1910

Friction in small air pipes

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---T H E S I S.---

for

BACHELOR OF SCIENCE IN CIVIL ENGINEERING.

F R I C T I O N I N S M A L L A I R P I P E S.

Albert Park

Howard Kelsey Peterson

Class 1910.

Approved---Approved E.A.-----

F R I C T I O N   I N   S M A L L   A I R   P I P E S.

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In the course in Compressed Air at the Missouri School of Mines our attention was called to the fact that no reliable data could be found relating to friction losses in pipes under three inches in diameter carrying compressed air.

Therefore the undersigned decided to undertake as a thesis the securing of the needed data and herein are recorded the results of our work.

The apparatus in the school equipment that could be made use of in this work were as follows:

One single stage air compressor of 77 cu. ft. per min. free air capacity and pressure up to 100 pounds per square inch gage. at 110 R.P.M.

One two-stage compressor of 100 cu. ft. free air capacity and pressure up to 150 pounds gage. at 110 R.P.M.

One detached air receiver of 25 cubic feet capacity.

One drum especially constructed for measuring air by orifices according to the method originated by Professor Dudley at McGill University and published in "Compressed Air" Vol. II. 1906-7, pp. 4181. This drum is supplied with orifices cut in copper plates Np.   and ranging from a half inch to three-and-one-half inches in diameter.

All necessary pipe fittings were found in the school supplies but the straight pipe was loaned for the purpose by a local hardware merchant.

The necessary pressure gages were in the school equipment and were tested and corrections determined by a gage tester which was also a part of the school equipment.

We found it necessary to construct for this work a special differential gage, and since the range of lost pressure ran as high as thirty pounds, the glass tubing was made six feet. Details of this gage are shown in Fig. 1. and 2. Mercury was used for the indicating fluid.

The assembly of the apparatus is illustrated in Fig. 3. in which the parts are as follows:

(a) The pipe leading from the compressor.

(b) Receiver.

(c) Pressure gage on receiver.

(d - d') Points of attachment of differential gage.

(e) Pressure gage showing initial pressure in air pipes.

(f - f') Loop of pipe in which friction is to be determined.

(g) Position of elbows.

(h) Throttle valve for controlling pressure.

(i) Orifice drum.

(j) U gage for measuring pressure (i) in drum.

(k) Position of thermometer.

METHOD OF PROCEEDING IN TAKING DATA.

The free air volume (symbol va.) was controlled by speed of compressors, the pipe connections being made so that the discharges could be united; but of-course, the pressure when both compressors were used was limited to that of the single stage machine.

The compressor being in steady operation the pressure was controlled by the throttle valve (h).

The size of orifice set in the drum was changed as required to keep the height (symbol i.) in the U gage within the range covered by Dudley in the experiments before alluded to.

In each run there were recorded:

Reading on differential gage.

Reading on U gage.

Initial pressure in pipe.

Temperature in drum.

Diameter and length of pipe and number of elbows.

Diameter of orifice.

With each size of pipe two sets of runs were made -- one with two elbows and one with sixteen or eighteen elbows as shown in the tabulated data.

In each set the range of pressure was from zero to about ten atmospheres.

FORMULAE USED IN COMPUTATIONS AND RESULTS.

The object of these experiments was to find the value of C in the friction formula $f = C. \frac{l}{d^5} . \frac{va^2}{r}$ taken from the text book "Compressed Air -- Theory and Computations" by Prof. E. G. Harris, Professor of Civil Engineering of the Missouri School of Mines.

The notation used is as follows:

f = loss of pressure in pounds per sq. in.

l = Length of pipe in feet.

va= Volume of free air passing -- cu. ft. per second.

d = Diameter of pipe in inches.

r = Ratio of compression.

c = Experimental coefficient.

In order to find volume of free air, va, we first found the weight of air passing per second.

Let this weight = Q and let wa = weight of cubic foot of free air. Then $va = \frac{Q}{wa}$. --wa in Rolla was found to be .073 pounds.

To find Q, the weight of air passing per second, we used the formula $Q = C' \times .1632\, d'^2 \left(\frac{i}{t}\, pa\right)^{1-2}$ which is a modification of Dudley's formula in article before alluded to. $Q = C' .1632\, d^2 \sqrt{\frac{i}{t} p_a}$

Notation as follows:

Q = wt. of air in lbs. passing per second.

d'= Diameter of orifice in inches.

i = Pressure of air back of orifice in measuring drum in inches of water.

t = Absolute temperature Farhrenheit of air in measuring drum.

C'= An expeimental coefficient determined at McGill University for i diff. to 6" and d' up to 3".

pa = atmospheric pressure in pounds per sq. in.

pa at Rolla was found to be 14.3

The f in the friction formula we calculated from the differential gage reading as follows:

$$f = \frac{62.5 \times 13.6}{1728} D$$ where D was the difference of height in Mercury columns in inches, and

$$f = \frac{62.5 \times 13.6}{1728 \times 2.54} D'$$

where D' was difference of mercury columns in centimeters.

The r used in the friction formula is the average r in the pipe and is obtained as follows:

Let P = Reading of pressure gage in lbs. per sq. in.

Then $r = \frac{P - 1\text{-}2f + pa}{pa}$. or $r = \frac{P - \frac{1}{2}f + p_a}{p_a}$

Since the length of the pipe with the sixteen or eighteen elbows was greater than that for the two elbows, the following correctionwas applied to friction losses in pipe with the two elbows:

Letting l_1 = length of pipe with most elbows

and l_2 = " " " " the two elbows.

The tabulated values of f for the pipe with the two elbows were corrected by multiplying by the factor $\frac{l_1}{l_2}$.

In order to find the loss in a single elbow so that elbow losses could be eliminated and values of f found for straight pipe only, we proceeded as follows:

First we plotted values of f with corresponding values of $\frac{v_a^2}{r}$ for pipe with most elbows and on same plate the corrected values of f and corresponding values of $\frac{va^2}{r}$ for pipe with two elbows of same diameter.

These points plotted for each size of pipe gave fairly straight lines. See Plates 1,2,3, and 4.

Next letting n equal larger number of elbows and f_e equal lost pressure in one elbow, also f_1 and f_2 = values of f for pipe with two elbows and for pipe with n elbows respectively for same value of $\frac{va^2}{r}$

then $f_e = \frac{f_2 - f_1}{n - 2}$.

To construct the line marked straight pipe on Plates 1,2,3,& 4, we took several values of $\frac{va^2}{\gamma}$ and doubled the corresponding values of f_e as marked out above and scaled off directly below line marked two elbows. Thru these points the line marked straight pipe was drawn. This line represents values of f for straight pipe without elbows.

By the aid of this line on Plates 1,2,3,& 4 we calculated values of C for each size of pipe.

$$C = \frac{fd^5}{1 \times \frac{va^2}{\gamma}} \quad \text{from friction formula.}$$

Here $\frac{f}{\frac{V^2}{\gamma}}$ is constant being tangent of the angle the line marked straight pipe makes with the horizontal axis considering scale values.

Having found that C varies only with the diameter the next step was to find an equation for this variation.

Coefficients for pipes from three to twelve inches in diameter were available from another source and these with our own enabled us to plot the points on Plate 5.

The straight line as shown comes more nearly to conforming to those points than does any other curve. From this the law of variation of C is the equation of the line which is $C = .08 - .003d$.

ELBOW LOSSES AND EQUIVALENT LENGTHS OF PIPE.

Having thus completed the main work of our thesis we next turned our attention to investigating elbow losses as far as our collected data would permit.

We decided that the best method would be to find for each size of elbow the length of pipe in which the same amount of pressure would be lost, here spoken of as the equivalent length of pipe.

From Plates 1, 2, 3, and 4 several values of $\frac{va^2}{r}$ and corresponding values of f_e were taken and equivalent lengths figured as follows: Letting l_e = equivalent length of pipe. $f_e = \frac{Cl_e}{d^5} \frac{va^2}{r}$ from which $l_e = \frac{f_e d^5}{\frac{va^2}{r}}$.

These values were tabulated with corresponding diameters. See table No.6. No reliable data being at hand for elbows larger than two inches in diameter we are not prepared to state any definite relation between elbow losses and diameters; however for conditions found in tables 1, 2, 3, and 4 the equivalent lengths seem to be fairly constant regardless of values of $\left(\frac{va^2}{r}\right)$.

If particular attention, however, be given to keep va constant while varying r and to keep r constant while varying va this might be found untrue

For conditions herein tabulated we recommend the following equivalent lengths of pipe for corresponding size of elbows:

Diameter of elbows.	Equiv. length of pipes
2"	2' to 3'
1"	4' to 5'
3-4"	4' to 5'
1-2"	10' to 12'

We are indebted to Mr. Holmes and Mr. Wander both of class 1910 for the construction and sketches of the differential gage used.

These gentlemen had same problem for thesis, using water instead of compressed air.

T A B L E N U M B E R O N E.

Data on 2' Pipe Part One — *2 elbows.*

Length of pipe 205.9'. Diameter of orifice 2.5".

No.	D"	i	r	t_c	va	S	f	$\frac{l_1}{l_2} \times f$	$\frac{va^2}{r}$
1.	1.3	2.7	3.6	19	2.27	28.9	0.63	0.64	1.43
2.	2.1	3.15	2.9	20	2.45	38.7	1.03	1.04	2.06
3.	2.8	3.9	2.4	20.5	2.72	51.96	1.37	1.39	3.08
4.	4.8	4.0	1.6	20.5	2.76	78.93	2.36	2.39	4.74
5.	5.7	3.95	1.2	21.0	2.74	104.6	2.80	2.84	6.24
6.	0.5	1.45	6.2	20.0	1.66	12.27	0.24	0.24	0.44
7.	0.8	2.6	7.3	20.5	2.22	13.95	0.39	0.39	0.67
8.	0.8	3.15	8.0	21.0	2.44	14.00	0.39	0.39	0.74

D" Diff. gage in. mercury. i U gage in water. r Ratio of comp.

t_c Temp. Cent. S Velocity. va Vol. of free air. f Loss in pressure.

T A B L E   N U M B E R   O N E.

Part Two

Data on two inch pipe. Sixteen elbows.

Length of pipe 208.1'. Diameter of orifice 2.5".

No.	D"	i	r	t_c	va	S	f	$\frac{va}{r}$
1.	0.3	1.0	9.60	24.0	1.37	6.54	.1476	.1954
2.	0.4	1.1	8.96	24.5	1.44	7.35	.1968	.2299
3.	0.5	1.7	8.19	25.0	1.78	9.98	.2460	.3881
4.	1.1	2.8	7.13	22.0	2.30	14.80	.5410	.7416
5.	1.6	3.6	6.21	21.0	2.61	19.30	.7871	1.0990
6.	2.3	4.2	4.80	20.5	2.83	26.90	1.1320	1.6610
7.	2.8	4.2	3.75	20.5	2.83	34.50	1.3780	2.1260
8.	3.6	4.2	2.68	20.5	2.83	48.30	1.7710	2.9750
9.	5.5	4.5	1.97	21.0	2.92	67.40	2.0760	4.3280
10.	8.6	5.5	1.41	22.0	3.22	104.8	4.2310	7.366

D" Diff.gage in Hg. i U gage in H_2O. r Ratio of comp. t_c Temp.Cent.

va Vol. free air per second. S Velocity. f Loss in pressure.

T A B L E   N U M B E R   T W O.

Part One

Data on one inch pipe. Two elbows.

Length of pipe 208.1'. Diameter of orifice 1.75".

No.	D"	i	r	t_c	va	S	f	$\frac{1_1}{l_2} f$	$\frac{va^2}{r}$
1.	1.7	1.5	10.7	30	.76	13	.84	.846	.054
2.	0.8	0.6	10.6	30	.52	8.9	.39	.398	.025
3.	2.5	1.7	9.7	30	.87	16.4	1.23	1.244	.077
4.	6.0	3.7	8.6	30	1.24	26.5	2.95	2.986	.179
5.	10.8	5.6	7.7	29	1.58	37.5	5.31	5.373	.322
6.	8.2	4.9	7.3	29	1.47	37.0	4.03	4.078	.297
7.	6.6	2.4	5.9	28.5	1.05	32.1	3.25	3.289	.180
8.	7.0	2.1	4.9	28	.966	36.15	3.44	2.481	.190
9.	10.0	2.1	3.6	28	.966	49.2	4.92	4.979	.259
10.	5.1	0.9	2.7	28	.632	42.9	2.50	2.530	.148
11.	8.2	1.0	1.9	28	.666	42.9	4.03	4.078	.233
12.	2.9	0.3	1.3	27	.366	19.5	1.43	1.447	.103

D" Diff.gage in.Hg. i U gage in H_2O. r= Ratio of compression. t_c Temp. Centigrade. va Vol.free air per sec. S Velocity. f Loss in pressure lbs. per square inch.

TABLE NUMBER TWO.

Part Two

Data on one inch pipe. Eighteen elbows.

Length of pipe 210.65'. Diameter of orifice 1.75".

No.	D"	i	r	t_c	va	S	f	va[illegible] / [illegible]
1.	7.4	1.1	2.62	35	.69	48.4	3.6	.1824
2.	9.9	1.0	1.87	35	.659	64.7	4.9	.2323
3.	8.1	.8	1.21	35	.589	89.4	4.0	.2872
4.	8.7	2.1	4.9	34	.956	35.8	4.3	.1868
5.	11.1	2.3	4.0	34	1.000	46.5	5.5	.2536
6.	4.0	1.0	3.03	34	.66	40.0	1.97	.1438
7.	9.8	3.0	5.5	34	1.143	38.5	4.8	.2403
8.	10.8	3.3	6.13	33.5	1.20	36.0	5.3	.2350
9.	7.0	2.5	7.0	33.5	1.05	27.5	3.5	.1566
10.	5.2	2.2	7.75	33	.981	23.2	2.6	.1241
11.	5.7	2.4	8.38	33	1.03	22.4	2.8	.1252
12.	4.1	2.0	10.7	32.5	.94	16.0	2.1	.0817
13.	8.4	4.3	9.94	32.5	1.37	25.0	4.1	.1894
14.	11.4	5.0	8.84	32.5	1.48	30.7	5.6	.2477

D" Diff.gage in.Hg. i U gage in H_2O. r Ratio of compression, t_c Temp. Cent. va Vol. free air cu.ft. per sec. S Velocity. f Loss in pressure,

T A B L E N U M B E R T H R E E.

Part One

Data on three-fourth inch pipe. Two elbows.

Length of pipe 201.8'. Diameter of orifice 1.75".

No.	D	i	r	t_c	va	S	f	$\frac{l_1}{l_2} f$	$\frac{va^2}{r}$
1.	37.3	.5	1.3	39.5	.426	116.0	7.21	7.43	.1647
2.	63.8	.9	1.62	40.0	.620	124.8	12.3	12.7	.2374
3.	116.3	2.4	2.5	40.0	1.013	135.3	22.5	23.2	.4204
4.	117.0	3.2	3.4	39.0	1.171	114.	22.6	23.3	.4096
5.	158.9	5.6	4.1	38.5	1.551	124	30.7	31.6	.5866
6.	73.5	3.4	5.7	39.0	1.207	69	14.21	14.7	.2558
7.	96.8	4.9	6.6	40.0	1.447	71	18.7	19.3	.3159
8.	78.8	4.5	7.5	40.0	1.387	61	15.3	15.8	.2520
9.	48.2	2.8	8.7	40.0	1.094	41	8.54	8.8	.1088
10.	39.6	2.9	9.96	48.5	1.110	36	7.64	7.9	.1239

D Diff.gage cm. Hg. i U gage in H_2O. r Ratio of comp. t_c Temp. Cent.
va Vol. free air cu.ft. per sec. f Loss in pres. pounds per sq. inch.
S Velocity per ft. sec.

T A B L E   N U M B E R   T H R E E.

Part Two

Data on three-fourth inch pipe, sixteen elbows.

Length of pipe 298.2'. Diameter of orifice 1.75".

No.	D	i	r	t_c	va	S	f	$\frac{va^2}{r}$
1.	7[illegible].0	.9	1.55	24.5	.6361	133.8	14.3	.2651
2.	41.5	.5	1.34	26.5	.4726	115.0	8.1	.1667
3 3.	81.4	1.1	2.2	28.0	.6992	103.6	15.74	.2220
4.	107.4	2.1	3.1	29.5	.9637	102.7	20.8	.3035
5.	141.4	2.9	3.96	30.5	1.131	93.1	27.4	.3228
6.	165.8	4.4	4.84	33	1.387	93.4	32.1	.3974
7.	164.5	5.2	6.04	34	1.506	81.3	31.8	.3751
8.	111.0	4.4	7.24	35.5	1.382	62.2	21.5	.2635
9.	117.2	5.1	8.24	38	1.481	58.6	22.7	.2662
10.	96.8	4.7	9.36	38	1.422	49.5	18.7	.2160
11.	47.9	2.8	10.5	37.5	1.099	38.2	9.19	.1153

D Diff. gage cm. Hg. i U gage in H_2O, r Ratio of comp. t_c Temp. Cent. va Vol. free air cu.ft. per second. S Velocity ft. per second. f Loss in pressure lbs per sq. inch.

T A B L E N U M B E R F O U R.

Part One

Data on one-half inch pipe. Two elbows.

Length of pipe 161.1'. Diameter of orifice three-fourths inch.

No.	D	i	r	t_c	va	S	f	$\frac{1}{1}$ f	$\frac{va^2}{r}$
1.	50.5	3.3	2.05	16	.2270	81.3	9.77	10.21	.0251
2.	41.5	4.3	3.76	15	.2596	50.6	8.03	8.4	.0178
3.	26.0	3.1	4.95	15	.2204	32.6	3.03	5.26	.0098
4.	7.2	1.3	5.63	14	.2430	18.6	1.39	1.46	.0036
5.	35.5	5.7	6.14	14	.2994	35.8	6.87	7.18	.0746
6.	42.0	7.0	6.31	14	.3318	38.6	8.12	8.49	.0174
7.	50.0	8.7	5.97	14	.3699	45.5	9.84	10.29	.0229
8.	27.2	4.6	6.83	22	.2653	28.5	5.26	5.51	.0103
9.	33.6	5.0	9.86	23	.2761	20.6	6.50	6.79	.0077

D Diff.gage cm.Hg. i U gage in water. r Ratio of comp. t_c Temp.Centigrade va Vol.of free air cu.ft.per second, S Velocity ft. per second. f Loss in pressure lbs per square inch.

T A B L E   N U M B E R   F O U R.

Part Two

Data on one-half inch pipe. Eighteen elbows.

Length of pipe 168.5'. Diameter of orifice three-fourths".

No.	D	i	r	t_c	va	S	f	$\frac{va^2}{f}$
1.	50.7	5.2	8.2	19.5	.283	25.4	9.81	.0097
2.	44.6	5.0	8.74	19.5	.278	23.3	8.63	.0088
3.	36.1	4.5	9.56	20.0	.263	20.2	6.98	.0072
4.	134.3	4.9	2.54	27.5	.273	78.8	25.9	.0293
5.	117.1	5.3	3.35	25.5	.283	62.0	22.7	.0239
6.	85.4	5.3	4.62	25.5	.283	45.0	16.5	.0173
7.	41.2	3.6	6.03	25.5	.233	28.4	7.97	.0090
8.	40.8	4.0	7.01	25.5	.246	25.7	7.91	.0086
9.	6.0	1.3	7.95	25.5	.140	12.9	1.16	.0025

D Diff. gage cm. Hg. i U gage in H_2O. r Ratio of Comp. t_c Temp. Cent. va Vol. of free air cu. ft. per second S velocity ft. per second. f Loss in pressure lbs. per square inch.

T A B L E N U M B E R F I V E.

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Values of C for different size pipes.

These values were used to construct Plate No. 5. The values of f and $\frac{vc^2}{r}$ were taken from Plates 1, 2, 3, and 4. The results are average of each set

Diameter of pipe. d	Length of pipe. l	$\frac{f}{\left(\frac{-va^2}{r}\right)}$	Cofficient. c
1/2"	168.5	406.016	.0763
3/4"	208.2	54.476	.0624
1"	210.35	15.557	.0786
2"	208.1	.474	.0735
3"	worked out elsewhere		.072
4"	" " "		.066
5"	" " "		.057
6"	" " "		.066
8"	" " "		.061
12"	" " "		.045

T A B L E   N U M B E R   S I X.

Equivalent lengths of pipe for one elbow.

Diam. of elbow.	$\frac{va^2}{r}$	Loss in pressure for 1 elbow. f_e lbs. per Sq. in.	Equiv. length of pipe. le
1/2"	.006	.150	10.2
"	.002	.375	12.7
"	.018	.475	10.8
"	.024	.700	11.9
"	.030	.800	10.8
"	.036	1.05	11.8
		Average	11.3
3/4"	.1	.1	3.12
"	.2	.3	4.68
"	.3	.4	4.17
"	.4	.6	4.68
"	.5	.7	4.40
"	.6	.8	4.16
		Average	4.2
1 "	.06	.030	6.6
"	.12	.046	5.1
"	.13	.060	4.4
"	.24	.070	3.8
"	.30	.105	4.3
		Average	4.3

T A B L E N U M B E R S I X.

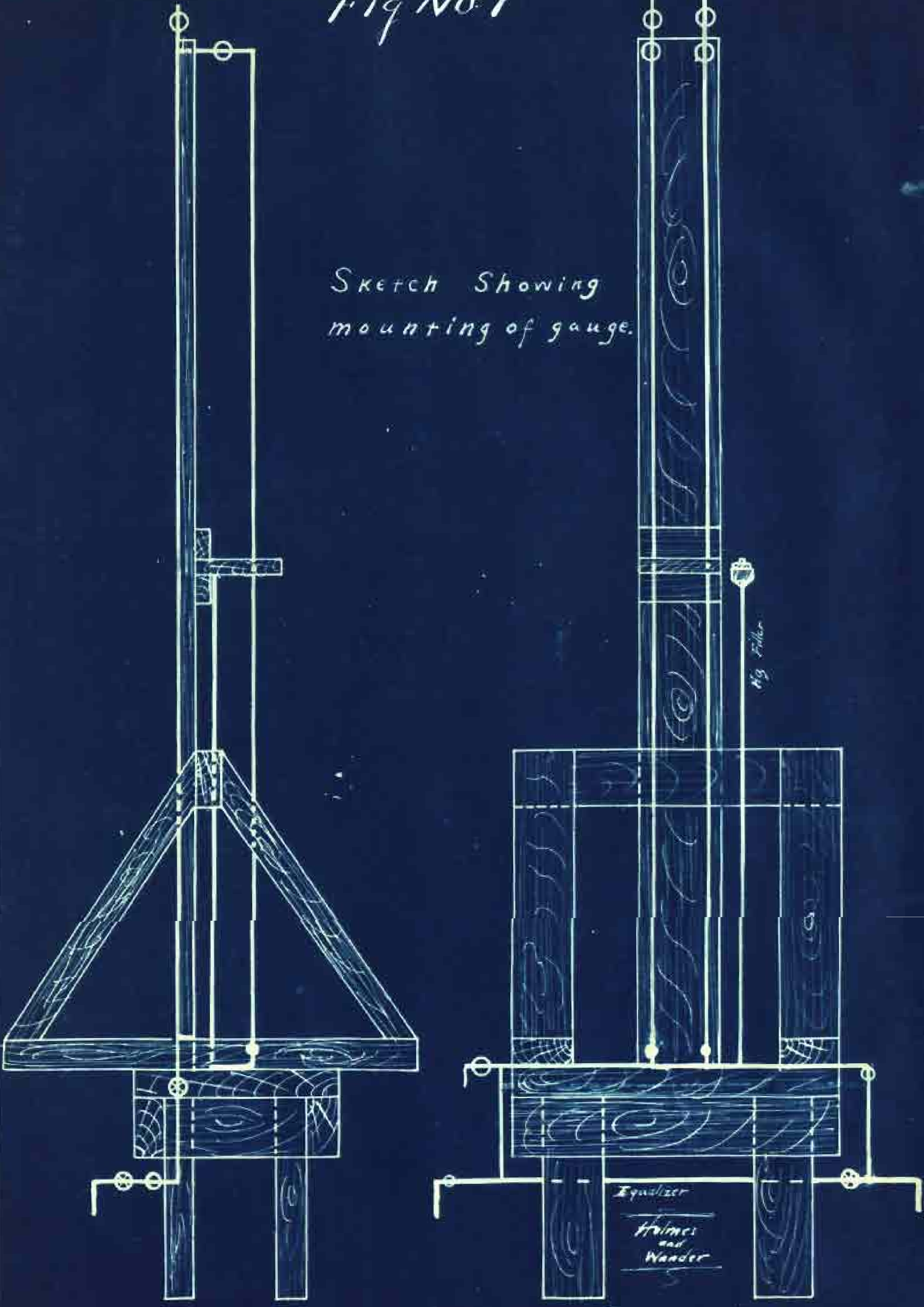
(Continued)

Equivalent lengths of pipe for one elbow.

Diam. of elbow.	$\frac{va^2}{r}$	Loss in pressure for 1 elbow. f_e lbs. per sq. in.	Equiv. length of pipe le
2"	1	.005	2.2
"	2	.015	3.3
"	3	.020	2.9
"	4	.030	3.3
"	5	.040	3.3
"	6	.045	3.3
		Average	3.1

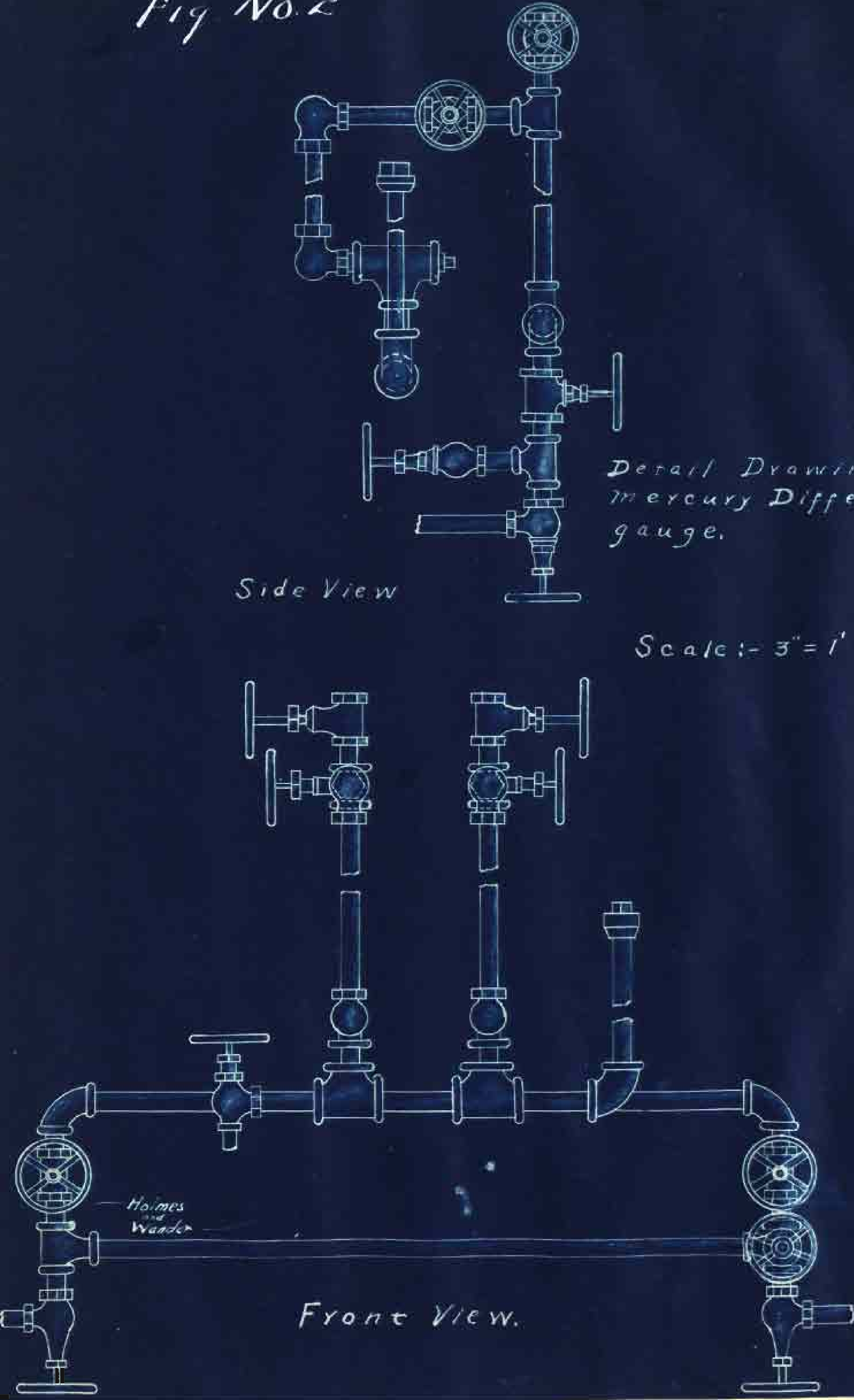
Fig No. 1

Sketch Showing mounting of gauge.



Side View.   Front View.

Fig No. 2



Detail Drawing of mercury Differential gauge.

Fig. No. 3.

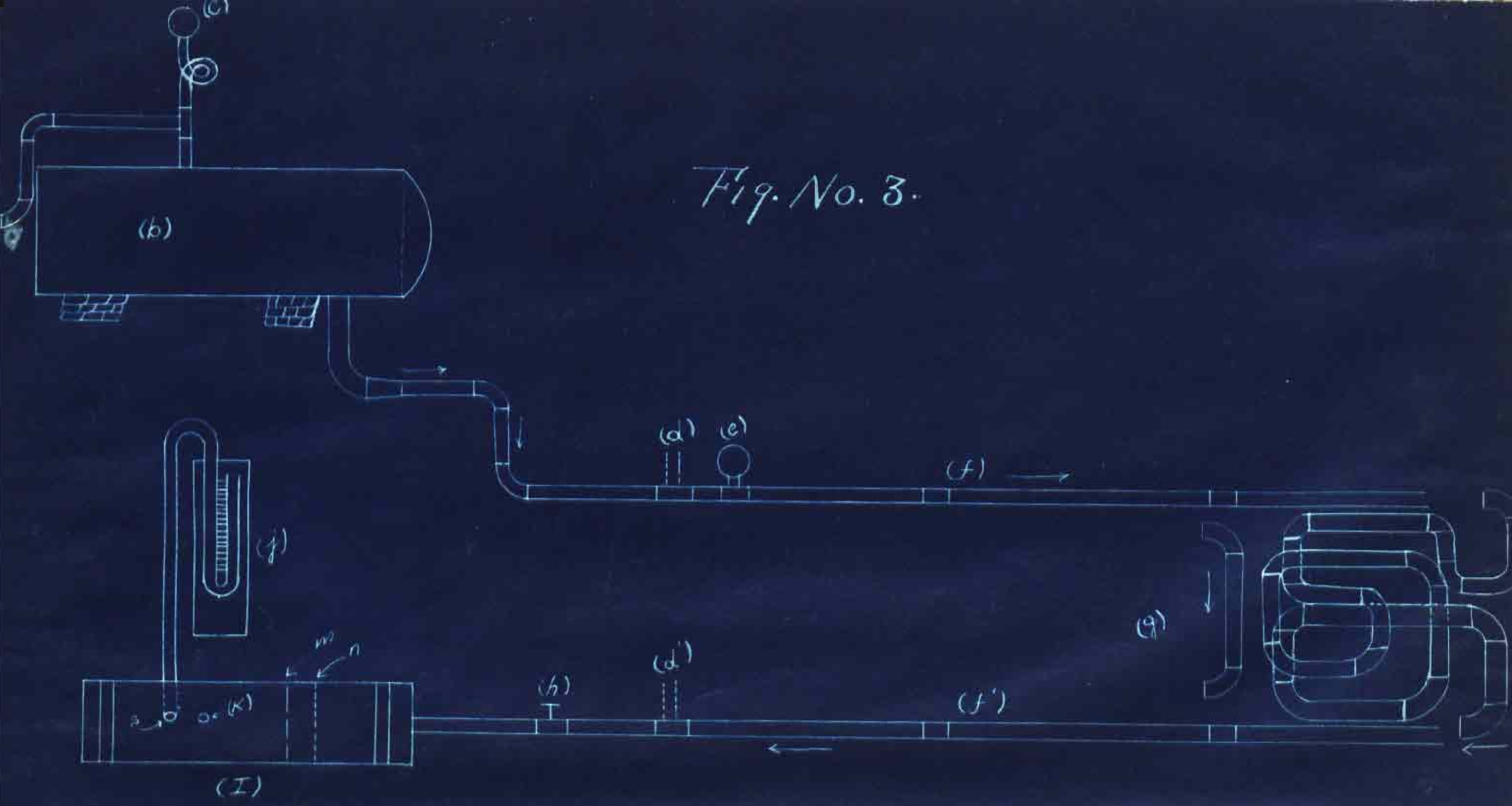


Plate No I

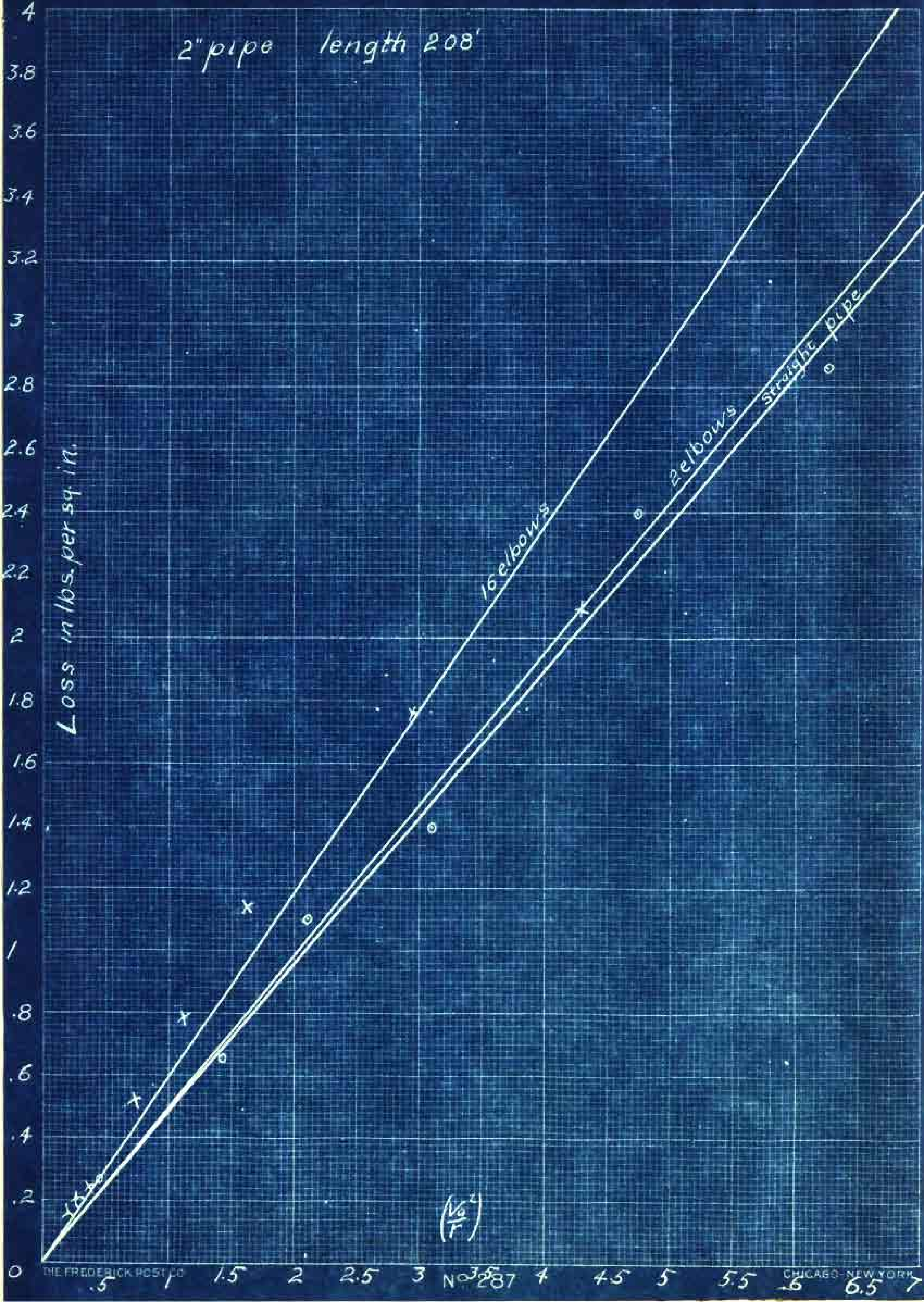
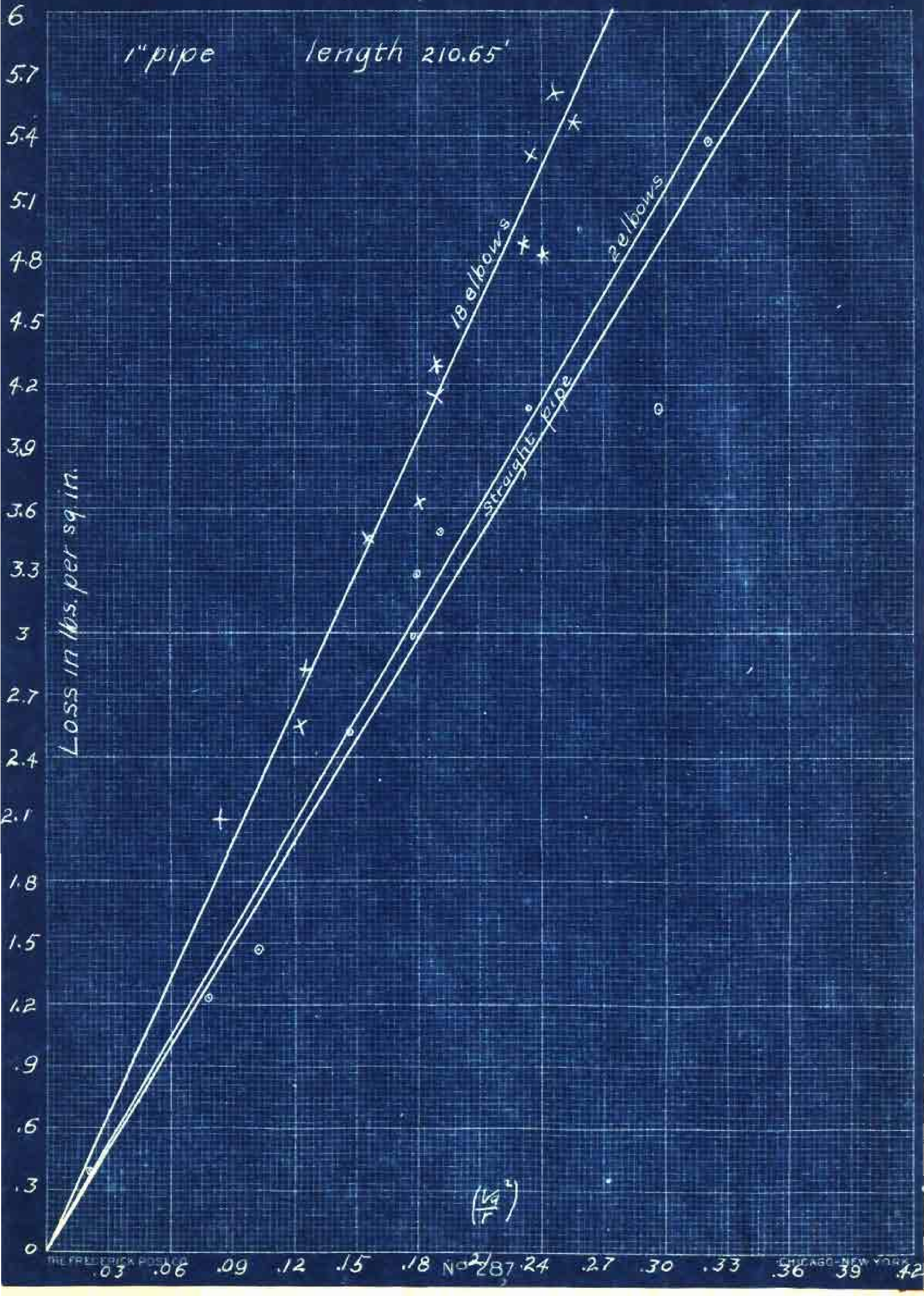
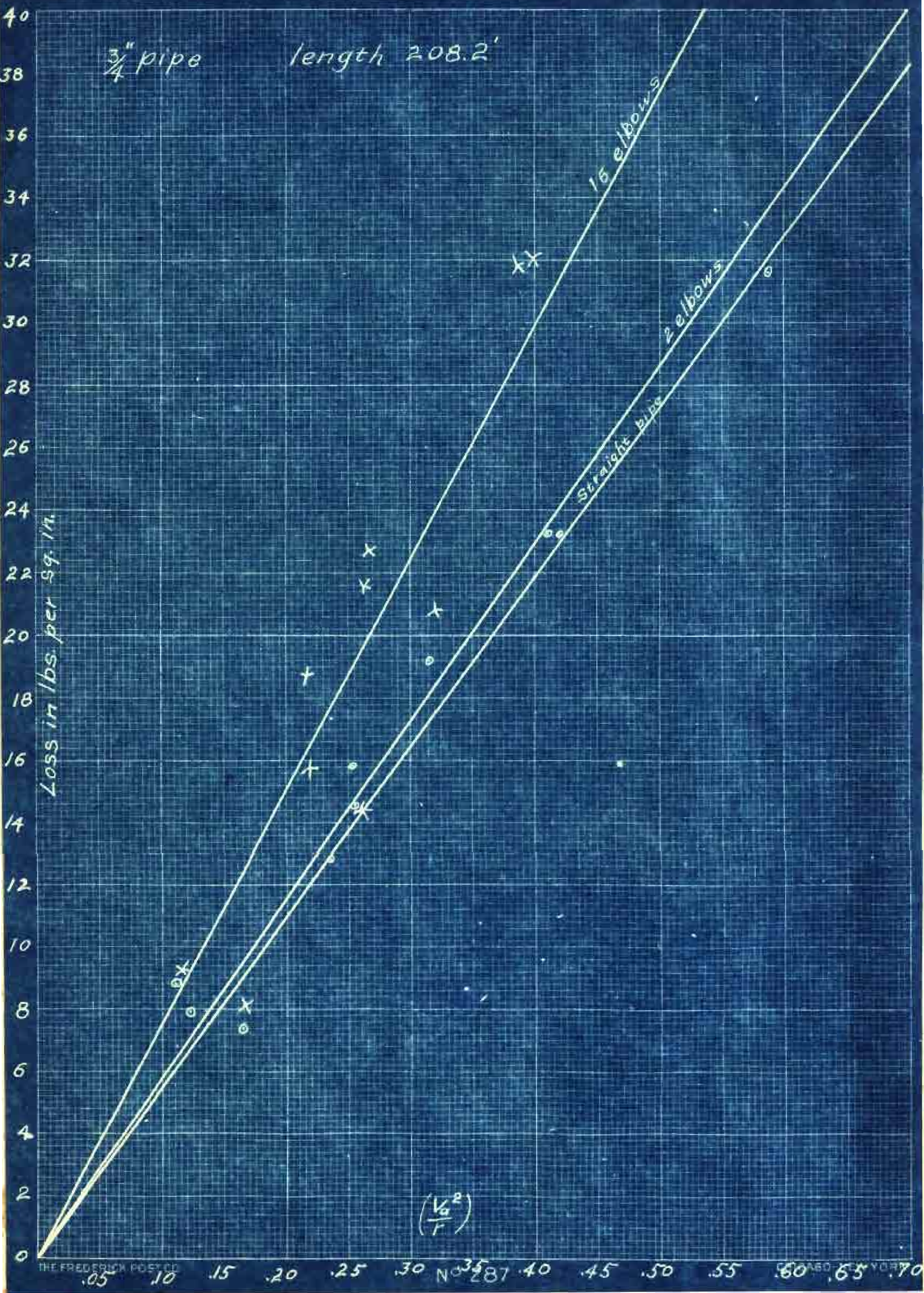

2" pipe length 208'
Loss in lbs. per sq. in.
16 elbows
2 elbows
Straight pipe
$\left(\frac{V_a^2}{r}\right)$
0
.2
.4
.6
.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
THE FREDERICK POST CO
No 287
CHICAGO-NEW YORK

Plate No 2



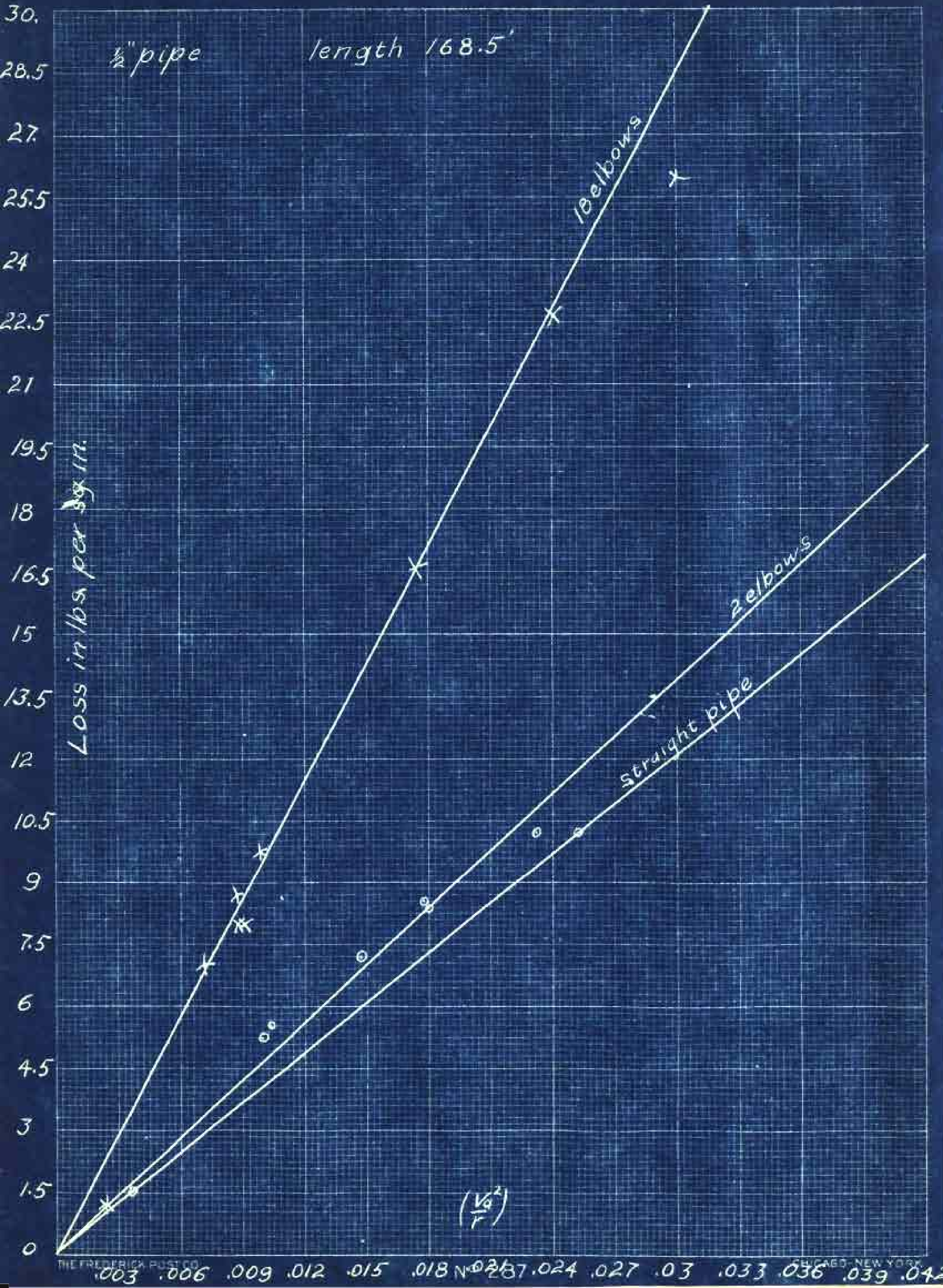
1" pipe
length 210.65'
18 elbows
2 elbows
straight pipe
Loss in lbs. per sq. in.
$\left(\frac{Vd}{r}\right)^2$
6
5.7
5.4
5.1
4.8
4.5
4.2
3.9
3.6
3.3
3
2.7
2.4
2.1
1.8
1.5
1.2
.9
.6
.3
0
.03
.06
.09
.12
.15
.18
.21
.24
.27
.30
.33
.36
.39
.42
No 287
CHICAGO-NEW YORK

Plate No. 3



3/4" pipe
length 208.2'
16 elbows
2 elbows
Straight pipe
Loss in lbs. per sq. in.
(Va²/r)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
.05 .10 .15 .20 .25 .30 .35 .40 .45 .50 .55 .60 .65 .70
THE FREDERICK POST CO
No 287

Plate No. IV



½" pipe
length 168.5'
18 elbows
2 elbows
Straight pipe
Loss in lbs per sq in.
$\left(\frac{Va^2}{r}\right)$
30.
28.5
27.
25.5
24
22.5
21
19.5
18
16.5
15
13.5
12
10.5
9
7.5
6
4.5
3
1.5
0
.003
.006
.009
.012
.015
.018
.021
.024
.027
.03
.033
.036
.039
THE FREDERICK POST CO.
No 287
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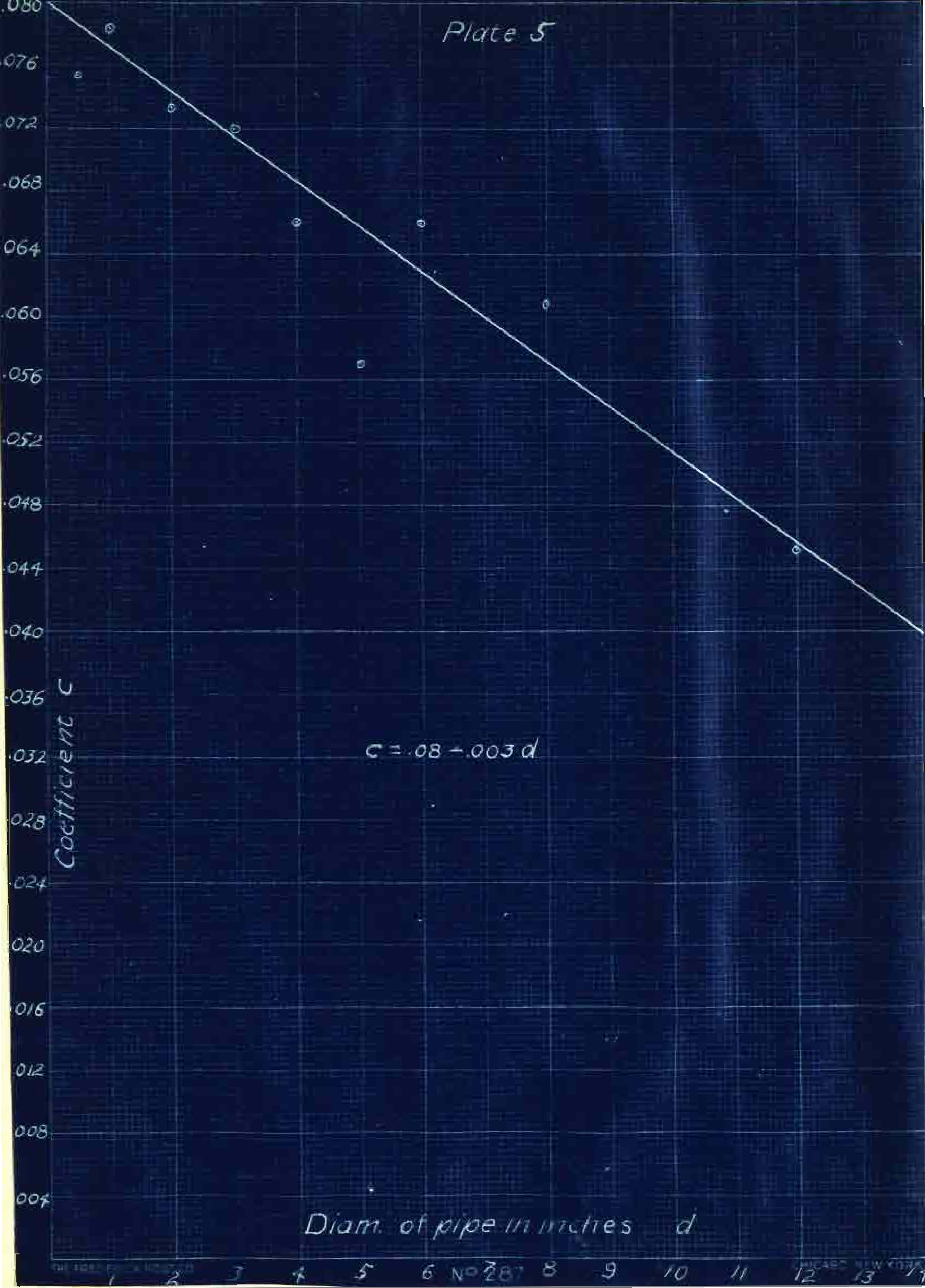
Plate 5
.080
.076
.072
.068
.064
.060
.056
.052
.048
.044
.040
.036
.032
.028
.024
.020
.016
.012
.008
.004
Coefficient c
c = .08 − .003 d
Diam. of pipe in inches d
1 2 3 4 5 6 7 8 9 10 11 12 13
No 287