CALIBRATION OF A VENTURI TUBE

FOR

MODEL PUMP TEST

Prepared for

Fairbanks-Morse, Inc.

Colorado State University
Engineering Research Center
Fort Collins, Colorado

January 1965

CER65SSK4

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General

Calibration of a 16 x $10\frac{1}{2}$ in. Simplex Type VT No. T8757 venturi tube was authorized through issuance of Purchase Order No. 155085-3 dated October 21, 1964 by Colt Industries, Inc., Fairbanks-Morse, Inc. Pump Division, Kansas City, Kansas.

The pump model test at Kansas City required that--

> "--The model discharge shall be measured directly by accurately calibrated gravimetric or volumetric equipment; or indirectly by means of a venturi tube,--provided the device used is calibrated in situ by gravimetric or volumetric equipment. The equipment or device as installed shall be capable of indicating and responding to a change in discharge not greater than plus or minus 0.5 percent of the model discharge at the range of discharge between 50 and 100 percent. Also, the maximum variance of the device at any model discharge, within the above range, shall not exceed plus or minus 0.5 percent from the true discharge, as determined by plotting the indicated values against true values. Proper corrections shall be made where necessary for the effect of temperature, barometric pressure, gravity, and local water density--.".

In view of the requirement quoted above, one section of the test loop at the Kansas City Laboratory of Faribanks-Morse was shipped and adapted to the calibration facility at the Engineering Research Center at Colorado State University. A schematic drawing of the calibration facility at CSU, including the portion of the test loop is shown in Fig. 1.

The Venturi Tube

The venturi tube is a well-known flow meter. The discussion herein is therefore intended only to lend completeness to this report. The venturi tube is a device to accelerate the fluid and temporarily lower its static pressure. Suitable pressure connections are provided to measure the magnitude of the reduced static pressure at the constricted section. A typical form of the hydraulic gradient is shown in Fig. 2. In the figure, h is the difference in the levels of the free fluid column attached to points 1 and 2, which is the difference in static pressures measured at the conduit wall. The magnitude of h is subject to variation depending upon the velocity of flow, the acceleration through the tube and the friction and form losses between sections 1 and 2.

Writing the Bernoulli equation along a streamline, in this case, the centerline of the pipe and venturi tube,

$$\frac{V_1^2}{2g} + \frac{p_1}{\rho g} = \frac{V_2^2}{2g} + \frac{p_2}{\rho g} + h_f \qquad (1)$$

where V = velocity at the point under consideration in ft/sec,

p = pressure at the same point in lb/ft^2,

g = local gravitational acceleration, ft/sec^2,

ρ = fluid mass density, lb-sec^2/ft^4,

h_f = energy loss per pound of fluid between point 1 and 2, ft-lb/lb,

subscripts 1 and 2 refer to successive points along the stream line.

From Fig. 2, and Eq. (1)

$$h = \frac{1}{\rho g}(p_1 - p_2) = \frac{1}{2g}(V_2^2 - V_1^2) + h_f \qquad (2)$$

For physical convenience, pressures are measured at the walls of the conduit rather than at the centerline. In practice therefore, differences in wall pressures are measured, rather than pressures at the centerline, and a calibration is generally performed to determine the relationship of h to volume flow rate Q. Where accurate flow measurement is desired, the venturi tube as all other flow meters, must be calibrated periodically when changes in wall roughness, or otherwise small changes in flow geometry are suspect.

The calibrated relationship of h to Q can most conveniently be expressed in graphical form. However, where a meter is calibrated at one location and is used at another, the relationship of h to Q determined at the calibration site requires correction at the location of use because of change in local gravitational acceleration and specific weights of the fluid. To be accurate within the limits specified heretofore, it is more convenient to determine a discharge coefficient for the flow meter. The discharge coefficient may be expressed as

$$C = \frac{\text{actual mass flow rate} \quad \rho Q_a}{\text{theoretical mass flow rate} \quad \rho Q_t} \tag{3}$$

or where the mass density is a constant,

$$C = \frac{Q_a}{Q_t} \tag{4}$$

where Q_a = actual volume rate of flow,

Q_t = theoretical volume rate of flow.

The coefficient of discharge is a function of wall roughness, conduit geometry, and flow and fluid properties. It can thus be expressed more conveniently as a function of Reynolds number, $R = \frac{V_2 d_2}{\nu}$, where d_2 is the venturi tube throat diameter.

Expressing the theoretical discharge in terms of the throat diameter and velocity,

$$Q_t = A_2 \sqrt{2g\left(\frac{p_1 - p_2}{\rho g}\right)} \left(\frac{1}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)}}\right) . \tag{5}$$

Let $\frac{A_2}{A_1} = \left(\frac{d_2}{d_1}\right)^2 = \beta^2$,

So that $Q_t = A_2 \sqrt{\frac{2\Delta p}{\rho}} \left(\frac{1}{\sqrt{1-\beta^4}}\right) .$ (6)

For the venturi meter calibrated the following quantities were used:

d_1 = 16 in.

d_2 = 10.5 in.

$A_2 = \frac{\pi d_2^2}{4} = 86.588 \text{ in.}^2 = 0.6013 \text{ ft}^2$

$\beta^4 = \left(\frac{10.5}{16}\right)^4 = .18547$

$g = 32.1441 \text{ ft/sec}^2$

ρ of water varies with temperature, see Fig. 3.

γ = ρg , of water varies with temperature, see Fig. 3.

ν = $\frac{\mu}{\rho}$ of water varies with temperature, see Fig. 4.

S = specific gravity of barium = 2.95.

Calibration Procedure

Water flow through the calibration system was supplied by a Fairbanks-Morse turbine pump. Discharge through the venturi was controlled by the valve downstream of the venturi tube shown in Fig. 1. At each change of discharge, sufficient time was allowed to establish steady flow. Pressure differential was measured with a differential barium-water manometer and a water-air differential manometer, which was also sloped for greater accuracy at the low discharges.

Discharge measurements were made volumetrically in a calibrated tank and with a calibrated clock measuring time to the nearest 0.01 second. The volumetric tank was calibrated by the weight method, and the scale used for this purpose was in turn calibrated with standard weights checked by the U.S. Bureau of Standards at Boulder, Colorado. The specific weight of water used in the calibration of the tank was corrected for temperature and local gravitational acceleration. Weight of water was corrected for air buoyancy. The clock or timer used was calibrated against standard time signal broadcast by the N.B.S., and the electrical line frequency at the laboratory was checked against N.B.S. traceable standard frequency and was found to be 60 00 c.p.s. The accuracy of the calibration system is given in the following table:

Table of Calibration Fixture Accuracies

Item	Method of Reading	Reading Accuracy	Accuracy Absolute Units	Total Capacity	Accuracy Percent
Large Volumes	Hook Gage	$\pm$0.001 ft	$\pm$2.0 gal	8800 gal	.022
Small Volumes	Hook Gage	$\pm$0.001 ft	$\pm$1.0 gal	3850 gal	.025
Time	Electric Clock	------	$\pm$ .01 sec	60 sec. (minimum)	.016
				Total Accuracy	.041 percent

There is another possible source of error in the diverting mechanism of the calibration stand. The diverting equipment is designed to operate with balanced time intervals between diverting flow into the tank and into the wasteway (see Fig. 1). The total time interval for a swing one way requires 1.4 seconds. Assuming that an error of .1 sec could occur in the swing time intervals and with maximum discharge through the calibration system, of 10,000 gpm, an error of 16.7 gallons can occur in the volumetric increment relative to the correct time interval. Thus an additional percent error of 0.189 could occur. Adding this to the accuracy of the fixture gives an overall accuracy of 0.227 percent, well within the ±0.5 percent required for the pump model tests.

Calibration Results

The results of the calibration are shown in Fig. 5 with discharge Q as a function of pressure differential Δp in psi, and discharge coefficient C as a function of Reynolds No. in Fig. 6. The calibration data are given in a separate table appended to this report. The curve in Fig. 5 is of course too small in scale to read within the desired accuracy of ±0.5 percent.

In Fig. 6, an average curve in solid line is drawn "by eye" through the data points. A dashed line is also drawn parallel to the curve to indicate the limits of the ±0.5 percent accuracy. It will be noted that all data points can be made to lie within the band, except at the lowest discharge, where the accuracy appears to be within ±0.7%. Also drawn as a broken line curve on Fig. 6 is an approximate "theoretical" curve offered by The Simplex Valve and Meter Co. for this valve on May 14, 1943. The term approximate is used here because the throat Reynolds numbers cannot be calculated without assuming a water temperature. It is to be noted that the "theoretical" curve lies within the 0.5 percent band.

As a supplement to the calibration of this venturi tube, several velocity profiles were taken in the approach pipe to the venturi tube at different discharges. The purpose of these profiles was to show that the flow conditions under which the calibration were made represented the flow conditions at the laboratory where the pump tests were to be performed. The velocity profiles taken at the Engineering Research Center of Colorado

State University are shown in Figures 7, 8 and 9. For comparison purposes, the velocity profiles taken at the Kansas City Laboratory are shown in Figs. 10, 11, and 12. Although the discharges do not correspond exactly, suitable comparisons can be made.

A Cole pitot meter supplied by the Fairbanks-Morse Company was used to make the velocity measurements. A differential Pace pressure transducer was used with the pitometer. The pressure transducer was calibrated at the site at the water temperature during the velocity measurements. The rating curve for the Cole pitometer was supplied by the Fairbanks-Morse Company and is shown as Fig. 13. The data and computations for the velocity traverses are appended.

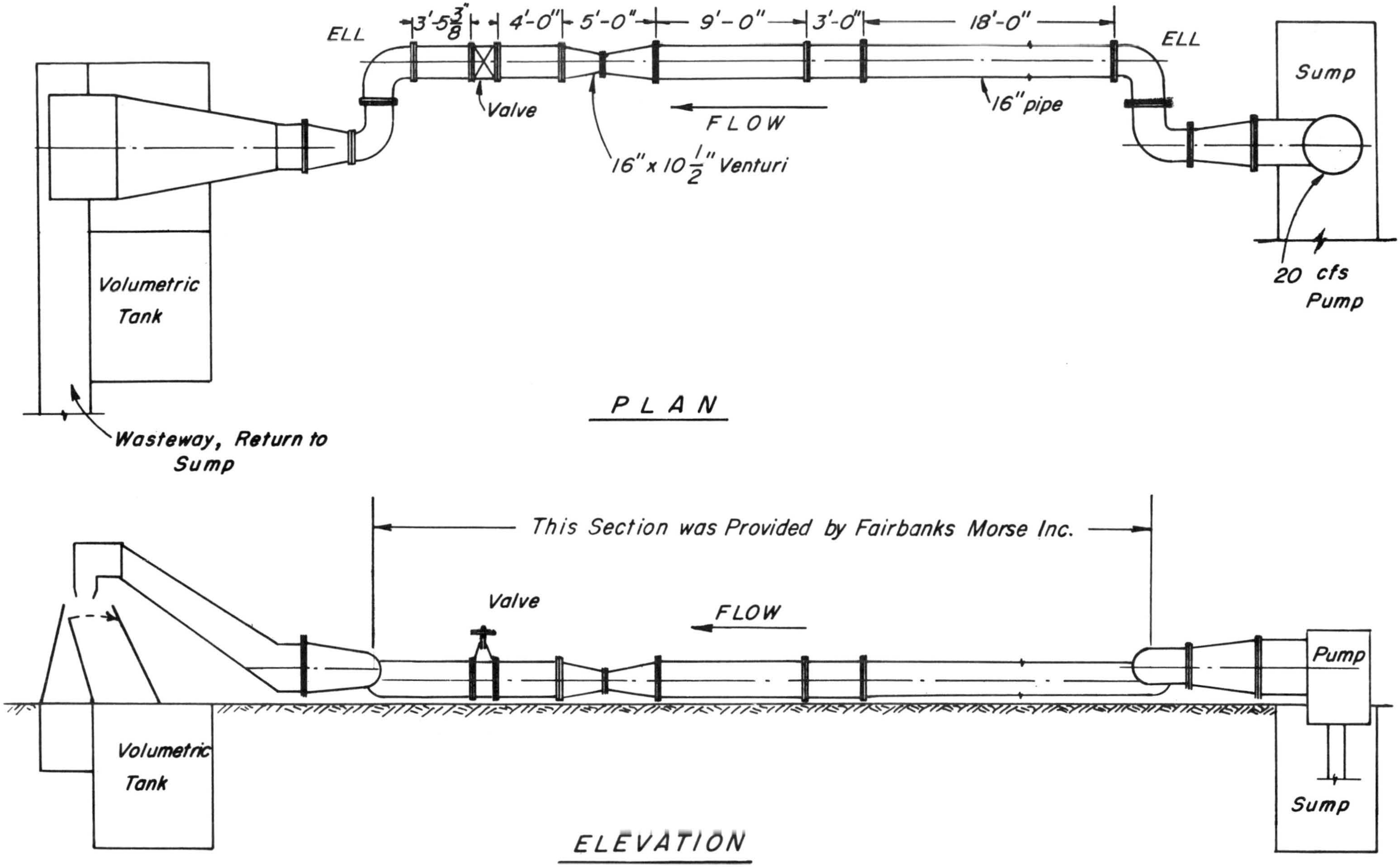

FIGURE 1 SCHEMATIC DRAWING OF CALIBRATION FACILITY

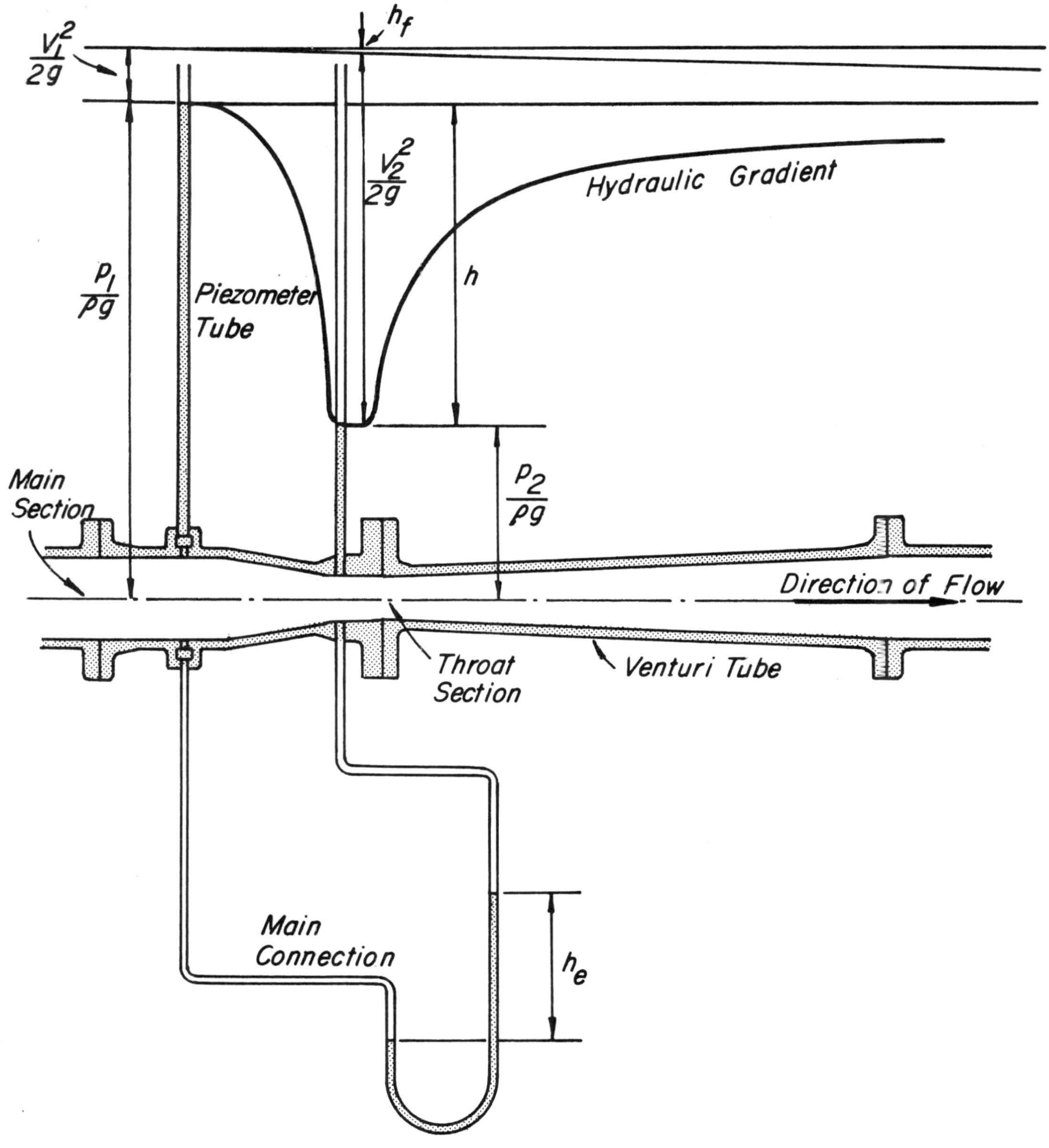

FIGURE 2 TYPICAL HYDRAULIC GRADIENT THROUGH VENTURI TUBE

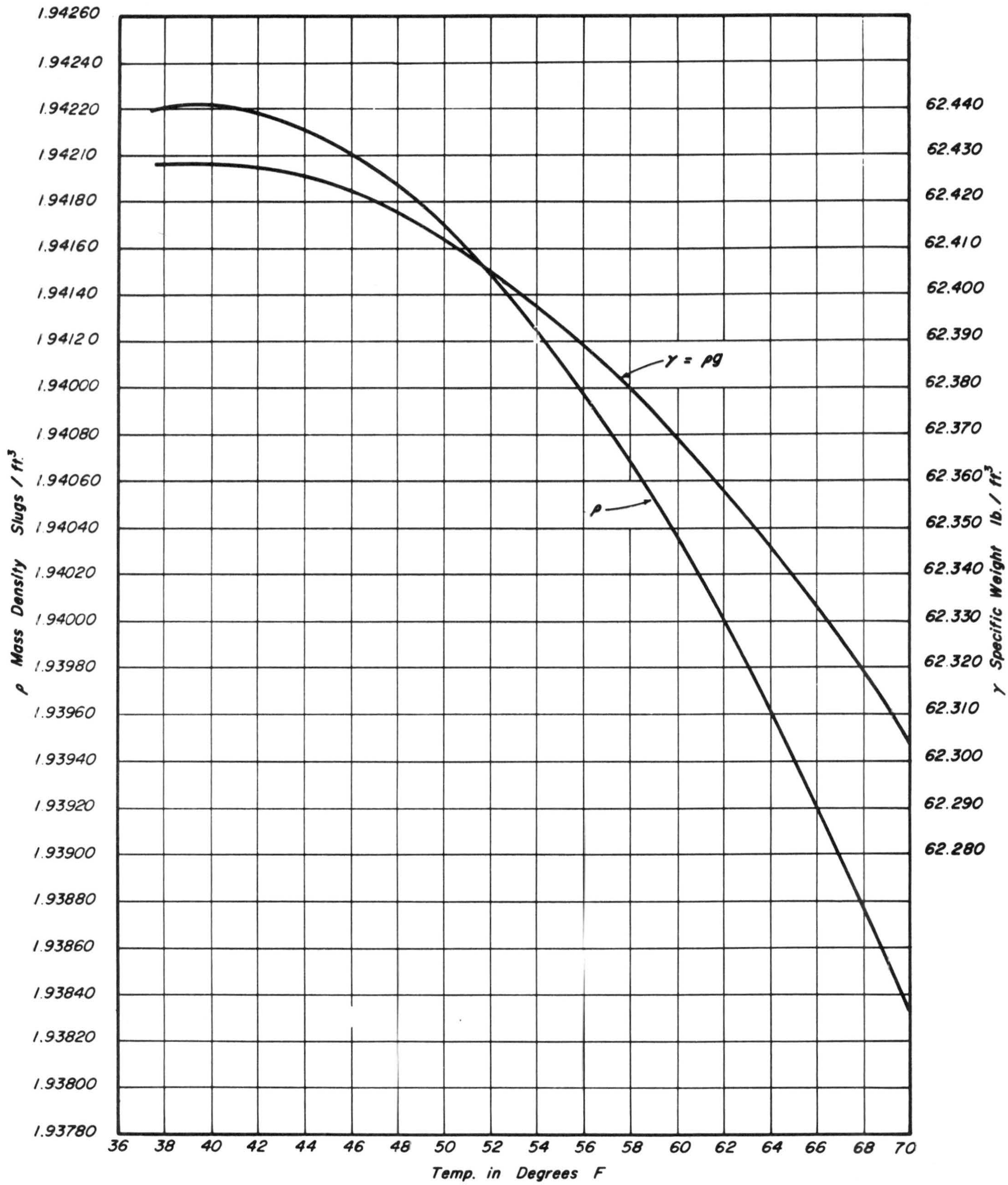

FIGURE 3 MASS DENSITY ρ AND SPECIFIC WEIGHT γ

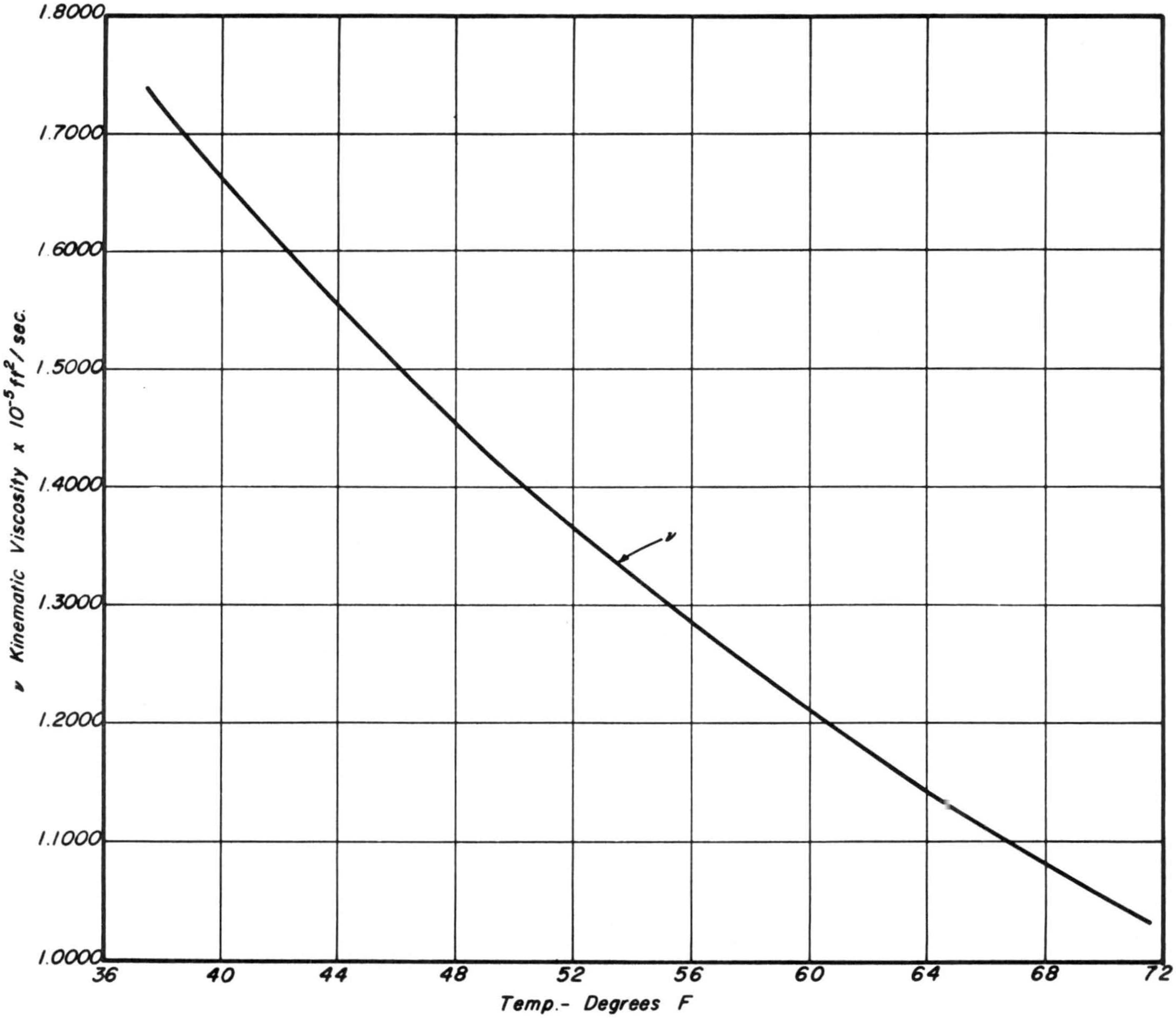

FIGURE 4 KINEMATIC VISCOSITY OF WATER

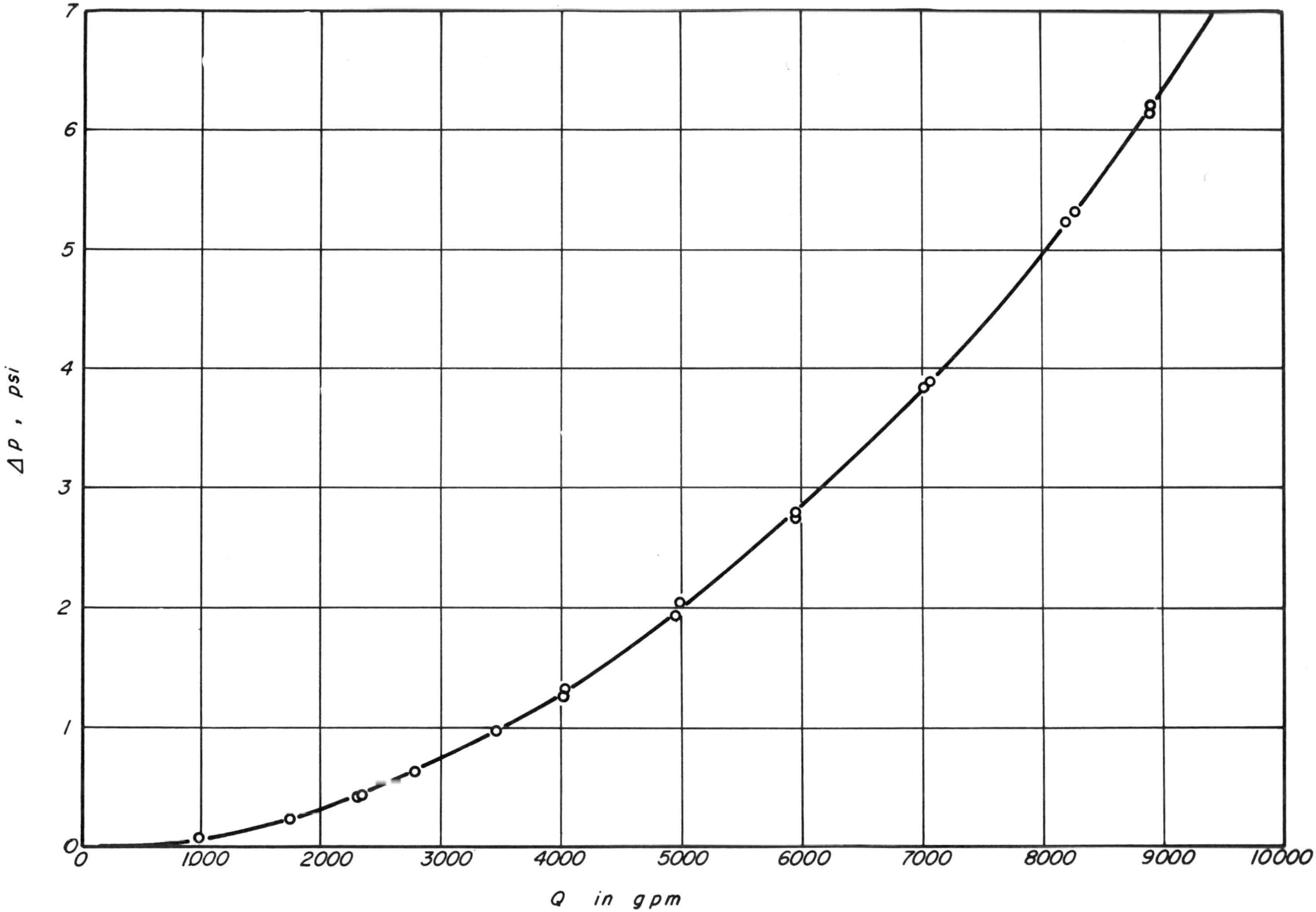

FIGURE 5 VARIATION OF DISCHAGE WITH DIFFERENTIAL PRESSURE

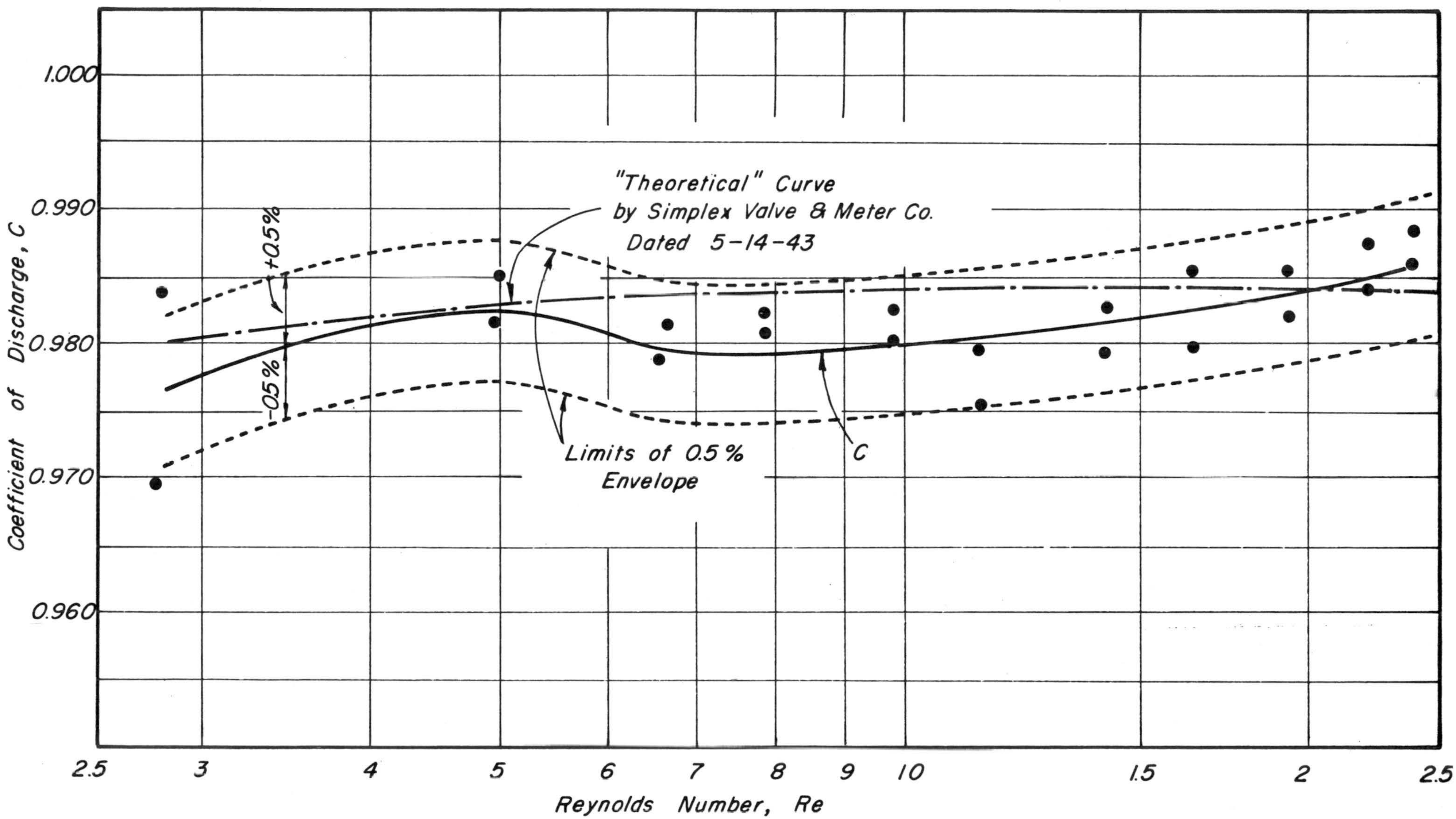

FIGURE 6 VARIATION OF DISCHARGE COEFFICIENT C WITH REYNOLDS NUMBER

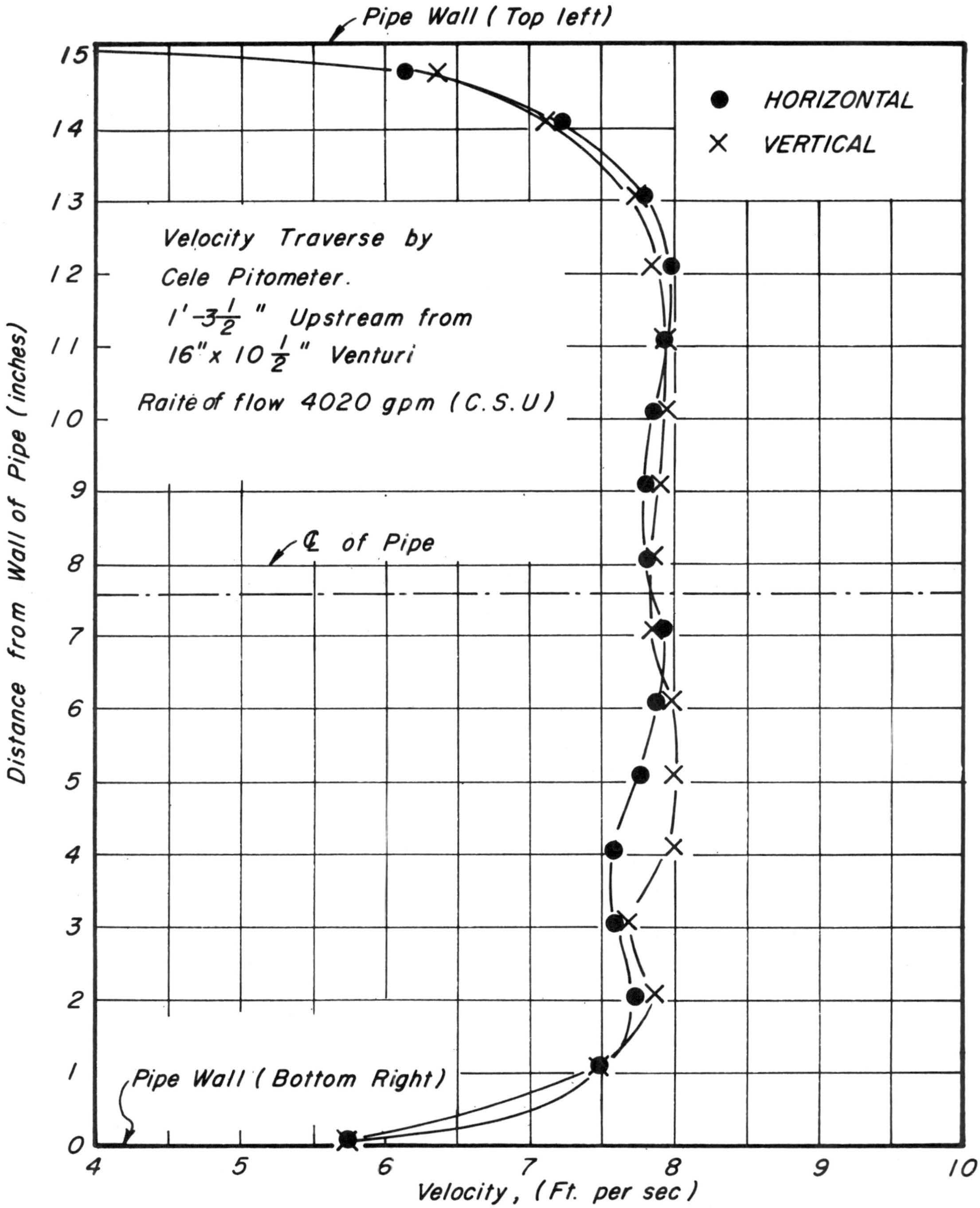

FIGURE 7 VELOCITY PROFILES

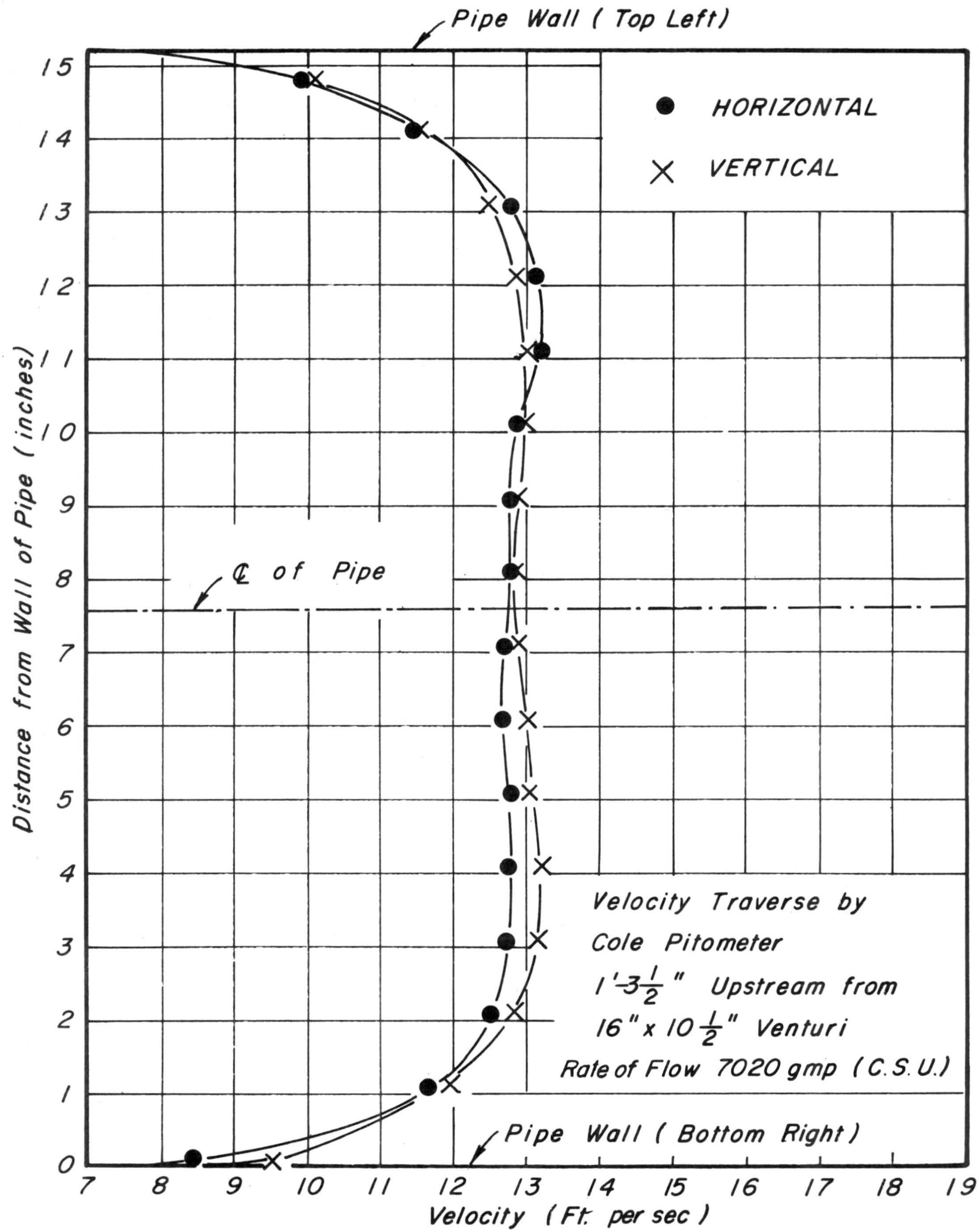

FIGURE 8 VELOCITY PROFILE

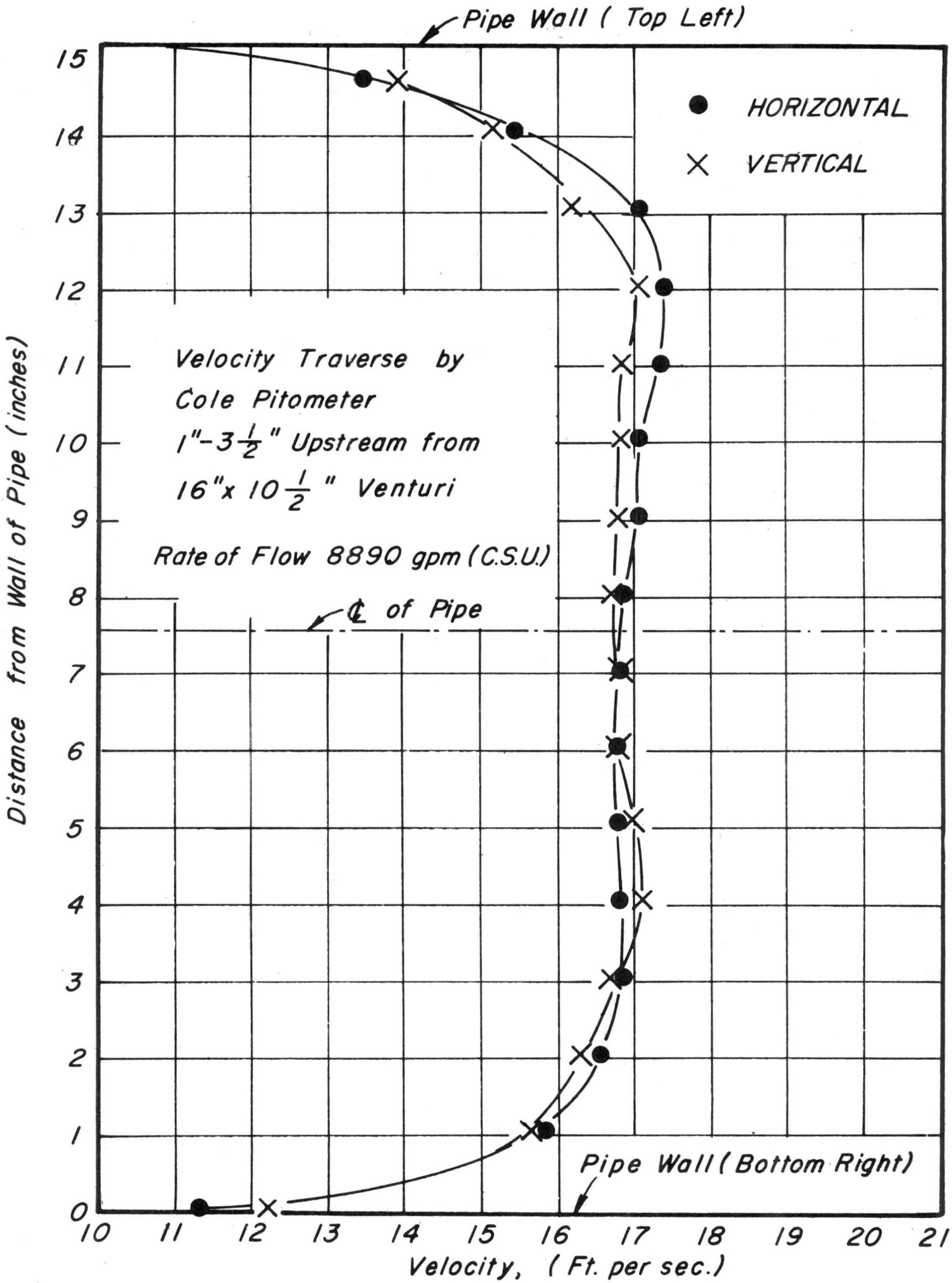

FIGURE 9 VELOCITY PROFILES

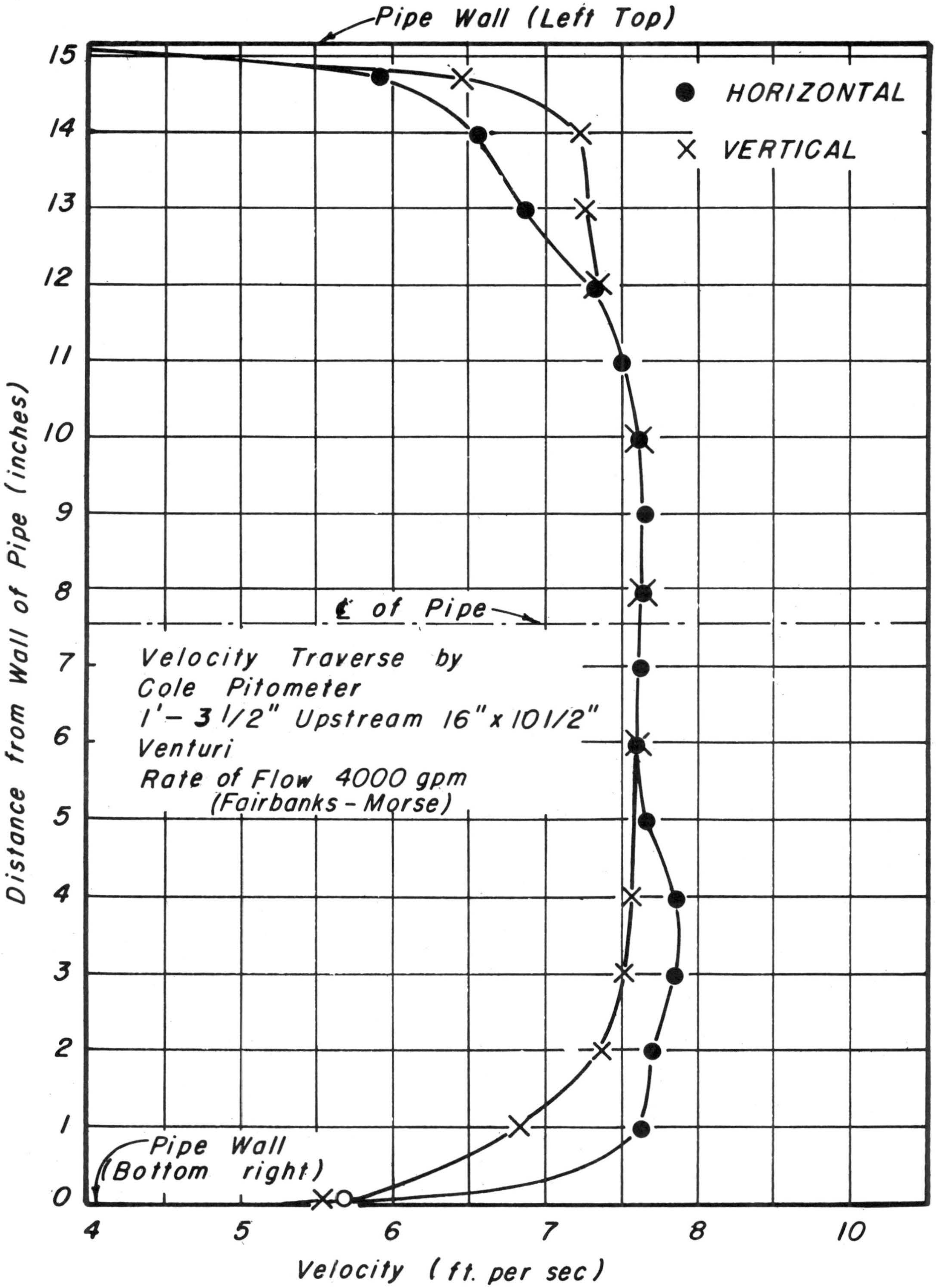

FIGURE 10 VELOCITY PROFILES

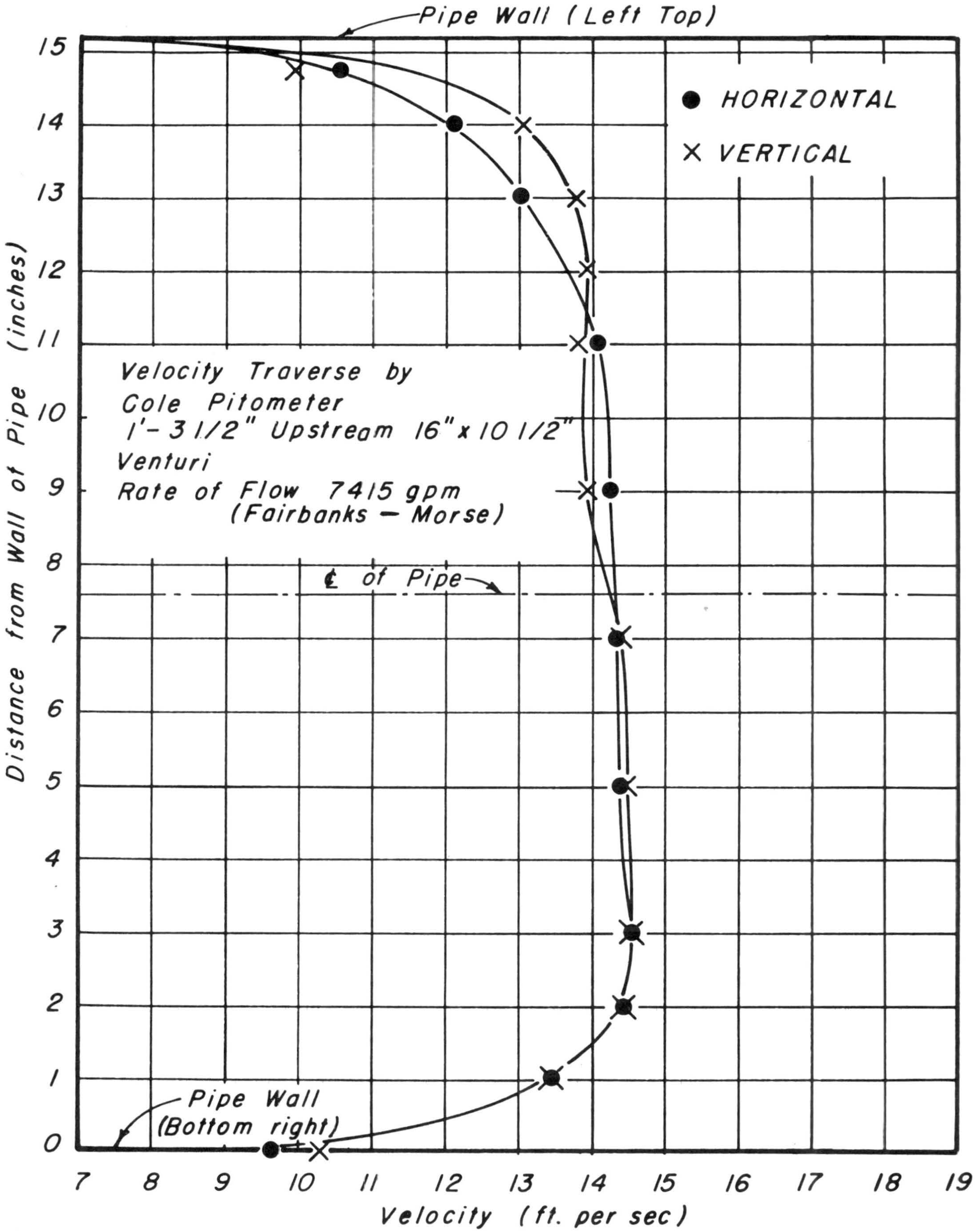

FIGURE 11 VELOCITY PROFILES

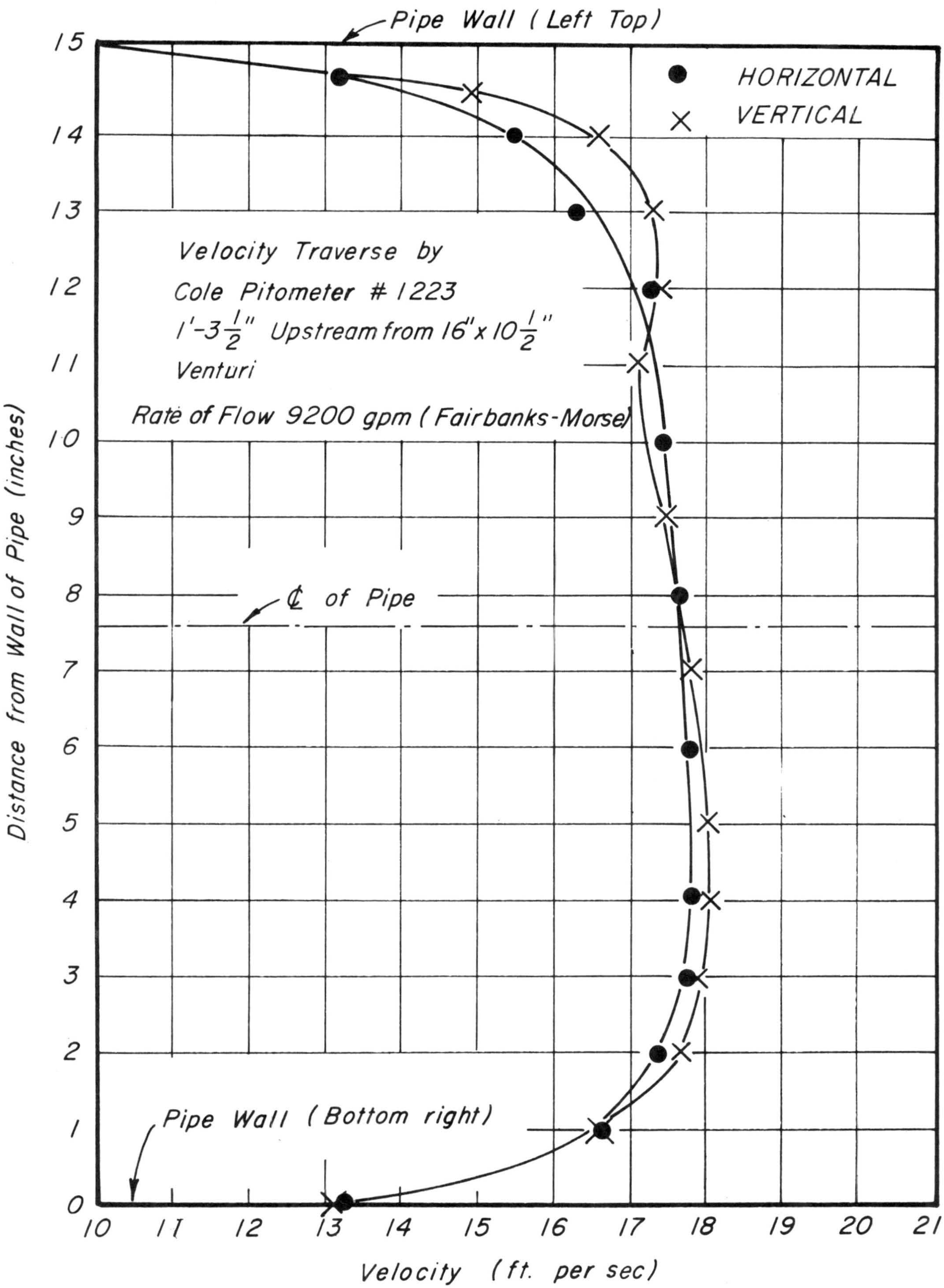

FIGURE 12 VELOCITY PROFILES

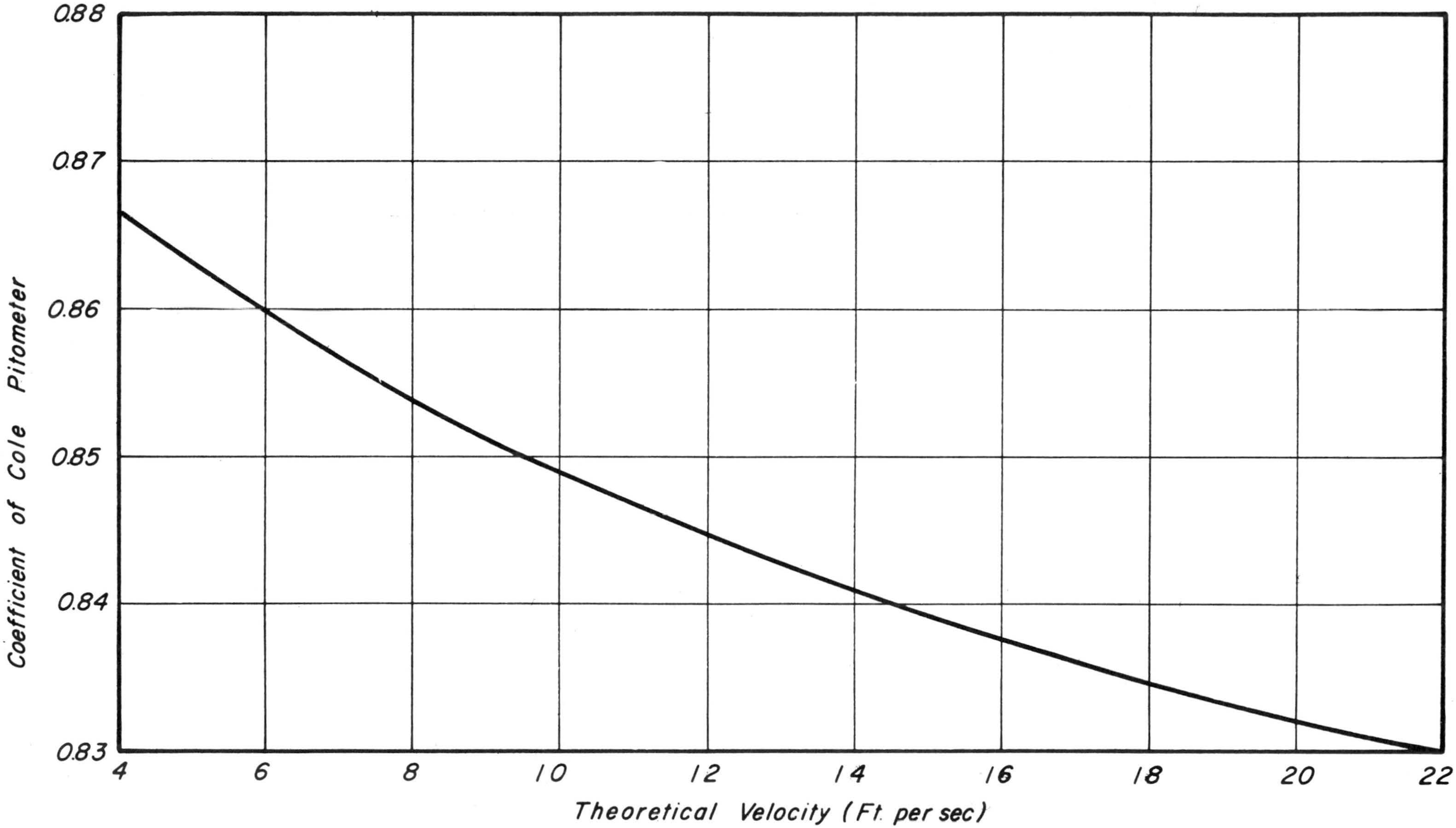

FIGURE 13 COLE PITOMETER RATING CURVE

APPENDIX

Tables of Data and Computation

TABLE 1. CALIBRATION DATA AND CALCULATIONS FOR FIGS. 5 AND 6.

Run No.	Time (Min)	Water Temp. (^oF)	Δh Manometer (Ft Ba)	Δh Manometer Ft of Water	Vol. Gal	γ	Δp psi.	Δp psi.	ρ	$\frac{\Delta p}{\rho}$	$\sqrt{\frac{\Delta p}{\rho}}$	Meas. Flow Rate gpm	Theo. Flow Rate gpm	C	V_2	$V_2 d_2$	ν	Re
1	0.9997	60.0	7.278	14.192	8,927.29	62.369	6.147	885.14	1.94035	456.18	21.358	8,929.97	9,032.73	.9886	33.086	28.950	$1.2111 \cdot 10^{-5}$	$2.3904 \cdot 10^{6}$
2	1.0002	60.0	7.293	14.221	8,918.67	62.369	6.159	886.95	1.94035	457.11	21.380	8,916.89	9,042.03	.9862	33.038	28.908	1.2111	2.3869
3	1.1337	60.0	6.284	12.254	9,397.54	62.369	5.307	764.27	1.94035	393.88	19.846	8,289.27	8,393.27	.9876	30.671	26.371	1.2111	2.2159
4	1.0835	60.5	6.212	12.113	8,898.66	62.366	5.246	755.44	1.94027	389.35	19.732	8,212.88	8,345.06	.9842	30.388	26.590	1.2007	2.2145
5	1.1000	61.0	4.586	8.943	7,772.47	62.363	3.873	557.71	1.94018	287.45	16,954	7,065.88	7,170.19	.9855	26.144	22.876	1.1938	1.9162
6	1.2503	62.0	4.555	8.882	8,775.13	62.358	3.846	553.86	1.93999	285.50	16.897	7,018.42	7,146.08	.9821	25.969	22.723	1.1770	1.9306
7	1.5003	62.0	3.296	6.427	8,935.76	62.358	2.783	400.77	1.93999	206.58	14.373	5,955.98	6,078.63	.9798	22.038	19.283	1.1770	1.6383
8	1.4983	62.0	3.259	6.355	8,926.67	62.358	2.752	396.29	1.93999	204.27	14.292	5,957.87	6,044.37	.9857	22.045	19.289	1.1770	1.6388
9	1.9170	64.0	2.285	4.458	9,538.26	62.345	1.930	277.93	1.93959	143.29	11.970	4,975.62	5,062.35	.9829	18.410	16.109	1.1445	1.4075
10	2.0000	64.0	2.287	4.460	9,918.99	62.345	1.931	278.06	1.95959	143.36	11.973	4,959.50	5,063.62	.9794	18.351	16.057	1.1445	1.4030
11	2.5007	64.0	-----	2.969	10,079.96	62.345	1.285	185.10	1.95959	95.432	9.7689	4,030.86	4,131.46	.9756	14.915	13.051	1.1445	1.1403
12	2.5007	64.0	-----	2.936	10,065.69	62.345	1.271	183.04	1.95959	94.370	9.7144	4,025.15	4,108.41	.9797	14.893	13.031	1.1445	1.1386
13	3,3518	64.0	-----	1.401	9,363.59	62.345	0.607	87.345	1.95959	45.032	6.7196	2,793.60	2,841.85	.9830	10.337	9.045	1.1445	.7897
14	3.5512	64.0	-----	1.392	9,868.81	62.345	0.603	86.784	1.95959	44.743	6.6890	2,779.01	2,828.91	.9824	10.283	8.998	1.1445	.7856
15	4.1523	64.0	-----	0.968	9,551.32	62.345	0.419	60.350	1.95959	31.115	5.5781	2,300.25	2,359.09	.9751	8.511	7.447	1.1445	.6502
16	1.6673	64.0	-----	0.968	3,850.48	62.345	0.419	60.350	1.95959	31.115	5.5781	2,309.41	2,359.09	.9789	8.545	7.477	1.1445	.6528
17	3.4840	64.0	-----	1.392	9,665.44	62.345	0.603	86.784	1.95959	44.743	6.6890	2,774.24	2,828.91	.9807	10.265	8.982	1.1445	.7842
18	2.7487	64.0	-----	2.165	9,507.00	62.345	0.937	134.98	1.95959	69.592	8.3422	3,458.73	3,528.08	.9803	12.798	11.198	1.1445	.9776
19	2.8340	64.0	-----	2.157	9,804.96	62.345	0.934	134.48	1.95959	69.334	8.3267	3,459.76	3,521.53	.9825	12.801	11.201	1.1445	.9779
20	4.0000	64.0	-----	0.1811	3,960.68	62.345	0.0784	11.291	1.95959	58.213	2.4129	990.17	1,020.46	.9703	3.664	3.206	1.1445	.2799
21	4.0008	64.0	-----	0.1772	3,948.97	62.345	0.0769	11.048	1.95959	56.960	2.3720	987,05	1,003.17	.9839	3.652	3.196	1.1445	.2790
22	2.2503	64.0	-----	0.5529	3,939.14	62.345	0.239	34.471	1.95959	17.772	4.2157	1,750.50	1,782.90	.9818	6.477	5.670	1.1445	.4948
23	2.2505	64.0	-----	0.5530	3,952.74	62.345	0.239	34.477	1.95959	17.775	4.2161	1,756.38	1,783.07	.9850	6.499	5.697	1.1445	.4974
24	3.9853	64.0	-----	0.9938	9,348.42	62.345	0.430	61.958	1.95959	31.944	5.6519	2,345.73	2,390.30	.9814	8.677	7.592	1.1445	.6628
25	4.0002	64.0	-----	0.1765	3,907.06	62.345	0.0764	11.004	1.95959	56.733	2.3819	976.72	1,007.35	.9696	3.614	3.162	1.1445	.2761
26	2.3852	64.0	-----	2.885	9,573.14	62.345	1.249	179.87	1.95959	92.736	9.6300	4,013.56	4,072.72	.9855	4.851	12.995	1.1445	1.1345

TABLE 2. COLE PITOT TUBE SURVEY

Q = 4020 gpm, Water Temperature 64°F

Pt.	Dist. In.	Δh	$\sqrt{\Delta h}$	Theo. Vel.	C	Act. Vel.	Remarks
Right to Left							
1	0.09	0.55	.74	5.93	.860	5.10	Right side
2	1.09	1.20	1.09	8.75	.852	7.45	
3	2.09	1.28	1.13	9.07	.851	7.71	
4	3.09	1.27	1.125	9.03	.851	7.57	
5	4.09	1.27	1.125	9.03	.851	7.57	
6	5.09	1.29	1.135	9.11	.851	7.75	
7	6.09	1.33	1.152	9.25	.851	7.86	
8	7.09	1.35	1.16	9.31	.850	7.91	
9	8.09	1.30	1.14	9.15	.851	7.78	
10	9.09	1.30	1.14	9.15	.851	7.78	
11	10.09	1.32	1.15	9.23	.851	7.85	
12	11.09	1.36	1.165	9.35	.850	7.94	
13	12.09	1.39	1.169	9.38	.850	7.97	
14	13.09	1.30	1.14	9.15	.851	7.78	
15	14.09	1.11	1.052	8.45	.853	7.21	
16	14.77	2.80	0.895	7.18	.856	6.14	Left side
Bottom to Top							
1	0.09	0.688	.83	6.65	.858	5.71	Bottom
2	1.09	1.18	1.085	8.71	.852	7.42	
3	2.09	1.32	1.15	9.23	.851	7.85	
4	3.09	1.26	1.12	8.99	.851	7.65	
5	4.09	1.38	1.17	9.39	.850	7.99	
6	5.09	1.37	1.17	9.39	.850	7.99	
7	6.09	1.37	1.17	9.39	.850	7.99	
8	7.09	1.32	1.15	9.23	.851	7.85	
9	8.09	1.32	1.15	9.23	.851	7.85	
10	9.09	1.34	1.156	9.27	.851	7.89	
11	10.09	1.36	1.165	9.35	.850	7.95	
12	11.09	1.35	1.16	9.31	.850	7.92	
13	12.09	1.32	1.15	9.23	.851	7.85	
14	13.09	1.28	1.13	9.07	.851	7.71	
15	14.09	1.08	1.04	8.35	.853	7.12	
16	14.64	0.86	.928	7.44	.855	6.36	Top

TABLE 3. COLE PITOT TUBE SURVEY

Q = 7020 gpm, Water Temperature 64°F

Pt.	Dist. In.	Δh	$\sqrt{\Delta h}$	Theo. Vel.	C	Act. Vel.	Remarks
Right to Left							
1	0.09	1.54	1.24	9.95	.849	8.45	Right
2	1.09	2.98	1.725	13.84	.8412	11.64	
3	2.09	3.42	1.85	14.85	.8395	12.48	
4	3.09	3.58	1.89	15.17	.8386	12.71	
5	4.09	3.60	1.897	15.21	.8388	12.78	
6	5.09	3.61	1.899	15.23	.8388	12.80	
7	6.09	3.54	1.88	15.09	.839	12.67	
8	7.09	3.58	1.89	15.17	.8386	12.71	
9	8.09	3.61	1.899	15.23	.8388	12.80	
10	9.09	3.61	1.899	15.23	.8388	12.80	
11	10.09	3.69	1.92	15.41	.8385	12.94	
12	11.09	3.85	1.96	15.73	.638	13.20	
13	12.09	3.80	1.95	15.65	.8381	13.12	
14	13.09	3.59	1.893	15.20	.8389	12.77	
15	14.09	2.86	1.69	13.58	.8416	11.42	
16	14.77	2.15	1.464	11.75	.8451	9.93	Left side
Bottom to Top							
1	0.09	1.97	1.402	11.25	.8462	9.51	
2	1.09	3.15	1.775	14.23	.8405	11.96	
3	2.09	3.61	1.90	15.25	.8388	12.80	
4	3.09	3.80	1.95	15.64	.8381	13.13	
5	4.09	3.85	1.96	15.72	.838	13.20	
6	5.09	3.74	1.93	15.5	.8385	13.01	
7	6.09	3.74	1.93	15.5	.8385	13.01	
8	7.09	3.64	1.91	15.33	.8386	12.88	
9	8.09	3.66	1.91	15.33	.8386	12.88	
10	9.09	3.66	1.91	15.33	.8386	12.88	
11	10.09	3.74	1.93	15.5	.8385	13.01	
12	11.09	3.76	1.94	15.57	.8382	13.07	
13	12.09	3.66	1.91	15.33	.8386	12.88	
14	13.09	3.47	1.86	14.92	.8393	12.52	
15	14.09	2.94	1.71	13.71	.8414	11.53	
16	14.79	2.24	1.495	12.00	.8446	10.14	Top

TABLE 4. COLE PITOT TUBE SURVEY

Q = 8890 gpm, Water Temperature 64°F

Pt.	Dist. In.	Δh	$\sqrt{\Delta h}$	Theo. Vel.	C	Act. Vel.	Remarks
Right to Left							
1	0.09	2.75	1.67	13.4	.842	11.3	Right
2	1.09	5.62	2.37	19.0	.833	15.8	
3	2.09	6.10	2.47	19.8	.832	16.5	
4	3.09	6.33	2.52	20.2	.832	16.8	
5	4.09	6.23	2.50	20.1	.832	16.75	
6	5.09	6.76	2.50	20.1	.832	16.75	
7	6.09	6.26	2.50	20.1	.832	16.75	
8	7.09	6.26	2.50	20.1	.832	16.75	
9	8.09	6.30	2.51	20.2	.832	16.8	
10	9.09	6.43	2.54	20.4	.832	17.0	
11	10.09	6.45	2.54	20.4	.832	17.0	
12	11.09	6.79	2.60	20.8	.831	17.3	
13	12.09	6.74	2.60	20.8	.831	17.3	
14	13.09	6.45	2.54	20.4	.832	17.0	
15	14.09	5.25	2.29	18.4	.834	15.35	
16	14.79	3.97	1.99	16.0	.838	13.4	Left
Bottom to Top							
1	0.09	3.28	1.81	14.52	.840	12.2	Bottom
2	1.09	5.49	2.34	18.80	.8335	15.68	
3	2.09	5.97	2.44	19.58	.8325	16.3	
4	3.09	6.28	2.50	20.07	.832	16.7	
5	4.09	6.55	2.56	20.54	.8315	17.1	
6	5.09	6.45	2.54	20.4	.8315	17.0	
7	6.09	6.38	2.52	20.2	.8315	16.8	
8	7.09	6.31	2.51	20.1	.832	16.75	
9	8.09	6.26	2.50	20.05	.832	16.7	
10	9.09	6.31	2.51	20.1	.832	16.75	
11	10.09	6.39	2.52	20.2	.8315	16.8	
12	11.09	6.39	2.52	20.2	.8315	16.8	
13	12.09	6.45	2.54	20.4	.8315	17.0	
14	13.09	5.86	2.42	19.4	.833	16.17	
15	14.09	5.07	2.25	18.07	.8345	15.1	
16	14.76	4.24	2.06	16.53	.837	13.85	Top