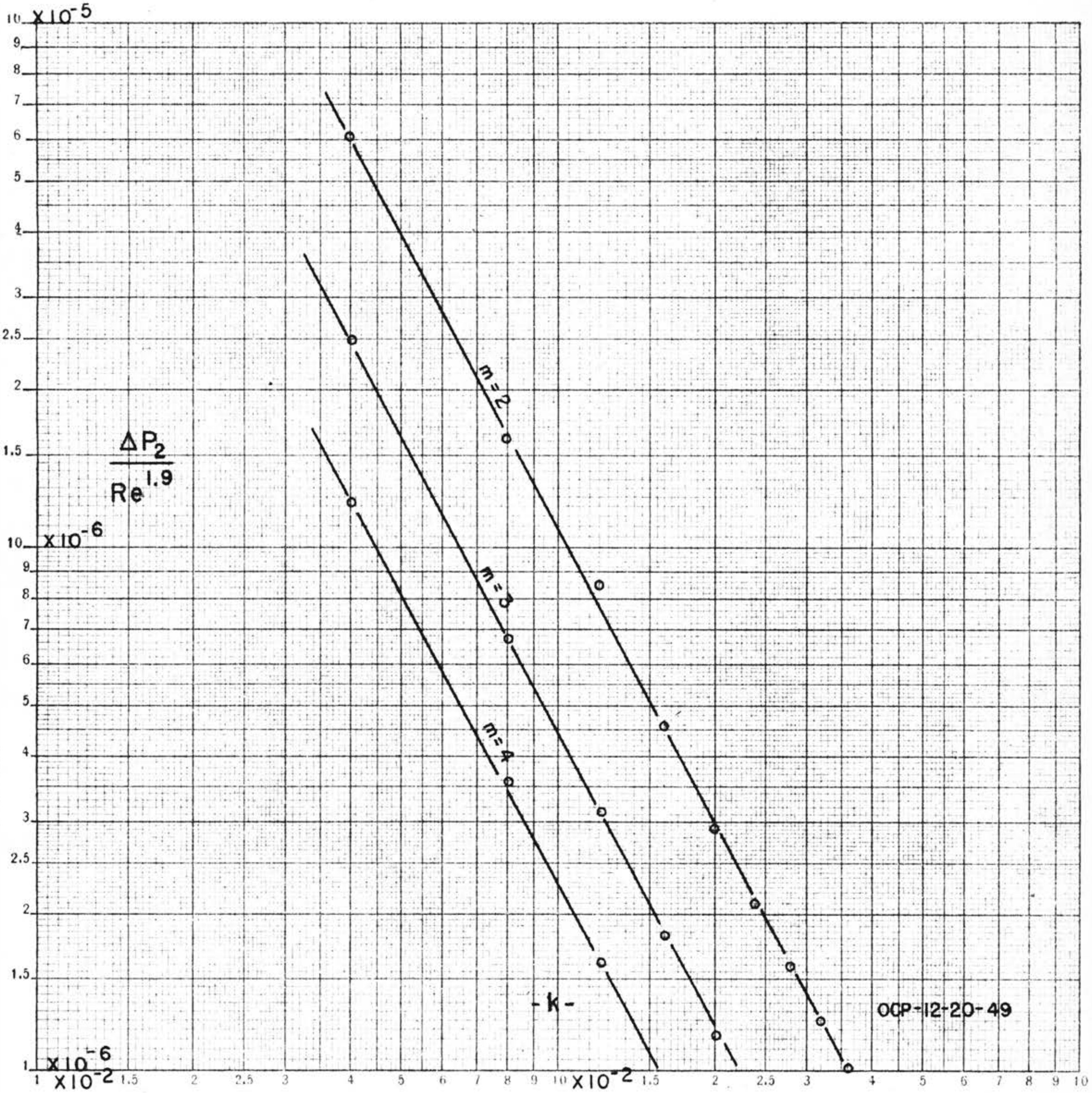

m = 4
ΔP_2
$\frac{D_e U \rho}{\mu}$
OCP-12-20-49
k = 0.04
k = 0.08
k = 0.12
k = 0.16
k = 0.20
k = 0.24
k = 0.28
k = 0.32
k = 0.36
k = 0.40
10 X 10^2
9
8
7
6
5
4
3
2.5
2
1.5
10 X 10
9
8
7
6
5
4
3
2.5
2
1.5
1 X 10
1 X 10^3
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10^3
1.5
2
2.5
3
4
5
6
7
8
9
10

Figure 10a



10 X10⁻⁵
9
8
7
6
5
4
3
2.5
2
1.5
ΔP₂ / Re^1.9
10 X10⁻⁶
9
8
7
6
5
4
3
2.5
2
1.5
1 X10⁻⁶
1 X10⁻² 1.5
2
2.5
3
4
5
6
7
8
9
10 X10⁻² 1.5
2
2.5
3
4
5
6
7
8
9
10
m = 2
m = 3
m = 4
- k -
OCP-12-20-49

Figure 11a

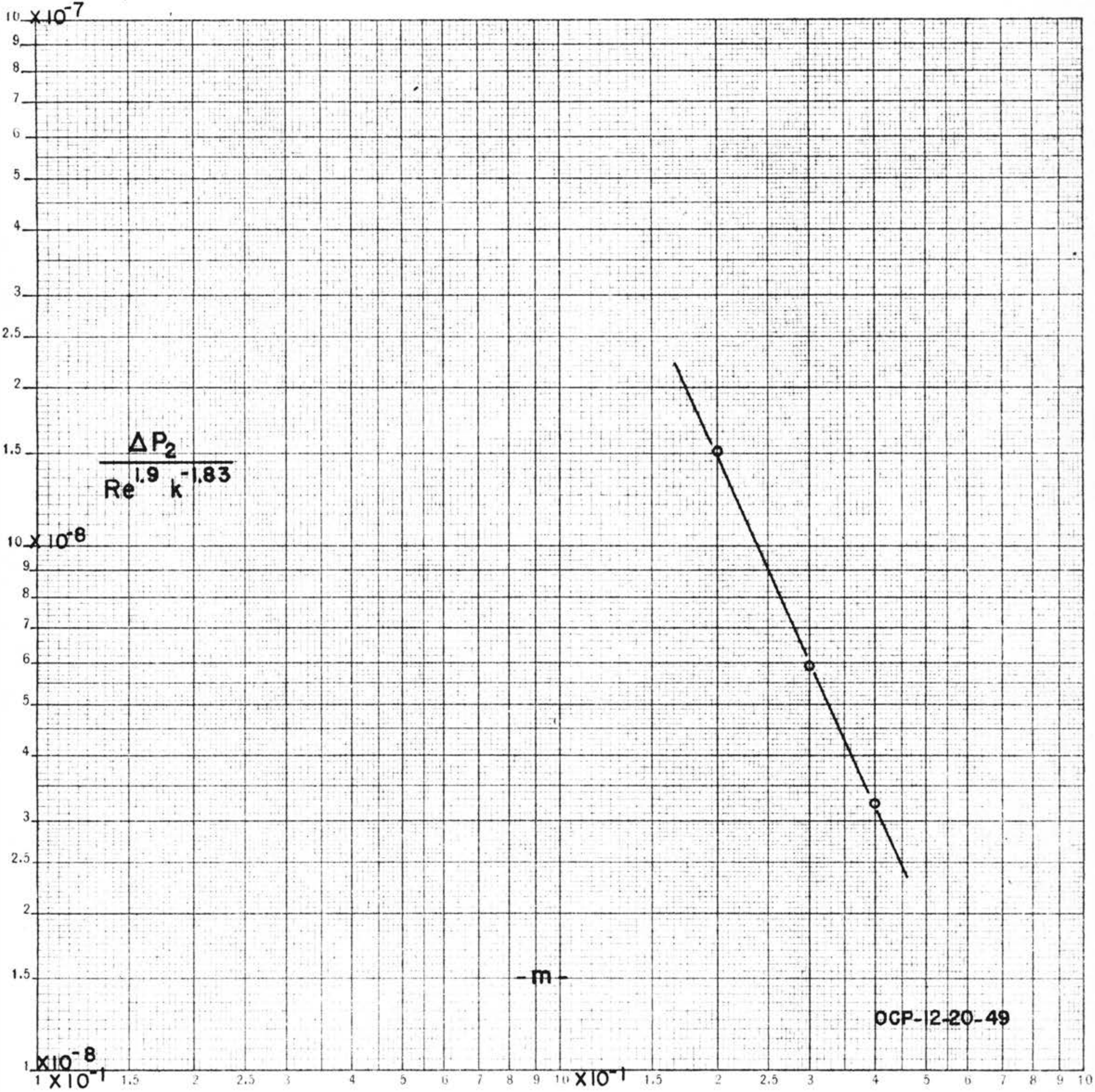

10 X 10^-7
9
8
7
6
5
4
3
2.5
2
1.5
ΔP_2 / Re^1.9 k^-1.83
10 X 10^-8
9
8
7
6
5
4
3
2.5
2
1.5
1 X10^-8
1 X 10^-1
1.5
2
2.5
3
4
5
6
7
8
9
10 X10^-1
1.5
2
2.5
3
4
5
6
7
8
9
10
- m -
OCP-12-20-49

Figure 12a

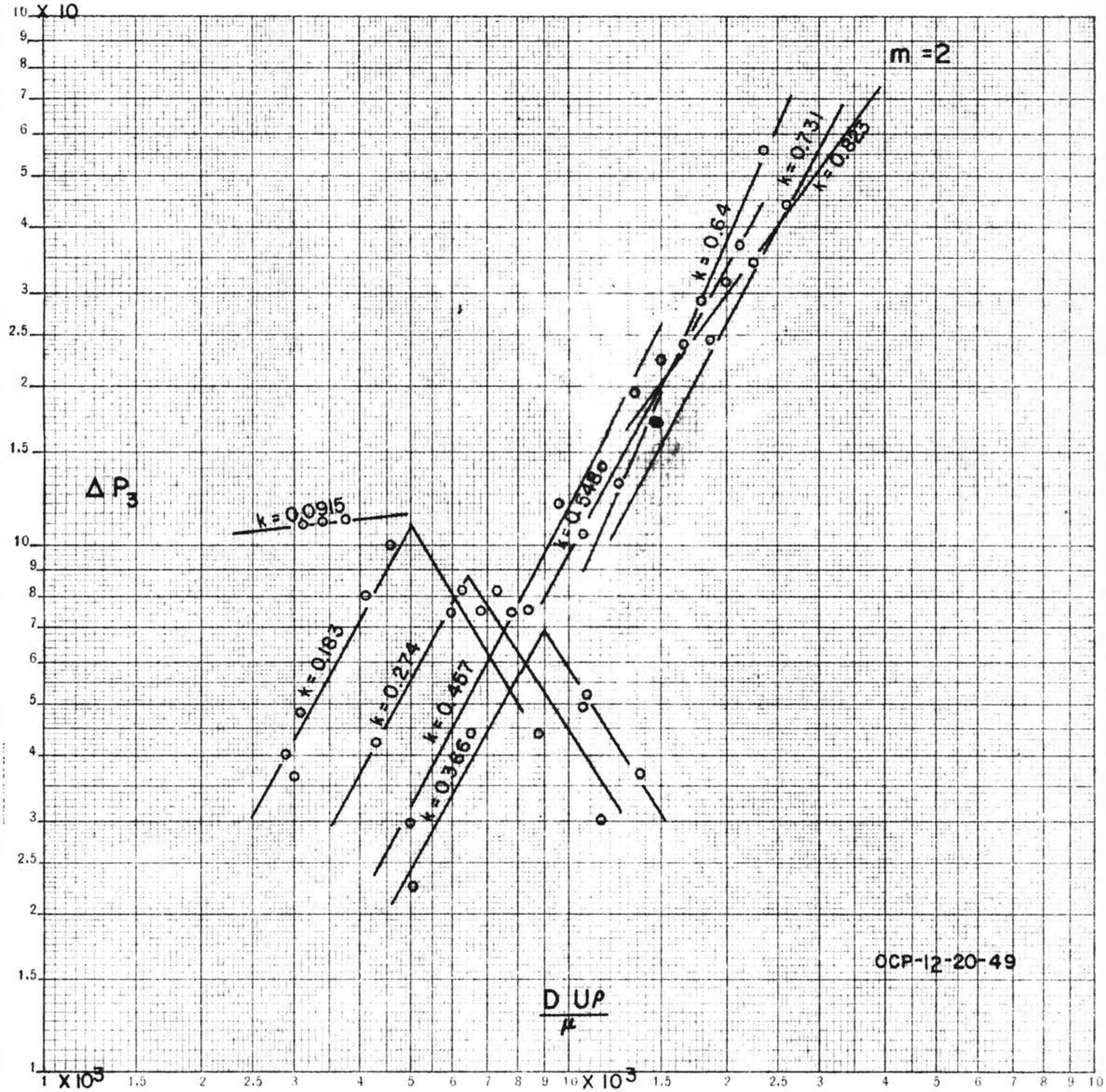
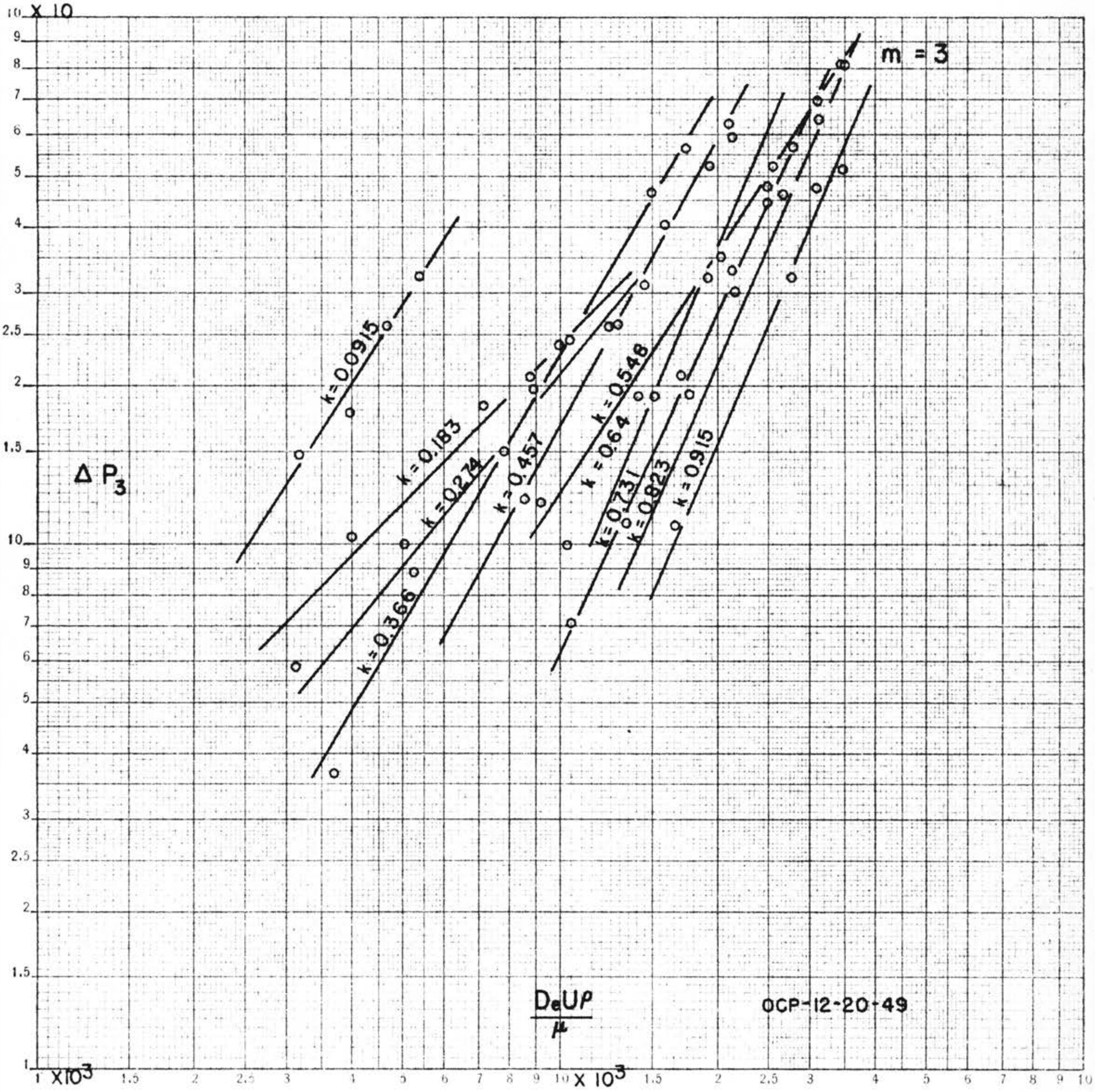
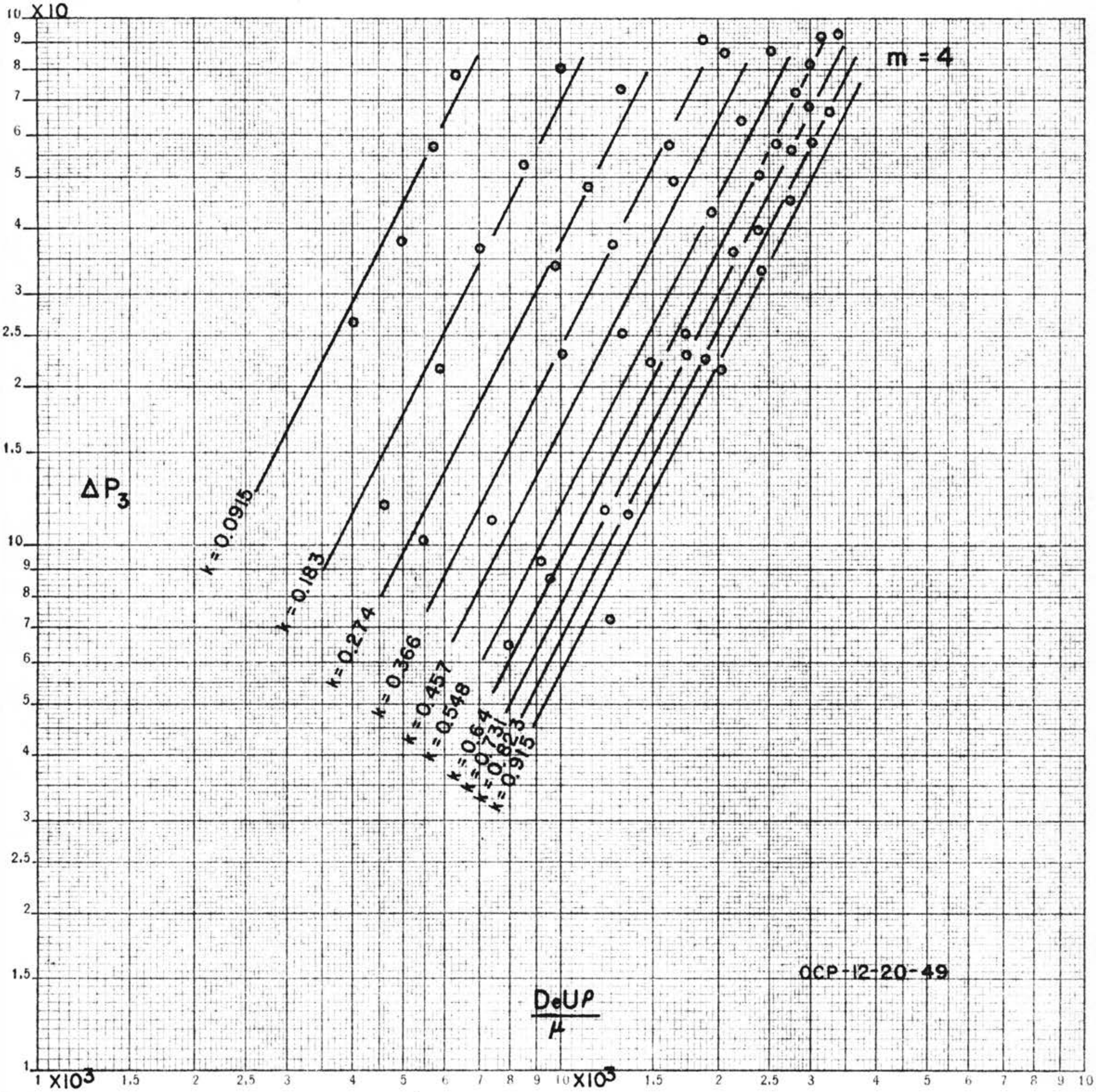

m =2
k = 0.0915
k = 0.183
k = 0.274
k = 0.366
k = 0.457
k = 0.548
k = 0.64
k = 0.731
k = 0.823
Δ P_3
$\frac{D\,U\rho}{\mu}$
10 X 10
9
8
7
6
5
4
3
2.5
2
1.5
10
9
8
7
6
5
4
3
2.5
2
1.5
1
1 X 10³
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10³
1.5
2
2.5
3
4
5
6
7
8
9
10
OCP-12-20-49

Figure 13a



m = 3
k = 0.0915
k = 0.183
k = 0.274
k = 0.366
k = 0.457
k = 0.548
k = 0.64
k = 0.731
k = 0.823
k = 0.915
ΔP_3
$\frac{D_e U \rho}{\mu}$
OCP-12-20-49
10 X 10
9
8
7
6
5
4
3
2.5
2
1.5
10
9
8
7
6
5
4
3
2.5
2
1.5
1
1 X10^3
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10^3
1.5
2
2.5
3
4
5
6
7
8
9
10

Figure 14a



10 X10
9
8
7
6
5
4
3
2.5
2
1.5
ΔP₃
10
1
1 X10³
1.5
2
2.5
3
4
5
6
7
8
9
10 X10³
m = 4
k = 0.0915
k = 0.183
k = 0.274
k = 0.366
k = 0.457
k = 0.548
k = 0.64
k = 0.731
k = 0.823
k = 0.915
DeUρ/μ
OCP-12-20-49

Figure 15a

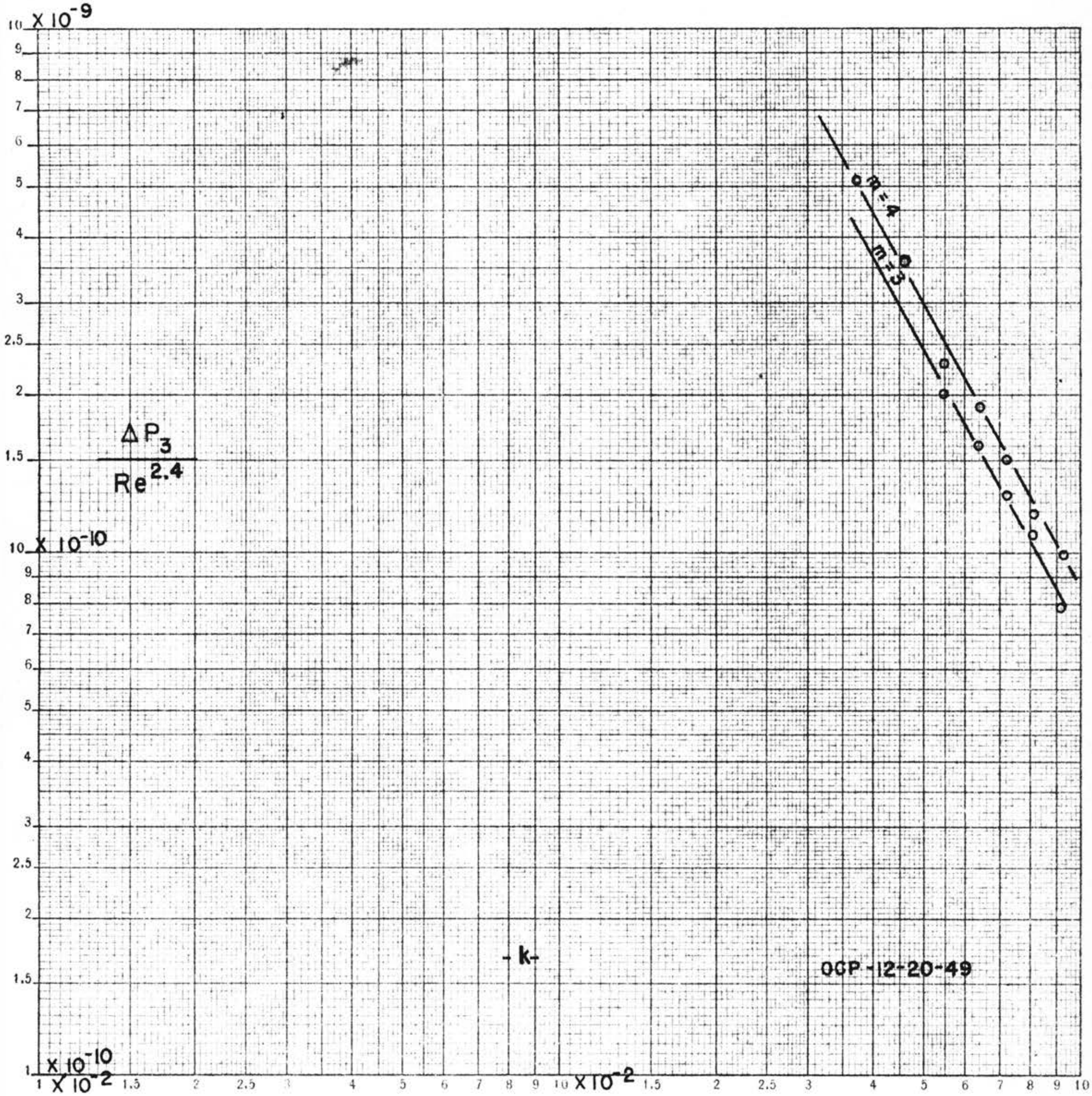
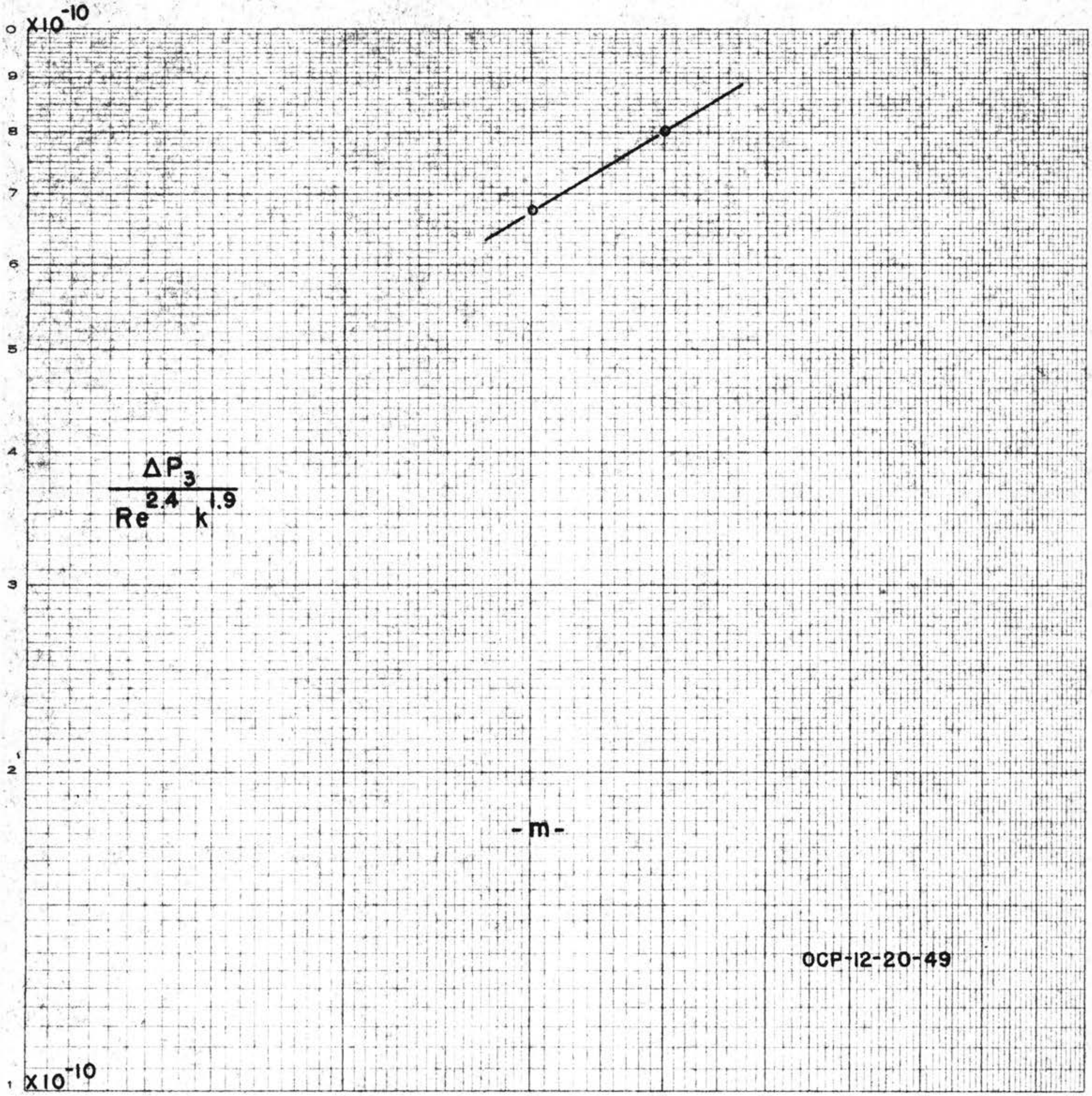

10 X 10^{-9}
9
8
7
6
5
4
3
2.5
2
1.5
$\frac{\Delta P_3}{Re^{2.4}}$
10 X 10^{-10}
9
8
7
6
5
4
3
2.5
2
1.5
1 X 10^{-10}
1 X 10^{-2}
1.5
2
2.5
3
4
5
6
7
8
9
10 X 10^{-2}
1.5
2
2.5
3
4
5
6
7
8
9
10
m = 4
m = 3
- k -
OCP - 12-20-49

Figure 16a


X10-10
X10-10
0
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
7
8
9
10
$\frac{\Delta P_3}{Re^{2.4} k^{1.9}}$
-m-
OCP-12-20-49

APPENDIX 3

ORIFICE CALIBRATION

The two orifices were calibrated by connecting the metering section to a flow system containing a venturi meter, the venturi meter being used as a primary standard. The orifice calibration chart, Figure 1a, is a plot of the calculated weight rates of flow versus orifice calculations made from the readings of the orifice manometers. At the low rates of flow the accuracy of the plot is naturally lessened due to the inability to read the small venturi manometer differences and a straight line extrapolation is made to permit the use of the chart at low flow rates.

The direction of flow was the same in the calibrations as in the experimental runs. The calming sections were installed in both cases to insure consistent results.

The method used in calculating the weight rates of flow from the venturi standard was as follows. From Badger and McCabe (2), page 48, the fundamental equation

$$(U_B^2 - U_A^2)^{\frac{1}{2}} = C_v (2g\Delta H)^{\frac{1}{2}} \qquad (1)$$

$$U_A = U_B \frac{(A_B)}{(A_A)} \qquad (2)$$

Substituting and rearranging,

$$U_B = \frac{C_v (2g\Delta H)^{\frac{1}{2}}}{(1 - \frac{(D_B)^4}{(D_A)})^{\frac{1}{2}}} \qquad (3)$$

$$W = U_B \rho_B A_B \qquad (4)$$

$$= 0.7875 (H_L)^{\frac{1}{2}} (\rho_{air})^{\frac{1}{2}} \qquad (5)$$

Where

C_v = Venturi Coefficient = 0.98

D_B = Downstream diameter of venturi = 1.5 inches

D_A = Upstream diameter of venturi = 3.0 inches

A_B = Area of downstream side of venturi

H_L = Pressure drop across venturi, feet of water

TABLE IIa

ORIFICE CALIBRATION DATA

Run	H_L	p_v	P_B	Temp. °F.	p_1	R_o	D_o
1	0.1825	25.5	742.3	97.0°	45	787	1 in.
2	0.1674	23.3	742.3	98.0°	42	721	1 in.
3	0.1500	19.9	742.3	98.8°	36	642	1 in.
4	0.1350	18.6	742.3	99.2°	34	571	1 in.
5	0.1158	15.55	742.3	100°	27	488	1 in.
6	0.0942	12.60	742.3	100°	23	387	1 in.
7	0.0909	9.90	742.3	101°	18	303	1 in.
8	0.0567	7.35	742.3	101°	14	224	1 in.
9	0.0408	4.90	742.3	101°	10	150	1 in.
10	0.02083	2.40	742.3	100°	5	72	1 in.
11	0.00833	0.60	742.3	99°	1	8	1 in.
12	0.1715	23.78	745.0	90°	40.7	732	1 in.
13	0.1510	20.85	745.0	90.5°	36.8	639	1 in.
14	0.1249	16.88	745.0	91.0°	30.9	521	1 in.
15	0.0841	10.94	745.0	91.7°	18.8	337	1 in.
16	0.0458	5.65	745.0	91.0°	9.5	172	1 in.
17	0.0358	4.21	745.0	91.0°	7.0	128	1 in.
18	0.0233	2.01	745.0	90.0°	3.3	59	1 in.
19	0.0125	0.69	745.0	90.0°	1.1	19	1 in.
20	0.00416	0.25	745.0	90.0°	0.4	7	1 in.
21	1.267	29.25	745.0	96.0°	29	401	1½ in.
22	1.025	23.25	745.0	97.0°	23	312	1½ in.
23	0.829	18.79	745.0	93.0°	18	254	1½ in.
24	0.642	14.50	745.0	98.0°	14	193	1½ in.
25	0.492	10.97	745.0	98.0°	10	144	1½ in.
26	0.475	10.75	745.0	89.0°	10	144	1½ in.
27	0.2415	5.34	745.0	98.0°	5	69	1½ in.
28	0.2234	5.13	745.0	85.0°	5	66	1½ in.
29	0.100	2.13	745.0	97.0°	2	29	1½ in.
30	0.0442	1.02	745.0	81.0°	2	14	1½ in.
31	0.0250	0.39	745.0	95.0°	1	5	1½ in.
32	0.0175	0.25	745.0	80.0°	1	2	1½ in.
33	1.254	28.40	742.1	111.0°	30	583	1½ in.
34	1.142	25.80	742.1	111.0°	26	526	1½ in.
35	1.023	22.70	742.1	111.0°	23	462	1½ in.
36	0.858	19.60	742.1	111.0°	20	387	1½ in.
37	0.678	15.10	742.1	111.0°	16	302	1½ in.
38	0.4825	10.70	742.1	111.0°	12	211	1½ in.
39	0.347	7.70	742.1	111.0°	10	149	1½ in.

TABLE IIa (CONTINUED)

Run	H_L	p_v	P_B	Temp. °F.	p_1	R_o	D_o
40	0.2625	5.74	742.1	111.0°	7	111	1½ in.
41	0.201	4.48	742.1	110.0°	5	83	1½ in.
42	0.1483	3.12	742.1	110.0°	5	62	1½ in.
43	0.1150	2.66	742.1	110.0°	4	47	1½ in.
44	0.0858	1.79	742.1	109.0°	4	39	1½ in.
45	0.0608	1.30	742.1	109.0°	2	22	1½ in.
46	0.0450	0.93	742.1	108.0°	2	14	1½ in.
47	0.1533	3.44	742.1	108.0°	4	64	1½ in.

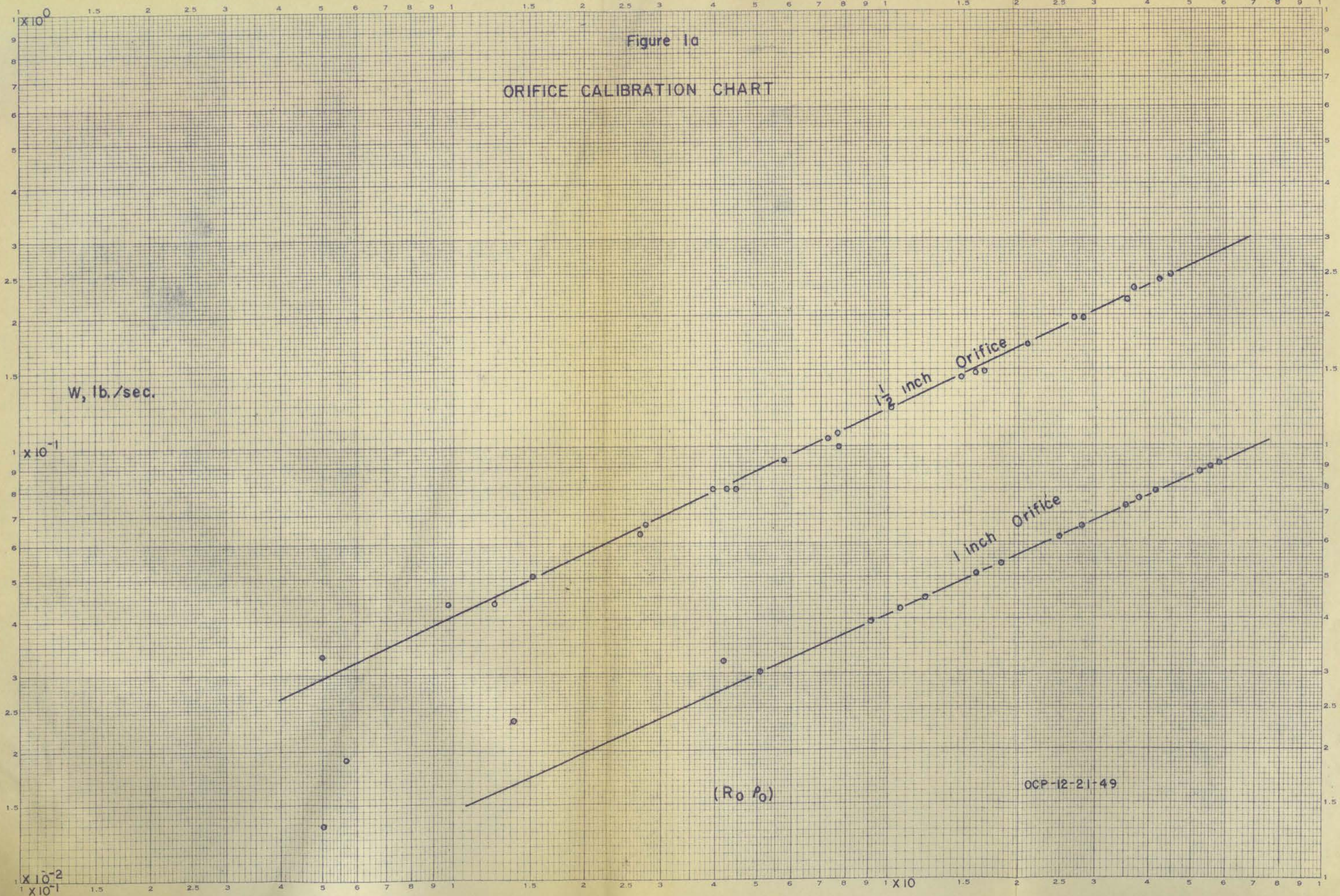


Figure 1a

ORIFICE CALIBRATION CHART

APPENDIX 4

TABLE IIIa - EXPERIMENTAL DATA

PART 1. APPARATUS AND FLOW DATA

The following table is a tabulated list of all of the experimental data taken during the course of the investigation.

Run	S	m	R_o	P1	Temp. °F.	P_B	D_o
1	0.04 in.	2	42	17	83.5	742	1 in.
2	"	"	31	15	83.5	"	"
3	"	"	23	15	83.5	"	"
4	0.08 in.	2	206	19	82.0	734	1 in.
5	"	"	144	15	82.0	"	"
6	"	"	108	11	82.0	"	"
7	"	"	61	6	82.0	"	"
8	"	"	44	5	82.0	"	"
9	"	"	22	4	82.0	"	"
10	0.12 in.	2	456	19	82.0	734	1 in.
11	"	"	361	15	82.0	"	"
12	"	"	228	11	82.0	"	"
13	"	"	124	6	82.0	"	"
14	"	"	52	5	82.0	"	"
15	"	"	25	2	81.8	"	"
16	0.16 in.	2	735	16	80.0	734	1 in.
17	"	"	433	13	80.0	"	"
18	"	"	280	8	80.0	"	"
19	"	"	145	4	80.0	"	"
20	"	"	80	4	80.0	"	"
21	"	"	32	3	79.6	"	"
22	0.20 in.	2	791	13	81.0	734	1 in.
23	"	"	656	11	81.0	"	"
24	"	"	460	7	81.0	"	"
25	"	"	314	6	81.0	"	"
26	"	"	173	4	79.8	"	"
27	"	"	82	2	79.6	"	"
28	0.24 in.	2	172	19	85.0	734	1½ in.
29	"	"	122	14	85.0	"	"
30	"	"	82	10	85.0	"	"
31	"	"	40	6	85.0	"	"

TABLE IIIa - PART 1 (CONTINUED)

Run	S	m	R_o	p_1	Temp. °F.	P_B	D_o
32	0.28 in.	2	213	19	85.5	734	1½ in.
33	"	"	154	14	85.5	"	"
34	"	"	100	11	85.5	"	"
35	"	"	54	6	85.5	"	"
36	0.32 in.	2	265	19	85.5	734	1½ in.
37	"	"	195	16	85.5	"	"
38	"	"	131	10	85.3	"	"
39	"	"	79	6	85.3	"	"
40	"	"	39	4	85.3	"	"
41	0.36 in.	2	340	22	73.0	743	1½ in.
42	"	"	274	17	73.0	"	"
43	"	"	188	14	73.0	"	"
44	"	"	113	12	73.0	"	"
45	"	"	53	6	73.0	"	"
46	"	"	35	4	73.0	"	"
47	0.04 in.	3	82	20	84.0	742	1 in.
48	"	"	60	15	84.0	"	"
49	"	"	46	12	84.0	"	"
50	"	"	25	8	84.0	"	"
51	"	"	14	6	84.0	"	"
52	0.08 in.	3	336	17	83.0	742	1 in.
53	"	"	254	15	83.0	"	"
54	"	"	161	10	83.0	"	"
55	"	"	98	7	83.0	"	"
56	"	"	48	3	83.0	"	"
57	"	"	28	3	83.0	"	"
58	0.12 in.	3	798	19	83.0	742	1 in.
59	"	"	538	15	83.0	"	"
60	"	"	382	11	83.0	"	"
61	"	"	264	9	83.0	"	"
62	"	"	165	6	83.0	"	"
63	"	"	80	4	83.0	"	"
64	"	"	36	2	83.0	"	"
65	0.16 in.	3	111	17	86.0	743	1½ in.
66	"	"	78	14	86.0	"	"
67	"	"	51	11	86.0	"	"
68	"	"	26	5	86.0	"	"

TABLE IIIa - PART 1 (CONTINUED)

Run	S	m	R_o	Pl	Temp. °F.	P_B	D_o
69	0.20 in.	3	176	16	88.5	743	$1\frac{1}{2}$ in.
70	"	"	135	14	88.5	"	"
71	"	"	92	11	88.5	"	"
72	"	"	60	8	88.5	"	"
73	"	"	25	4	88.3	"	"
74	0.24 in.	3	254	19	89.0	743	$1\frac{1}{2}$ in.
75	"	"	201	16	89.0	"	"
76	"	"	144	13	89.0	"	"
77	"	"	83	9	89.0	"	"
78	"	"	33	4	88.5	"	"
79	0.28 in.	3	364	21	89.1	743	$1\frac{1}{2}$ in.
80	"	"	297	19	89.2	"	"
81	"	"	234	16	89.4	"	"
82	"	"	155	13	89.0	"	"
83	"	"	81	7	89.0	"	"
84	"	"	37	4	89.0	"	"
85	0.32 in.	3	476	24	88.0	743	$1\frac{1}{2}$ in.
86	"	"	386	21	88.0	"	"
87	"	"	307	18	88.0	"	"
88	"	"	239	14	88.0	"	"
89	"	"	173	11	88.0	"	"
90	"	"	106	9	88.0	"	"
91	"	"	38	5	88.0	"	"
92	0.36 in.	3	520	24	75.0	742	$1\frac{1}{2}$ in.
93	"	"	384	19	75.0	"	"
94	"	"	272	15	75.0	"	"
95	"	"	171	10	75.0	"	"
96	"	"	111	7	75.0	"	"
97	"	"	62	5	75.0	"	"
98	"	"	26	2	75.0	"	"
99	0.40 in.	3	521	22	76.0	742	$1\frac{1}{2}$ in.
100	"	"	384	16	76.0	"	"
101	"	"	303	14	76.0	"	"
102	"	"	220	10	76.0	"	"
103	"	"	134	7	76.0	"	"
104	"	"	71	4	76.0	"	"
105	"	"	26	4	76.0	"	"

TABLE IIIa - PART 1 (CONTINUED)

Run	S	m	R_o	P_1	Temp. °F.	P_B	D_o
106	0.04 in.	4	124	18	87.0	742	1 in.
107	"	"	97	13	87.0	"	"
108	"	"	72	11	87.0	"	"
109	"	"	45	7	87.0	"	"
110	0.08 in.	4	348	17	87.0	742	1 in.
111	"	"	227	13	87.0	"	"
112	"	"	142	8	87.0	"	"
113	"	"	104	5	87.0	"	"
114	"	"	60	3	87.0	"	"
115	0.12 in.	4	625	16	84.5	742	1 in.
116	"	"	438	13	84.5	"	"
117	"	"	319	9	84.5	"	"
118	"	"	189	5	84.5	"	"
119	"	"	88	3	84.5	"	"
120	0.16 in.	4	137	19	74.5	742	1½ in.
121	"	"	96	14	74.5	"	"
122	"	"	54	7	74.5	"	"
123	"	"	33	6	74.5	"	"
124	0.20 in.	4	213	21	74.5	742	1½ in.
125	"	"	158	16	74.5	"	"
126	"	"	96	9	74.5	"	"
127	"	"	68	6	74.5	"	"
128	0.24 in.	4	310	24	74.5	742	1½ in.
129	"	"	285	19	74.5	"	"
130	"	"	204	15	74.5	"	"
131	"	"	139	10	74.5	"	"
132	"	"	69	7	74.5	"	"
133	"	"	41	4	74.5	"	"
134	0.28 in.	4	413	26	76.0	742	1½ in.
135	"	"	386	20	76.0	"	"
136	"	"	252	15	76.0	"	"
137	"	"	173	11	76.0	"	"
138	"	"	111	5	76.0	"	"
139	"	"	35	5	76.0	"	"

TABLE IIIa - PART 1 (CONTINUED)

Run	S	m	R_o	P1	Temp. °F.	P_B	D_o
140	0.32 in.	4	497	23	76.0	742	1½ in.
141	"	"	384	19	76.0	"	"
142	"	"	300	15	76.0	"	"
143	"	"	213	12	76.0	"	"
144	"	"	105	6	76.0	"	"
145	"	"	50	6	76.0	"	"
146	0.36 in.	4	504	22	76.0	742	1½ in.
147	"	"	382	16	76.0	"	"
148	"	"	305	14	76.0	"	"
149	"	"	217	11	76.0	"	"
150	"	"	128	7	76.0	"	"
151	"	"	57	4	76.0	"	"
152	0.40 in.	4	438	21	76.0	742	1½ in.
153	"	"	369	18	76.0	"	"
154	"	"	297	16	76.0	"	"
155	"	"	222	12	76.0	"	"
156	"	"	155	9	76.0	"	"
157	"	"	64	5	76.0	"	"
158	"	"	21	4	76.0	"	"

TABLE IIIa - EXPERIMENTAL DATA

PART 2. U-TUBE READINGS

Run	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
1	3.40	3.89	12.40	5.89	7.20	8.98	10.82	11.82	12.35	12.50
2	4.38	4.59	11.82	6.35	7.45	8.90	10.43	11.32	11.78	11.93
3	5.48	5.64	11.16	6.89	7.75	8.84	10.00	10.70	11.10	11.25
4	2.54	2.86	12.55	7.25	7.28	9.33	11.35	12.35	12.73	12.72
5	4.39	4.58	11.69	7.31	7.68	9.13	10.60	11.36	11.74	11.75
6	5.41	5.54	11.19	7.63	7.92	9.04	10.22	10.85	11.18	11.28
7	6.83	6.85	10.40	8.10	8.31	8.99	9.69	10.10	10.35	10.49
8	7.38	7.39	10.40	8.05	8.47	8.92	9.50	9.84	10.02	10.13
9	8.14	8.15	9.55	8.60	8.71	8.97	9.25	9.44	9.53	9.59
10	2.57	2.94	12.41	7.15	7.32	9.26	11.29	12.25	12.68	12.72
11	3.90	4.15	11.82	7.45	7.62	9.16	10.74	11.59	11.96	12.06
12	5.63	5.81	10.94	7.90	8.04	9.05	10.13	10.69	11.00	11.10
13	7.06	7.15	10.17	8.10	8.44	9.00	9.60	9.97	10.15	10.26
14	8.15	8.19	9.55	8.70	8.75	9.00	9.26	9.43	9.52	9.58
15	8.55	8.57	9.29	8.83	8.86	9.00	9.13	9.22	9.27	9.32
16	3.55	3.82	11.75	7.66	7.65	9.26	10.93	11.79	12.20	12.15
17	5.74	5.86	10.82	8.09	8.11	9.09	10.13	10.70	11.02	11.09
18	6.90	7.00	10.24	8.37	8.41	9.04	9.72	10.10	10.34	10.40
19	7.79	7.84	9.72	8.63	8.67	9.02	9.42	9.66	9.78	9.84
20	8.30	8.32	9.47	8.80	8.82	9.02	9.25	9.39	9.48	9.51
21	8.69	8.71	9.25	8.92	8.94	9.02	9.14	9.19	9.24	9.25
22	5.09	5.20	11.20	8.07	8.01	9.15	10.37	11.01	11.33	11.56
23	5.71	5.83	10.90	8.19	8.17	9.11	10.14	10.69	11.00	11.20
24	6.64	6.73	10.40	8.39	8.39	9.07	9.82	10.25	10.49	10.68
25	7.36	7.43	10.05	8.59	8.59	9.05	9.59	9.89	10.07	10.23
26	8.10	8.13	9.64	8.78	8.78	9.05	9.35	9.32	9.63	9.74
27	8.58	8.60	9.36	8.93	8.93	9.05	9.20	9.30	9.35	9.39
28	3.40	3.55	12.00	7.82	7.74	9.30	11.01	11.90	12.36	12.85
29	5.01	5.10	11.26	8.14	8.10	9.22	10.43	11.10	11.48	11.87
30	6.28	6.35	10.65	8.40	8.37	9.15	10.04	10.52	10.80	11.10
31	7.70	7.75	9.96	8.75	8.75	9.14	9.59	9.84	10.00	10.14
32	3.91	4.06	11.75	7.96	7.79	9.25	10.81	11.67	12.15	12.90
33	5.28	5.36	11.10	8.22	8.14	9.18	10.35	11.00	11.40	11.81
34	6.55	6.69	10.52	8.47	8.45	9.15	9.92	10.40	10.68	11.00
35	7.71	7.75	9.93	8.75	8.74	9.14	9.58	9.84	10.02	10.20

TABLE IIIa - PART 2 (CONTINUED)

Run	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
36	4.12	4.18	12.05	7.95	7.92	9.20	10.65	11.55	12.05	12.63
37	5.36	5.50	11.25	8.25	8.23	9.21	10.28	10.94	11.38	11.83
38	6.60	6.65	10.60	8.52	8.50	9.15	9.90	10.39	10.73	11.04
39	7.62	7.67	10.05	8.77	8.76	9.15	9.60	9.90	10.10	10.33
40	8.40	8.44	9.64	8.95	9.00	9.15	9.40	9.54	9.63	9.77
41	3.80	3.92	12.10	8.06	8.10	9.44	11.00	11.95	12.40	12.75
42	4.95	5.03	11.80	8.24	8.29	9.36	10.60	11.34	11.80	12.13
43	6.25	6.26	11.05	8.53	8.56	9.30	10.20	11.73	11.07	11.36
44	7.52	7.56	10.23	8.84	8.85	9.28	9.80	10.10	10.33	10.53
45	8.35	8.36	9.82	9.04	9.05	9.28	9.54	9.74	9.84	9.94
46	8.97	8.99	9.48	9.20	9.22	9.29	9.38	9.44	9.50	9.52
47	2.25	2.50	12.80	6.75	8.12	9.34	10.78	11.22	12.15	12.59
48	3.90	4.06	11.79	7.32	8.24	9.17	10.27	10.55	11.33	11.68
49	5.24	5.41	10.98	7.66	8.35	9.04	9.86	10.07	10.70	10.94
50	6.60	6.72	10.22	7.96	8.50	8.91	9.43	9.59	9.97	10.17
51	7.45	7.55	9.65	8.20	8.60	8.86	9.17	9.28	9.51	9.65
52	3.03	3.25	12.60	9.74	8.83	9.84	11.06	11.40	12.28	12.60
53	4.62	4.79	11.89	9.55	8.93	9.70	10.64	10.90	11.60	11.88
54	6.14	6.25	11.20	9.46	9.03	9.58	10.25	10.44	10.95	11.20
55	7.34	7.40	10.61	9.30	9.16	9.51	9.94	10.09	10.44	10.63
56	8.35	8.37	10.06	9.30	9.27	9.46	9.69	9.76	9.94	10.05
57	8.75	8.77	9.82	9.30	9.33	9.45	9.58	9.63	9.75	9.83
58	2.50	2.80	12.50	10.73	8.83	9.80	10.95	11.32	12.20	12.63
59	4.58	4.79	11.65	10.19	8.94	9.65	10.49	10.75	11.42	11.77
60	5.84	5.99	11.16	9.83	9.02	9.54	10.19	10.40	10.93	11.26
61	6.88	6.98	10.70	9.59	9.10	9.47	9.93	10.10	10.49	10.76
62	7.72	7.83	10.25	9.46	9.17	9.42	9.74	9.85	10.10	10.29
63	8.50	8.52	9.89	9.39	9.26	9.40	9.58	9.64	9.78	9.90
64	8.90	8.93	9.63	9.61	9.32	9.39	9.49	9.52	9.60	9.65
65	2.35	2.55	10.35	9.00	7.50	8.20	9.15	9.45	10.25	11.00
66	4.00	4.10	9.75	8.55	7.55	8.10	8.80	9.05	9.63	10.17
67	5.25	5.32	9.25	8.27	7.67	8.05	8.53	8.70	9.10	9.50
68	6.50	6.53	8.77	8.04	7.77	8.00	8.25	8.36	8.58	8.81
69	2.57	2.80	10.07	9.20	7.55	8.17	9.05	9.34	10.07	10.90
70	3.60	3.80	9.75	8.85	7.63	8.12	8.82	9.08	9.68	10.38
71	4.90	5.03	9.28	8.46	7.66	8.04	8.55	8.75	9.17	9.71
72	5.97	6.04	8.86	8.20	7.73	7.98	8.32	8.46	8.76	9.12
73	2.05	7.08	8.36	8.00	7.84	7.95	8.10	8.17	8.30	8.45

TABLE IIIa - PART 2 (CONTINUED)

Run	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
74	2.40	2.63	10.32	9.20	7.55	8.17	9.04	9.37	10.15	10.85
75	3.50	3.70	9.90	9.85	7.60	8.10	8.80	9.10	9.74	10.27
76	4.70	4.84	9.37	8.51	7.66	8.04	8.58	8.79	9.26	9.70
77	6.00	6.10	8.82	8.20	7.75	8.00	8.30	8.44	8.74	9.00
78	7.09	7.13	8.30	7.98	7.83	7.92	8.07	8.14	8.26	8.43
79	2.37	2.55	10.21	9.05	7.61	8.19	9.00	9.33	10.12	11.02
80	3.15	3.30	9.93	8.85	7.62	8.10	8.83	9.14	9.82	10.63
81	4.10	4.21	9.55	8.62	7.67	8.04	8.63	8.90	9.45	10.10
82	5.32	5.43	9.04	8.33	7.71	8.00	8.40	8.58	8.96	9.44
83	6.50	6.55	8.53	8.07	7.79	7.94	8.17	8.28	8.50	8.76
84	7.23	7.25	8.20	7.96	7.85	7.90	8.02	8.08	8.18	8.32
85	2.15	2.20	10.30	8.95	7.72	8.15	9.00	9.38	10.22	11.30
86	3.10	3.22	9.90	8.75	7.70	8.09	8.79	9.10	9.82	10.75
87	4.00	4.07	9.57	8.55	7.70	8.04	8.62	8.88	9.46	10.22
88	4.80	4.89	9.20	8.35	7.72	7.99	8.45	8.67	9.15	9.76
89	5.63	5.70	8.85	8.18	7.75	7.94	8.30	8.46	8.80	9.27
90	6.24	6.27	8.51	8.04	7.78	7.91	8.14	8.25	8.46	8.75
91	7.31	7.34	8.12	7.93	7.84	7.89	7.98	8.02	8.12	8.22
92	2.87	2.95	10.06	8.75	7.84	8.18	8.90	9.28	10.04	11.15
93	4.02	4.10	9.63	8.56	7.83	8.12	8.68	8.98	9.57	10.45
94	5.13	5.17	9.20	8.37	7.86	8.07	8.50	8.70	9.15	9.78
95	6.14	6.17	8.78	8.20	7.87	8.02	8.30	8.43	8.73	9.15
96	6.75	6.78	8.51	8.10	7.92	8.01	8.19	8.29	8.48	8.75
97	7.27	7.29	8.27	8.04	7.94	7.99	8.10	8.15	8.26	8.41
98	7.70	7.72	8.09	8.00	7.96	7.98	8.02	8.05	8.10	8.15
99	3.75	3.80	9.80	8.59	7.98	8.21	8.77	9.05	9.65	10.36
100	4.80	4.84	9.36	8.43	7.95	8.13	8.55	8.78	9.25	9.80
101	5.42	5.47	9.11	8.32	7.93	8.09	8.44	8.63	9.00	9.45
102	6.08	6.12	9.06	8.23	7.93	8.05	8.31	8.45	8.74	9.07
103	6.78	6.81	8.50	8.10	7.94	8.01	8.19	8.26	8.45	8.65
104	7.33	7.35	8.25	8.03	7.95	8.00	8.08	8.14	8.22	8.34
105	7.70	7.72	8.07	8.00	7.96	7.99	8.02	8.04	8.07	8.12
106	2.46	2.79	12.14	8.37	8.76	9.71	10.60	11.14	11.50	12.60
107	4.13	4.34	11.54	8.34	8.74	9.46	10.19	10.62	11.04	11.80
108	5.55	5.72	10.74	8.42	8.75	9.30	9.81	10.15	10.49	11.00
109	6.76	6.90	10.17	8.52	8.79	9.15	9.50	9.75	9.95	10.31

TABLE IIIa - PART 2 (CONTINUED)

Run	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
110	2.81	3.04	11.28	10.42	9.04	9.67	10.29	10.65	10.89	11.96
111	4.82	4.95	10.63	9.68	9.01	9.44	9.87	10.14	10.37	11.08
112	6.28	6.35	10.10	9.33	8.98	9.26	9.55	9.75	9.93	10.41
113	7.25	7.30	9.68	9.15	8.94	9.15	9.35	9.49	9.62	9.91
114	8.05	8.07	9.40	9.04	8.96	9.07	9.17	9.25	9.33	9.49
115	3.55	3.74	11.36	11.42	9.47	9.94	10.42	10.75	10.92	11.91
116	5.48	5.63	10.69	10.57	9.38	9.71	10.06	10.30	10.48	11.13
117	6.54	6.63	10.34	10.14	9.33	9.59	9.85	10.02	10.18	10.64
118	7.78	7.83	9.92	9.70	9.31	9.46	9.61	9.72	9.84	10.09
119	8.57	8.59	9.63	9.47	9.31	9.39	9.46	9.52	9.57	9.71
120	2.43	2.65	11.41	11.90	9.32	9.88	10.43	10.81	11.06	12.30
121	4.81	4.96	10.65	10.78	9.20	9.60	10.00	10.25	10.50	11.29
122	6.61	6.69	10.13	10.02	9.14	9.40	9.65	9.82	10.00	10.52
123	7.58	7.63	9.80	9.65	9.14	9.30	9.49	9.59	9.70	10.02
124	2.36	2.55	11.14	12.17	9.31	9.84	10.44	10.82	11.11	12.73
125	4.27	4.40	10.67	11.20	9.24	9.64	10.10	10.38	10.64	11.82
126	6.29	6.38	10.12	10.25	9.17	9.45	9.73	9.92	10.12	10.80
127	7.59	7.64	9.75	9.70	9.15	9.34	9.50	9.60	9.75	10.10
128	2.58	2.73	11.80	12.67	9.70	10.20	10.73	11.18	11.50	13.00
129	4.00	4.11	11.43	11.93	9.65	10.08	10.54	10.89	11.14	12.33
130	5.49	5.57	11.00	11.24	9.59	9.93	10.29	10.54	10.79	11.67
131	6.82	6.91	10.56	10.59	9.53	9.79	10.05	10.25	10.44	11.03
132	8.13	8.17	10.14	10.05	9.52	9.67	9.82	9.94	10.05	10.36
133	8.95	8.99	9.84	9.76	9.55	9.62	9.68	9.75	9.79	9.92
134	3.00	3.11	11.90	12.42	9.70	10.18	10.71	11.14	11.50	12.90
135	4.25	4.33	11.50	11.80	9.66	10.05	10.51	10.89	11.20	12.32
136	5.92	5.98	10.95	11.04	9.61	9.92	10.25	10.50	10.74	11.53
137	7.01	7.05	10.58	10.57	9.59	9.82	10.06	10.25	10.43	10.96
138	8.13	8.16	10.19	10.13	9.57	9.75	9.88	10.00	10.10	10.42
139	9.06	9.08	9.84	9.78	9.62	9.65	9.72	9.76	9.80	9.92
140	2.44	2.50	9.77	10.02	8.00	8.32	8.80	9.20	9.56	11.13
141	3.60	3.65	9.39	9.52	7.97	8.25	8.62	8.95	9.25	10.50
142	4.47	4.52	9.12	9.18	7.95	8.20	8.50	8.75	9.00	10.00
143	5.42	5.46	8.81	8.81	7.92	8.10	8.34	8.53	8.73	9.42
144	6.66	6.68	8.38	8.34	7.93	8.01	8.14	8.25	8.35	8.70
145	7.31	7.35	8.16	8.11	7.95	7.96	8.03	8.08	8.14	8.30

TABLE IIIa - PART 2 (CONTINUED)

Run	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
146	3.14	3.45	9.44	9.60	8.09	8.26	8.68	9.00	9.27	10.55
147	4.52	4.54	9.09	9.14	8.03	8.19	8.50	8.75	9.00	9.94
148	5.13	5.15	8.91	8.91	8.01	8.14	8.41	8.60	8.82	9.60
149	5.90	5.94	8.66	8.62	7.98	8.08	8.30	8.43	8.59	9.14
150	6.73	6.75	8.37	8.32	7.97	8.02	8.15	8.25	8.34	8.65
151	7.55	7.57	8.08	8.05	7.98	7.92	8.00	8.04	8.06	8.16
152	4.05	4.08	9.30	9.24	8.20	8.25	8.57	8.83	9.10	10.02
153	4.62	4.66	9.12	9.06	8.17	8.20	8.50	8.72	8.95	9.75
154	5.28	5.31	8.90	8.84	8.13	8.15	8.40	8.58	8.78	9.40
155	5.98	6.02	8.66	8.60	8.06	8.09	8.28	8.42	8.57	9.03
156	6.59	6.61	8.45	8.38	8.03	8.05	8.17	8.27	8.38	8.68
157	7.18	7.19	8.25	8.19	8.03	8.00	8.08	8.14	8.20	8.36
158	7.59	7.60	8.10	8.05	8.00	7.98	8.01	8.04	8.06	8.15

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