STUDY OF THE COX FLOWMETER
(Modified Hall Pitot Tube)

REPORT

to

Board of Water Commissioners
City and County of Denver
Colorado

by

A. R. Robinson

Colorado State University
Fort Collins, Colorado

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ACKNOWLEDGMENT

The study of the Cox Flowmeters was made possible through a contract with the Board of Water Commissioners, City and County of Denver, Mr. R. B. McRae, Chief Engineer. Mr. W. A. Tolle, Hydraulic Engineer for the Board worked closely with the project personnel in directing the progress of the study. The instruments were tested and calibrated in the Hydraulics Laboratory of Colorado State University. H. S. Nagabhushanaiah, graduate assistant, conducted much of the testing. Assistance in technical and administrative leadership of the project was given by S. Karaki, Assistant Civil Engineer. The interest of the Agricultural Research Service, Western Soil and Water Conservation Research Branch is also acknowledged.

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INTRODUCTION AND REVIEW

The Cox Flowmeter has been calibrated for a range of discharges and pipe sizes in the Hydraulics Laboratory at Colorado State University. This meter, also known as the modified Hall Pitot tube and historically, as the Frank tube, has been used with varying degrees of success for many years.

The earliest work on an integrating pitometer was done by Sante Pini in 1886 and by Albert Frank in 1888. The first known published description was made by Frank in 1888 (1). This pitometer was described as a steel tube with a row of holes connected to one common manometer. The instrument was developed for a direct measurement of mean velocity along a vertical plane in open channels or across the diameter in a pipe. Originally, the device was thought to integrate the velocity to produce the mean value on an indicating device.

In his original studies, an accuracy of ± 1.6 % in measurement of average velocity along a vertical was claimed by Frank (2). Later studies by Amsler-Laffon (3) pointed out the inadequacy of the Frank tube for measuring mean velocity. It stated that "all pitometers measure the square of velocity and therefore are not suitable for integration." Beyerhaus (4) states that errors as large as 20 percent in determining mean velocity could result from the use of the Frank tube. Deisha (5) confirmed the conclusions of Beyerhaus and stated that the tube measures only surface velocity in the case of open channel flow. This would mean that maximum or near maximum velocities are measured using the tube.

Hanning (6) located a tube across a pipe with 12 holes drilled and spaced so that each served an equal cross-sectional area. This tube was connected to one common piezometer. It was found that the discharge could be determined within an accuracy of 5 to 10 $^0/_0$ using the device.

Recent calibration studies have been made by the California Division of Water Resources, Department of Public Works (7). Deviations in determining discharges of approximately ± 5 percent were noted for some tests. Later observations gave differences as large as 16 percent. In this case, the indicated flow by the meter was always less than that measured volumetrically.

The present studies were made for the purpose of calibrating the meters and to make an evaluation regarding the accuracy and reliability.

DESCRIPTION OF EQUIPMENT

The Cox Flowmeter, shown schematically in fig. 1, basically consists of a series of 3/16" diameter holes drilled in a 3/4" diameter tube. These holes face directly into the flow when a discharge determination is being made to afford some measure of the stagnation pressure. For the static determination there are two holes at right angles to the flow and on opposite sides, as well as one at the same level on the downstream side. All three static ports are at the center line when the meter is inserted in the large pipe and have a common connection to one pressure tap whereas the series of 3/16" diameter holes are connected to the other. A rubber hose connects each of these to an inverted U-tube manometer which is used to determine a difference in pressure. The manometer boards which are supplied with the Cox meter have a calibrated movable rod attached. The rod reading times the area of pipe in square inches is reported to give the discharge in gallons per minute.

Each of the meters has a removable tip on the lower end. With tips of different lengths, one meter can be used over a range of pipe diameters. Each of two sets of Cox meters calibrated contained the following meters: (1) 6-12, (2) 12-18, (3) 19-24, and (4) 25-30. The numbers indicate the range of pipe sizes for which each meter can be used.

In the laboratory, a 60 HP, low head, propeller type pump was used to supply the flow through a 19-inch diameter discharge line. In this line, at 20 diameter distance away from the pump, are placed orifice plates for the determination of discharges. These plates were calibrated in-place, volumetrically, immediately before this study.

There was approximately 34 feet of straight pipe immediately upstream from the test section. Each test section was 25 feet in length containing either diverging or converging upstream and downstream sections depending on whether the test pipe was larger or smaller than the 19-inch supply line. An expansion on the end of a 12-inch test section can be seen in fig. 2. These test sections were attached to the supply and discharge lines using Victaulic couplings for easy insertion and removal. The Cox meters were installed near the downstream end of the test sections as shown in figs. 2 and 3. Except for the 30-inch diameter pipe, each of the test sections contained straightening vanes which were installed at the beginning of the section.

In order to insure that the pipes were flowing full, a butterfly valve was placed in the line downstream from the test section. This was adjusted so that positive pressures from 2-5 psi existed in the test section for each determination.

The sizes of pipe used for testing as well as the number of different meters for each size were as follows:

Pipe Diameter Inches	Numbers of Meters	Meters Used
12	2	6-12
	2	12-18
16	2	12-18
18	2	12-18
20	2	19-24
24	2	19-24
30	2	25-30

Because of the overlap of sizes, made possible by the change of tips, the same meters were used for two of the series on the 12-inch diameter as well as for the 16 and 18-inch pipes.

PROCEDURES FOR TESTING

The Cox meter was inserted into the pipe as shown in figs. 2, 3, and 4. In each case the meter was bottomed and then pulled back 1/16 to 1/4 inches in order to center the holes within the pipe. With water flowing in the line, the procedure given in "Instructions for Operating the Hall Tube Flowmeter" was followed for removing all air from the meter and the lines. This procedure was followed between each reading in order to insure against an accumulation of air.

After a stabilization period for a set discharge, two readings were made on the manometer from the orifice plate in the pump discharge line. Two determinations were then made using the Cox meter. For these readings, fluctuations of the water columns were damped by clamping the rubber hoses and adjusting the bleeder valves. This increased the accuracy of reading. Two additional readings were then made of the discharge in the pump line. The range of discharges for each size pipe was selected so that velocities ranged from approximately 2 to 7 feet per second.

For the entire study, the manometers furnished with the Cox meters were used. The relationship between the manometer reading using the Cox scale as compared to the same reading in inches of water is given in fig. 5. Since the reading M on the Cox scale multiplied by the area of pipe is an indication of discharge then, M is actually a velocity term. From fig. 5 it is noted that this calibration (furnished with meters) shows that for lower velocities the velocity is proportional to $(\Delta h)^{0.74}$ whereas at the higher velocities this proportionality is to $(\Delta h)^{0.54}$.

For some of the tests, the downstream hole of the three static openings was plugged. This was done in order to determine if a difference might exist by only using the two holes at right angles to the flow.

In an attempt to more nearly define the velocity being measured by the Cox meter, a piezometer was added to the pipe for an ambient pressure determination for three sizes of test pipe. This piezometer was attached to one leg of a Cox manometer with the other to the stagnation side of the Cox meter.

ANALYSIS

Calibration of Meters

The basic principles involved in the operation of the Cox Flowmeter are the same as those for the Pitot tube. This can be illustrated by one form of the Bernoulli equation which is

$$\frac{V^2}{2g} = \frac{\Delta p}{\gamma} = \Delta h \qquad (1)$$

or

$$V = \sqrt{2g\Delta h} \qquad (2)$$

where Δp represents the difference in pressure between the tip of the Pitot tube and a point along the side. At the tip of the tube, the stagnation pressure represents total head which includes the pressure due both to velocity and to ambient pressure. The pressure along the side at some distance from the tip is the ambient pressure. The difference in these is represented by the Δh on an inverted U-tube manometer and is directly proportional to velocity head as shown in eq. 1. Since losses in the Pitot tube are involved, a coefficient is needed in eq. 2 so that

$$V = C\sqrt{2g\Delta h}$$

or

$$Q = CA\sqrt{2g\Delta h} \qquad (3)$$

with Q in cubic feet per second, Δh in feet of water and A the pipe area in square feet. Eq. 3 assumes that the measured velocity is equal to the average velocity.

The relationship which is furnished with the Cox meters indicates that

$$Q = AM \qquad (4)$$

where Q is in gallons per minute, A is area in square inches and M is the reading on the calibrated scale of the manometer furnished with the Cox meter. If eq. 3 has the same units as eq. 4 , then

$$Q = 7.22\ CA\sqrt{\Delta h} \qquad (5)$$

with Δh in inches of water. Combining eqs. 4 and 5 results in

$$M = 7.22\ C\sqrt{\Delta h} \qquad (6)$$

The relationship of M and difference in head in inches of water given by Cox is plotted on fig. 5. This indicates that the relationships are

$$M = 4.40\ \Delta h^{0.74} \qquad \Delta h < 1 \text{ inch} \qquad (7)$$

$$M = 4.40\ \Delta h^{0.54} \qquad \Delta h > 1 \text{ inch} \qquad (8)$$

These relationships become questionable when it is noted that the exponents are both greater than 0.5 as shown in eq. 6. Combining eqs. 6 and 8 and assuming that $\Delta h^{0.04}$ is unity then

$$C = 0.61$$

which is evidently an average value chosen for the coefficient for the case when $\Delta h > 1.0$ inch of water.

A compilation of the data obtained in this study is given in Table 1. A study of the deviation of discharges obtained from using the Cox scale to the actual discharge reveals that the Cox scale is generally in error. The following approximate deviations can be noted from the data of Table 1.

Pipe Size and Meter	Deviation for $V \approx 7$ ft/sec Percent	Deviation for $V \approx 2$ ft/sec Percent
12 (6-12.)	+ 1.9	-12.4
12 (12-18)		
(13-18)	- 3.7	- 8.2
16 (12-18)		
(13-18)	+ 9.4	- 8.2
18 (12-18)		
(13-18)	+12.9	- 2.9
20 (19-24)	+19.0	+ 1.9
24 (19-24)	+21.3	+ 3.7
30 (25-30)	+12.4*	+ 4.7

*For velocity near 3.8 ft/sec only.

The data from this tabulation show that when using the Cox calibrated scale, at a velocity near 7 feet per second, the deviation is near zero for the smaller pipe. This deviation from the correct discharge increases with pipe size to the 24 inch diameter where the Cox scale indicates 20+ percent more discharge. For the lower velocity the deviation is -12.4 for the smallest size of pipe and increases to +4.7 percent for the largest size calibrated.

From the foregoing tabulation and from Table 1, it can be stated that the accuracy when using the Cox calibrated scale might be within the range of -12 to +20 percent for the range of velocities and pipe sizes tested. Since this accuracy is not sufficient for most measurement requirements, another method of using the calibration results was devised.

On figs. 6 to 12 are plotted the results of the tests with the discharge as a function of head difference across the meter in inches of water. This results in a general equation in the form of

$$Q = C_a \Delta h^n \tag{9}$$

where the discharge is in cubic feet per second and Δh in inches of water. Fig. 6, which gives the calibration for the 6-12" meters in a 12" pipe, indicates that a slightly different calibration exists for each individual meter. This difference is about 4 percent at the higher flows. A difference also was noted for the 12-18 meters in the 12" pipe as shown in fig. 7. Here the difference is near 6 percent. From the results shown on figs. 6 and 7 it would seem advisable to use individual rating curves for each of the meters used in the 12" pipe. However, the results for all other meters indicated that a single relationship was sufficient for each of the sizes (see figs. 8-12).

A study of figs. 6-12 indicated that a reasonably accurate representation of the data was possible using eq. 9 with a constant exponent n of 0.49. From the calibration curves for each pipe size the values of C_a in eq. 9 and C in eq. 5 were determined. These parameters as a function of the square of pipe diameter are shown in fig. 13. The relationship between C and C_a is

$$C_a = 2.32\ CA \tag{10}$$

where A is pipe area in square feet and the exponent of Δh is assumed to be 0.49 for both equations.

The use of fig. 13 in determining the proper coefficient to use in eq. 9 can best be illustrated by an example. For a 14-inch pipe, d^2 equals 1.361. From fig. 13 the value of C_a is 1.65 so that the equation

$$Q = 1.65\ \Delta h^{0.49} \tag{11}$$

can be used for determining the discharge. The discharge determined in this manner could be expected to be less than 4.0 percent in error.

Velocity Measured by the Cox Meter

Of particular interest is the velocity which is measured by the Cox meter. Some claim has been made that the device integrates the velocity profile in the pipe to produce a measure of average velocity. Assuming that the difference in head between the stagnation and static pressure openings of the tube represented a velocity head, this velocity can be determined by

$$V_c = \sqrt{2g\Delta h} \tag{12}$$

This is then compared to the average velocity determined by continuity

$$V = \frac{Q}{A} \tag{13}$$

where Q is the actual discharge for the pipe of area A.

It was recognized that the static pressure openings of the Cox meter indicated a pressure that was not ambient. Fig. 14 which was adapted from Rouse (8) illustrates this point. This shows that for a range of Reynolds numbers of 1.86×10^5 to 6.7×10^5, which is within the range covered in the Cox meter tests, that pressures less than ambient existed at the location of the static openings ($p_t < p$). Since at point A the pressure will be the full impact presure, i.e. static pressure plus velocity head, and the pressures at points C are something less than static, then the pressure difference between points A and C results in an indicated head greater than the true velocity head.

In order to measure a true velocity head it was necessary to install a piezometer in the pipe wall as shown in figs. 3 and 4. This piezometer was connected to one side of the U-tube manometer with the other connection to the impact (upstream) side of the Cox meter. With this setup on three sizes of pipe, a velocity V_* was determined using a relationship similar to that given by eq. 12. Ratios of $\frac{V_c}{V}$ and $\frac{V_*}{V}$ were determined for each discharge and found to be almost constant for a given size pipe. The following tabulation gives the average values.

Pipe Size Inches	$\frac{Vc}{V}$	$\frac{V_*}{V}$
16	1.59	1.09
24	1.76	1.21
30	1.71	1.16

The parameter $\frac{V_*}{V}$ should represent the ratio of velocity being measured by the Cox meter to the average. Using the static openings on the Cox meter the indicated velocity head was 1.6 - 1.7 times the average velocity. Using a static piezometer on the pipe then the ratio of velocity being measured to the average was 1.1 - 1.2. In the following section it will be shown that the ratio of maximum velocity to average, for the pipe and conditions used in these tests, was approximately 1.17.

Effect of Pipe Roughness on the Velocity Profile

The relative velocity distribution in a circular pipe has been given by Rouse (8) as:

$$\frac{v}{V} = \sqrt{f}\left(2.15 \log_{10} \frac{y}{r_o} + 1.43\right) + 1 \tag{14}$$

where v is the velocity at a distance y from the pipe wall, V is the average velocity, f is the Darcy-Weisbach resistance coefficient and r_o is the pipe radius. From this equation, it is noted that the relative velocity is a function of position and resistance coefficient f. Of particular interest is the ratio of maximum velocity (center) to the average. At this point $\frac{y}{r_o}$ equals unity and eq. 14 reduces to

$$\frac{v}{V} = 1.43\sqrt{f} + 1 \tag{15}$$

For the purpose of comparison, two values of the roughness coefficient K were used to determine f. These values were

$K_1 = 0.0004$ ft - Asphalted cast iron
$K_2 = 0.01$ ft - Very rough pipe as cast iron with rust carbuncles.

Using these values of roughness in the Reynolds number range of $(1.5 \text{ to } 8) \times 10^5$ the following values were determined from relationships given by Rouse (8) and eq. 15.

Pipe Dia. Inches	$\frac{D}{K_1}$	f_1	$\frac{D}{K_2}$	f_2	$\left(\frac{v}{V_1}\right)$	$\left(\frac{v}{V_2}\right)$
16	3325	0.0152	133	0.035	1.18	1.27
24	5000	.0140	200	.031	1.17	1.25
30	6250	.0135	250	.029	1.16	1.24

Selecting an average value from this table the maximum velocity is 1.17 times the average for the smooth pipe (K = .0004) and 1.25 for the rough pipe (K = 0.01). The pipe used in the present study would compare in roughness to the smooth pipe case. The velocity ratio $\left(\frac{v}{V_1}\right)$ of 1.17 compares favorably with values of $\frac{V_*}{V}$ determined previously for the same sizes of pipe. This would indicate that when using the difference in the ambient pressure and total impact, as is the case with the piezometer opening in the pipe, then the Cox meter actually gives a measure of maximum pipe velocity. However, when using the static openings provided in the meter then an indicated velocity is obtained which is much greater than maximum.

Of interest is the effect of pipe roughness on the velocity profile using the relationship given by eq. 14. Assuming an average velocity of 5 feet per second in the 30-inch pipe, the velocity profiles given in fig. 15 was determined. The difference in center-line velocities is approximately 7 percent with the roughest pipe having the highest velocity.

COMMENTS AND INTERPRETATIONS

The study of Cox Flowmeters has shown that individual calibrations may be necessary if each meter is to be considered accurate within 5 percent. This is particularly true for meters for the smallest size of pipe (12") used in this study. For the larger sizes, a comparison of ratings on two meters of each size did not reveal a significant difference. A coefficient was determined for each size which when plotted against the square of diameter gave the relationship shown on fig. 13. This plot and eqs. 5 or 9 can then be used to determine the discharge equation for Cox meters within the limits of the plot. Extending the relationship to sizes greater than 36-inches diameter is not recommended.

For accuracy, the calibrated scale on the Cox manometers should not be used. Instead the difference in heights of the water columns should be accurately determined in inches and calibration curves for the particular meter and pipe size should be used. Rating tables or curves such as those given in figs. 6 to 12 should be prepared.

It was shown that the velocity measured by the Cox meter was near maximum when the ambient pressure was determined from a piezometer in the pipe wall. Much higher Δh values, and hence indicated velocities, were determined when using the static pressure openings on the Cox meter. The static port on the trailing side of the tube was deliberately plugged for some of the tests. No differences were observed in Δh readings when this opening was closed. All calibrations presented in this report were made using the Cox meter in the prescribed manner, i.e. one leg of the U-tube manometer connected to the upstream port and the other leg to the downstream one.

The effect of difference in roughness and the resultant change in maximum velocity should exert a relatively minor influence on the accuracy of measurement with the Cox meter. For a change in roughness coefficient from 0.0004 to 0.01 it was shown that the maximum velocity was increased in the order of 7 percent. These roughness values should represent the extremes of roughness from

from new pipe to that which has been in use for many years. One of the biggest problems is in determining the effective area of a pipe which has become corroded with age. Unless some means is available for making an accurate determination, this could be the source of most of the errors in determining discharge.

RECOMMENDATIONS FOR FIELD USE

For accurate readings of the fluid heights in the columns of the U-tube manometer, the fluctuations should be damped by using clamps or shut-off cocks on the lines. It is not possible to read fluctuating columns with sufficient accuracy to determine the correct Δh reading.

The procedure given in the instructions on use of the Cox meters for bleeding air out of the instrument and tubes is correct and should be followed. For repeated readings at the same installation, care should be taken between each reading to see that the columns balance according to the prescribed procedure. If they do not, then air is trapped in the system and must be removed.

Static or ambient pressure determinations are not possible by using the center fitting on the head of the Cox meter. If these pressures are necessary, they should be obtained using a tap on the main pipe.

An accurate measure of diameter and area is necessary for an exact determination of discharge. This becomes increasingly important as the pipe ages and deteriorates.

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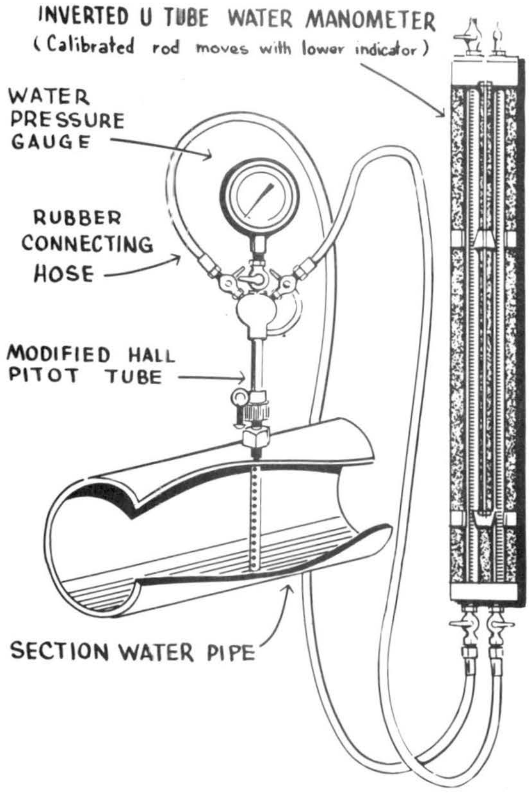

Fig. 1 Diagram of the Cox Flowmeter.

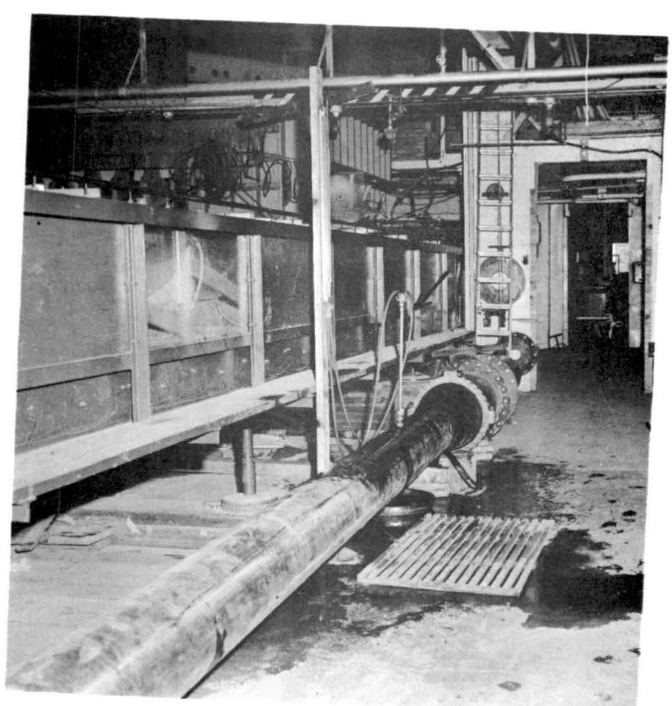

Fig. 2 Meter Installed in a 12-inch Diameter Pipe.

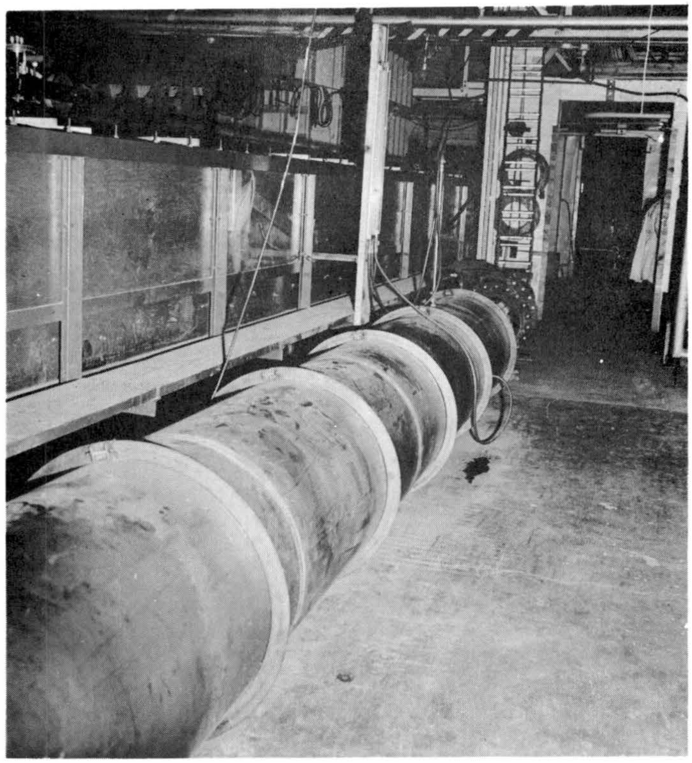

Fig. 3 Meter Installed in 30-Inch Diameter Pipe.

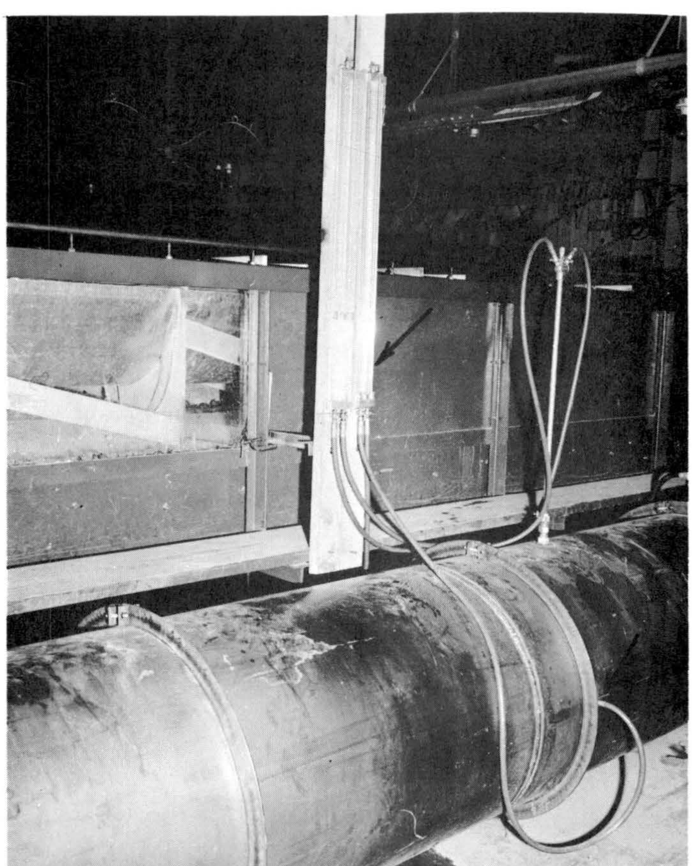

Fig. 4 Installed Cox Flowmeter Showing Manometer Boards and Static Pressure Tap in Pipe.

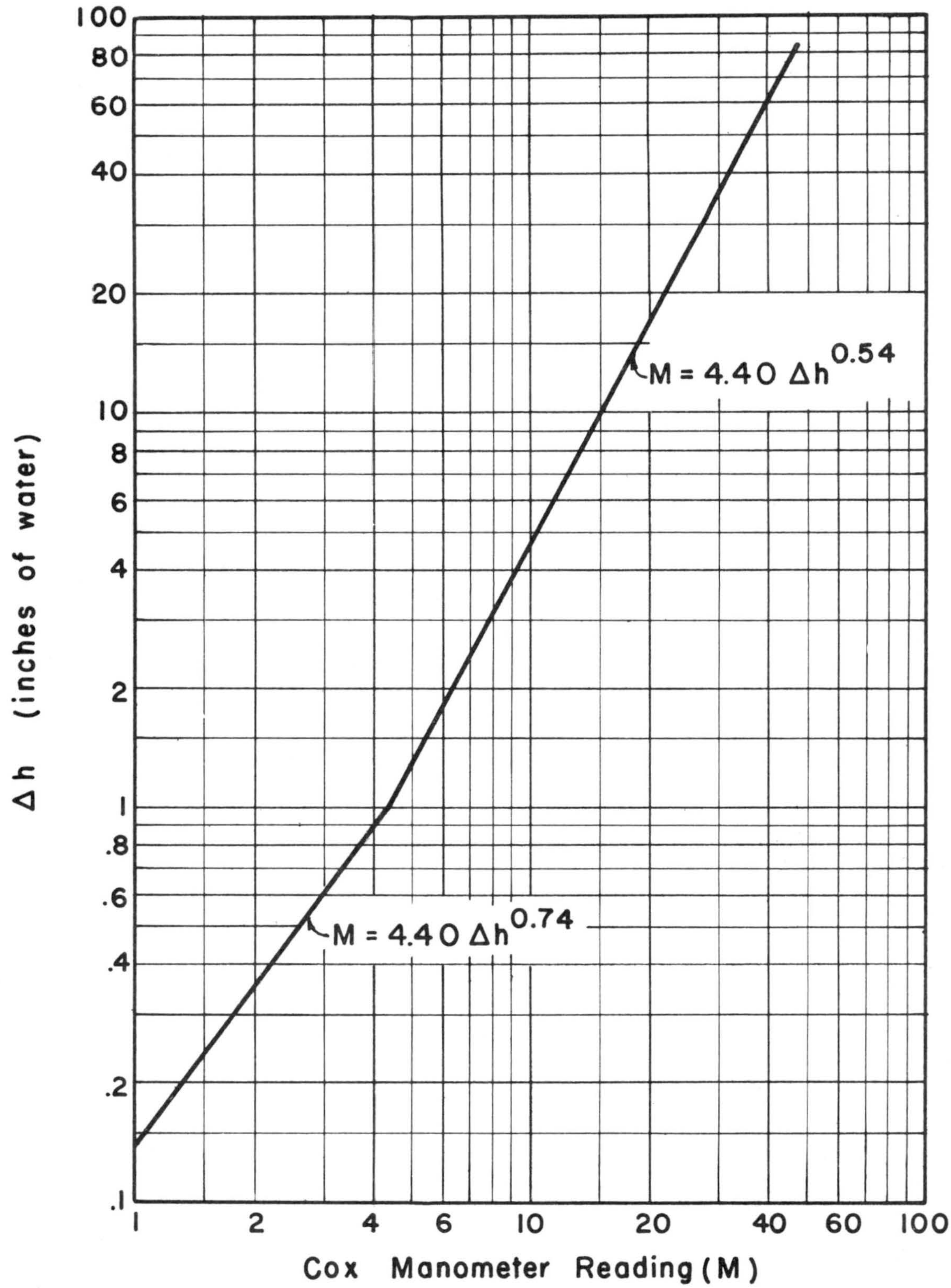

Fig. 5 Relationship of Cox calibration scale to difference in head in inches of water.

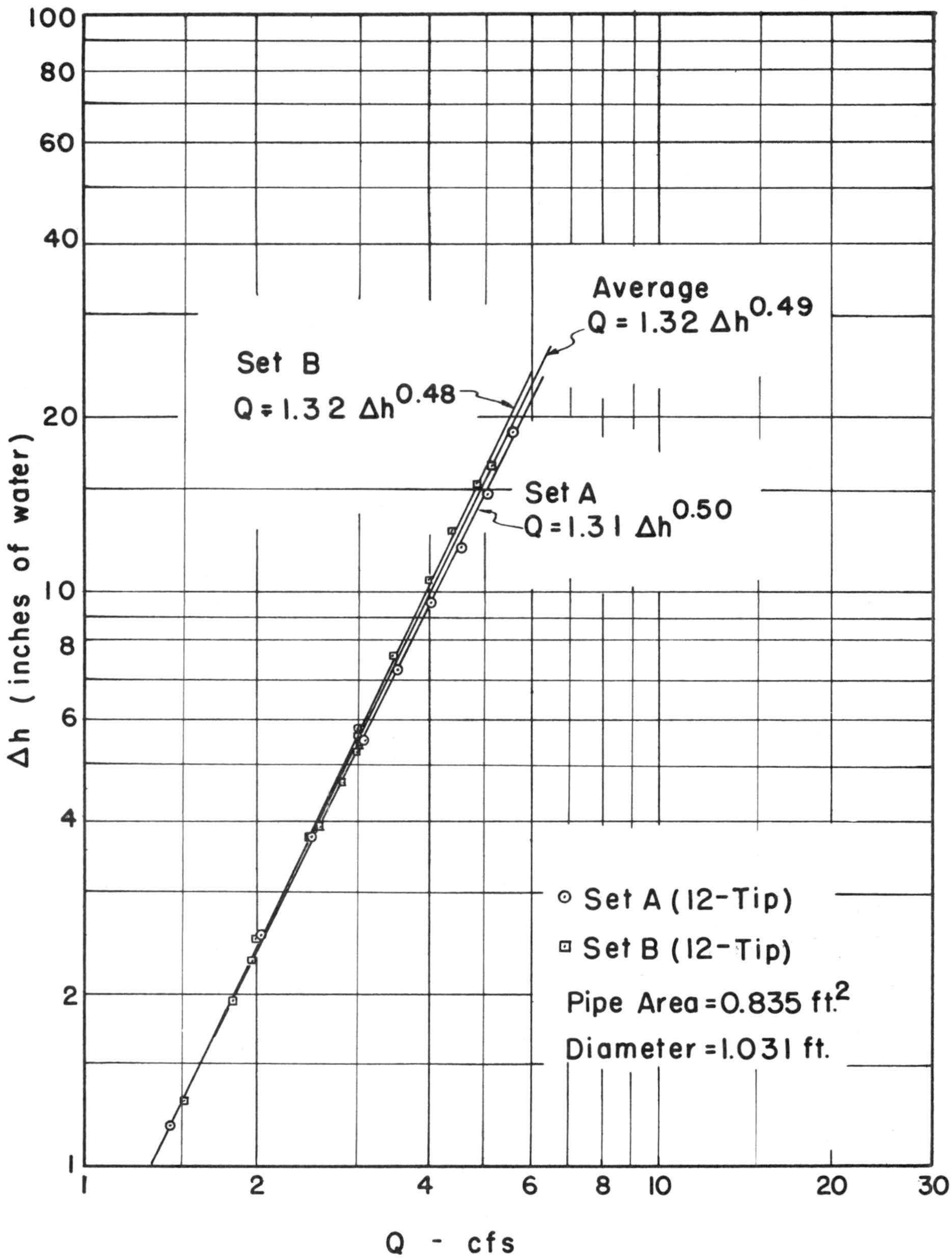

Fig. 6 Cox meter calibration, Sets 6–12 in 12" line.

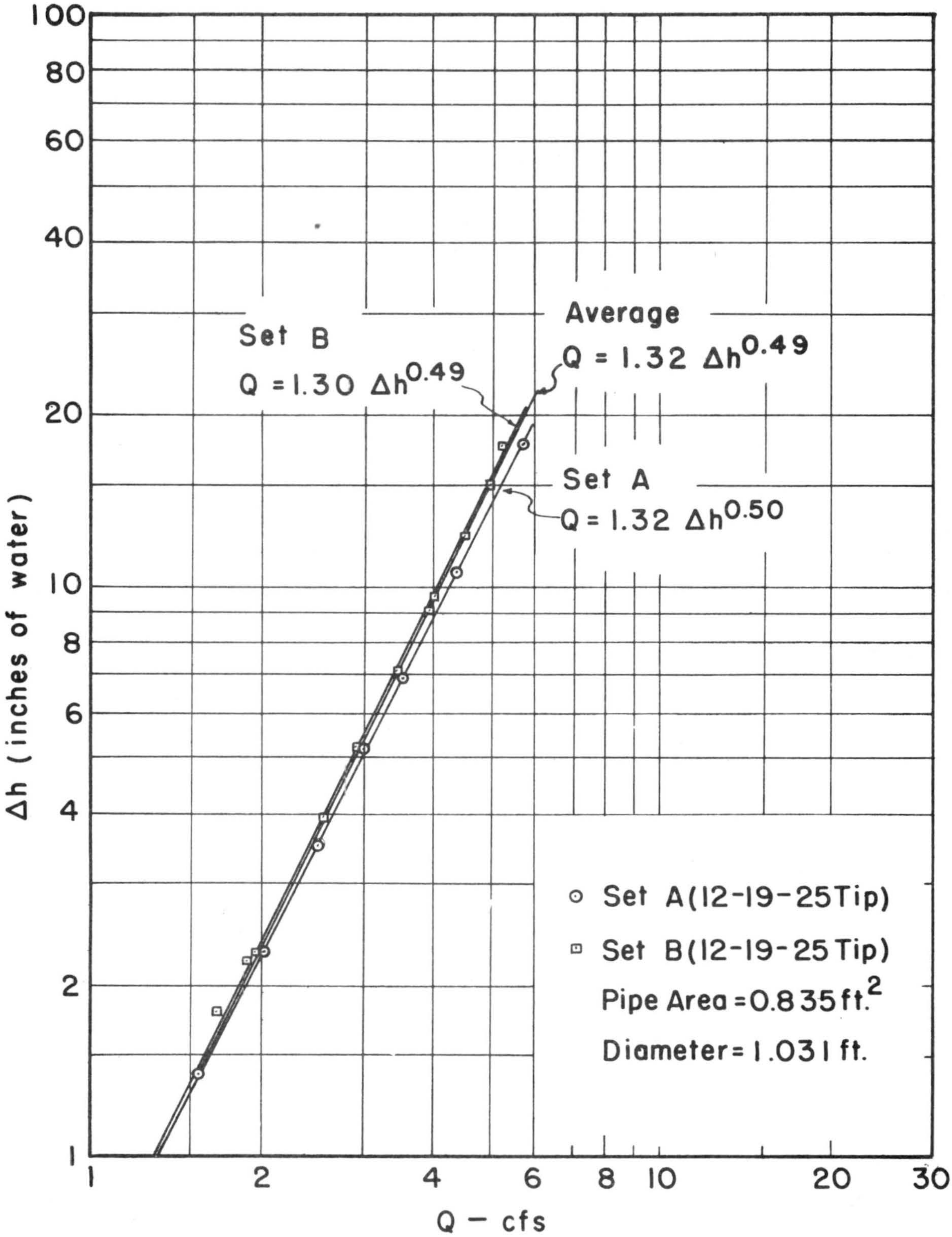

Fig. 7 Cox meter calibrations, Sets 12 – 18 in 12" line.

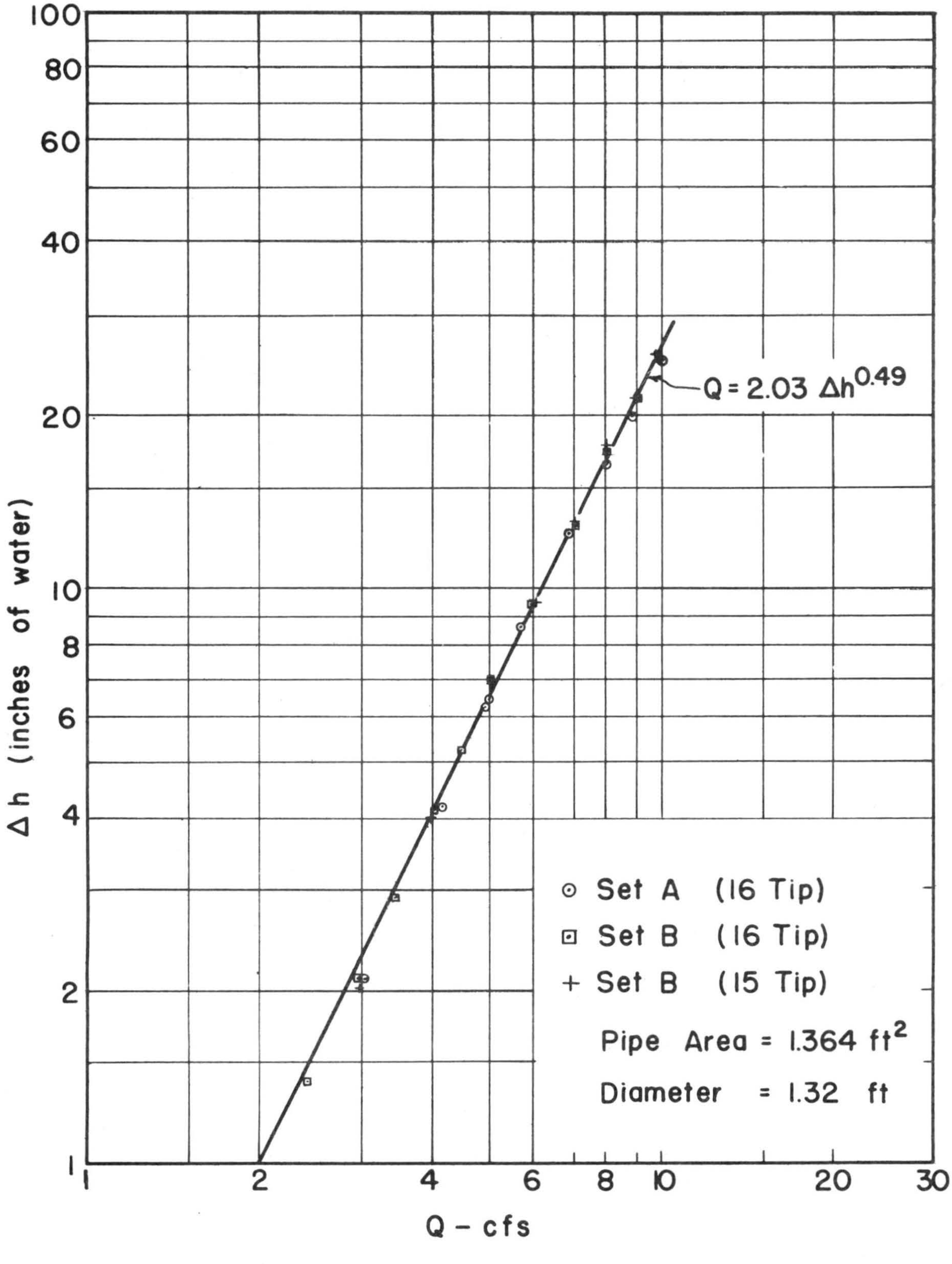

Fig. 8 Cox meter calibration, Sets 12-18 in 16" line

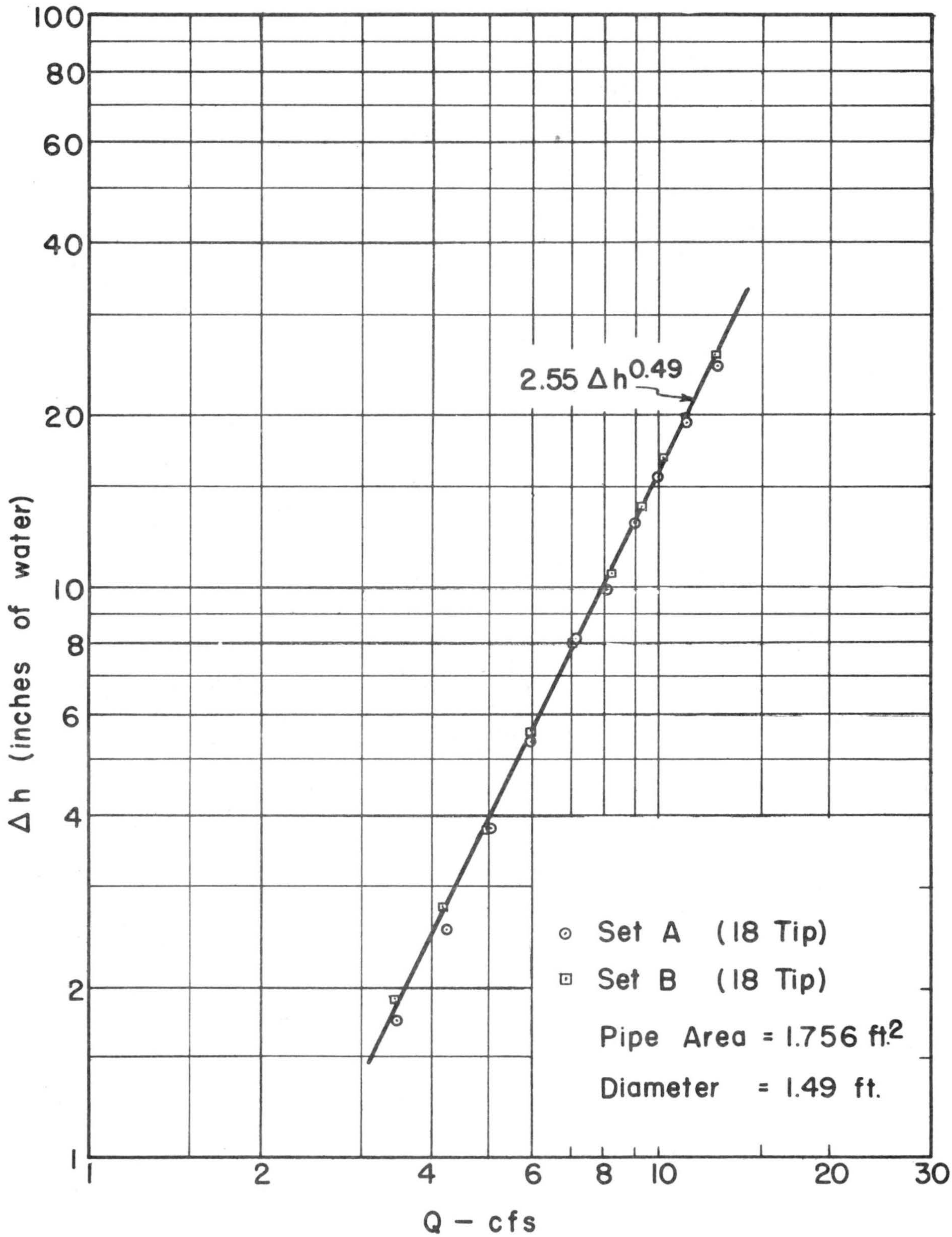

Fig. 9 Cox meter calibrations, Sets 12-18 in 18" line.

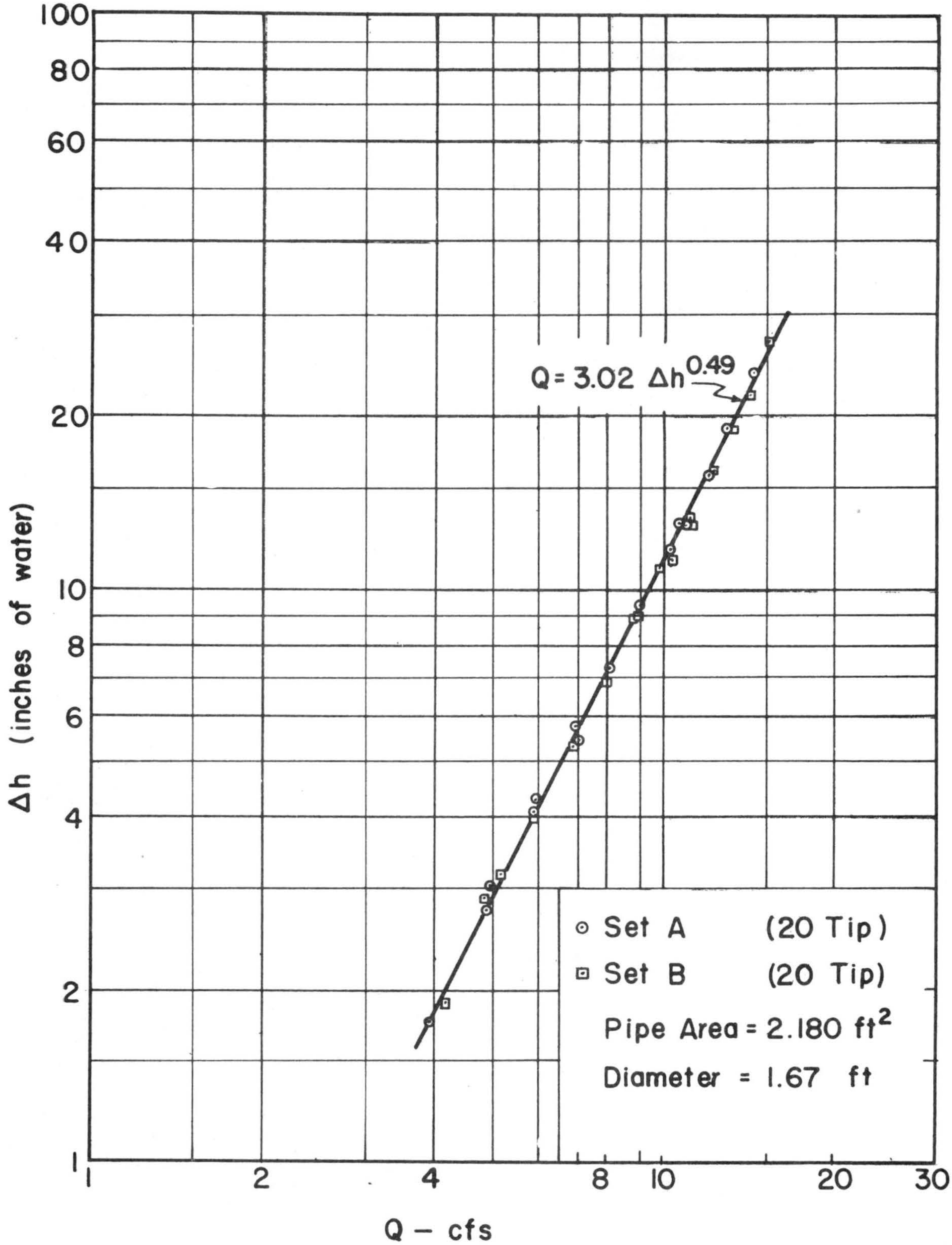

Fig. 10 Cox meter calibration, Set 19 - 24 in 20" pipe

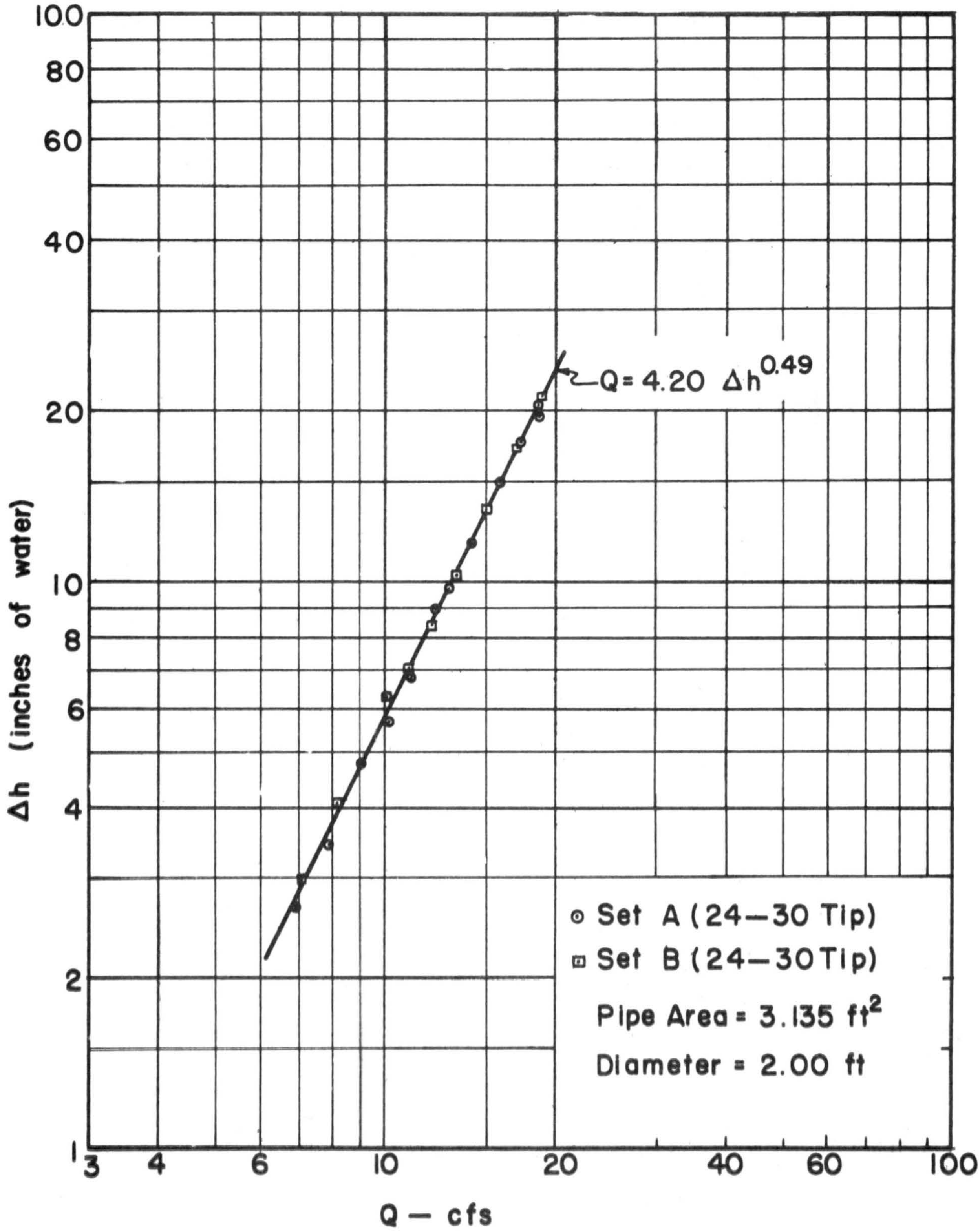

Fig. 11 Cox meter calibration, Set 19—24 in 24" pipe

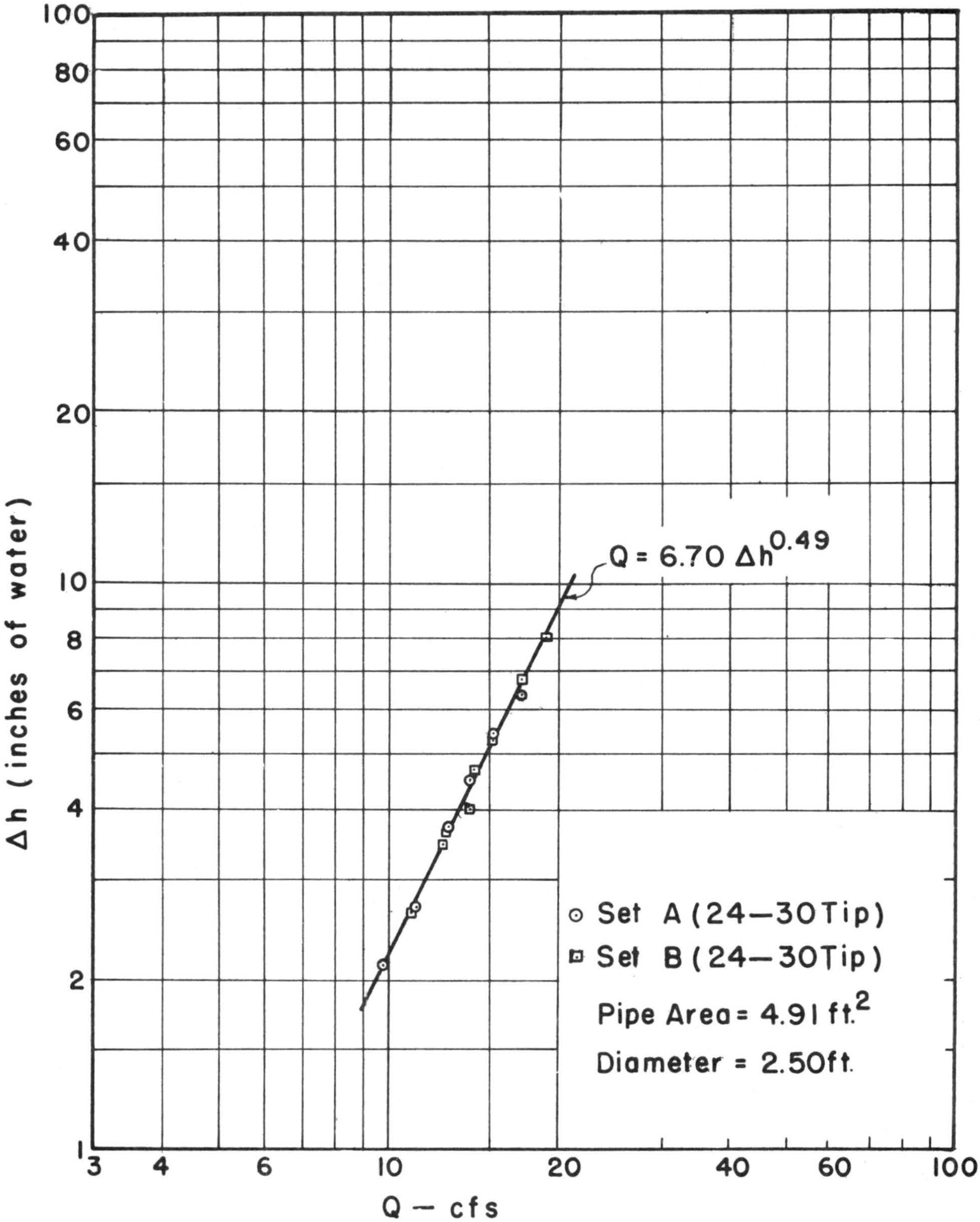

Fig. 12 Cox meter calibration, Set 25—30 in 30" pipe

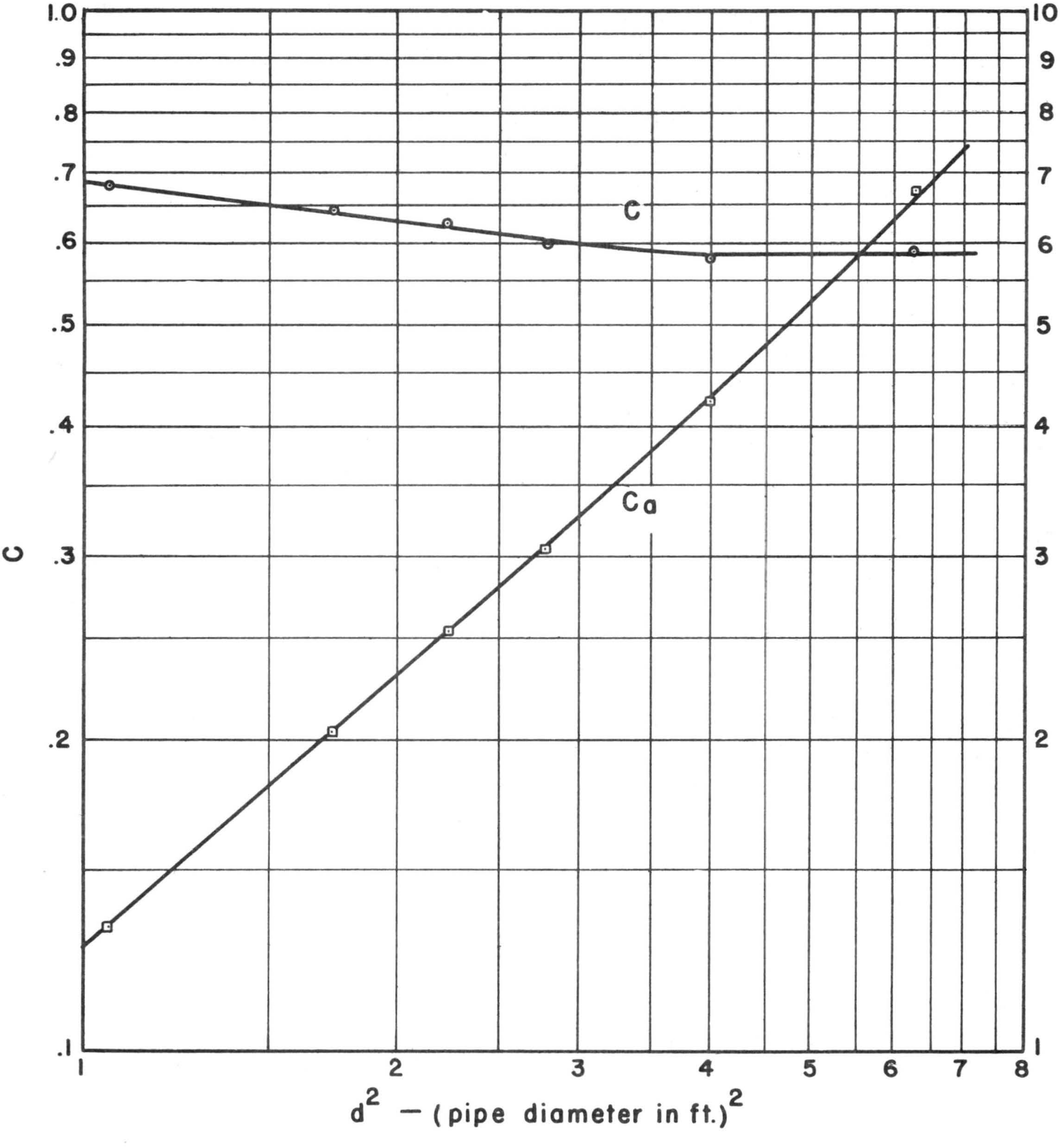

Fig. 13 Relationship of meter coefficients to pipe diameter.

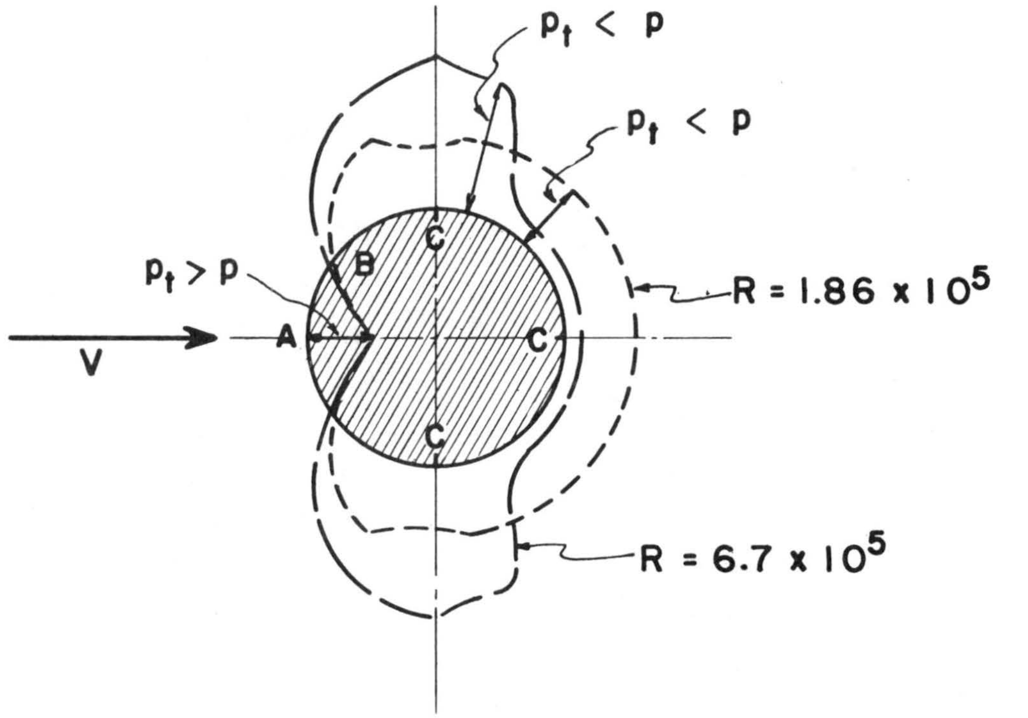

Fig. 14 Distribution of pressure for two-dimensional flow past a cylinder.

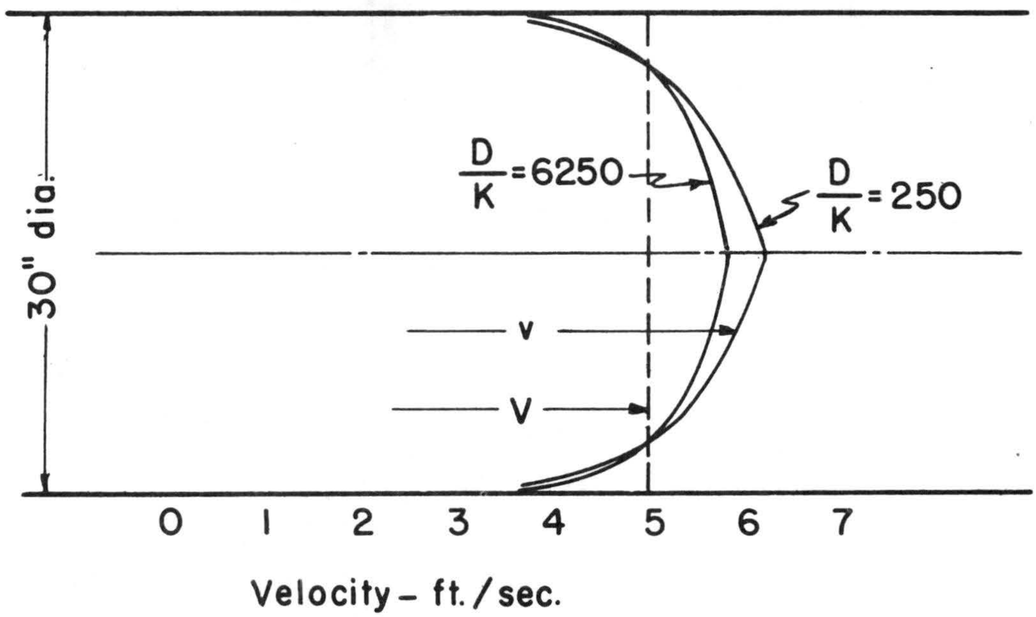

Fig. 15 Velocity profiles as a function of roughness for 30 inch pipe–average velocity of 5 ft./sec.

TABLE I

SUMMARY OF TESTS - COX FLOWMETER STUDY

Pipe Size	Pipe Area A (ft^2)	Meter No.	Q_o* (cfs)	Rdg Cox M	Rdg Cox Δh (inches water)	Q_c* (cfs)	Deviation Q_c from Q_o (%)
12	0.835	A(6-12)	5.57	21.15	18.9	5.65	+ 1.4
			5.04	18.65	14.7	5.00	- 0.9
			4.52	16.58	11.9	4.44	- 1.8
			4.04	14.72	9.5	3.94	- 2.4
			3.54	12.73	7.3	3.41	- 3.8
			3.04	10.95	5.5	2.93	- 3.6
			2.50	8.80	3.74	2.36	- 5.8
			2.04	7.15	2.54	1.91	- 6.3
			1.43	4.65	1.17	1.24	-13.2
12	0.835	B(6-12)	4.80	18.97	15.10	5.07	+ 5.6
			4.40	17.08	12.60	4.58	+ 4.1
			3.99	15.37	10.40	4.10	+ 2.8
			3.48	13.05	7.70	3.50	+ 0.6
			3.01	10.88	5.40	2.91	- 3.3
			2.47	8.90	3.85	2.38	- 3.6
			1.96	6.72	2.28	1.81	- 7.6
			1.50	4.95	1.30	1.32	-11.7
			3.00	10.72	5.35	2.87	- 4.3
			2.78	9.95	4.65	2.66	- 4.5
			2.00	7.05	2.50	1.89	- 5.5
			2.58	9.02	3.86	2.42	- 6.2
			1.82	6.20	1.94	1.66	- 8.8
			3.01	11.18	5.80	2.99	- 0.7
			3.00	11.05	5.60	2.96	- 1.4
			3.96	14.85	9.70	3.97	+ 0.3
			5.18	19.75	16.50	5.31	+ 2.4
12	0.835	A(13-18)	1.55	5.13	1.39	1.38	-10.6
			2.01	6.73	2.28	1.80	-10.5
			2.50	8.50	3.50	2.28	- 9.0
			3.00	10.45	5.20	2.80	- 6.8
12	0.835	A(13-18) Cont'd.	3.53	12.33	6.90	3.30	- 6.6
			4.40	15.63	10.60	4.19	- 4.8
			5.74	20.55	17.70	5.50	- 4.2
12	0.835	B(12-18)	5.62	20.35	17.50	5.44	- 3.2
			5.01	18.80	14.90	5.04	+ 0.5
			4.53	16.93	12.30	4.54	+ 0.2
			3.90	14.33	9.10	3.84	- 1.5
			3.48	12.75	7.20	3.41	- 2.1
			2.94	10.67	5.25	2.85	- 3.1
			2.57	9.12	3.95	2.44	- 5.2
			1.90	6.63	2.21	1.78	- 6.6
			1.68	5.93	1.81	1.58	- 5.9
			5.20	20.70	17.90	5.54	+ 6.6
			4.00	14.80	9.60	3.96	- 1.0
			3.05	10.47	5.20	2.80	- 8.2
			1.97	6.75	2.28	1.81	- 8.1
16	1.364	A(13-18)	4.20	9.40	4.20	4.10	- 2.3
			4.98	11.69	6.25	5.10	+ 2.5
			5.02	11.85	6.40	5.17	+ 2.9
			3.05	6.40	2.10	2.78	- 8.8
			5.74	13.91	8.60	6.06	+ 5.6
			6.92	16.98	12.50	7.40	+ 6.9
			8.01	19.82	16.50	8.65	+ 8.0
			8.92	21.95	20.00	9.58	+ 7.4
			10.03	24.85	25.00	10.90	+ 8.5
16	1.364	B(12-18)	2.96	6.45	2.12	2.82	- 4.9
			4.05	9.28	4.12	4.05	0.0
			5.06	12.28	7.00	5.35	+ 5.6
			4.52	10.65	5.30	4.65	+ 2.9
			3.48	7.73	2.90	3.38	- 2.7

*Q_o is exact discharge.
Q_c discharge determined by MA

TABLE I (cont'd)

SUMMARY OF TESTS - COX FLOWMETER STUDY

Pipe Size	Pipe Area A	Meter No.	Q_o^*	Rdg Cox M	Rdg Cox Δh	Q_c^*	Deviation Q_c from Q_o
	ft^2		cfs		inches water	cfs	%
16	1.364	B(12-18)	2.44	5.15	1.40	2.25	- 7.6
		Cont'd.	9.80	24.80	25.00	10.82	+10.4
			9.04	22.90	21.50	10.00	+10.6
			8.01	20.40	17.50	8.89	+11.0
			7.10	17.25	12.90	7.54	+ 6.2
			6.04	14.72	9.50	6.44	+ 6.6
16	1.364	B(12-18)	2.99	6.32	2.03	2.76	- 7.7
		15 tip	4.00	9.22	4.06	4.04	+ 1.1
			5.06	12.31	7.00	5.39	+ 6.4
			6.10	14.76	9.60	6.44	+ 5.6
			7.11	17.50	13.3	7.65	+ 7.5
			8.10	20.42	17.5	8.94	+10.4
			9.02	22.88	21.5	10.00	+10.8
			9.79	25.10	25.5	10.96	+12.0
18	1.756	A(13-18)	12.48	24.69	24.5	13.90	+11.4
			11.03	21.68	19.6	12.20	+10.6
			9.88	19.10	15.6	10.73	+ 8.6
			9.02	17.30	13.0	9.72	+ 7.8
			8.00	15.13	10.1	8.50	+ 6.3
			7.12	13.50	8.2	7.60	+ 6.7
			5.96	10.88	5.5	6.10	+ 2.3
			5.09	8.95	3.85	5.02	- 1.4
			4.24	7.18	2.55	4.03	- 5.1
			3.46	5.85	1.79	3.29	- 4.9
18	1.756	B(12-18)	3.45	6.08	1.90	3.42	- 0.9
			4.17	7.45	2.75	4.19	+ 0.5
			5.00	8.85	3.78	4.97	+ 0.3
			5.00	8.83	3.78	4.96	- 0.8
			5.94	11.05	5.70	6.20	+ 4.4
			6.99	13.2	7.90	7.41	+ 6.0

Pipe Size	Pipe Area A	Meter No.	Q_o^*	Rdg Cox M	Rdg Cox Δh	Q_c^*	Deviation Q_c from Q_o
	ft^2		cfs.		inches water	cfs	%
18	1.756	B(12-18)	8.18	15.7	10.70	8.82	+ 7.8
		Cont'd.	9.23	18.1	14.1	10.18	+11.4
			10.03	20.0	17.0	11.24	+12.0
			11.00	22.1	20.0	12.41	+12.8
			12.45	25.3	26.0	14.24	+14.4
20	2.18	A(19-24)	10.58	17.28	12.8	12.00	+13.5
			9.08	14.60	9.4	10.15	+11.8
			8.09	12.67	7.3	8.81	+ 8.9
			7.02	11.11	5.8	7.74	+10.2
			6.06	9.48	4.28	6.60	+ 8.9
			4.99	7.86	3.03	5.49	+10.0
			3.94	5.78	1.71	4.02	+ 2.1
			4.97	7.50	2.76	5.23	+ 5.2
			6.00	9.22	4.02	6.42	+ 7.0
			7.12	10.95	5.55	7.62	+ 7.0
			10.25	16.41	11.8	11.42	+11.4
			11.00	17.30	13.0	12.05	+ 9.6
			11.95	19.30	15.9	13.41	+12.2
			12.78	21.22	19.0	14.80	+15.8
			14.15	24.13	23.9	16.80	+18.7
			15.05	25.48	26.2	17.75	+18.0
20	2.18	B(19-24)	10.35	16.26	11.5	10.97	+ 6.0
			8.99	14.22	9.0	9.90	+10.2
			8.02	12.22	6.9	8.52	+ 6.2
			6.99	10.68	5.35	7.42	+ 6.2
			8.88	14.25	9.1	9.93	+11.9
			5.98	9.15	4.0	6.36	+ 6.4
			4.90	7.70	2.90	5.35	+ 9.0
			4.19	6.12	1.89	4.26	+ 1.7
			5.20	8.08	3.18	5.62	+ 8.1

TABLE I (cont'd)

SUMMARY OF TESTS - COX FLOWMETER STUDY

Pipe Size	Pipe Area A	Meter No.	Q_o^*	Rdg Cox M	Rdg Cox Δh	Q_c^*	Deviation Q_c from Q_o
	ft^2		cfs		inches water	cfs	%
20	2.18	B(19-24)	11.10	17.45	13.0	12.15	+ 9.5
		Con't.	15.05	25.94	27.0	18.05	+19.9
			14.00	23.10	22.0	16.10	+15.0
			13.05	21.58	19.3	15.00	+14.9
			12.05	19.61	16.1	13.68	+13.5
			11.05	17.66	13.4	12.30	+11.3
			9.85	15.65	10.7	10.9	+10.7
24	3.14	A(19-24)	6.94	7.40	2.70	7.43	+ 7.0
			7.93	8.50	3.50	8.54	+ 7.7
			8.93	10.10	4.85	10.14	+13.5
			10.13	11.22	5.85	11.30	+11.6
			11.03	12.22	6.80	12.30	+11.5
			12.45	14.20	9.00	14.28	+14.7
			12.95	14.90	9.80	14.95	+13.4
			14.10	16.50	11.80	16.58	+18.3
			17.20	20.60	17.70	20.70	+20.4
			18.50	21.65	19.60	21.80	+17.8
			18.40	22.28	20.50	22.40	+21.7
			15.98	18.95	15.10	19.02	+19.0
			15.05	17.80	13.70	17.89	+18.9
			18.80	22.57	21.0	22.60	+20.2

Pipe Size	Pipe Area A	Meter No.	Q_o^*	Rdg Cox M	Rdg Cox Δh	Q_c^*	Deviation Q_c from Q_o
	ft^2		cfs		inches water	cfs	%
24	3.14	B(19-24)	5.70	5.70	1.70	5.72	+ 0.4
			7.09	7.80	3.00	7.84	+10.6
			8.20	9.22	4.10	9.26	+12.8
			8.91	10.00	4.75	10.02	+12.4
			10.01	11.70	6.30	11.75	+17.4
			10.95	12.45	7.00	12.50	+14.2
			12.03	13.70	8.40	13.78	+14.5
			13.30	15.28	10.30	15.30	+15.0
			15.02	17.58	13.20	17.65	+17.5
			17.00	20.53	17.50	20.60	+21.2
			18.80	22.90	21.40	23.00	+22.4
30	4.91	A(25-30)	18.70	13.38	8.1	21.00	+12.3
			17.15	11.80	6.4	18.60	+ 8.4
			15.72	10.83	5.45	17.15	+ 9.1
			13.85	9.75	4.50	15.30	+10.5
			12.75	8.78	3.70	13.80	+ 8.2
			11.18	7.43	2.73	11.70	+ 4.6
			9.65	6.50	2.15	10.21	+ 5.8
30	4.91	B(25-30)	18.83	13.45	8.10	21.18	+12.5
			16.90	11.40	6.00	17.90	+ 5.9
			15.20	10.65	5.30	16.75	+10.2
			13.70	9.15	4.00	14.40	+ 5.1
			12.45	8.50	3.50	13.40	+ 7.6
			12.55	8.68	3.65	13.65	+ 8.8
			11.00	7.30	2.65	11.50	+ 4.6
			9.85	6.50	2.15	10.20	+ 3.6
			14.09	9.95	4.70	15.65	+11.1
			17.08	12.20	6.80	19.18	+12.3