PIPE INSERT FLOW METER

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INTRODUCTION

Measurement of Rate of Flow in Closed Conduits

Flow meters are used to give direct information about the quantity of liquid flowing under pressure within a pipe. The rate of flow is usually indicated by manometers, pointers, or traces on charts.

Commonly used devices for flow measurement are the venturimeter and the orifice plate meter, but many other devices are used such as the pitot tube, the current meter, the pipe bend meter, the rotary meter, and positive displacement meters.

(A) The Venturimeter

This meter consists of a streamlined constricted portion which is inserted between two flanges in a pipe line for the purpose of accelerating the water and causing a local pressure drop. Figure 1 shows a schematic section of a venturimeter. The entrance cone has a total angle of about 21^0 and leads to the short cylindrical throat. The diameter of the throat is usually between 1/2 and 1/4 of the entrance or pipe line diameter. The end of the throat leads into the exit cone or diffuser, which has a total angle of about 5^0 to 7^0. The function of the long diverging cone is to decelerate the fluid smoothly and restore the pressure as nearly as possible to the value at the meter entrance. The overall energy loss is 10 to 20% of the velocity head in the throat of the meter. The loss decreases as the speed of flow increases or as the meter is made larger.

Location: If accurate measurements are required, it is essential that the venturimeter not be located immediately after a valve, elbow or other irregularity in the pipe line but should be preceded by a length of five or more diameters of straight pipe to assure suitable flow conditions.

Formula of Flow: The following equation for rate of flow in a venturi meter can be derived by applying Bernoulli's theorem and the equation of continuity.

$$Q = C_d \frac{a}{\sqrt{1 - \beta 4}} \sqrt{2 g \frac{\Delta P}{\gamma}} \quad \text{where:} \quad (1)$$

Q is the rate of discharge

A is the area of the pipe line of diameter D

a is the area of throat of diameter d

C_d is the coefficient of discharge

β is the ratio of $\frac{d}{D}$

g is the acceleration due to gravity, and

$\frac{\Delta P}{\gamma}$ is the differential pressure head between the inlet and the throat.

The coefficient of discharge varies between 0.935 and 0.988 according to the sizes and diameter ratios of the meter. For small pipes or low rates of flow, lower values of C_d may be expected.

Cavitation: Cavitation will begin when the pressure at the throat reaches an absolute pressure equal to the vapor pressure of the liquid. This critical condition occurs when separation from the venturi develops downstream of the throat of the meter. At and beyond this critical condition, cavities filled with liquid vapor alternately develop and collapse in the low pressure region, causing damage to the surface in the critical region and reduced efficiency of the meter.

Advantages and Disadvantages: The venturimeter is a simple and reliable instrument suitable for a large range of pipe sizes. It has the advantage of high efficiency which is affected by conversion of its velocity head in the throat to pressure head in the divergent portion. However, it is an expensive meter and is not easy to manufacture. An appreciable change in discharge characteristics can occur if deposits occur on the walls of the meter changing its effective diameter. So the entrance and throat surfaces must be maintained in the same condition as they were during calibration.

(B) The Orifice Plate Meter

This meter is one of the oldest known devices for measuring the flow of fluids. The most widely used one is the concentric type. Other orifices such as the eccentric, the segmental, and the orifice segment, figure 2, are used for special purposes where it is required to measure fluid flow in which solid materials are transported.

Location: To ensure accurate flow measurements, it is essential that the fluid should pass through the orifice with a fully developed velocity profile free from vortices. This requires certain lengths of straight pipe both preceding and following the orifice. Elbows or open valves must be located at least 5 pipe diameters upstream from the orifice for small values of $\frac{D}{d}$ and as many as 25 diameters upstream from the orifice for large values of $\frac{D}{d}$. No elbows should be placed nearer than 5 diameters from the downstream face of the orifice. Control valves must be located on the outlet side of the orifice.

Formula of Flow: The following equation for rate of flow through a pipe orifice can be derived by applying Bernoulli's theorem and the equation of continuity.

$$Q = \frac{C_d A}{\sqrt{1 - C_d^2 \beta^4}} \sqrt{2g \left(\frac{P_1 - P_2}{\gamma} \right)} \qquad (2)$$

where:

Q is the rate of discharge

A is the area of the pipe line of diameter D

a is the area of the orifice of diameter d

C_d is the coefficient of discharge

β is the ratio of $\frac{d}{D}$

g is the acceleration due to gravity, and

P_1 and P_2 are the pressures upstream and downstream of the orifice respectively.

The coefficient of discharge varies with the ratio β and with the location of the pressure taps.

R.G. West Instrument: To reduce the sensitivity of the standard design of orifice plate to variations in the parameters influencing performance, R.G. West suggested an instrument consisting of a conventional thin-plate orifice, which features an upstream projection in the form of a ring, figure 3. It is designed to minimize the effects of upstream velocity distribution, pipe wall roughness, symetrical flow distribution and poor installation.

Advantages and Disadvantages: An orifice has the advantage that it is easy to manufacture and thus is less expensive than the venturimeter especially when used to measure large rates of flow.

On the other hand, overall loss of head may be as high as 80% of the differential head, and no provision has been made for recovering the lost velocity head. Hence, it is used where the overall loss of energy is not important. Also the pressure at the downstream connection should preferably be larger than atmospheric pressure to avoid the risk of air entering into the differential pressure tap which would adversely affect the differential head reading.

(C) Pipe Bends Used as Meters

The differential head generated when water flows around a pipe bend under free vortex conditions can sometimes be related to the discharge, figure 4. The rate of discharge is:

$$Q = C_d \sqrt{2gh} \; \frac{R^2 - C^2}{\sqrt{RC}} \; \pi \left[R - \sqrt{R^2 - C^2} \right] \quad \text{where:} \qquad (3)$$

Q is the rate of discharge

R is the radius of the axis of the bend

C is the radius of the pipe

h is the differential head between inside and outside corners of the bend

C_d is the discharge coefficient ranges from about 1.02 when $\frac{R}{C} = 6$ to about 1.25 when $\frac{R}{C} = 2$. So long as the main velocity in the pipe does not fall below about 4 ft/sec., the value of C_d is little affected either by velocity changes or by turbulent conditions upstream of the bend. For making rough comparative measurements, the bend meter has the advantage that it entails no additions or alterations to an existing pipe system, except for the drilling of the pressure taps.

(D) The Pitot Tube

The pitot tube is a simple device for measuring point velocity. The differential pressure "h" is proportional to the square of the velocity as indicated in the equation

$$V = C \quad 2\,gh \qquad (4)$$

where

C varies between 0.90 and 0.95.

To measure the discharge in a pipe, point velocities are measured along tow traverse diameters from which the mean velocity of flow is computed. The discharge is the product of the mean velocity and the area of pipe. The local velocity measured at three fourths the radius from the wall is very nearly identical with the mean velocity. Thus a single pitot tube measurement can be used to estimate the discharge.

(E) The Current Meter

The current meter has rotating vanes or cups which rotate at a speed proportional to the velocity of liquid. The same procedure used for the pitot tube can be used to measure the discharge in pipes.

The conventional current meter is not well adapted to pipe flow measurements. It is a relatively delicate device and may be easily damaged. It cannot be removed for inspection easily. A special system must be provided to place the current meter at a desired point in the pipe cross section and to orient it correctly. These disadvantages have been minimized to some extent by the development of special midget meters with magnetic heads and compatable recording instruments which continuously or periodically records the velocity or discharge based upon the speed of the meter.

(F) Rotary and Positive Meters

These meters measure the volume of flow passing through the pipe in a certain time. The discharge is computed by dividing this volume by the time. These meters are accurate, reliable but expensive.

THE PROPOSED PIPE INSERT METER

Many excellent devices have been developed to measure discharge both directly and indirectly but perhaps better devices can be developed. The need for a simple, accurate, economical method of measuring flow in pipes prompted the investigation of this meter which was proposed by D. B. Simons, Colorado State University.

Description: The suggested flow meter is simple to construct and is smaller in cost than other comparable meters. No accuracy is sacrificed when it is used for an essentially clean fluid free of fiberous stringy material. It consists of a streamlined body which is centered within the pipe. The streamlined insert can be made of plastic, steel, ply wood, or some other suitable material. The surface of the insert should be treated to assure its inertness and smoothness. Figure 5 is a schematic of the meter. It consists of 3 parts: the leading streamlined cone of length L_1 which accelerates the water, lowers the pressure head, and diverts the flow smoothly into the annular space of length L_2; the cylindrical portion of diameter d_1 and length L_2; and the trailing streamlined cone of length L_3, which is of sufficient length to decelerate the fluid smoothly and to limit separation, cavitation and energy loss.

Upstream from the leading edge, at a distance of one pipe diameter, the wall of the pipe is tapped, or several taps leading to a piezometric ring may be used. In the pipe surrounding the cylindrical portion, another tap or taps are located. The differential head between the two taps can be measured and related to discharge.

The insert is installed in the pipe by means of bolts 1/4" in diameter. One is located in the upstream cone and the other in the downstream cone as indicated in figure 5. They are adjusted to align the meter along the center of the pipe. Other types of support can be substituted as dictated by meter requirements.

As is the case for the venturimeter, it is essential to have a length of five or more diameters of straight pipe upstream of the meter.

Theory: Most of the flow meters accelerate the flow to decrease the pressure at the throat or the vena-contracta. The proposed meter accomplishes this by accelerating the flow as it passes the streamlined insert. The area of flow at the constriction is the total area of the pipe of diameter D less the area of the cylindrical portion of the insert of diameter d_1.

Writing the energy equation between sections (1) and (2) of figure 5

$$\frac{V_1^2}{2g} + \frac{P_1}{\gamma} = \frac{V_2^2}{2g} + \frac{P_2}{\gamma} + h_L$$

where:

V_1 is the average velocity in the pipe line at section (1)

V_2 is the average velocity in the pipe line at section (2)

P_1 is the pressure at section (1)

P_2 is the pressure at section (2), and

h_L is the energy loss between sections (1) and (2).

Using the continuity equation

$$V_1 A_1 = V_2 A_2 \tag{5}$$

where:

A_1 is the area $\frac{\pi D^2}{4}$ of the pipe line of diameter D at section (1)

A_2 is the area $\left(\frac{\pi D^2}{4} - \frac{\pi d_1^2}{4}\right)$ of the annular water way around the streamlined body of diameter d_1 at section (2)

In terms of D and d_1

$$V_1 = V_2 \left(\frac{D^2 - d_1^2}{D^2}\right)$$

Substituting this relation for V_1 in the energy equation

$$\frac{V_2^2}{2g}\left[\frac{D^2 - d_1^2}{D^2}\right] + \frac{P_1}{\gamma} = \frac{V_2^2}{2g} + \frac{P_2}{\gamma} + h_L$$

and solving for V_2

$$V_2 = \sqrt{\frac{2g\left(\frac{P_1 - P_2}{\gamma} - h_L\right)}{1 - \left(\frac{D^2 - d_1^2}{D^2}\right)^2}}$$

The energy loss is taken care of by using a coefficient C_d hence

$$Q = C_d A_2 V_2 = \frac{C_d A_2}{\sqrt{1 - \left[\frac{D^2 - d_1^2}{D^2}\right]^2}} \sqrt{2g\left(\frac{P_1 - P_2}{\gamma}\right)} \quad (6)$$

and

$$Q = \frac{C_d A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \sqrt{2g\left(\frac{P_1 - P_2}{\gamma}\right)} \quad (7)$$

or

$$Q = K\sqrt{\frac{\Delta P}{\gamma}} \quad (8)$$

where $K = \frac{C_d A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \sqrt{2g}$, and

$\frac{\Delta P}{\gamma}$ is the differential pressure head.

Design: The length of the leading cone of the insert L_1 was designed to give a smooth streamlined convergence, while the length L_3 was designed to assure uniform divergence and recovery of the pressure, see figure 5. The length of the cylindrical portion L_2 is equal to the diameter of the pipe line D but could be made longer. In designing the diameters of the cylindrical portion of the meter, different ratios of $\frac{d_1}{D}$ between 0.60 and 0.75 yielding ratios of areas $\frac{A_1}{A_2}$ between 1.50 and 1.70 were tested. Three pipes of diameters 2", 4", and 8" were tested with two inserts of different diameter as shown in figure 6.

For D = 2", d_1 = 1.5" and 1.2",
L_1 = 2", L_3 = 5.5"

For D = 4", d_1 = 3.0" and 2.5",
L_1 = 4", L_3 = 12"

For D = 6", d_1 = 6.0" and 4.8",
L_1 = 8", L_3 = 21"

Installation: The meter insert was centered within the test pipe by means of two steel or aluminum 1/4" diameter bolts threaded through the leading and trailing cones. The bolts were attached to the pipe walls through pressure fittings. Other methods of supporting the insert may be preferred, depending upon flow conditions and the characteristics of the fluid.

Loss of Energy: Due to the gradual expansion of the flow downstream from the cylindrical middle-portion of the insert, there is an efficient conversion of the velocity energy into pressure energy. The head loss in the meter can be expressed as

$$h_L = C_L V_2^2/2g$$

The loss coefficient C_L depends on the ratio of the area of the pipe to the minimum area in the meter and varies with the Reynolds number. It is approximately equal to 0.1, as is the case for the venturimeter.

Cavitation: As the pressure in the meter is decreased to an absolute value equal to the vapor pressure at the prevailing temperature cavitation begins. Bubbles of air and of vapor form and collapse immediately as they pass beyond this zone. An action is induced on the boundaries which causes pitting and damage to the walls of the downstream cone. The initiation of cavitation was observed on the inserts placed in the plastic pipes. Thus, at high velocities cavitation imposes a limitation on the use of the meter. This can be minimized by lengthening the insert to obtain a more streamlined body.

Advantages and Disadvantages: The proposed meter is a simple device which is economical to construct and install. The error in measuring discharge will not exceed 1/2%. A disadvantage is that stringy materials being transported by the flow may collect on the insert supports, causing some disturbance in the flow and inaccurate readings.

TEST PROGRAM

Experimental Equipment and Procedure: The experiments were conducted in the Hydraulics laboratory at Colorado State University. Water was pumped in a closed circuit from a sump to the pipe line which contained a discharge control valve. Smooth convergent sections with sufficient lengths upstream of the meter were provided for the dif-diameters of pipes tested. Water discharged was measured by two volumetric tanks. The time required to collect a given volume was recorded by an electric counter. The differential pressures were measured with differential transducers and recording equipment.

Instrumentation: The pressure measuring instrumentation consisted of D.C. output, Model CP51, variable reluctance differential pressure transducer coupled with an appropriate recorder and/or direct reading meter. Two transducers were used to cover the range of differential pressures experienced. The ranges were 0 - 1.5 PSI and 0-75 PSI with 0-2.5 VDC out in both cases.

The transducers were mounted in an instrument box with their power supply. There were convenient taps for pressure input and electrical output. A valving system was provided to bleed the lines on both sides of the transducers thus making it possible to purge air from the differential pressure measuring system.

Transducer calibration certificates were provided by the manufacturer. The calibration certificates were checked and the resulting data indicated that the transducer output was well within the accuracy limits stated by the manufacturer. The accuracy according to the specifications is: Linearity, ± 1/2 percent from the best straight line; Hystersis, 1/2 percent pressure excursion.

The major source of error in such a pressure measuring system as indicated by prior experience is the entrapment of air in the lines from the flow meter to the transducers. Error due to air in the lines becomes more significant at the lower differential pressures. A small bubble of air causes a fairly large percentage of error in the differential pressure. The greater incidence of bubbles in the low pressure side of the transducer is attributed to removal of air from solution by the negative pressure encountered. Transparent lines were used to transmit pressure from the flow meter to the transducers to facilitate observation of bubble incidence. As a matter of procedure, immediately prior to data collection, the lines were subjected to cross flow from the high to the low pressure tap and the transducers were bled at their pressure cavity vent.

Meters Tested: Three diameters of pipes, 2" 4" and 8" were used. Six meters were constructed by using two different inserts in each of the three pipes.

1.5" and 1.2" diameter inserts for the 2" diameter pipe

3.0" and 2.5" diameter inserts for the 4" diameter pipe

6.0" and 4.85" diameter inserts for the 8" diameter pipe

The test length of the 2" and 4" diameter pipes and the inserts were made of plastic. The inserts were painted black. The transparent pipes enabled us to observe the flow pattern and the critical conditions at which cavitation occured. Figure 7 is a photograph of the 4" diameter, clear plastic pipe with insert.

Experimental Results: A large range of discharge was run through each meter. Testing was not carried out at discharges large enough to cause flow separation and cavitation.

The discharges were computed knowing the volume of water collected in a recorded time. The differential pressures in PSI were computed from the transducer charts. Then the differential pressure heads in feet of water and their square roots were calculated.

Plots of discharge versus differential pressure head (ΔH) and discharge versus $\sqrt{\Delta H}$ for the six experimental meters are presented in figures 8 through 19.

Smooth curves join all the points in the preceeding Q versus $\sqrt{\Delta H}$ relations. The graphs of Q versus $\sqrt{\Delta H}$ prove that all the points of each set fit a straight line beginning from the origin. These straight lines verify that the discharge is proportional to the square root of the differential pressure head which agrees with equation 8 for the proposed meter

$$Q = K \sqrt{\Delta H} \qquad (8)$$

and that K depends upon the diameter of the pipe, the diameter of the insert, the roughness of the pipe and insert, and the Reynolds number.

Figure 20 presents logarithmic plots of Q versus ΔH for all insert flow meters. A family of parallel straight lines with a slope 0.50 results as predicted by equation 8. Using the data and equation 8, the coefficient K was computed for all sizes of meters which were tested, see table 7.

From equation 7

$$C = \frac{A_2}{1 - \frac{A_2^{\,2}}{A_1}} \qquad (9)$$

Using this relation the values of C for all meters were computed (table 7) and plotted against the corresponding values of K, figure 21. They fall on a straight line beginning at the origin. This curve helps to determine the value of K for any other meter in any pipe knowing the value of C.

Velocity Range: Since the 2 inch and 4 inch diameter pipes were transparent, it was possible to limit the maximum discharges to avoid cavitation. For the 2 inch pipe, with 1.5 inch and 1.2 inch inserts, the maximum discharges were 0.711 cfs and 0.956 cfs. The corresponding velocities were 32.70 fps and 43.9 fps, and the Reynolds numbers were 4.1×10^5 and 6.2×10^5 respectively, (tables 1 and 2). For the 4 inch pipe, with 3 inch and 2.5 inch inserts, the maximum discharges were 1.59 cfs and 2.85 cfs. The corresponding velocities were 18.2 fps and 32.5 fps and the Reynolds numbers were 4.07×10^5 and 8.92×10^5 respectively, (tables 3 and 4). For the 8 inch diameter pipe, with 6.0 inch and 4.8 inch inserts, the maximum discharges were 2.212 cfs and 3.527 cfs. The corresponding velocities were 6.39 fps and 10.15 fps and the Reynolds numbers were 2.69×10^5 and 4.25×10^5 respectively, (tables 5 and 6). Hence, these meters can accomodate relatively large flows and velocities without damage from cavitation.

CONCLUSIONS

In this experimental program using the 2 inch, 4 inch, and 8 inch diameter pipes with inserts of different diameters, the following conclusions were reached:

1. The Q versus ΔH relations are smooth curves and the Q versus ΔH relations are straight lines in accordance with the meter formula $Q = K \Delta H$ as is the case for the venturi and the orifice plate meter.

2. The coefficient K is a function of:

$$A_1 \quad \frac{A_1}{A_2}^{2} - 1$$

and can be accurately estimated for meters of various dimensions.

3. The manufacture of the meter is simple. The inserts can be made from a variety of materials, such as wood or similar materials, if waterproofed with fiberglass

4. The installation of the inserts is simple, quick and economical.

5. Although the vertical rods used in these tests to fix the insert in the center line of the pipe were satisfactory, other methods of mounting the insert can be used to minimize complications in the presence of stringy debris in the moving fluid.

6. This meter is efficient from the view point of minimizing energy loss.

7. The meter is more economical and just as accurate as other comparable flow meters.

Table 1

$D = 2.0''$, $d_1 = 1.5''$

Run No.	Q CFS	Press. diff. PSI	ΔH Feet	$\sqrt{\Delta H}$	V FPS	μ lb sec/ft² x 10^5	Re x 10^{-5}
1	0.466	11.54	26.623	5.16	21.49	2.585	2.685
2	0.402	8.70	20.071	4.48	18.50	2.585	2.310
3	0.376	7.60	17.533	4.19	17.30	2.585	2.155
4	0.323	5.65	13.035	3.61	14.90	2.585	1.870
5	0.270	4.00	9.228	3.04	12.40	2.585	1.550
6	0.215	2.60	5.998	2.45	9.90	2.585	1.240
7	0.173	1.80	4.153	2.04	7.95	2.585	0.995
8	0.0977	0.505	1.165	1.08	4.48	2.585	0.560
9	0.711	27.25	62.866	7.92	32.70	2.585	4.10
10	0.629	21.40	49.370	7.026	28.90	2.585	3.61
11	0.542	15.90	36.681	6.06	25.10	2.585	3.14

Table. 2

$D = 2.0''$, $d_1 = 1.2''$

Run No.	Q CFS	Press diff. PSI	ΔH Feet	$\sqrt{\Delta H}$	V FPS	μ lb sec/ft² x 10^5	Re x 10^{-5}
1	0.706	10.00	23.07	4.803	32.45	2.44	4.60
2	0.567	6.48	14.95	3.86	26.00	2.44	3.69
3	0.476	4.60	10.61	3.25	21.50	2.44	3.05
4	0.375	2.96	6.70	2.59	17.20	2.44	2.45
5	0.307	2.00	4.55	2.13	14.10	2.44	2.00
6	0.237	1.115	2.65	1.63	10.90	2.44	1.55
7	0.164	0.515	1.19	1.09	7.55	2.44	1.07
8	0.956	17.90	41.30	6.43	43.90	2.44	6.20
9	0.872	14.95	34.60	5.90	40.30	2.44	5.71
10	0.783	12.15	28.03	5.29	36.00	2.44	5.10

Table 3

D = 4.0", d_1 = 3.0"

Run No.	Q CFS	Press. diff. PSI	ΔH Feet	$\sqrt{\Delta H}$	V FPS	μ lb sec/ft² x 10^5	Re x 10^{-5}
1	0.965	4.05	9.35	3.06	11.00	2.875	2.45
2	1.300	7.35	16.96	4.11	14.08	2.875	3.15
3	1.590	10.85	25.04	5.01	18.20	2.875	4.07
4	0.504	1.175	2.71	1.648	5.78	2.875	1.29
5	0.158	0.11	0.254	0.504	1.81	2.875	0.405
6	0.096	0.045	0.1039	0.322	1.10	2.875	0.246

Table 4

D = 4.0", d_1 = 2.5"

Run No.	Q CFS	Press. diff. PSI	ΔH Feet	$\sqrt{\Delta H}$	V FPS	μ x 10^5	Re x 10^{-5}
1	2.850	14.55	33.58	5.79	32.50	2.35	8.92
2	2.373	9.50	21.92	4.68	27.20	2.35	7.48
3	1.899	6.21	14.33	3.79	21.65	2.35	5.99
4	1.490	3.80	8.77	2.96	17.00	2.35	4.70
5	1.270	2.65	6.12	2.47	14.50	2.35	4.00
6	1.101	2.05	4.73	2.17	12.60	2.35	3.45
7	0.979	1.66	3.83	1.96	11.20	2.35	3.06
8	0.903	1.48	3.42	1.85	10.35	2.35	2.84
9	0.719	0.89	2.05	1.43	8.22	2.35	2.26
10	0.240	0.097	0.22	0.47	2.75	2.35	0.755

Table 5

D = 8.0", d_1 = 6.0"

Run No.	Q CFS	Press. diff. PSI	ΔH Feet	ΔH	V FPS	μ x 10^5	Re x 10^{-5}
1	2.212	1.211	2.795	1.671	6.39	3.075	2.69
2	2.042	1.038	2.396	1.548	5.83	3.075	2.45
3	1.782	0.79	1.823	1.350	5.11	3.075	2.155
4	1.537	0.582	1.343	1.160	4.42	3.075	1.86
5	1.245	0.380	0.877	0.936	3.57	3.075	1.50
6	0.948	0.209	0.482	0.694	2.71	3.075	1.14
7	0.740	0.125	0.289	0.537	2.12	3.075	0.895
8	0.440	0.042	0.098	0.314	1.16	3.075	0.487

Table 6

D = 8.0", d_1 = 4.85"

Run No.	Q CFS	Press. diff. PSI	ΔH Feet	ΔH	V FPS	μ x 10^5	Re x 10^{-5}
1	3.020	0.73	1.68	1.29	8.70	3.075	3.65
2	2.140	0.35	0.805	0.895	6.14	3.075	2.58
3	2.721	0.56	1.29	1.135	7.85	3.075	3.30
4	2.404	0.45	1.035	1.017	6.90	3.075	2.90
5	2.024	0.30	0.69	0.83	5.80	3.075	2.44
6	1.866	0.282	0.648	0.805	5.35	3.075	2.25
7	1.435	0.165	0.379	0.62	4.12	3.075	1.735
8	1.015	0.074	0.170	0.412	2.91	3.075	1.225
9	0.802	0.05	0.115	0.338	2.30	3.075	0.965
10	3.527	1.00	2.30	1.52	10.15	3.075	4.25
11	3.178	0.80	1.84	1.36	9.11	3.075	3.82

Table 7

D inches	d_1 inches	K	C
2	1.5	0.0875	0.0105
2	1.2	0.148	0.181
4	3.0	0.32	0.45
4	2.5	0.507	0.665
8	6.0	1.35	0.171
8	4.85	2.32	0.29

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Appreciation is also expressed for the cooperation given by S. S. Karaki, Associate Professor of Civil Engineering and G. L. Smith, Associate Civil Engineer for their assistance with data collection and to F.J. Watts, Instructor in Civil Engineering.

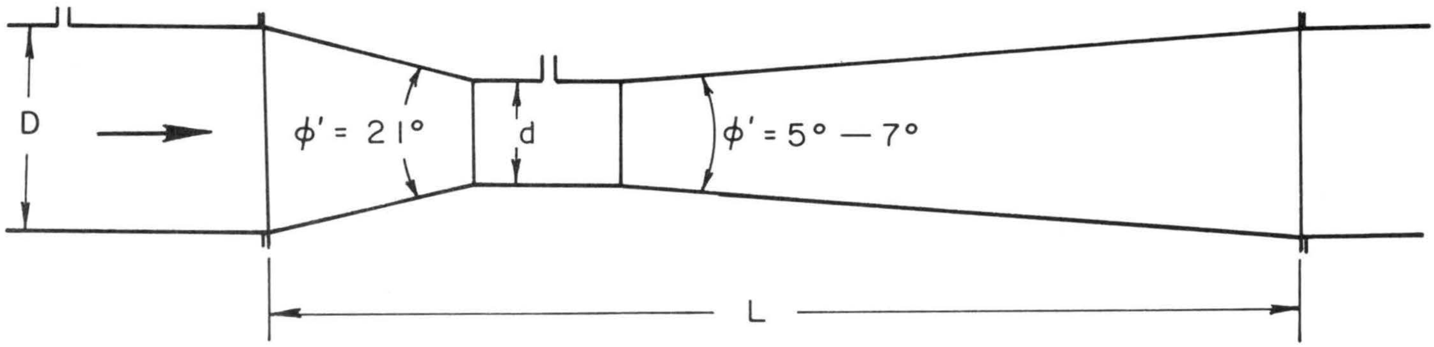


FIG. 1 SCHEMATIC SECTION OF A CLASSICAL VENTURIMETER

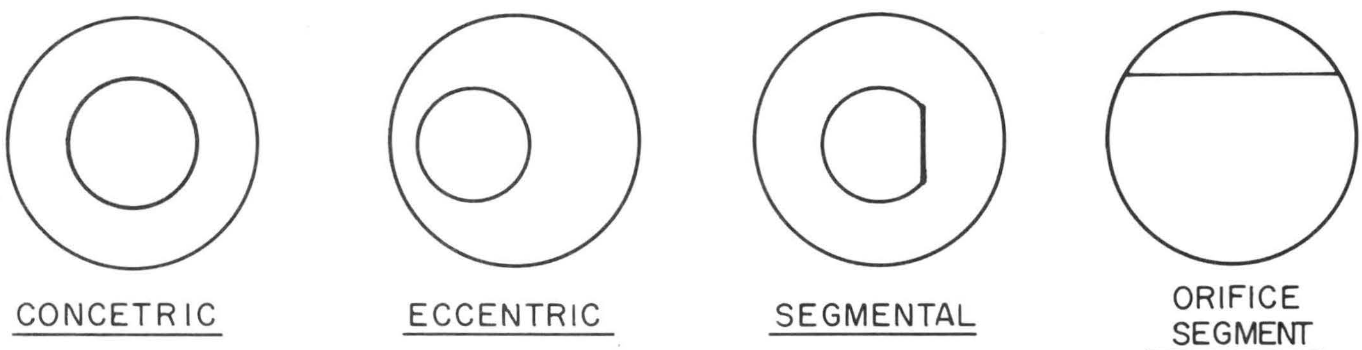


FIG. 2 TYPES OF ORIFICE PLATE METERS

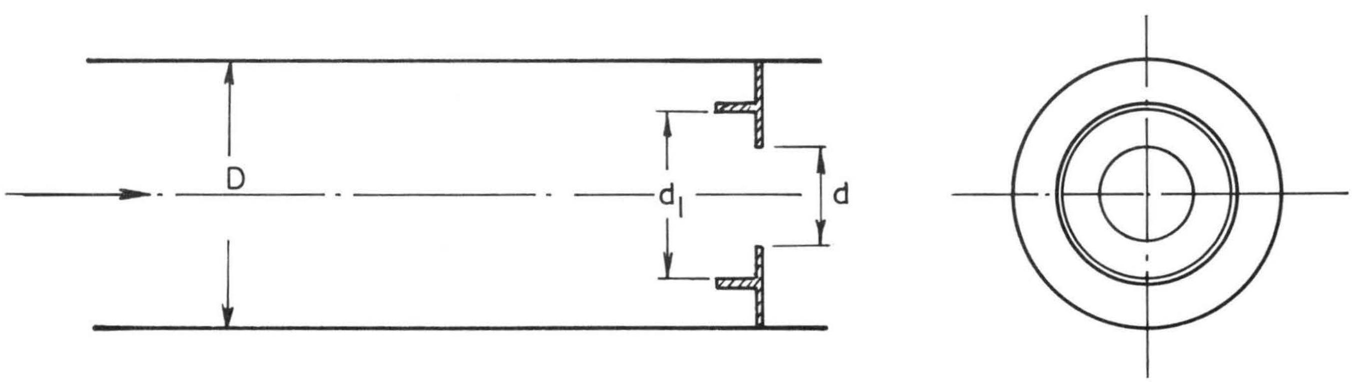


FIG. 3 R. G. WEST INSTRUMENT

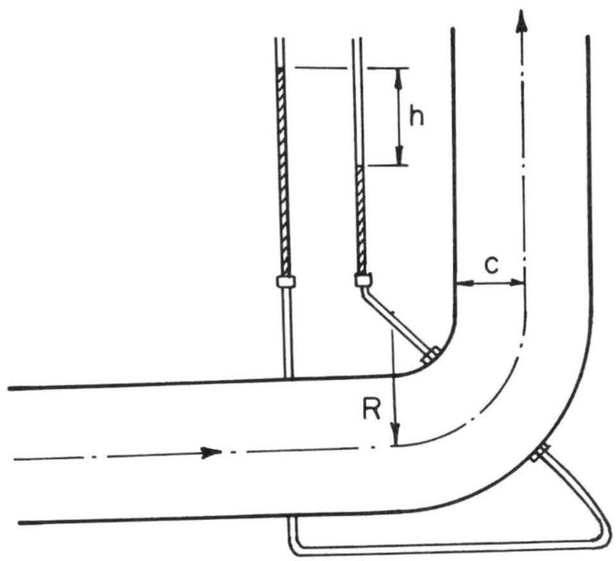


FIG. 4 PIPE BEND USED AS METER

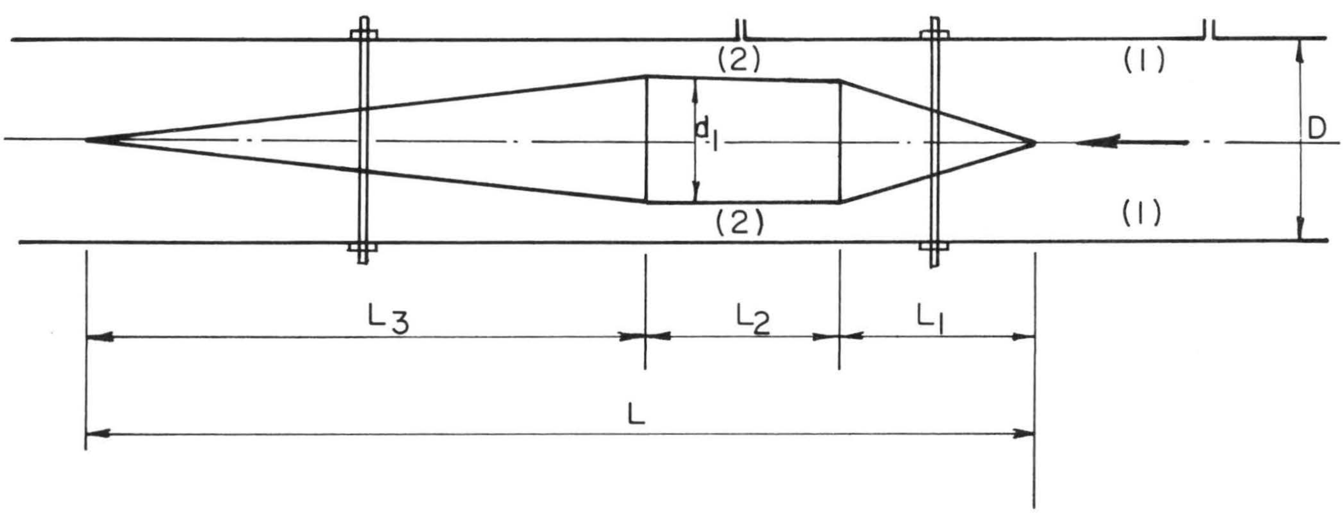


FIG. 5 SCHEMATIC SECTION OF THE PROPOSED METER

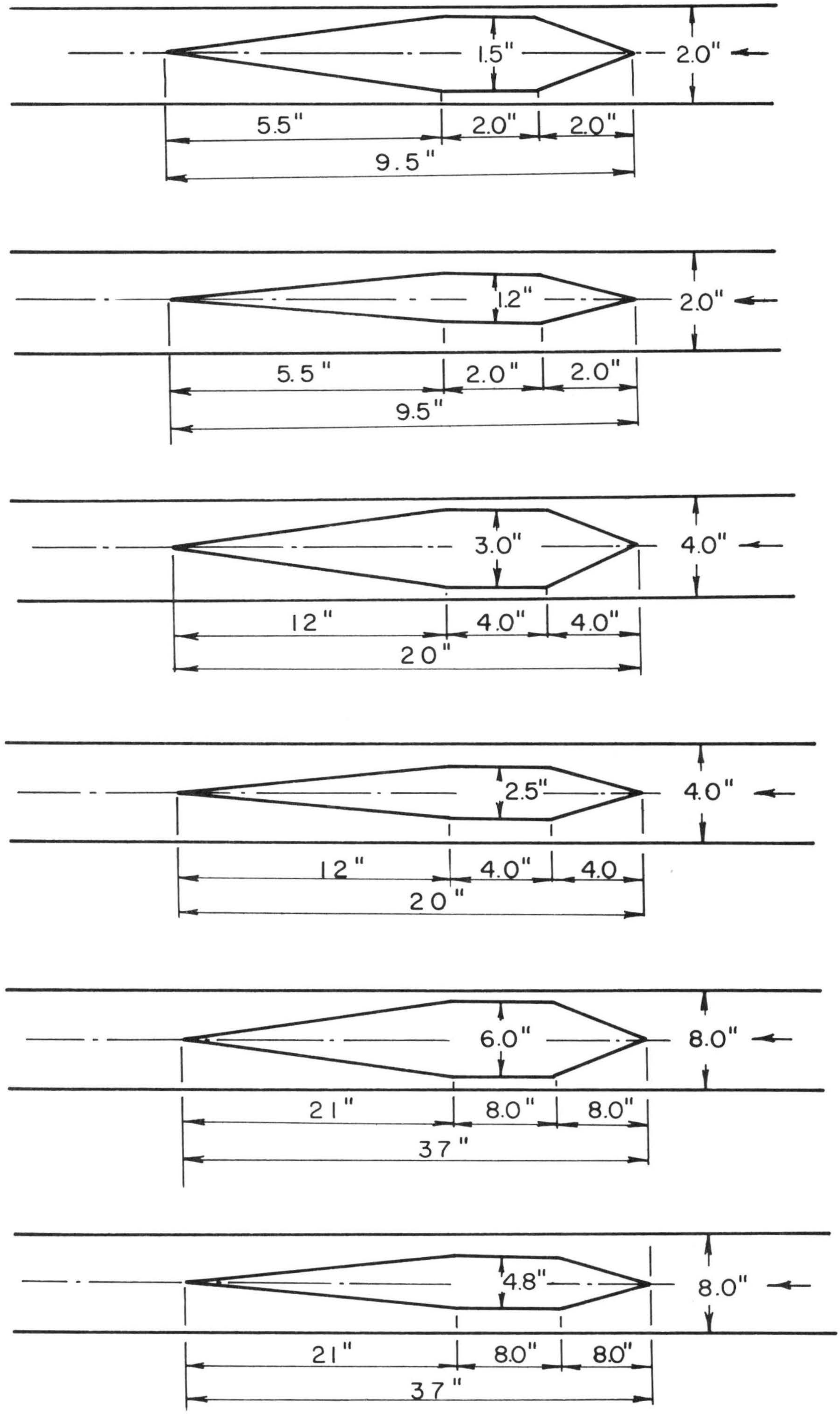


FIG. 6 PIPES AND METERS USED

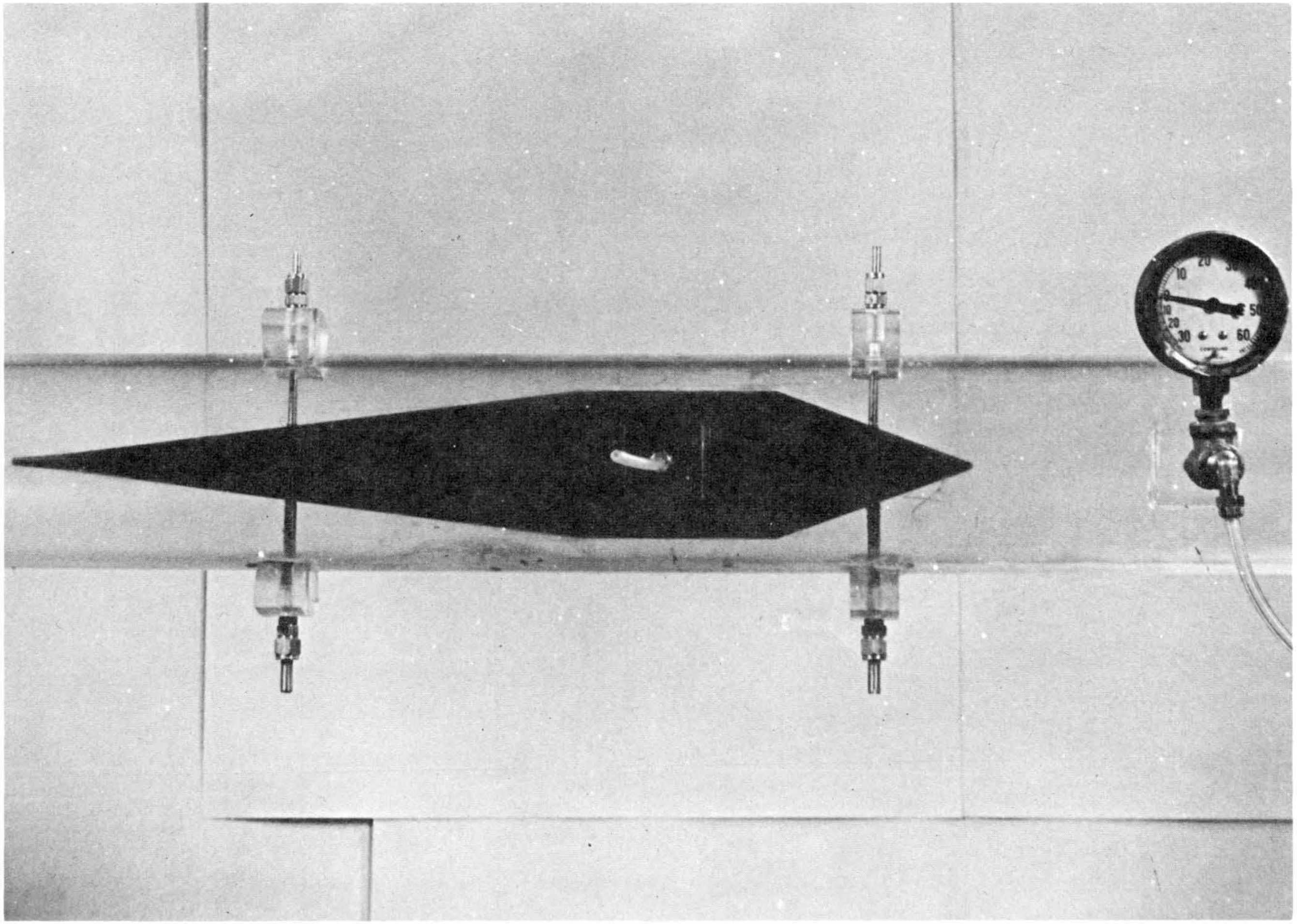
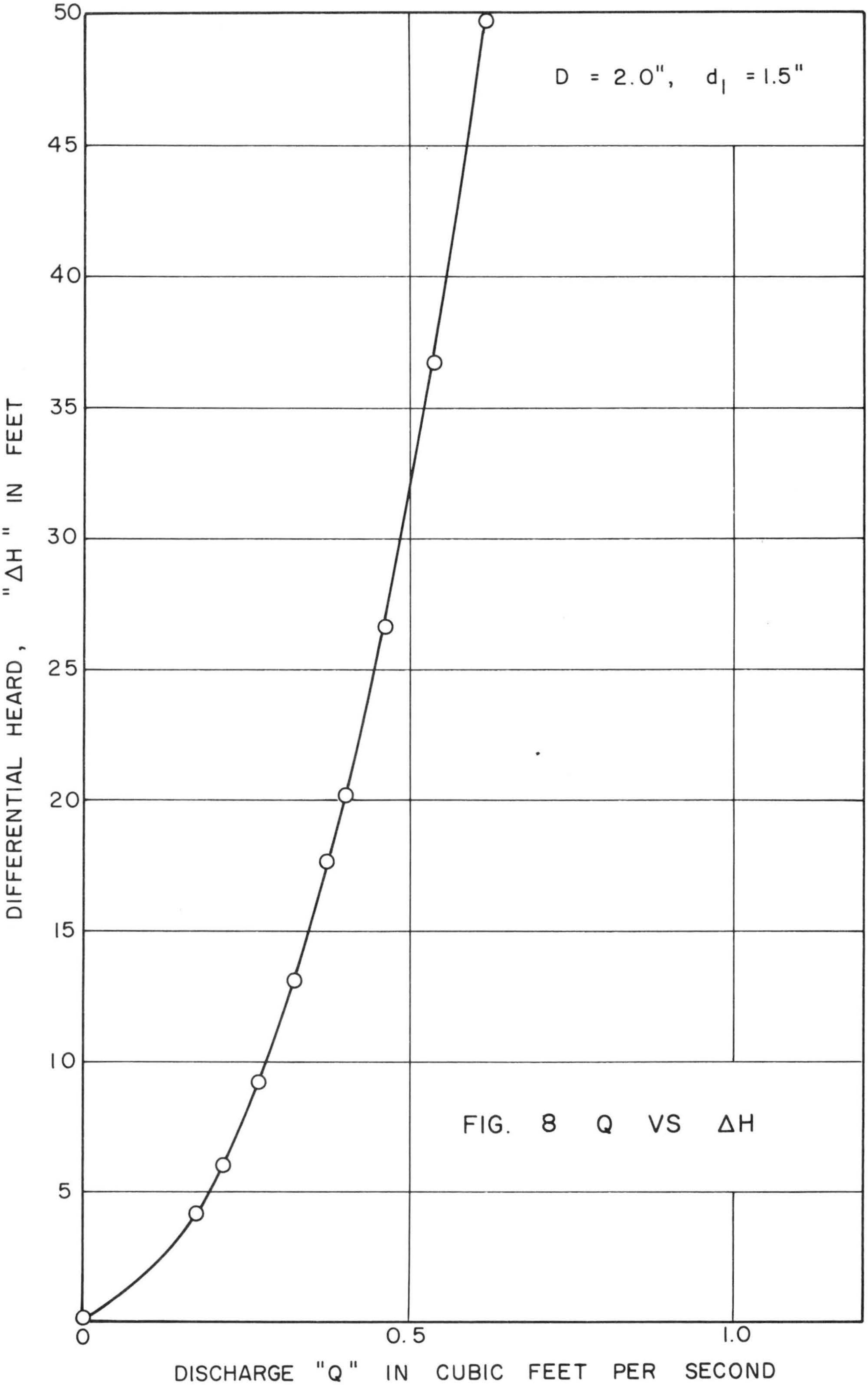


FIG. 7 PIPE INSERT FLOW METER



D = 2.0", d1 = 1.5"
DIFFERENTIAL HEARD, "ΔH" IN FEET
DISCHARGE "Q" IN CUBIC FEET PER SECOND
50
45
40
35
30
25
20
15
10
5
0
0.5
1.0

FIG. 8 Q VS ΔH

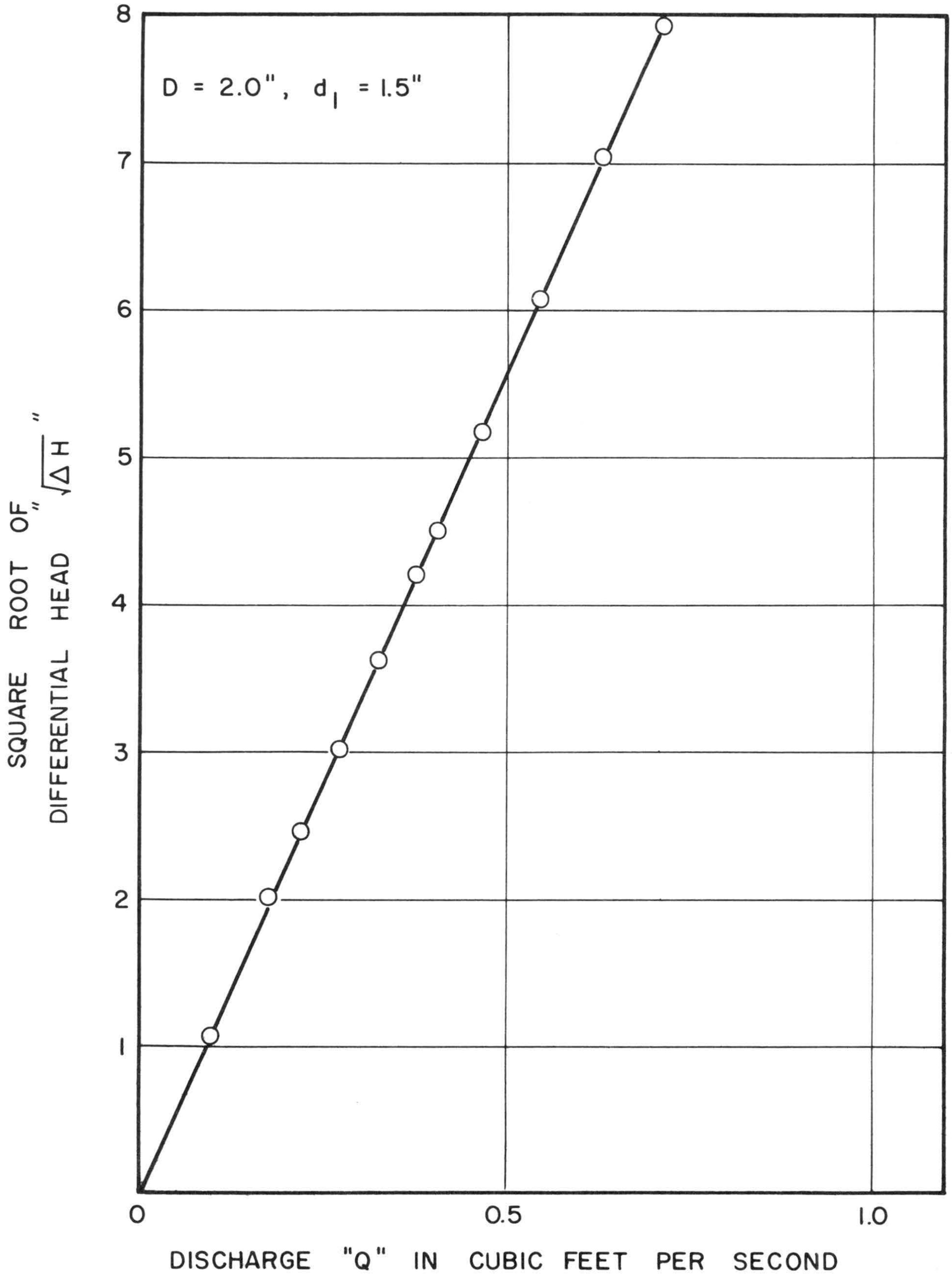
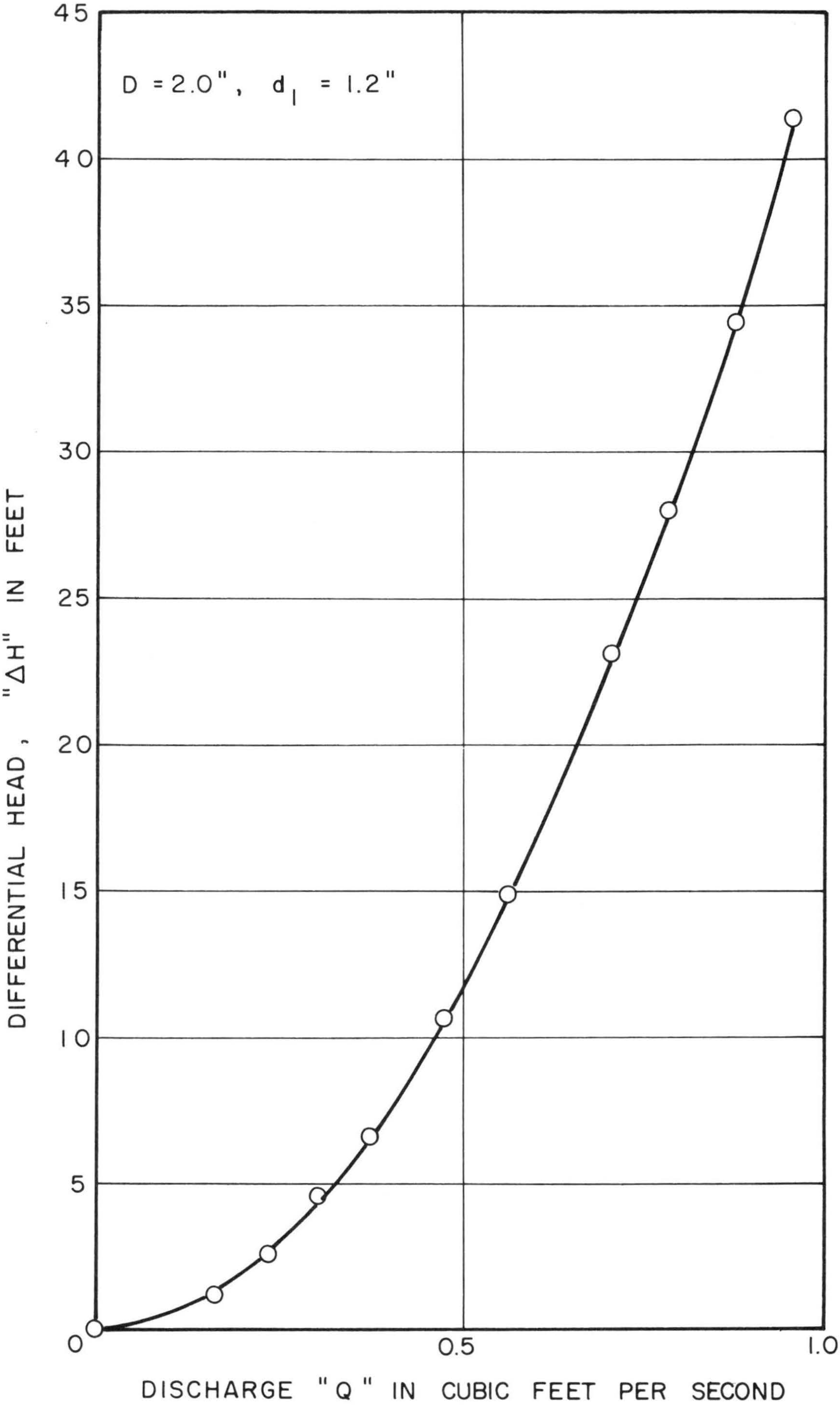


FIG. 9 Q VS $\sqrt{\Delta H}$



D = 2.0", d_1 = 1.2"
DIFFERENTIAL HEAD, "ΔH" IN FEET
45
40
35
30
25
20
15
10
5
0
0.5
1.0
DISCHARGE "Q" IN CUBIC FEET PER SECOND

FIG. 10 Q VS ΔH

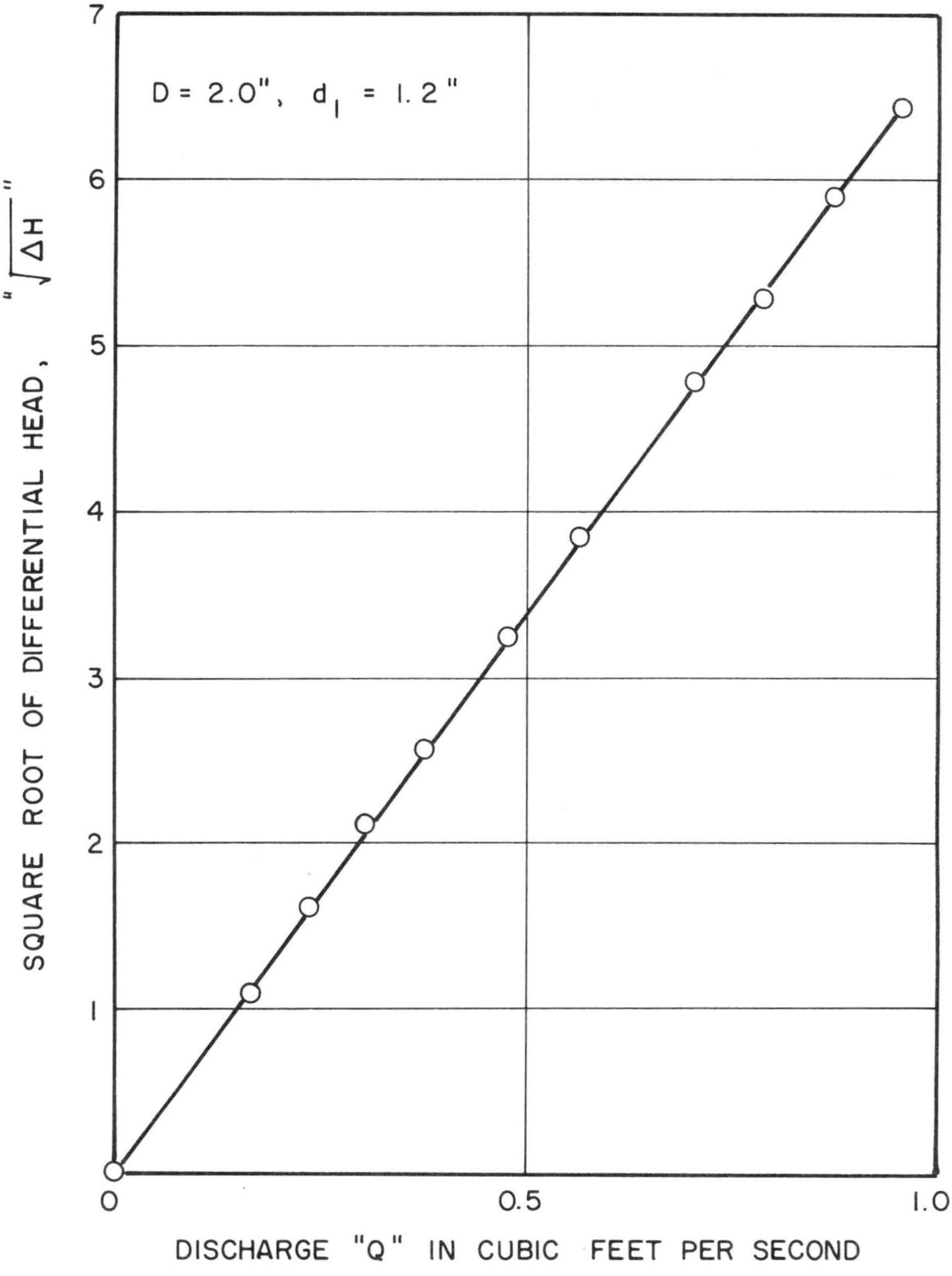


FIG. 11 Q VS $\sqrt{\Delta H}$

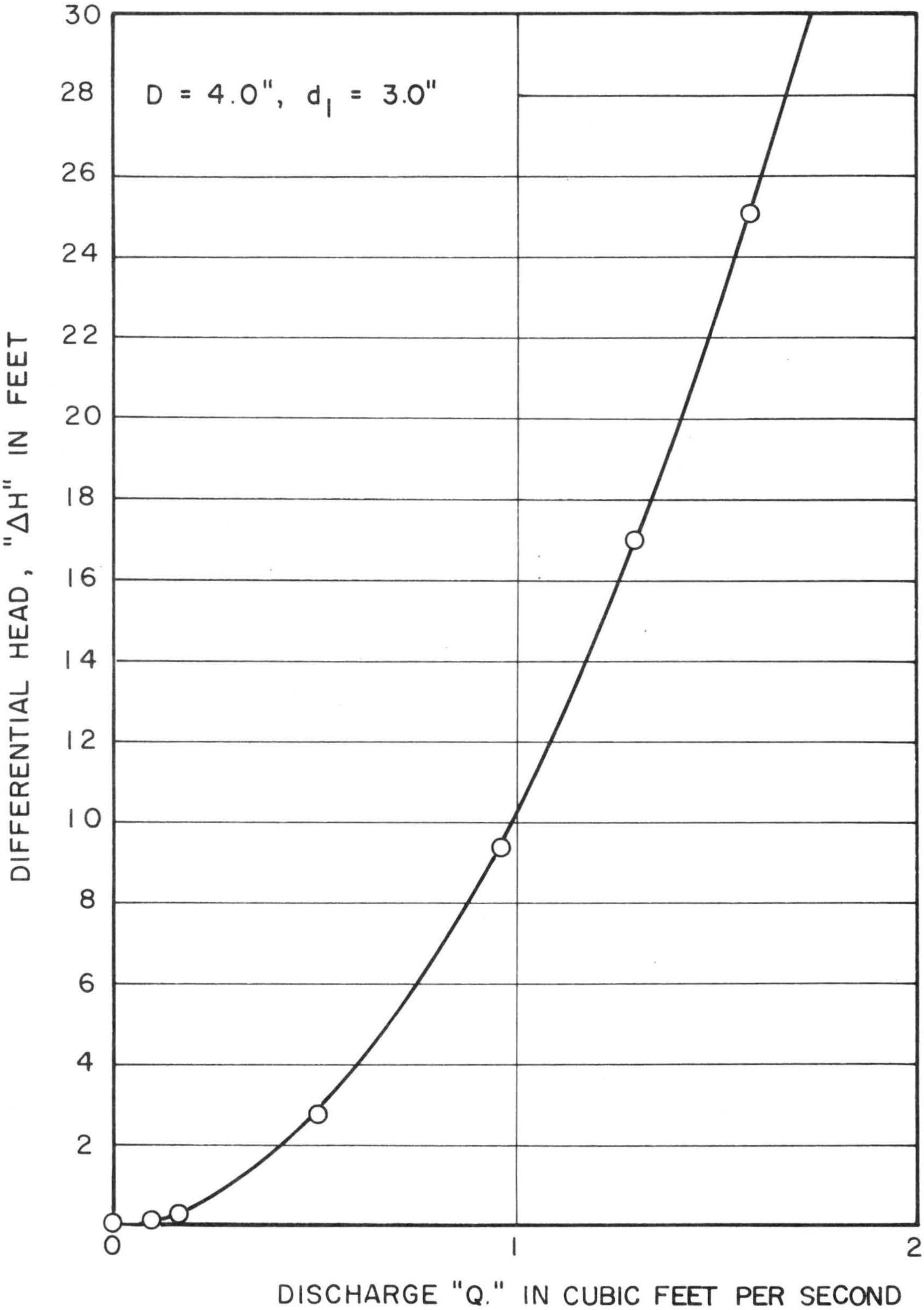

D = 4.0", d_1 = 3.0"
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
1
2
DIFFERENTIAL HEAD, "ΔH" IN FEET
DISCHARGE "Q." IN CUBIC FEET PER SECOND

FIG. 12 Q VS ΔH

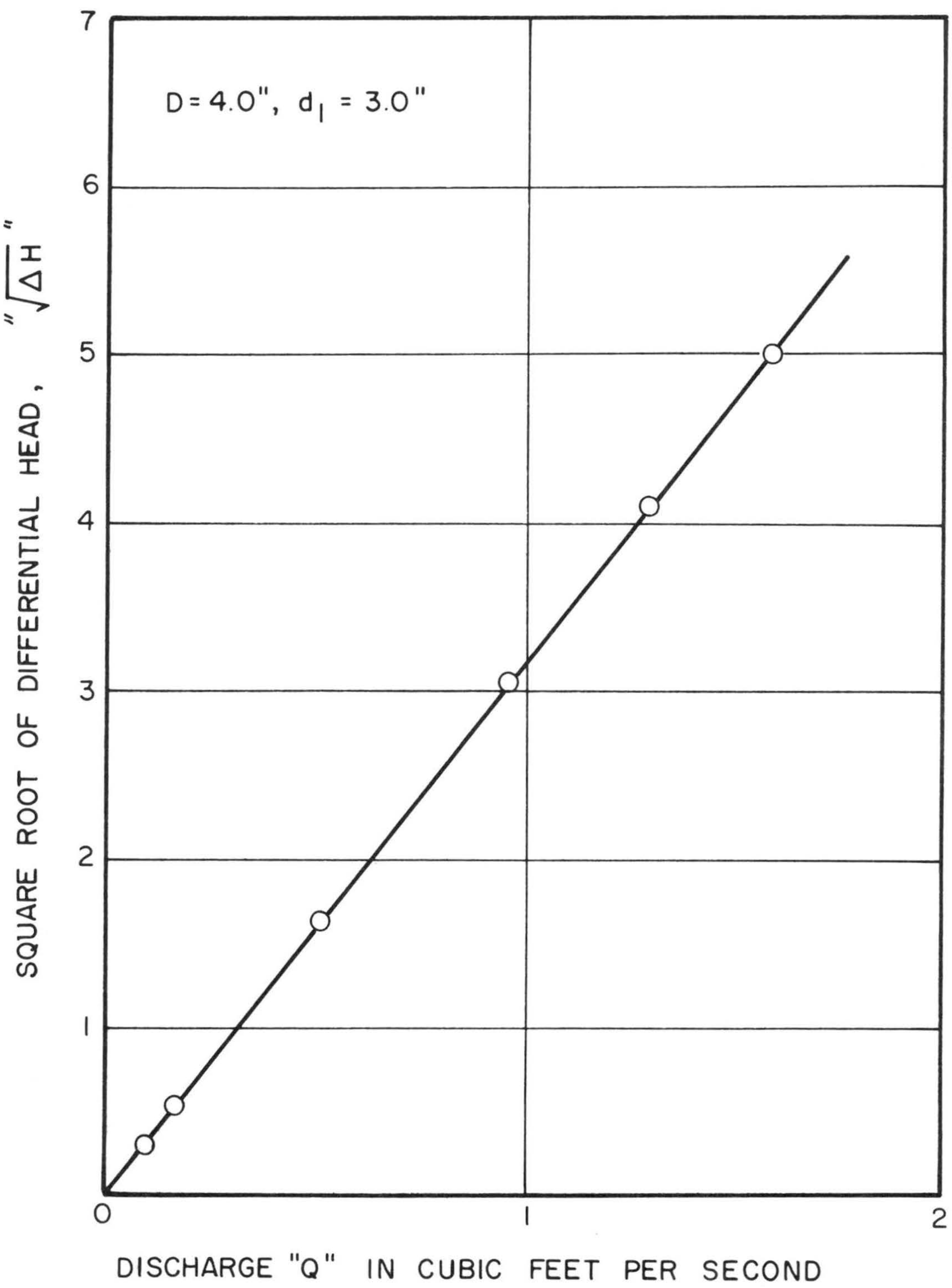
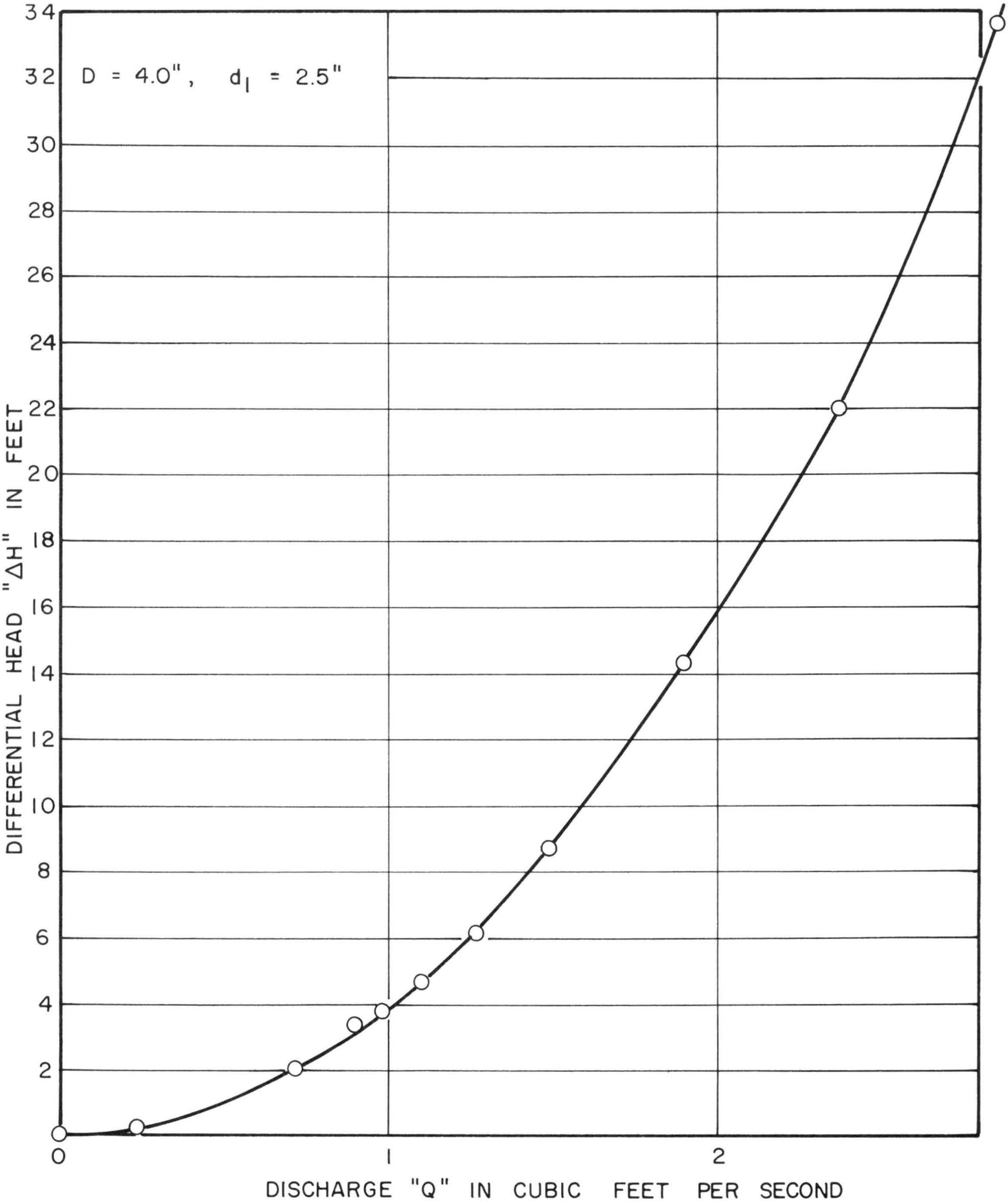


FIG. 13 Q VS $\sqrt{\Delta H}$



D = 4.0", d_1 = 2.5"
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
1
2
DIFFERENTIAL HEAD "ΔH" IN FEET
DISCHARGE "Q" IN CUBIC FEET PER SECOND

FIG. 14 Q VS ΔH

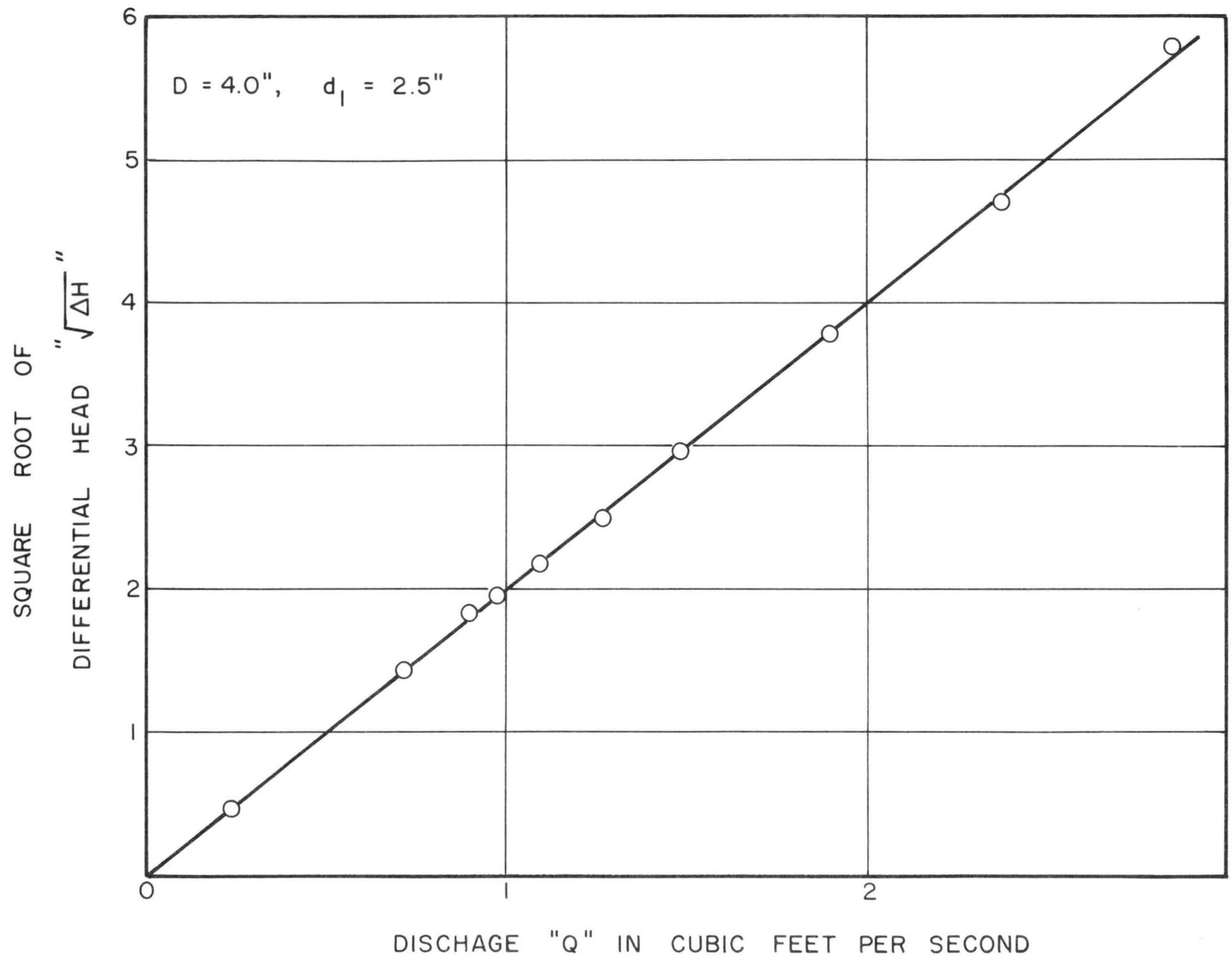
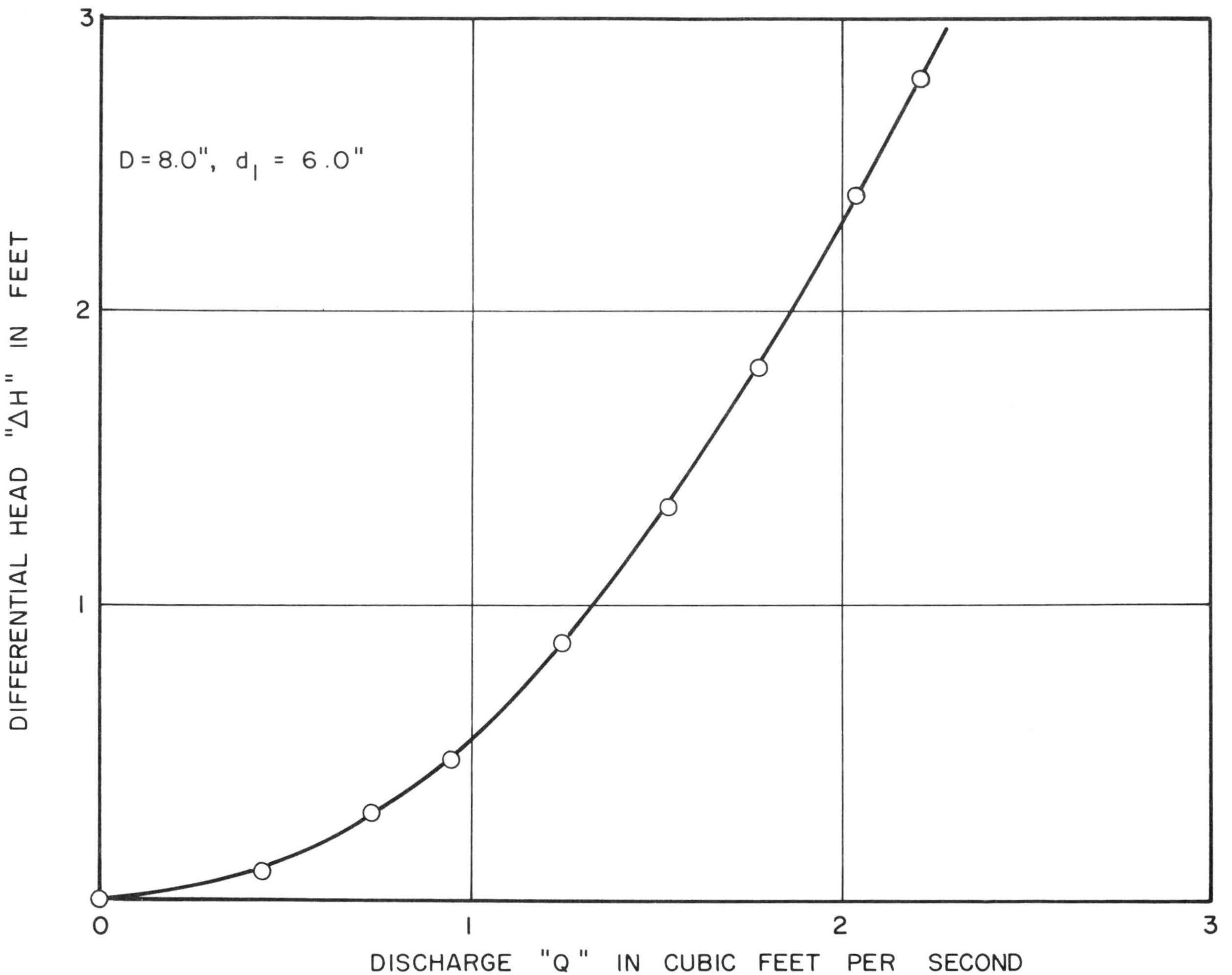


FIG. 15 Q VS $\sqrt{\Delta H}$



D = 8.0", d₁ = 6.0"
DIFFERENTIAL HEAD "ΔH" IN FEET
DISCHARGE "Q" IN CUBIC FEET PER SECOND
0
1
2
3

FIG. 16 Q VS ΔH

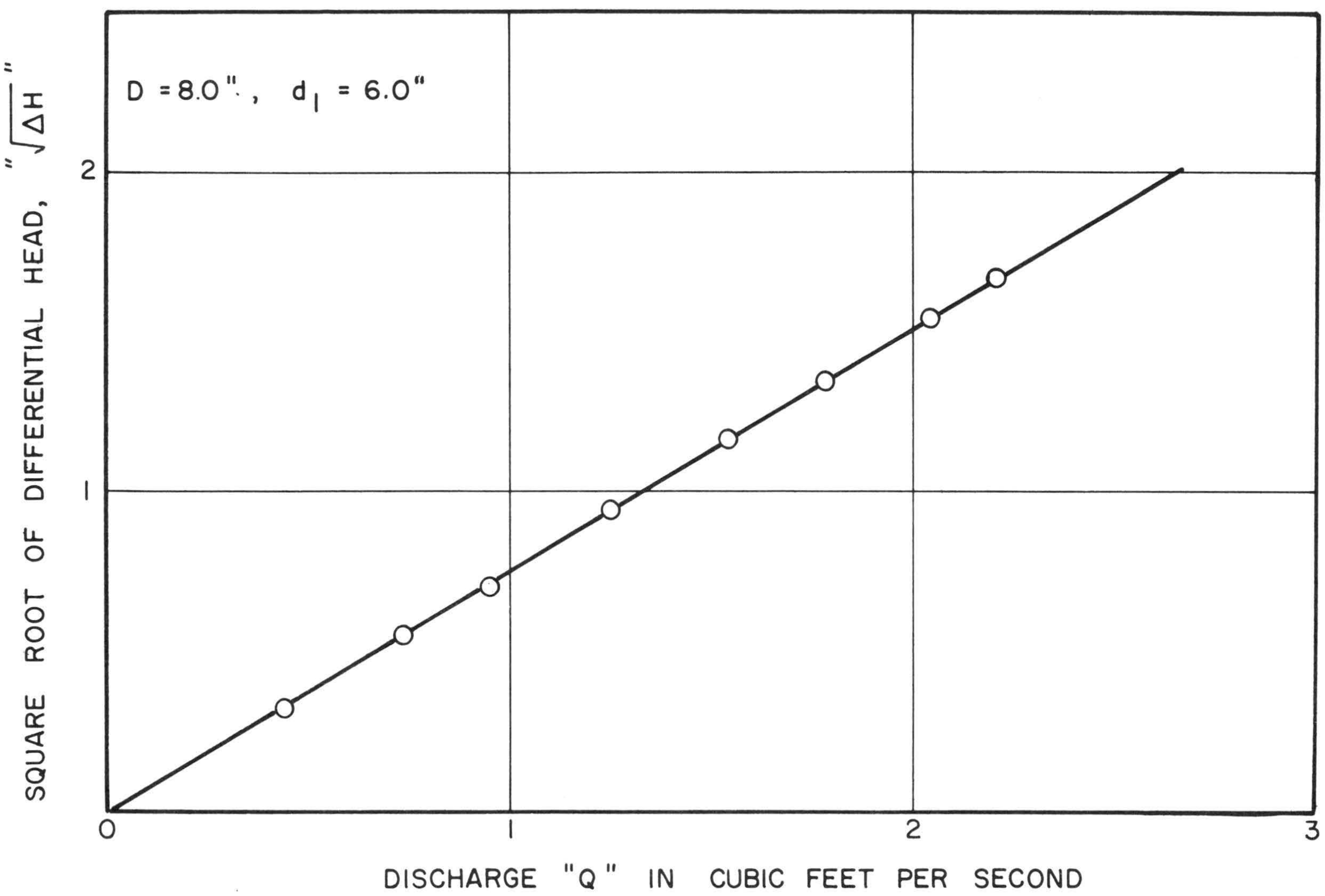


FIG. 17 Q VS $\sqrt{\Delta H}$

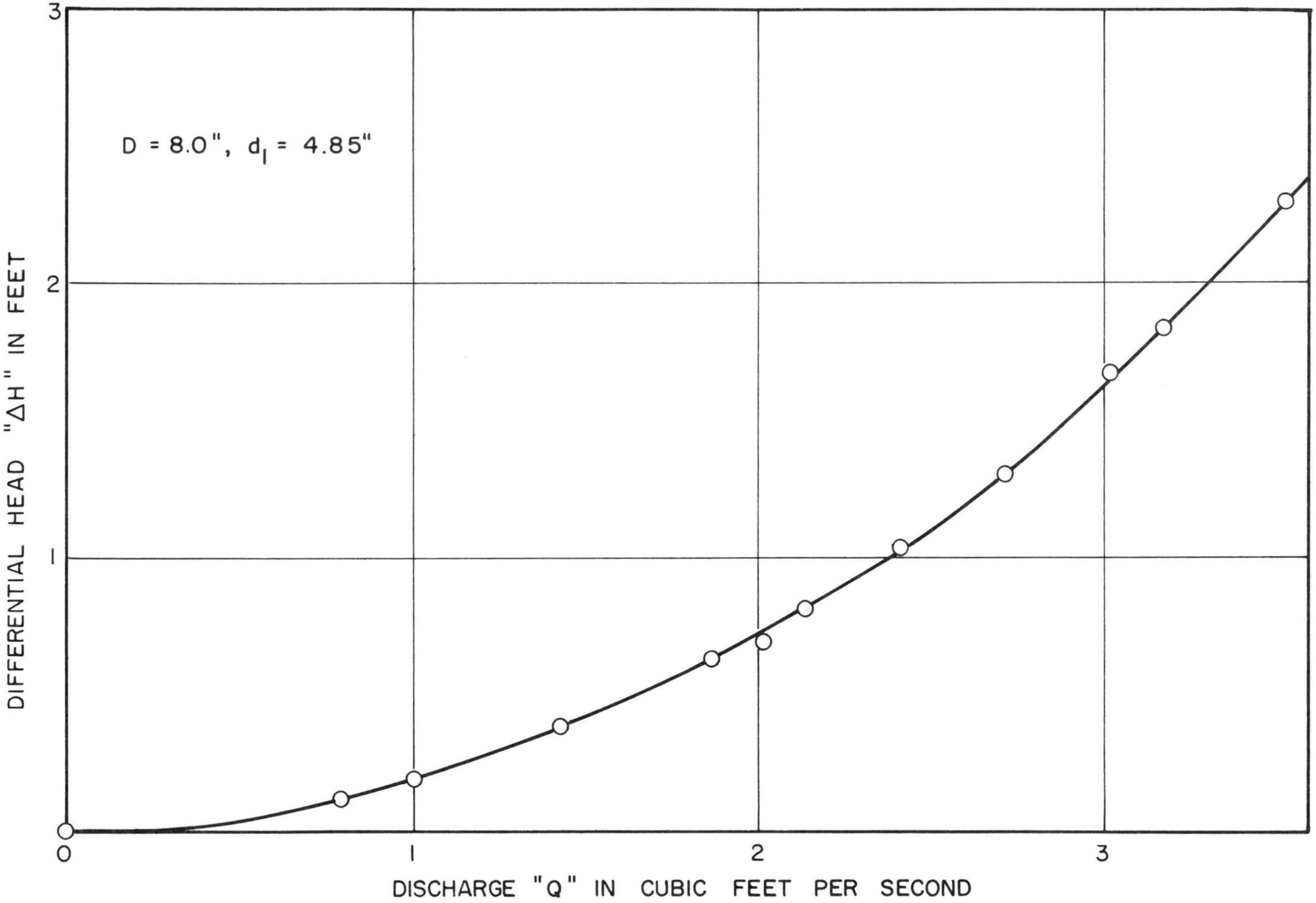

D = 8.0", d_1 = 4.85"
DIFFERENTIAL HEAD "ΔH" IN FEET
DISCHARGE "Q" IN CUBIC FEET PER SECOND
0
1
2
3

FIG. 18 Q VS ΔH

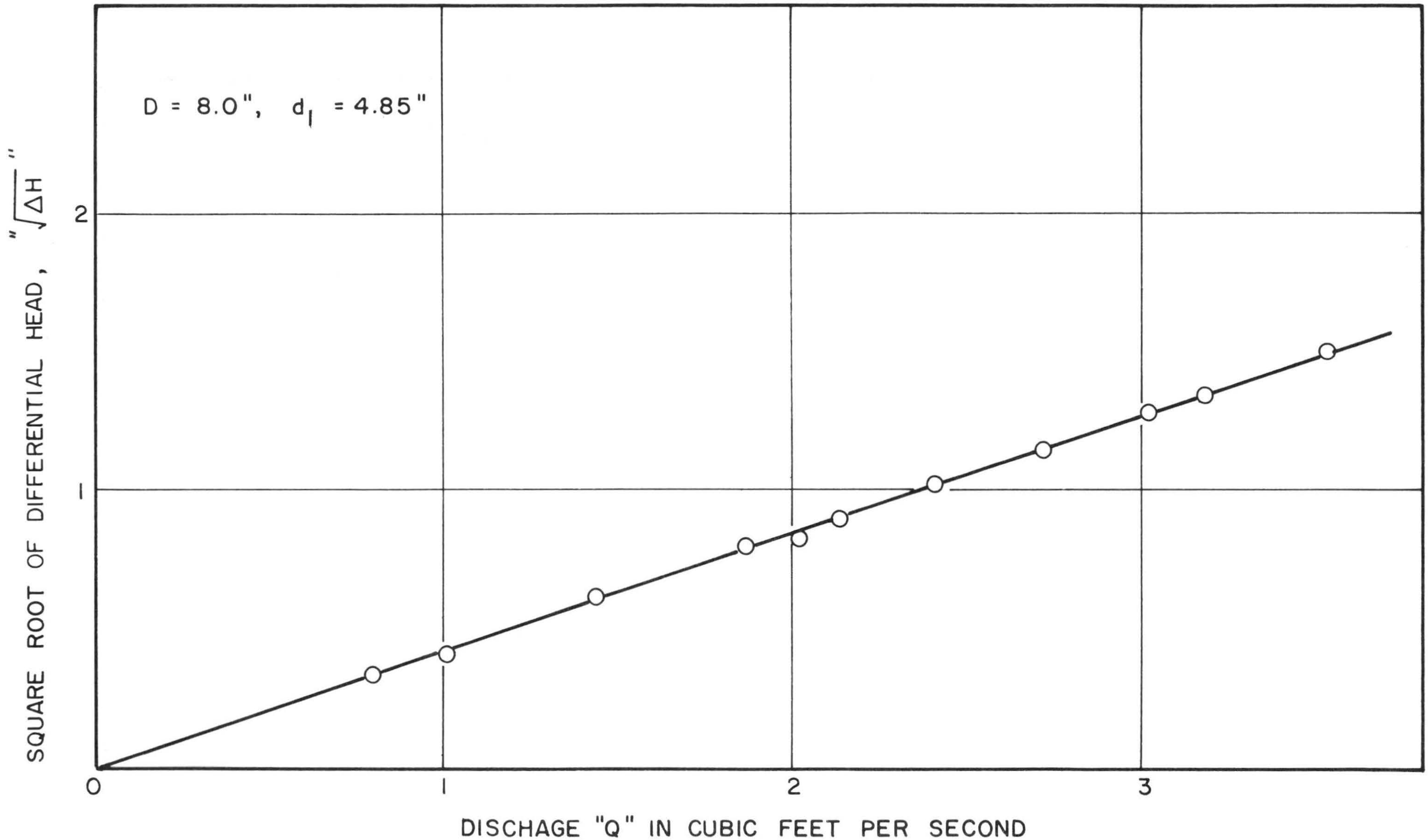
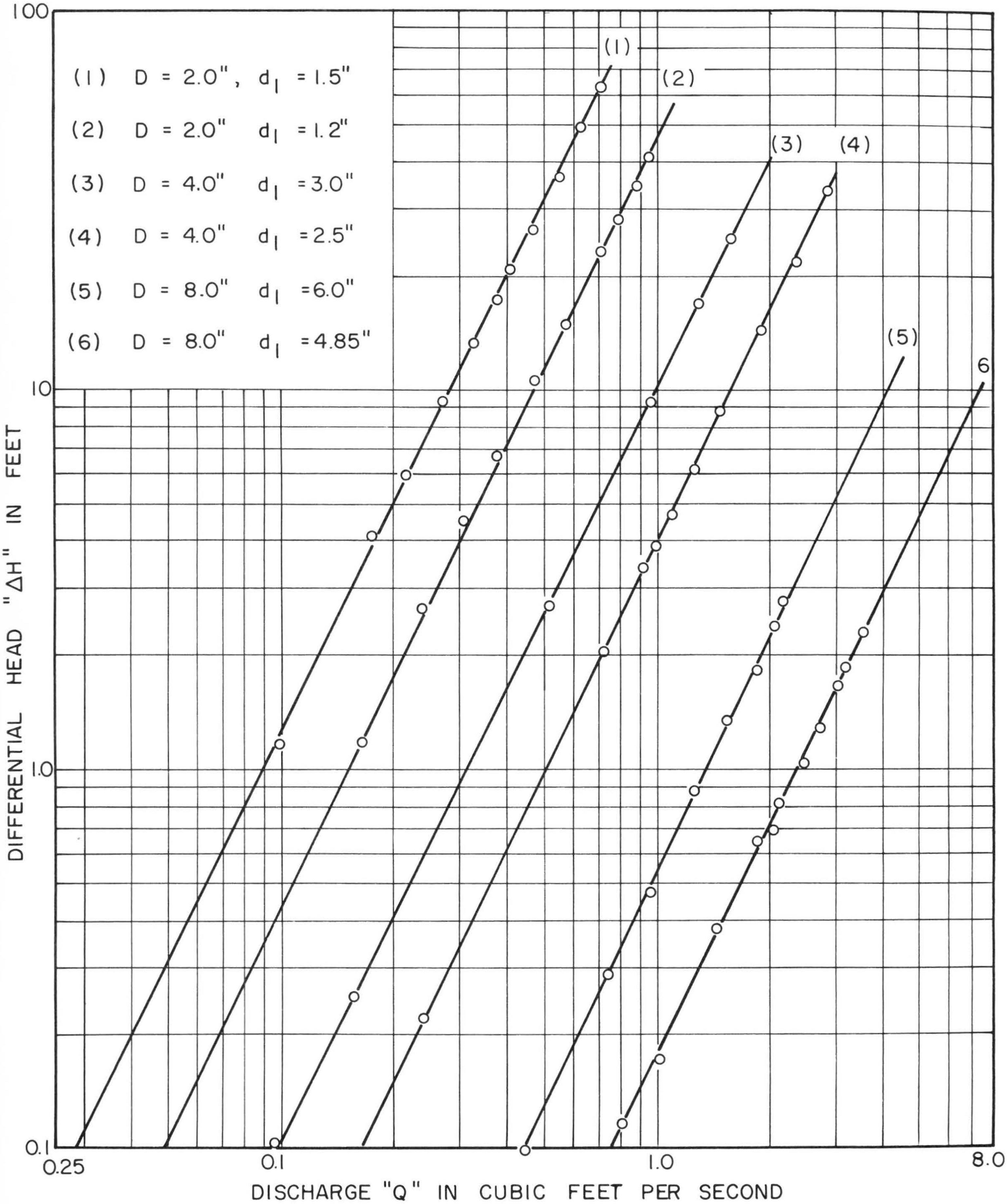


FIG. 19 Q VS $\sqrt{\Delta H}$



(1) D = 2.0", d$_1$ = 1.5"
(2) D = 2.0" d$_1$ = 1.2"
(3) D = 4.0" d$_1$ = 3.0"
(4) D = 4.0" d$_1$ = 2.5"
(5) D = 8.0" d$_1$ = 6.0"
(6) D = 8.0" d$_1$ = 4.85"
(1)
(2)
(3)
(4)
(5)
6
100
10
1.0
0.1
0.25
0.1
1.0
8.0
DIFFERENTIAL HEAD "ΔH" IN FEET
DISCHARGE "Q" IN CUBIC FEET PER SECOND

FIG. 20 Q VS ΔH

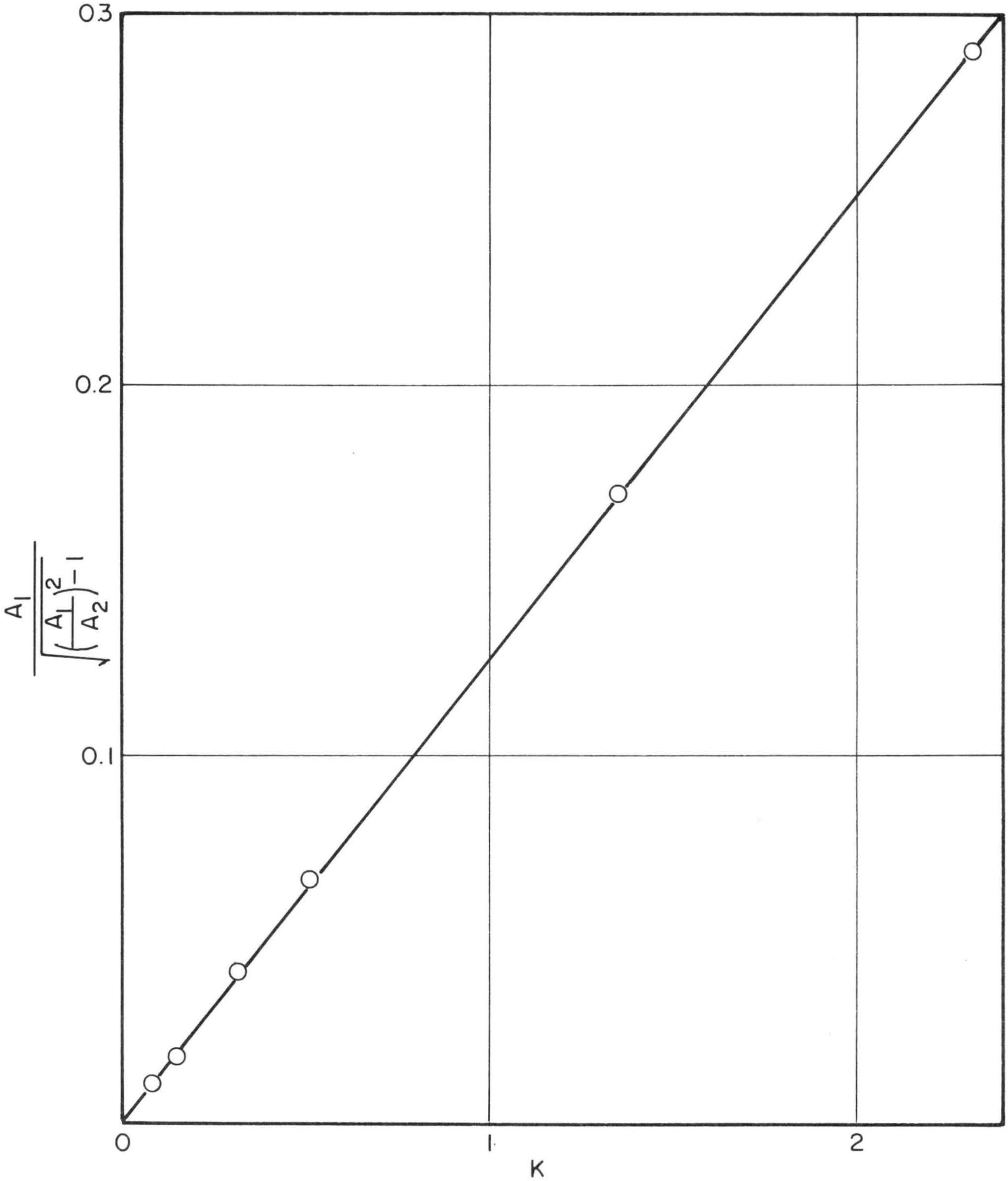


FIG. 21 K VS $\frac{A_1}{\sqrt{\left(\frac{A_1}{A_2}\right)^2 - 1}}$