A STUDY OF HYDRAULIC JUMP

THESIS FOR THE DEGREE OF B. S.

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A STUDY OF HYDRAULIC JUMP

The protection of stream beds below spillways and weirs against erosion has long been a problem for the hydraulic engineer to solve. Large sums have been spent in constructing aprons, weirs, cushion pools and other structures below dams to protect the stream beds against damaging erosion. In 1838 the phenomena of the hydraulic jump was noticed and study was made of the mathematical formulas which would govern it. It remained for the Miami Conservancy District engineers in 1915 to make the first real study for the control of the hydraulic jump and use of it to prevent stream erosion. Since that time more interest has been aroused in the subject and today the control of the standing wave or jump below a spillway is considered to be one of the essential parts of the design of dams. The authors of this thesis took up the study for two reasons. The first was to improve their knowledge of the control of stream erosion and the mathematics of hydraulic jump. The second was to build a model which could be used for this study and for future study of dam construction and design in the hydraulic laboratory of Michigan State College.

The first step was to build a model in the form of a trough with glass sides in which a model dam or weir could be mounted and the action of the water observed while passing over this dam. In addition a study was made of the available data and experiments that had been made in regard

to stream erosion. It was interesting to note that one of the first laws, The Conservation of Momentum, is still used and is one of the basic laws regarding hydraulic jump. With the aid of the model the results obtained were compared with the existing laws and compared very closely with experiments which had been conducted in years past along this line.

The Hydraulic Jump or Standing Wave gets its name from the wave which forms below a dam under certain conditions. It remains at the same height and stationary. This formation translated from a German article is called a surface roller. This is due to the rolling appearance of the standing wave. It is difficult to discuss this formation without bringing in the mathematical discussion. The mathematics of the formation will be discussed later. It has been noticed that as the water reaches the toe of a spillway it is traveling at a high velocity. If this velocity is maintained over the toe and out on the stream bed a large amount of material would be carried away, resulting in time in the undermining of the toe of the dam and the failure of the structure.

As the water strikes the toe and the standing wave is formed the kinetic energy of the water is taken up by the impact with the wave. The velocity of the stream is reduced and water flows away at the normal velocity of the stream. In other words, the energy of the falling water is dissipated by the impact with the water below and is used

in piling up the wave into a frothy, foamy formation that cuts down the velocity or absorbs it and dissipates it in the form of heat.

One of the most effective ways of dissipating energy is to introduce friction. In some structures a weir is constructed below the toe to introduce a tumble bay or a cushion pool so as to increase the resistance to flow. As water is usually considered incompressible this body of water offers considerable friction to the mass flowing into it at a high velocity. The friction of the bottom and the friction introduced by the mass of water directly in its path absorbs the velocity of the stream and causes the water to pile up. The cushion pool in the model was introduced by raising the end gate (see drawing of model). With this end gate down the high velocity of the stream continued throughout the length of the model and no standing wave was introduced. By raising and lowering the end gate the position of the jump could be varied from the toe of the dam out to the end gate. When gravel and sand were placed in the stream the wave would form with the end gate down. This would indicate that there must be friction in some form or other in order to overcome the velocity of stream enough to allow the water to pile up. Also a higher elevation of the end gate was needed to start the jump than to maintain it. After the jump was once started the end gate could be lowered considerably and the wave seemed to maintain itself.

The time limit on this thesis doesnot allow much study on erosion of the stream bed. A few runs were made, some using fine sand for a bed and others using coarse gravel. The main deduction from these was that the jump itself should occur on an apron of material that would not be eroded by the action of water. Where the jump occurred below the apron it hollowed out the bed to a considerable depth below the apron. This shows that the position of the jump is a necessary part of the design of a spillway. However, the material eroded by the jump will be redeposited a short distance below the point of occurrence of the jump. It is therefore necessary to have the jump occur as near the toe of the dam as possible to have economical design of structure. In the February 3, 1927 issue of Engineering News Record, page 190 is a very good article on the costly erosion below the Wilson Dam of the Muscle Shoals project. Had the engineers in charge of this project designed the spillway such that the jump had occurred on a concrete apron the costly repairs to the structure could have been eliminated. The only way in which the authors of this discussion can recommend that the position of the jump be determined before the structure is built is by the use of a model. This method has been used throughout Europe and is being used more and more in the United States. By its use the toe of the dam and the apron can be so arranged that with the laws of similitude and the assumed flow the

designer can be reasonably sure that costly erosion will not occur. So far no one seems to have been able to place the point of occurrence of the jump in a mathematical formula which will allow the designer to predetermine the standing wave and design his apron accordingly. The mathematics of the standing wave or surface roller will now be discussed.

MATHEMATICS OF JUMP.

Unwins formula for conservation of momentum [see Encyclopedia Brittanica, 9th Edition, Vol. 12, p. 499.] [Belonger 1838].

$$D = -\frac{d}{2} + \sqrt{\frac{d^2}{4} + \frac{2 d V_1^2}{g}}$$

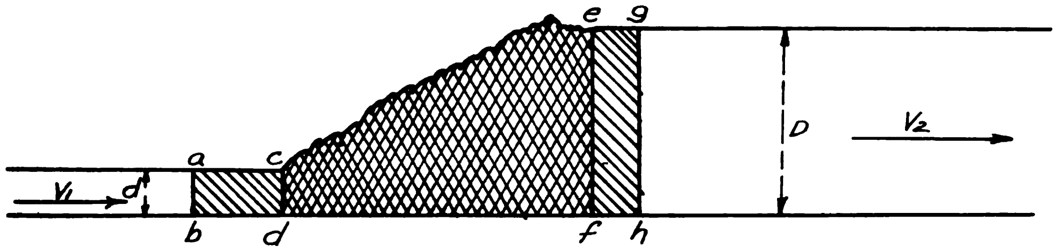
d = depth above the jump

D = depth below the jump

V_1 = velocity above the jump

g = acceleration of gravity

Derivation of the above formula is as follows: (see sketch)



d = depth of stream entering hydraulic jump

V_1 = velocity of stream entering hydraulic jump

D = depth of stream leaving hydraulic jump

V_2 = velocity of stream leaving hydraulic jump

D_c = depth of same stream at critical flow

V_c = velocity at critical flow

Then $V_c^2 = g D_c$

Q = quantity in second feet of flow per unit width of stream.

$$Q = V_1 d = V_2 D = V_c D_c = \sqrt{g D_c^3} \qquad (1a)$$

$$x = \frac{d}{D_c} \tag{1b}$$

$$y = \frac{D}{D_c} \tag{1c}$$

Mass of water flowing/sec. = w Q/g (1d)

w = unit wt. of water (1e)

Change of velocity = $V_1 - V_2$ (1f)

Change of momentum/sec. = $\frac{wQ}{g}(V_1 - V_2)$ (1)

Substituting $\frac{V_1 d}{D} = V_2$

$$= \frac{wQ}{g}\left(V_1 - \frac{V_1 d}{D}\right) \tag{2}$$

$$= \frac{wQV_1}{g\,D}(D - d) \tag{3}$$

Static pressure acting on the face (a - b)

$$= \frac{wd^2}{2} \tag{4}$$

Static pressure acting on the face (e - f)

$$= \frac{wD^2}{2} \tag{5}$$

Hence:

$$\frac{wQV_1}{g\,D}(D - d) = \frac{w}{2}(D^2 - d^2) \tag{6}$$

Dividing both sides by w(D - d)

$$\frac{QV_1}{g\,D} = \frac{d + D}{2} \tag{7}$$

Multiplying thru

$$D^2 + Dd = \frac{2\,QV_1}{g} \tag{8}$$

Substituting ($Q = V_1 d$)

$$D^2 + Dd = \frac{2\,V_1^2 d}{g} \tag{9}$$

$$D^2 + dD - \frac{2V_1^2d}{g} = 0 \qquad (10)$$

$$D = \frac{-d \pm \sqrt{d^2 + \frac{4x\,2V_1^2d}{g}}}{2} \qquad (11)$$

$$= -\frac{d}{2} \pm \sqrt{\frac{d^2}{4} + \frac{4x\,2V_1^2d}{4\,g}} \qquad (12)$$

$$D = \pm\sqrt{\frac{2V_1^2d}{g} + \frac{d^2}{4}} - \frac{d}{2} \qquad (13)$$

By substituting $\frac{Q}{d}$ for V_1 in (8)

$$D^2 + Dd = \frac{2Q^2}{g\,d} \qquad (14)$$

$$dD\frac{(D + d)}{2} = \frac{Q^2}{g} = D_c^3 \qquad \text{(see 1a)} \qquad (15)$$

$$dD\frac{(D + d)}{2} = D_c^3 \qquad (16)$$

Dividing thru by D_c^3 and substituting x and y (1b and 1c) for their equivalents

$$xy\,(x + y) = 2 \qquad (17)$$

Equation (16) shows that when $d = D_c$ D also equals D_c

Substituting: in (16)

$$D_cD\frac{(D + D_c)}{2} = D_c^3 \qquad (18)$$

$$\frac{D_cD^2 + D_c^2D}{2} = D_c^3 \qquad (19)$$

Substituting $D = D_c$

$$\frac{D_c^3 + D_c^3}{2} = D_c^3 \qquad (20)$$

$$D_c^3 = D_c^3 \qquad (21)$$

The equation (16) is symmetrical in d and D. If d is less than D_c, then D must consequently be greater. If d is greater than D_c (impossible) then D would have to be

less than D_c. As there seems to be no physical phenomenon that would cause a reversal of the jump, the conclusion is that the jump can occur only when (d) is less than (D_c) and (D) is greater than (D_c).

When the conditions are right, so that the jump occurs, it will always take place at the critical depth.

The action of the hydraulic jump is a continuous violent inelastic impact internally, by which the kinetic energy of the swiftly moving stream entering the jump is converted into heat.

To plot the results of the experiment the formula

$$D = \pm\sqrt{\frac{2V_1^2 d}{g} + \frac{d^2}{4}} - \frac{d}{2}$$

is reduced to the following form

Let $$J = \frac{D}{d}$$

h_1 = velocity head of stream entering jump.

$$h_1 = \frac{V_1^2}{2g}$$

Then $$D + \frac{d}{2} = \pm\sqrt{\frac{2V_1^2 d}{g} + \frac{d^2}{4}} \qquad (22)$$

$$D^2 + dD + \frac{d^2}{4} = \frac{2V_1^2 d}{g} + \frac{d^2}{4} \qquad (23)$$

Dividing thru by (d^2)

$$\frac{D^2}{d^2} + \frac{D}{d} + \frac{1}{4} = \frac{2V_1^2}{gd} + \frac{1}{4} \qquad (24)$$

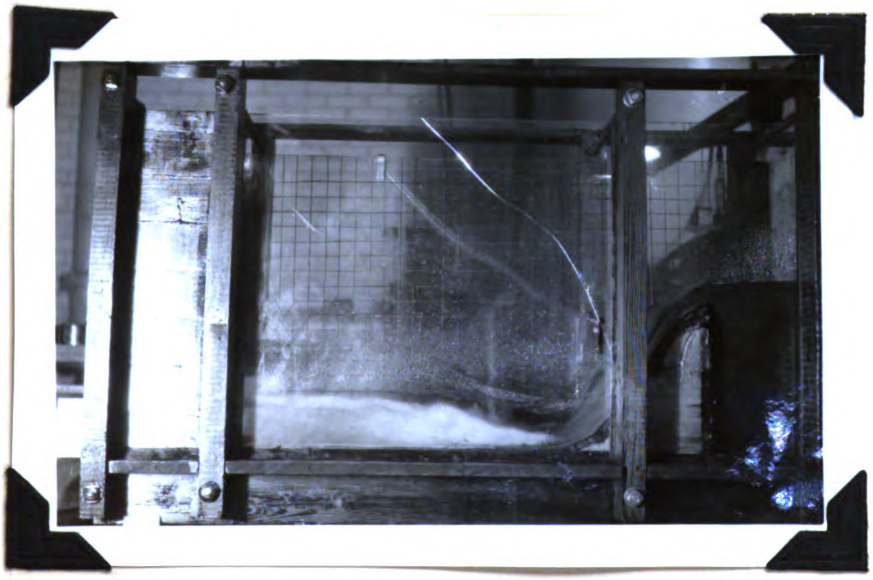
Substituting $J = \frac{D}{d}$ and $h_1 = \frac{V_1^2}{2g}$

$$J^2 + J = \frac{2V_1^2}{gd} = \frac{4h_1}{d}$$

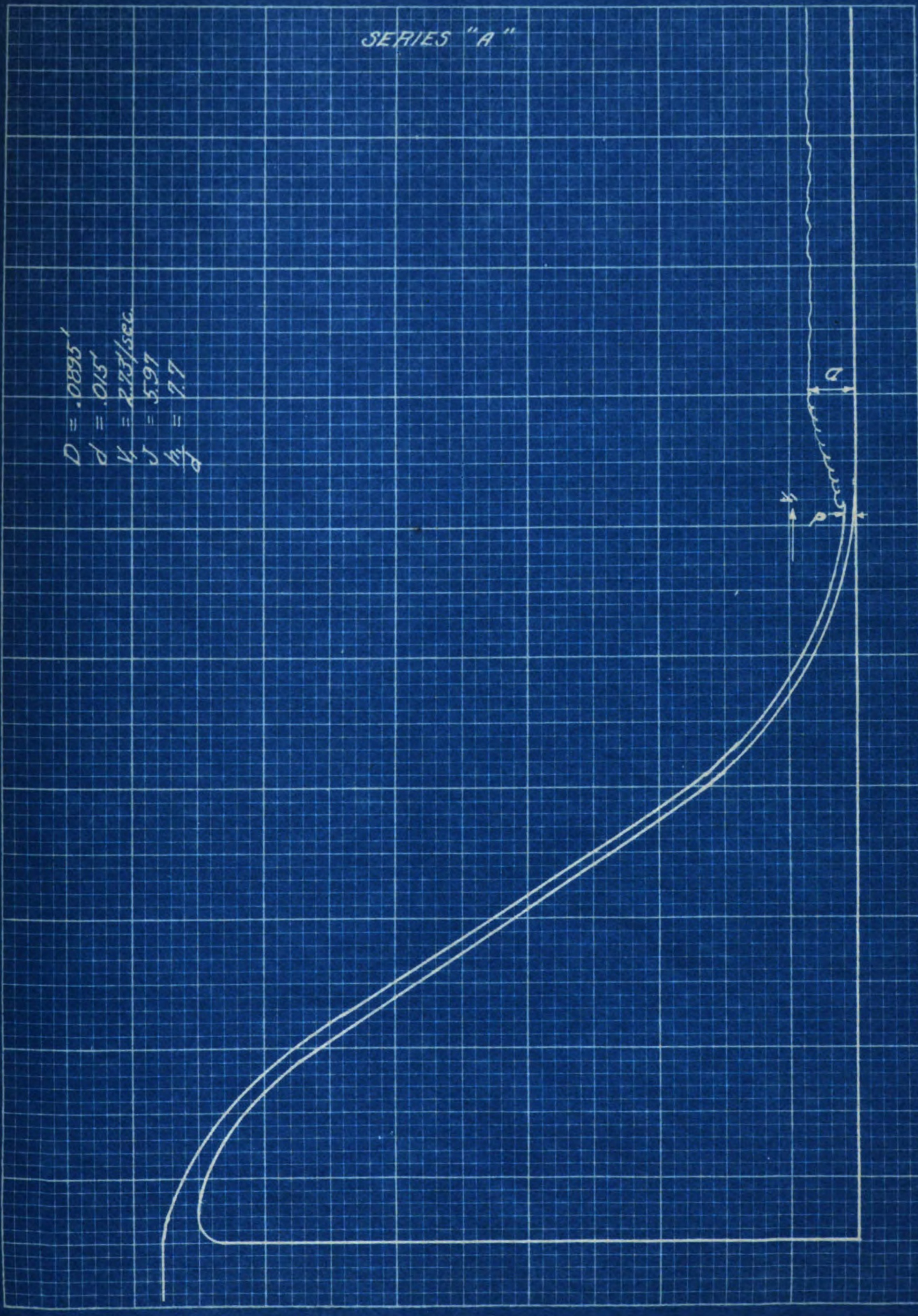
$$J^2 + J = \frac{4h_1}{d} \qquad (25)$$

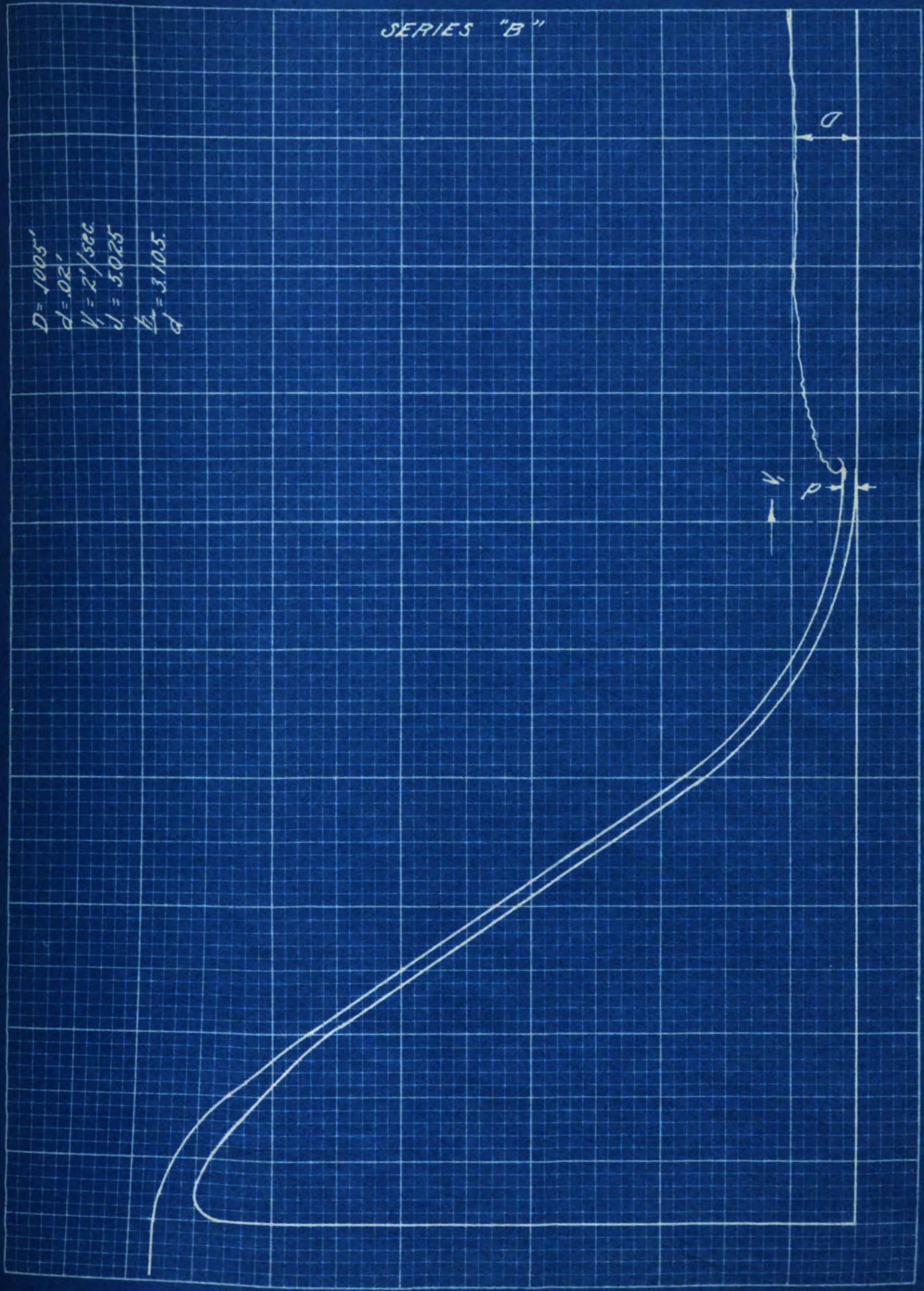
Values of J as ordinates have been plotted against values of (h_1/d) as abscissa.

PICTURES OF MODEL SHOWING JUMP IN ACTION

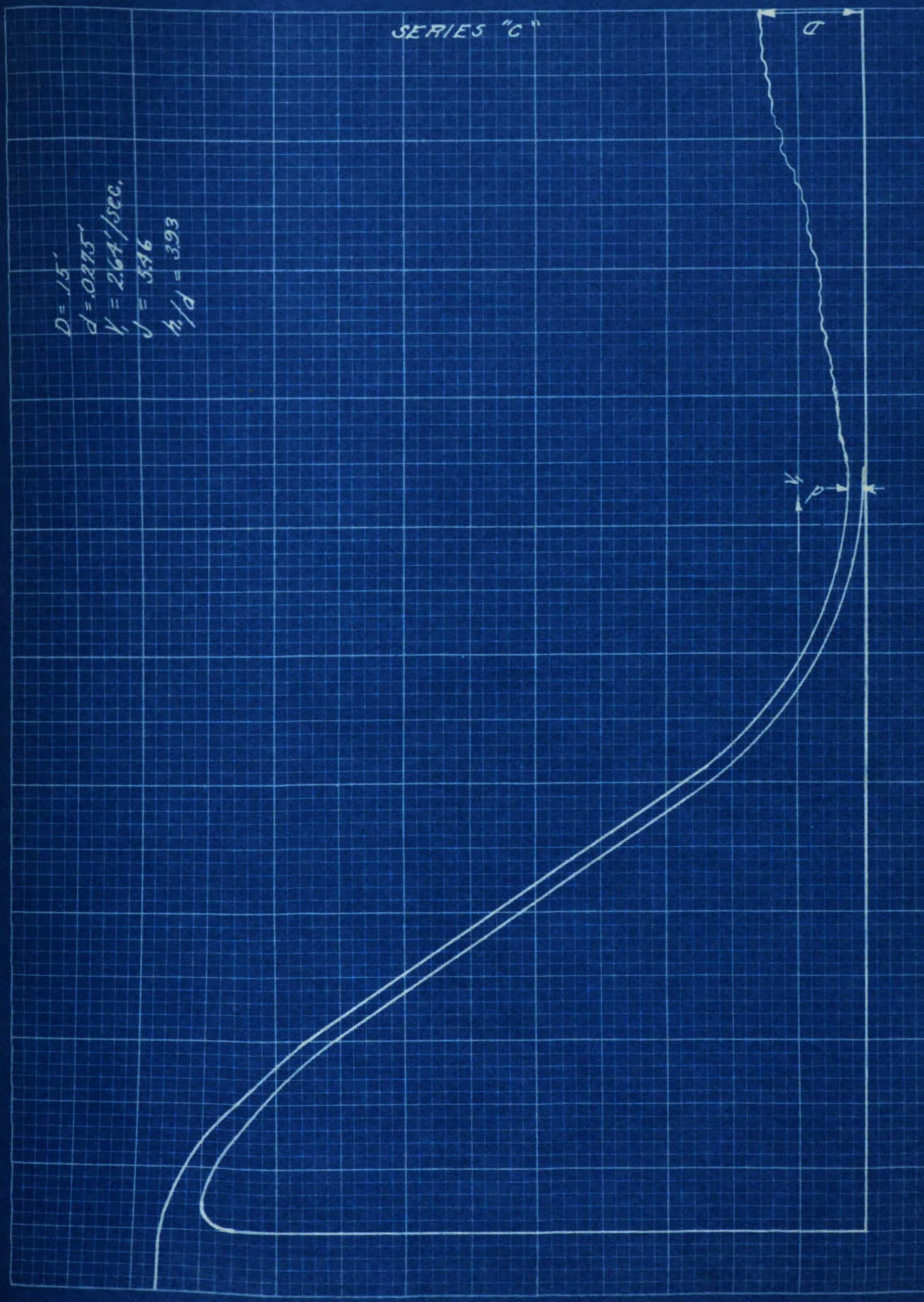


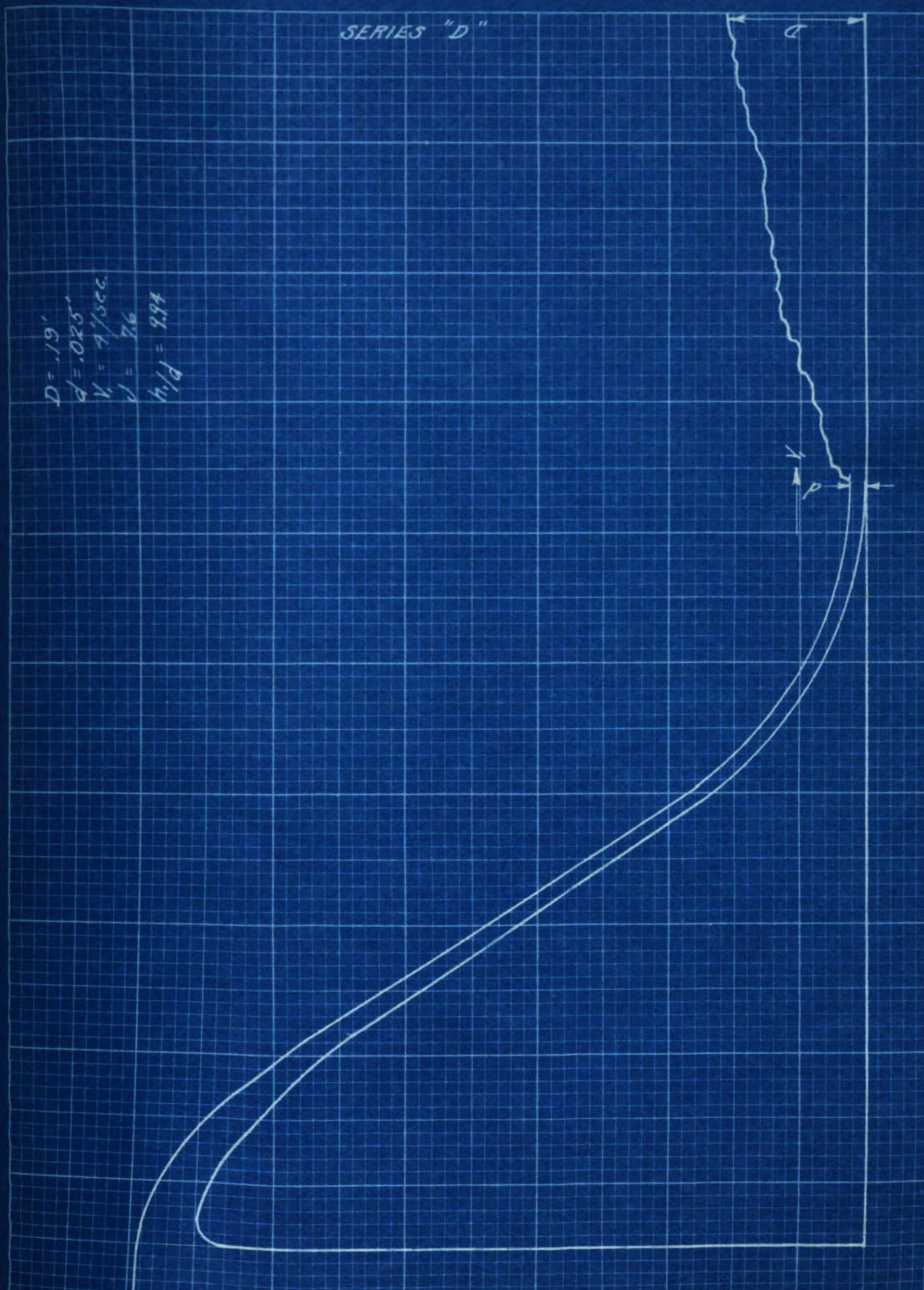
SERIES "A"

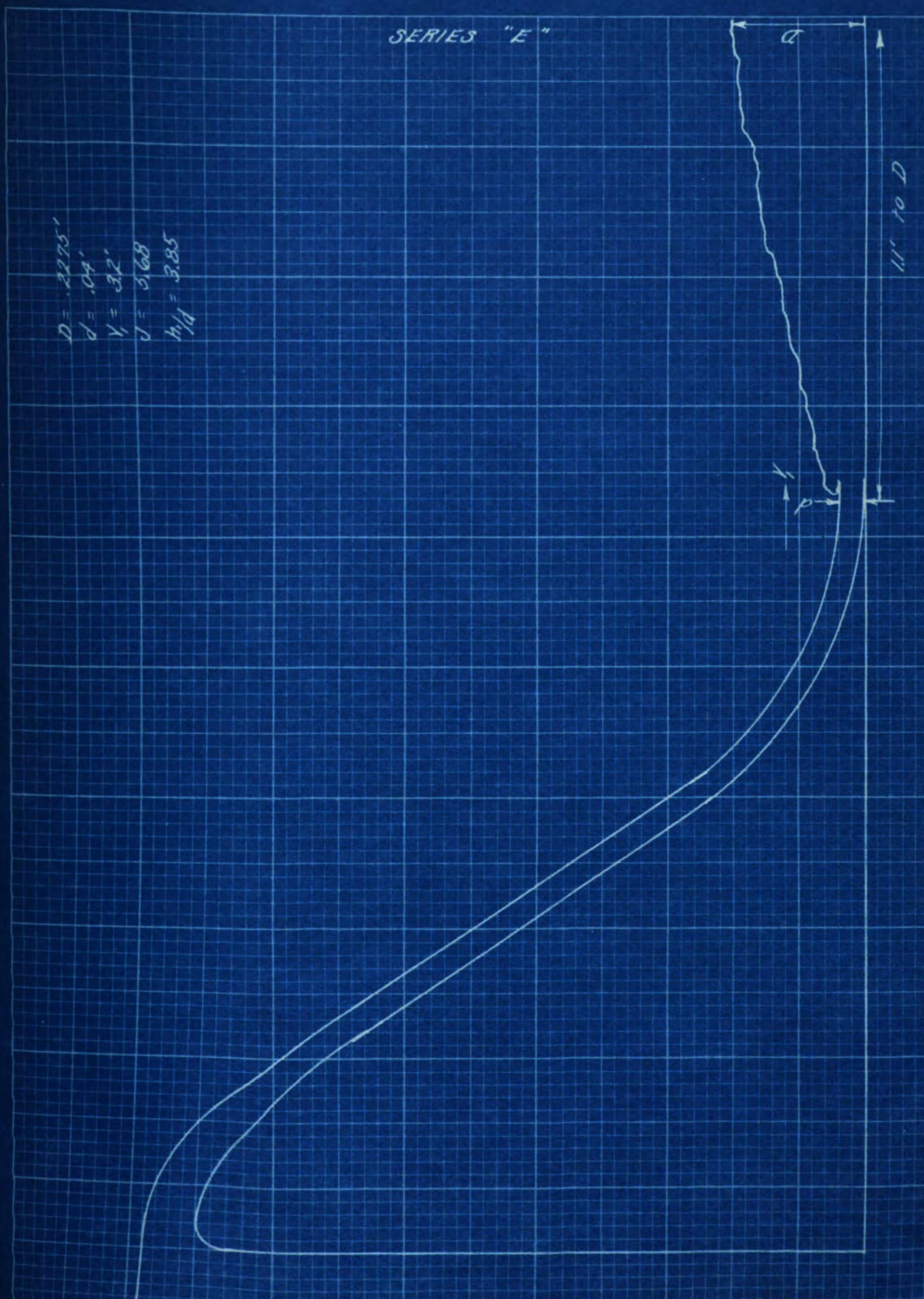


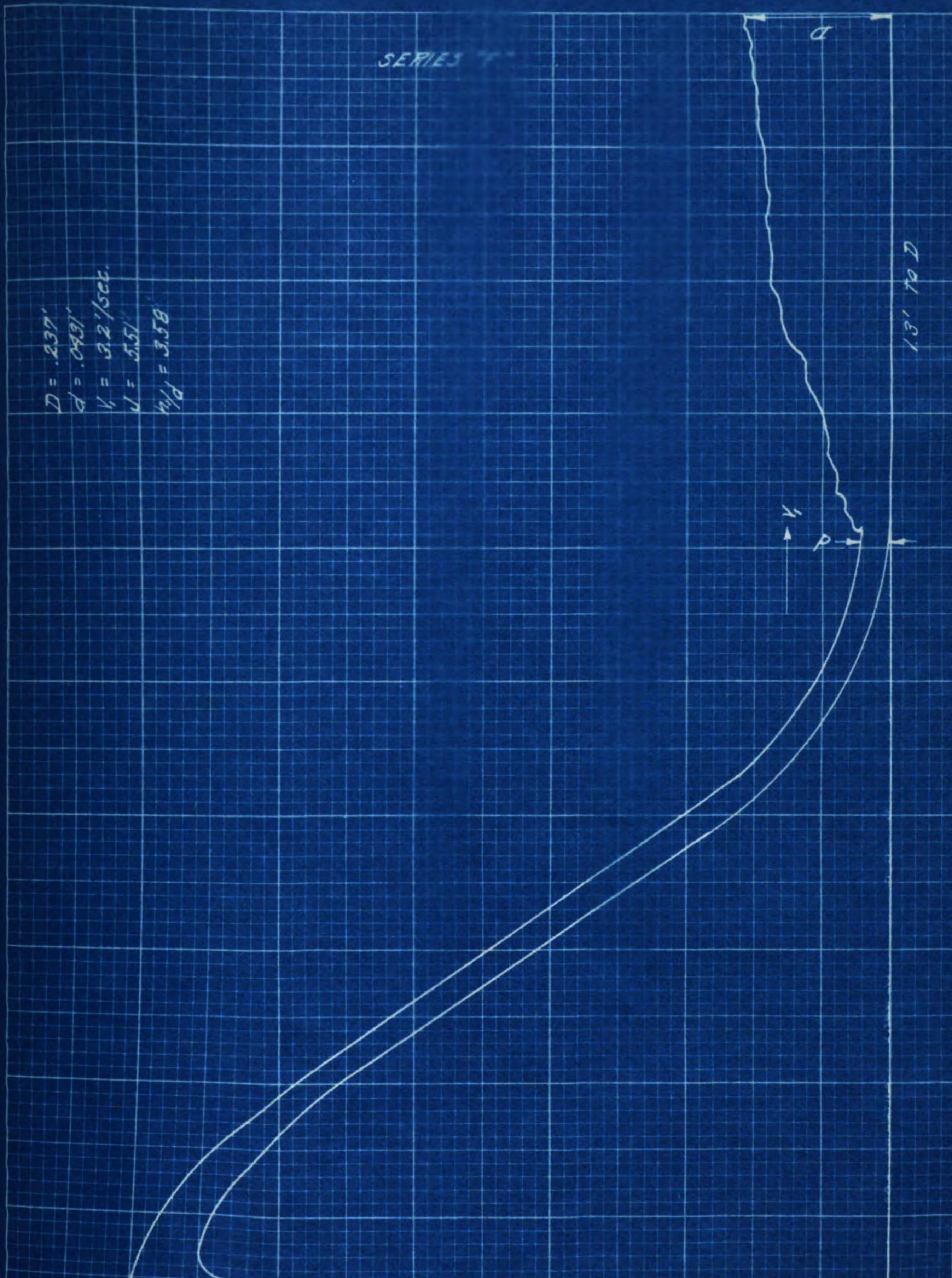


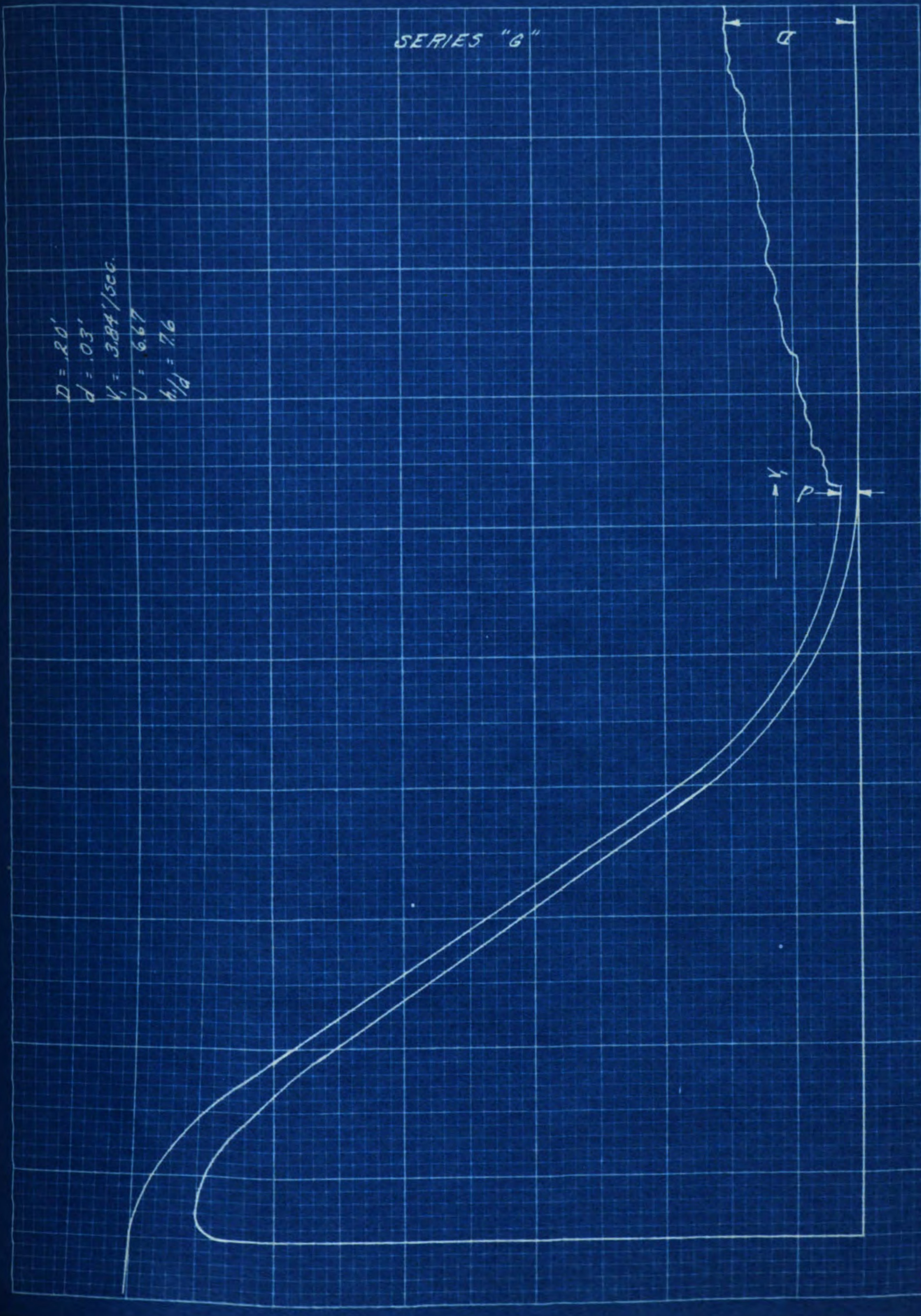
SERIES "B"
D = .1005'
d = .02'
V1 = 2'/sec.
J1 = 5.025
b/d = 3.105.
a
V1
p

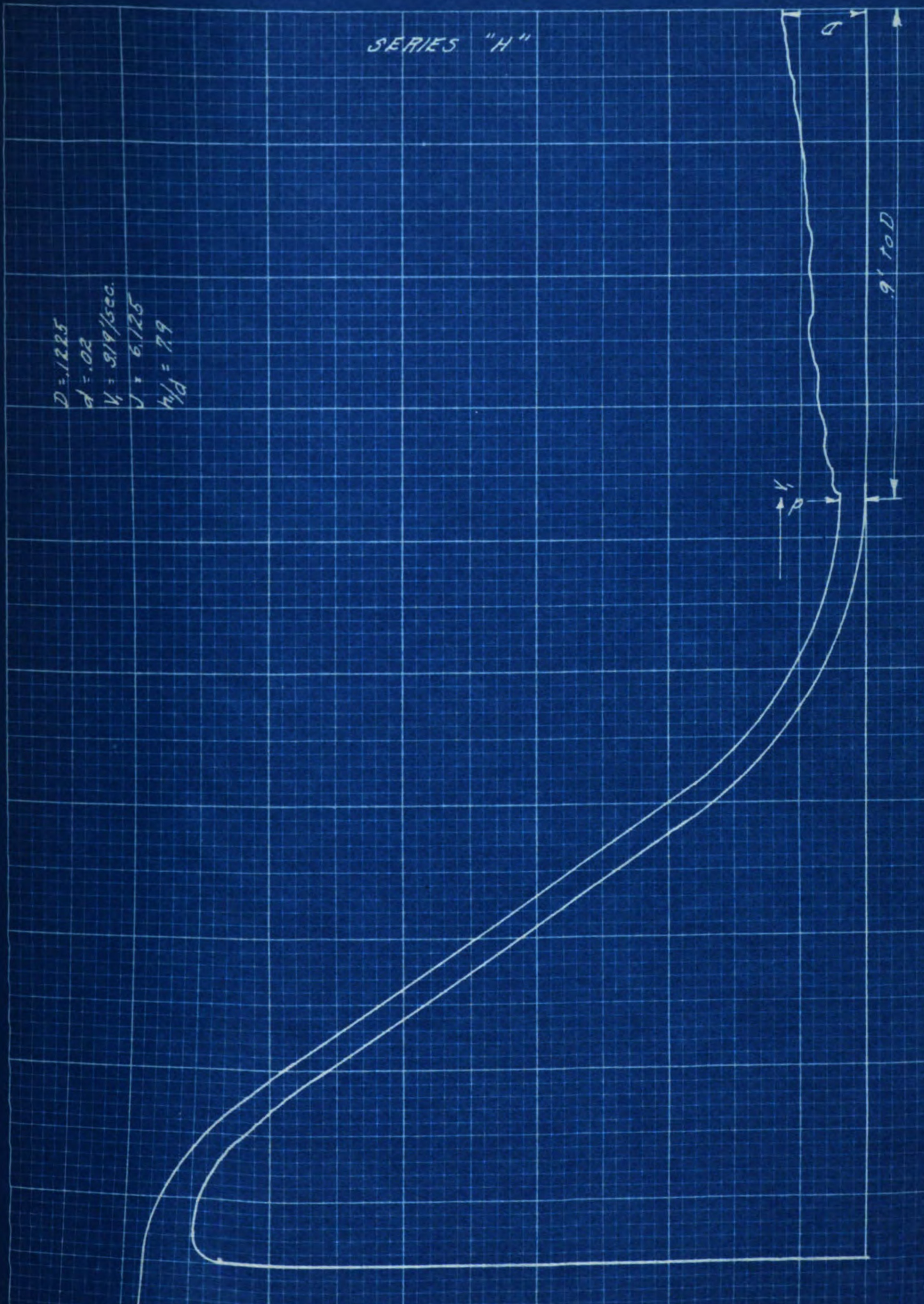

SERIES "C"
D
D = 1.5'
d = .0275'
V₁ = 2.64'/sec.
J = 3.46
h₁/d = 3.93
d


SERIES "D"
D
d
D = .19'
d = .025'
V_1 = 4'/sec.
J = 7.6
h/d = 9.94

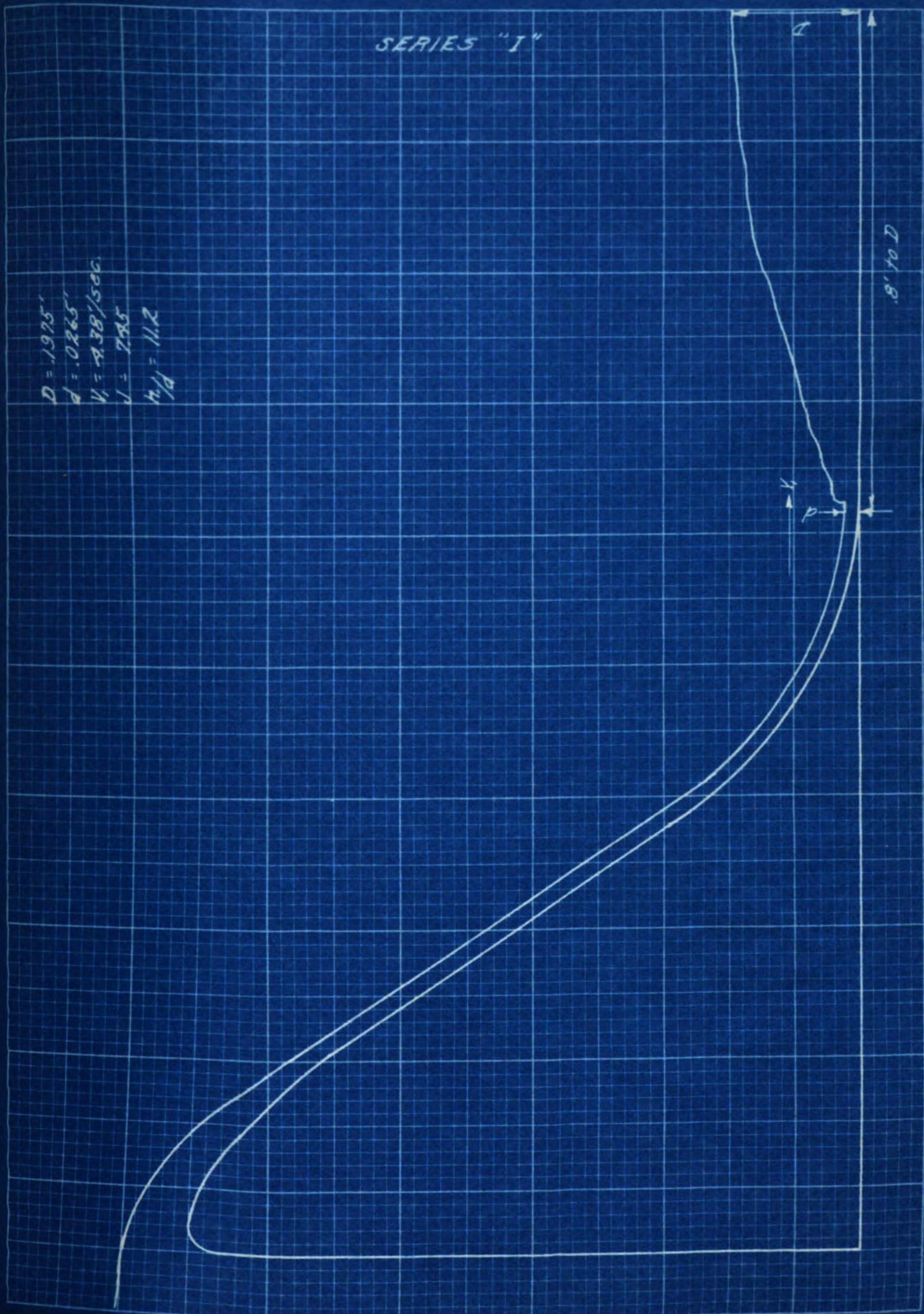

SERIES "E"
D = .2275"
d = .07"
Y1 = 3.2"
J = 3.68
h/d = 3.85
a
Y
p
11' to D

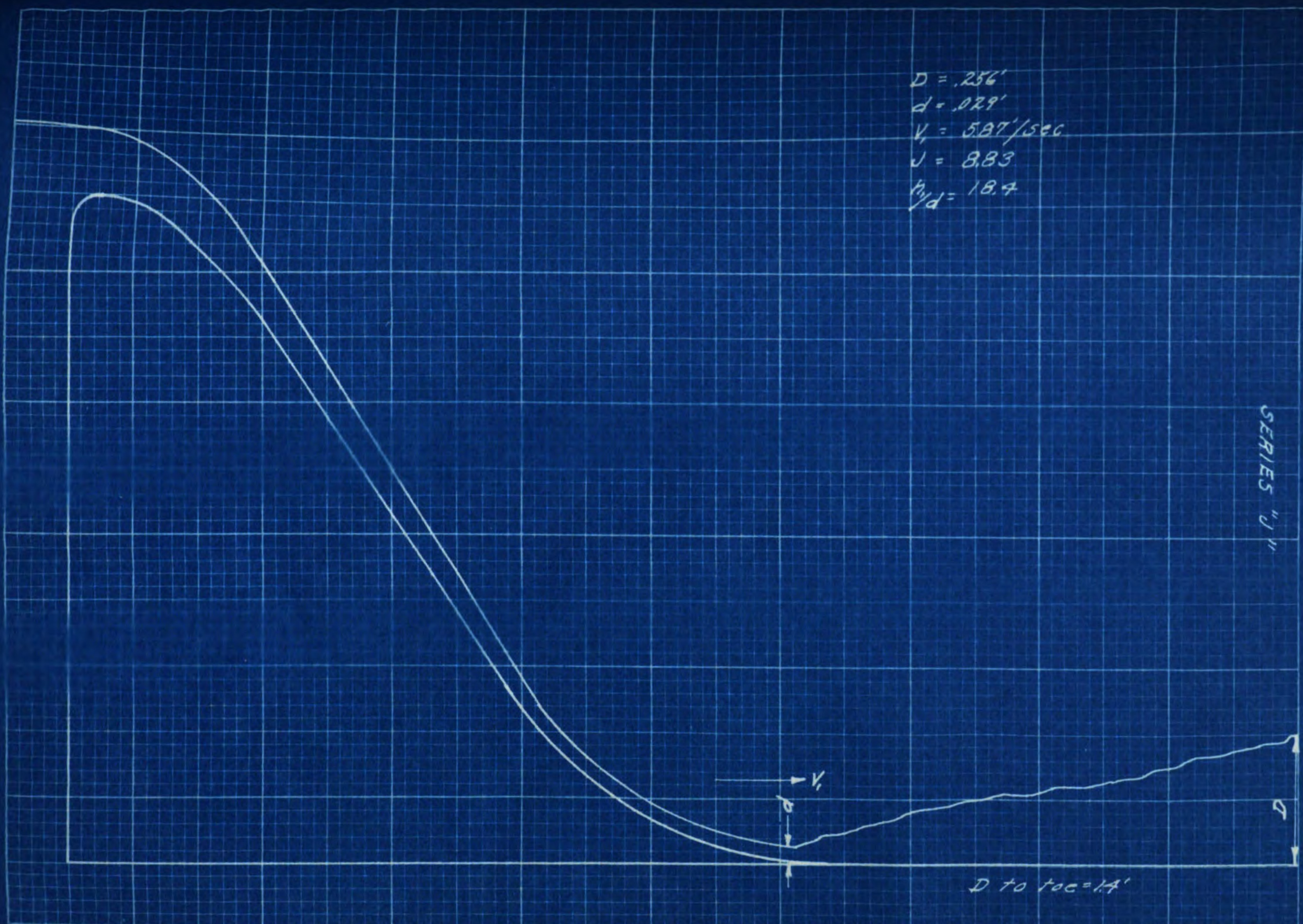

SERIES
D = .237'
d = .0431'
V1 = 3.2'/sec.
L = 5.51'
h/d = 3.58
d
1.3' to D
V1
P


SERIES "G"
D = .20'
d = .03'
V1 = 3.84'/sec.
J = 6.67
h1/d = 7.6

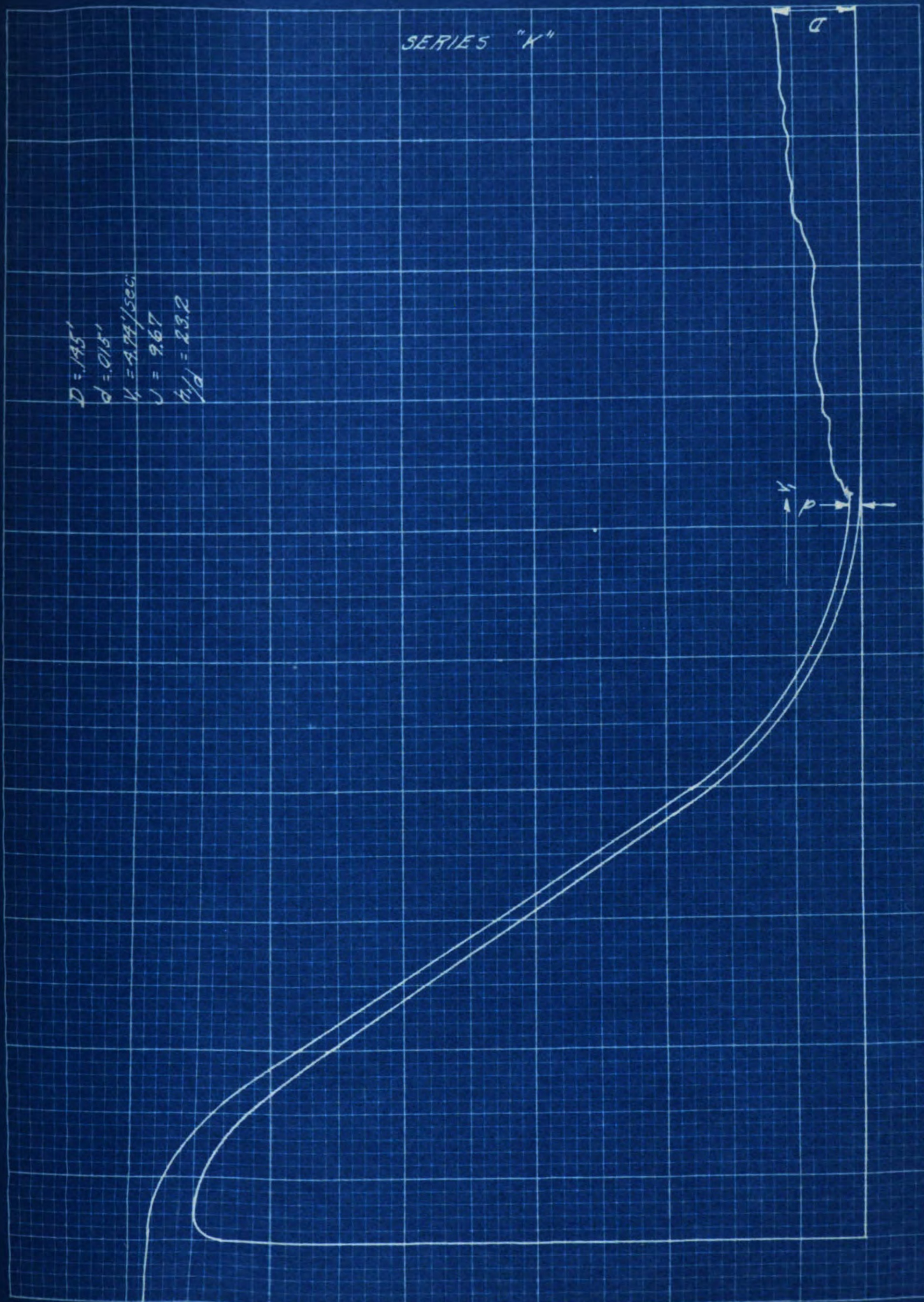


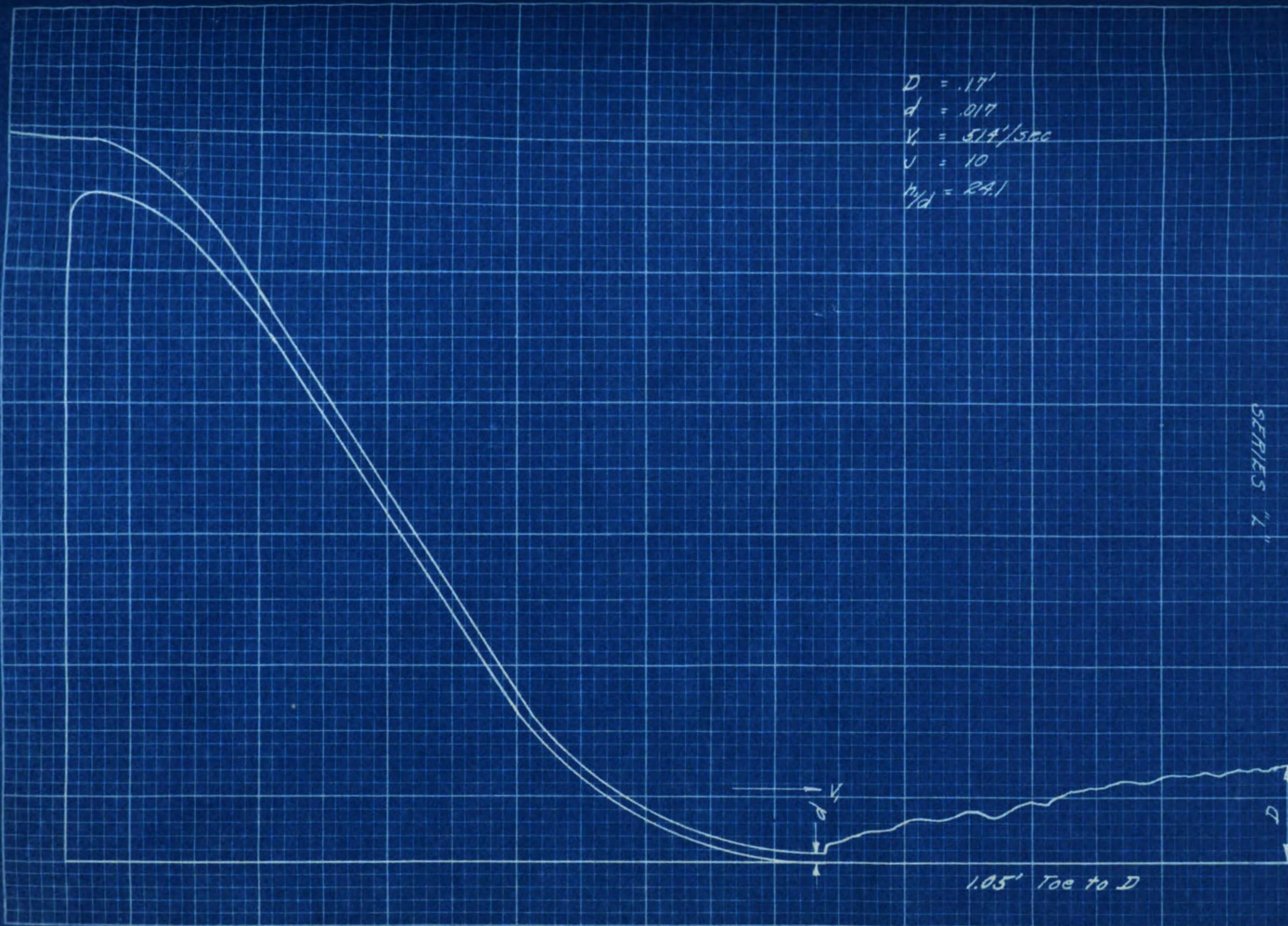
SERIES "H"
D = .1225
d = .02
V1 = 9.19'/sec.
J = 6.125
h/d = 7.9
9' to D
D
V1
P


SERIES "I"
D = .1975"
d = .0265"
V₁ = 8.38'/sec
J = 2.85
h/d = 11.2
d
h
p
.8' to D

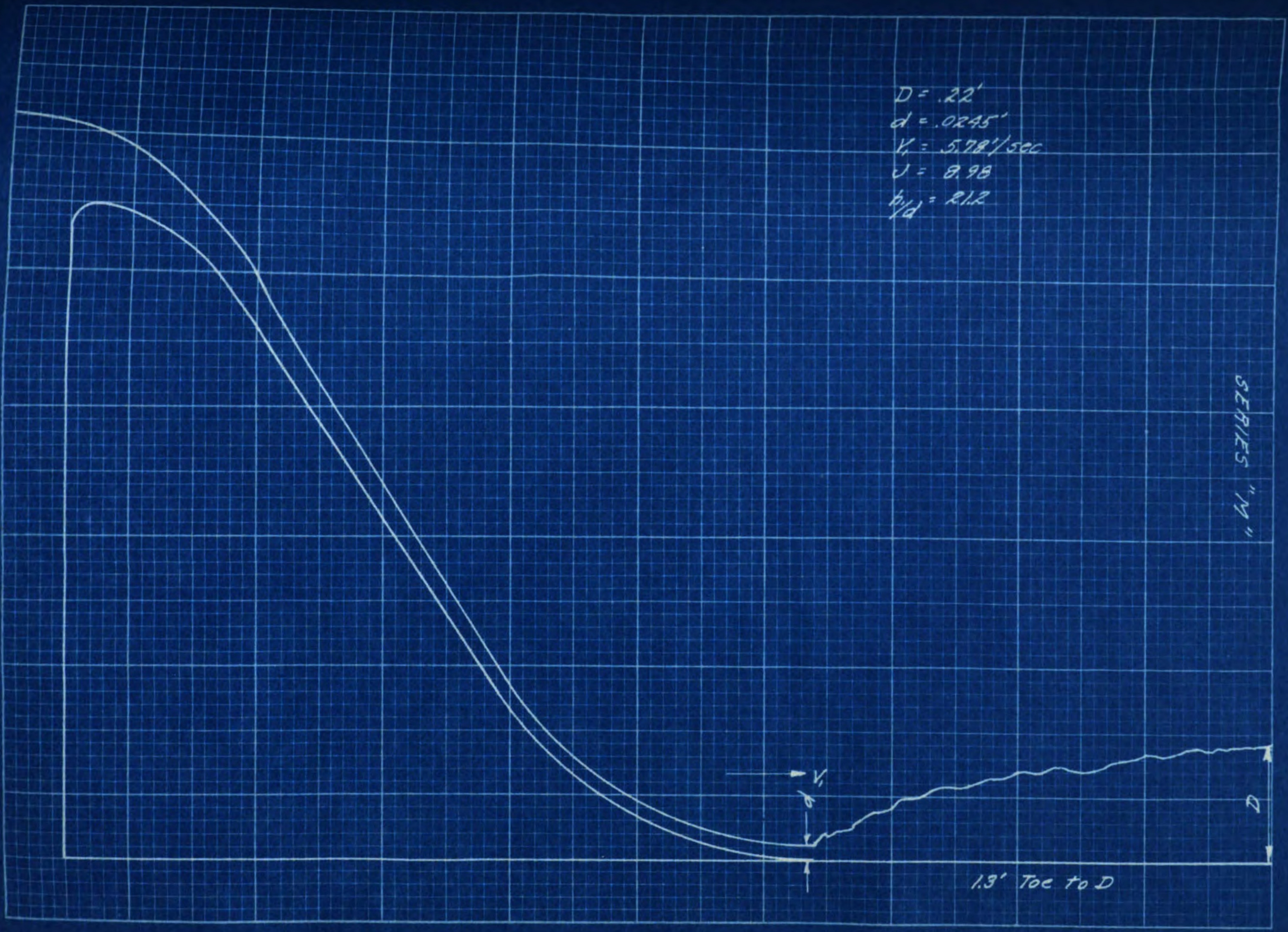


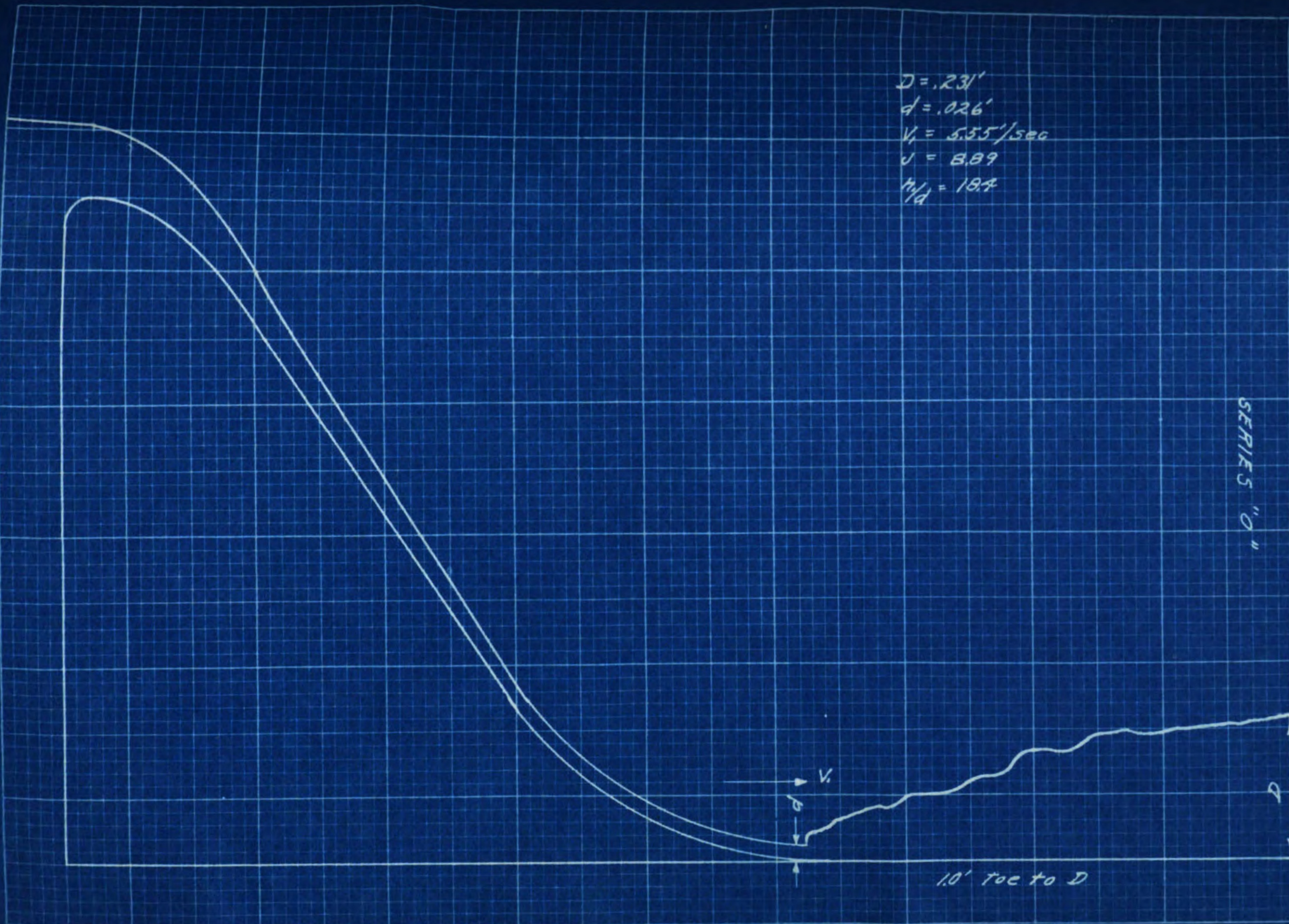
D = .256'
d = .029'
V_1 = 5.87'/sec
J = 8.83
h_1/d = 18.4
SERIES "J"
V_1
d
D
D to toe = 1.4'

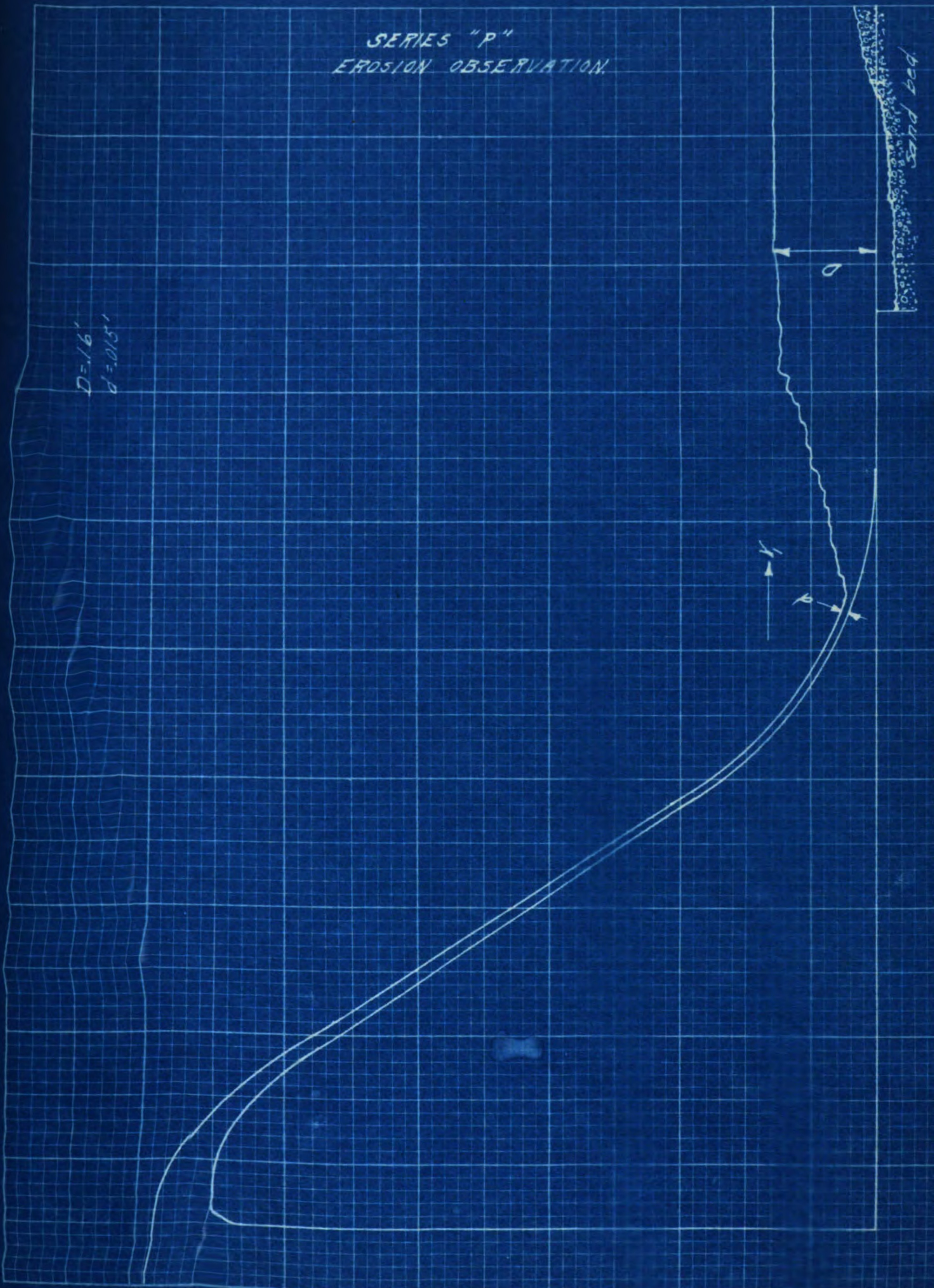

SERIES "K"
D = .145'
d = .015'
V1 = 4.74'/sec.
J = 9.67
h/d = 23.2
a
p



SERIES "L"
D = .17'
d = .017
V₁ = 5.14'/sec
V = 10
h/d = 24.1
V₁
d
D
1.05' Toe to D


D = .22'
d = .0245'
V1 = 5.78'/sec
J = 8.98
b/d = 21.2
V1
d
D
1.3' Toe to D
SERIES "M"


SERIES "O"
D = .231'
d = .026'
V1 = 5.55'/sec
J = 8.89
h/d = 18.4
V1
d
D
1.0' Toe to D


SERIES "P"
EROSION OBSERVATION.
Sand bed
D=1.6'
d=.015'
a
b

LAWS OF HYDRAULIC SIMILITUDE

The relation between the dimensions for structures in nature and for models of such structures follow:

Subscript m is used to denote model.

n is used to denote scale ratio

Measurement	Equation
Linear	$L : L_m :: n : 1$
Area	$A : A_m :: n^2 : 1$
Volume	$Q : Q_m :: n^3 : 1$
Weight	$W : W_m :: n^3 : 1$
Velocity (friction neglected)	$V : V_m :: \sqrt{n} : 1$
Velocity	$V : V_m :: \sqrt{gn} : \sqrt{gm}$
Mass	$M : M_m :: n^3 : 1$
Time	$T : T_m :: \sqrt{n} : 1$
Force	$F : F_m :: n^3 : 1$
Moments	$M : M_m :: n^4 : 1$
Work	$K : K_m :: n^4 : 1$
Energy	$E : E_m :: n : 1$
Rate of Discharge	$Q : Q_m :: n^{5/2} : 1$

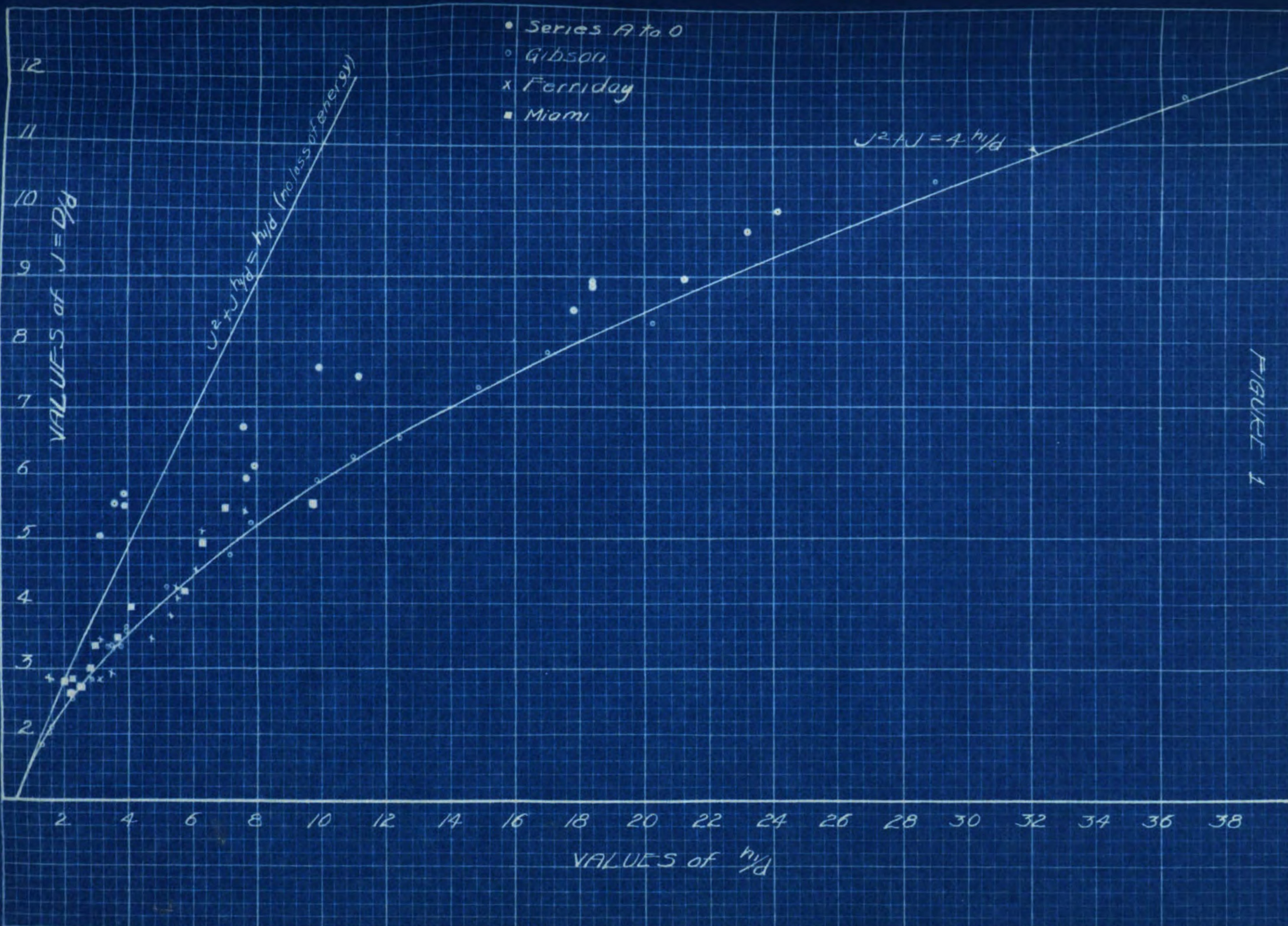
In the construction of the model, the principle object was to obtain a model which would be satisfactory in determining the reliability of the law of conservation of momentum. No effort was made to correlate the model to existing conditions at some particular dam site. The ogee spillway was made to scale, however, representing type I of spillway shown on page 697 of the Engineering News-Record, of May 3, 1928. For all the purposes of this experiment no consideration of the laws of similitude was necessary. If further experiments had been run, however, with the purpose of determining the location and effect of the hydraulic jump for some proposed dam, the model would have been erected so as to closely resemble the conditions at the particular site, and in order to correlate the results from such a model to the dam, the laws of similitude would be used in all cases.

The model as constructed is shown by the drawings, Plates 1, 2, and 3. The inside width of the trough is 1.00 feet, the height 2.00 feet, the overall length 5.00 feet. The sides and floor are of wood construction with joints waterproofed with asphalt paint. The joints so waterproofed were satisfactory during the period the experiments were run. No perceptible leakage occurred after the first day. The greatest difficulty encountered was to obtain a watertight spillway. After the first day

the ogee spillway, made of white pine lumber and paraffined, began to swell. The gasket used between the spillway and the glass sides consisted of old rubber inner tubing. This gasket did not effectively check water seeping thru from the back of the dam. It did not compress sufficiently to allow for the expansion of the dam. The consequences of the expansion of the dam was that the glass sides were put under too great a strain. One side which had been marked for cross-sectioning had several long cracks which followed these markings. The glass sides, 1/4" x 2' x 3-1/2' plate glass, were the most costly part of the model. It is to be recommended that no scratching or cutting of the surface of the glass be done in cross-sectioning. The ogee spillway if made of wood should have sufficient clearance to allow for swelling of wood. The wood, waterproofed with paraffin, swelled considerably. Creosote is recommended for waterproofing a spillway built of wood. Felt, impregnated in oil is to be recommended for a gasket, rubber does not compress sufficiently. The spillway should be made of concrete, steel or some material which will not expand when immersed in water.

The coke baffle, (coke broken up into small sizes) worked very efficiently in quieting any turbulence above the spillway.

The results of this experiment are best shown by Fig. I.



Series A to O
Gibson
Ferriday
Miami
J² + J = 4 h/d
J² + J h/d = h/d (no loss of energy)
VALUES of J = D/d
VALUES of h/d
FIGURE 1

Bidone made a rectangular trough 1.066 feet wide and conducted a series of experiments to verify the law. (Transactions, Royal Society of Turin, 1819 pp. 22-80). His greatest difficulty was in the magnitude of the jump occurring, it being too small to be of value in verifying any law. Following is a table of values from Bidone's experiments.

TABLE I

Bidone's Observations on Hydraulic Jump

Series	Observations in series	d feet	V_1 ft/sec	D feet	J	h_1	$\frac{h_1}{d}$
I	4	0.154	4.47	0.431	2.80	0.310	2.02
II	5	.209	5.57	0.630	3.01	.481	2.30
III	3	.243	6.35	.749	3.08	.627	2.58
IV	4	.150	4.57	.414	2.76	.324	2.16

Darcy and Bazin made some observations with a timber trough 6.53 feet wide. Their experiments were made in 1856. They are of no particular value in verifying the law. Observations were made at the Lehigh University in 1894 by Robert Ferriday. His experiments were conducted with a trough 0.66 foot wide. His results are plotted in Fig. I. His experiments verify the law quite closely. (See Transactions, Am. Soc. C.E., Vol. 80, p. 385.)

TABLE II

Ferriday's Observations on the Hydraulic Jump.

Series	Observation in series	d feet	V_1 ft/sec	D feet	J	h_1 feet	$\frac{h_1}{d}$
I	3	0.050	2.18	0.143	2.86	0.074	1.48
II	5	.044	2.98	.150	3.41	.138	3.14

Table II (Continued)

Series	Observation in series	d feet	V_1 ft/sec	D feet	J	h_1 feet	$\frac{h_1}{d}$
III	6	.036	3.56	.153	4.25	.196	5.45
IV	5	.033	3.66	.168	5.10	.207	6.28
V	3	.095	4.39	.267	2.81	.298	3.14
VI	4	.083	5.02	.285	3.44	.390	4.70
VII	3	.071	5.02	.290	4.08	.390	5.50
IX	4	.055	3.50	.162	2.95	.190	3.46
X	4	.046	3.95	.175	3.80	.242	5.26
XI	5	.042	4.06	.188	4.48	.255	6.08
XII	4	.038	4.33	.205	5.40		

Professor A. H. Gibson (see Proceeding Inst. C.E., Vol. 197, p. 233. Also Trans. Am. Soc. C.E., Vol. 80, p. 413), of Dundee Scotland conducted a series of experiments in a trough three feet wide. His results check the law very closely. The results of his experiments are given in Table III.

TABLE III

Gibson's Observations on the Hydraulic Jump

Series	d feet	V_1 ft/sec	D feet	J	h_1 feet	$\frac{h_1}{d}$
A	0.0735	4.30	0.265	3.61	0.288	3.92
	.0731	5.82	.350	4.79	0.526	7.20
	.0730	7.20	.455	6.23	0.805	11.03
	.0729	8.33	.530	7.28	1.079	14.82
	.0728	8.95	.570	7.83	1.245	17.11
	.0730	9.74	.612	8.39	1.474	20.22
	.0728	11.66	.760	10.44	2.110	29.00
	.0727	13.12	.850	11.69	2.676	36.80
B	0.1465	3.45	0.267	1.82	0.185	1.26
	.1395	5.68	.467	3.35	0.501	3.59
	.1390	6.82	.587	4.22	0.723	5.20
	.1390	8.39	.726	5.22	1.093	7.86
	.1390	9.40	.808	5.81	1.372	9.88
	.1390	10.53	.910	6.55	1.725	12.41

Table III (Continued)

Series	d feet	V_1 ft/sec	D feet	J	h_1 feet	$\frac{h_1}{d}$
C	0.2075	4.43	0.419	2.02	0.305	1.47
	.2070	4.53	.440	2.12	.318	1.54
	.2048	5.34	.530	2.59	.443	2.16
	.2046	6.09	.575	2.81	.575	2.82
	.2040	6.65	.678	3.32	.684	3.36
	.2043	7.05	.684	3.34	.772	3.77
	.2043	7.24	.733	3.59	.813	3.98

The researches of the Miami Conservancy District (see The Hydraulic Jump as a Means of Dissipating Energy, by Ross M. Riegel and John C. Beebe also. Theory of the Hydraulic Jump and Backwater Curves, by Sherman M. Woodward, Technical reports, Part III, Dayton, Ohio, 1917).

TABLE IV

The Miami Conservancy Districts Observations on the

Hydraulic Jump, Series 2

Run	Position of Jump. Feet.	d feet	V_1 ft/sec	D feet	J	h_1 feet	$\frac{h_1}{d}$
100	5.5	0.32	6.60	0.84	2.62	0.675	2.11
101	11.0	.22	5.73	0.60	2.73	0.510	2.32
102	9.0	.24	6.15	0.73	3.04	0.586	2.44
111	14.2	.17	7.95	0.70	4.11	0.980	5.76
112	10.0	.24	7.57	0.85	3.54	0.890	3.71
113	7.5	.34	6.68	1.00	2.94	0.691	2.03
114	5.4	.39	7.27	1.06	2.72	0.818	2.10
119	4.3	.48	8.35	1.35	2.82	1.080	2.25
120	9.3	.31	7.75	1.05	3.39	0.932	3.01
121	13.3	.21	8.52	.87	4.14	1.125	5.36
122	12.5	.24	9.45	1.07	4.46	1.385	5.78
124	9.0	.32	9.25	1.27	3.97	1.330	4.15
125	6.3	.38	10.10	1.38	3.63	1.580	4.16
129	3.7	.55	11.05	1.77	3.22	1.890	3.44
130	6.2	.42	10.83	1.59	3.78	1.820	4.34
131	8.9	.33	10.72	1.43	4.33	1.780	5.40
132	11.7	.27	10.28	1.30	4.81	1.640	6.07
133	11.8	.29	10.93	1.43	4.94	1.850	6.38
134	9.0	.35	11.26	1.59	4.54	1.965	5.62
137	6.5	.40	12.50	1.70	4.25	2.420	6.04

Table IV (Continued

Run	Position of Jump. Feet.	d Feet	V_1 ft/sec	D feet	J	h_1 feet	$\frac{h_1}{d}$
138	4.5	0.49	12.83	1.90	3.88	0.550	5.20
139	2.0	.85	10.37	2.07	2.44	1.660	1.95
142	2.0	.87	11.18	2.24	2.58	1.930	2.23
143	4.5	.52	13.62	2.07	3.98	2.875	5.54
144	8.5	.36	12.88	1.74	4.83	2.560	7.12
145	11.0	.34	11.12	1.54	4.53	1.920	5.65
146	13.5	.30	11.78	1.64	5.47	2.150	7.17
147	9.5	.33	14.50	1.83	5.55	3.260	9.83
148	5.0	.54	13.70	2.10	3.89	2.910	5.39
149	3.5	.64	13.82	2.25	3.52	2.960	4.63
150	3.0	.69	13.77	2.32	3.36	2.940	4.26

The plotted results of the different experiments will be found in Fig. I.

The experiments were run on the model in the following manner. From Series A to P (see graphs) a smooth apron was run from the toe to the end gate. The coefficient of friction of this apron was very low. The wave was controlled and maintained by raising or lowering the end gate. In all of the observations taken the wave was maintained in a stable form directly at the point where the toe joined the apron. Once it was spotted at this point it would maintain itself for that flow. But upon increasing or decreasing the flow the position of the wave would immediately change. The quantity of water flowing was found by weighing the water and timing the flow for a quantity of 100 pounds. The area of the water at D and d was found by measuring with a thin rule calibrated to .01 feet. Several trials were taken on each series in order to insure

a mean value as near correct as possible. The drawings on the series of runs are self-explanatory. The surface of water was plotted over the entire spillway, and the position of D or maximum depth relative to the toe is shown on each graph. Following is a sample computation:

Series A

$$V_1 = \frac{Q}{a_1} = \frac{100}{62.5 \times .015 \times 39.05} = 2.73' \text{ per sec.}$$

$$h_1 = \frac{V_1^2}{2g} = \frac{(2.73)^2}{64.4} = .115$$

$$J = \frac{D}{d} = \frac{.0895}{.015} = 5.97$$

The results obtained from the series of runs do not check exactly with the theoretical formula. This would seem to indicate that an emperical value should be given this machine. Other experiments which have been carried on in the past seemed to bear this up. Whether or not a large structure such as a dam would require this empirical coefficient it is not known. If such a coefficient is needed it might be found that each change in shape of spillway would effect the values obtained in a different manner. It was noted that a very small change in head had a very marked effect upon the standing wave. In some cases a slight increase would cause the jump to disappear entirely. In other cases a slight decrease would cause the jump to extend up the face of the spillway. It was deducted from this that the coefficient of friction of the bed was so

low that any slight change in the velocity would overcome the friction or be overcome by it so that the character of the hydraulic jump was changed very much.

When the sand was substituted for the smooth stream bed the jump was much more stable. A greater change in head was necessary to cause it to vary. The jump occurred after the stream came into contact with the sand bed. This caused the wave to hollow out the bed into an oval shaped pool. After this pool had been formed and the flow continued there was very little change in the shape of the bottom. Along the bottom there was noticed considerable backroll which tended to carry the sediment upstream instead of down. Only the larger particles were left in the pool the smaller ones having been carried down onto a bar directly below the jump. This showed that an artificial pool formed by placing a sill across the apron would probably solve the problem of locating the jump. This has been done on various dams and works very well. The position and size of the sill has to be designed very carefully to insure proper results. A description of the dentated sill is given in Freeman's Hydraulic Laboratory Practice on page 184. With the gravel used as a bed the jump was much more pronounced. This condition was very similar to rip rap or broken rock used below a spillway. The sand and gravel bed observation bears up the statement previously made that friction plays a large part in the position and stability of the jump and is a necessary part of its formation.

CONCLUSION

The results of the experiments run in this thesis were very satisfactory. A more accurate method of obtaining the quantities and measuring the depths is to be recommended.

The hydraulic jump may be used as a means for destroying the energy of the discharge of a spillway and thereby preventing stream bed erosion.

A rough surface below the spillway which will not produce vibration is to be recommended. This will prevent the usual wide variation in the jump under conditions of slight friction or a smooth apron.

The quantities measured are very small. A slight difference in the value of one measurement will cause a large variation in the calculations based upon these measurements.

The length of the jump is approximately 4 to 5 times the depth of the stream leaving the jump.

By dropping a colored fluid in the stream above the spillway, the diminishing velocity of the stream throughout the jump was observed and traced.

The model as now built and with a few minor corrections may be used for further interesting study of stream bed erosion, spillway discharge, and other hydraulic studies.

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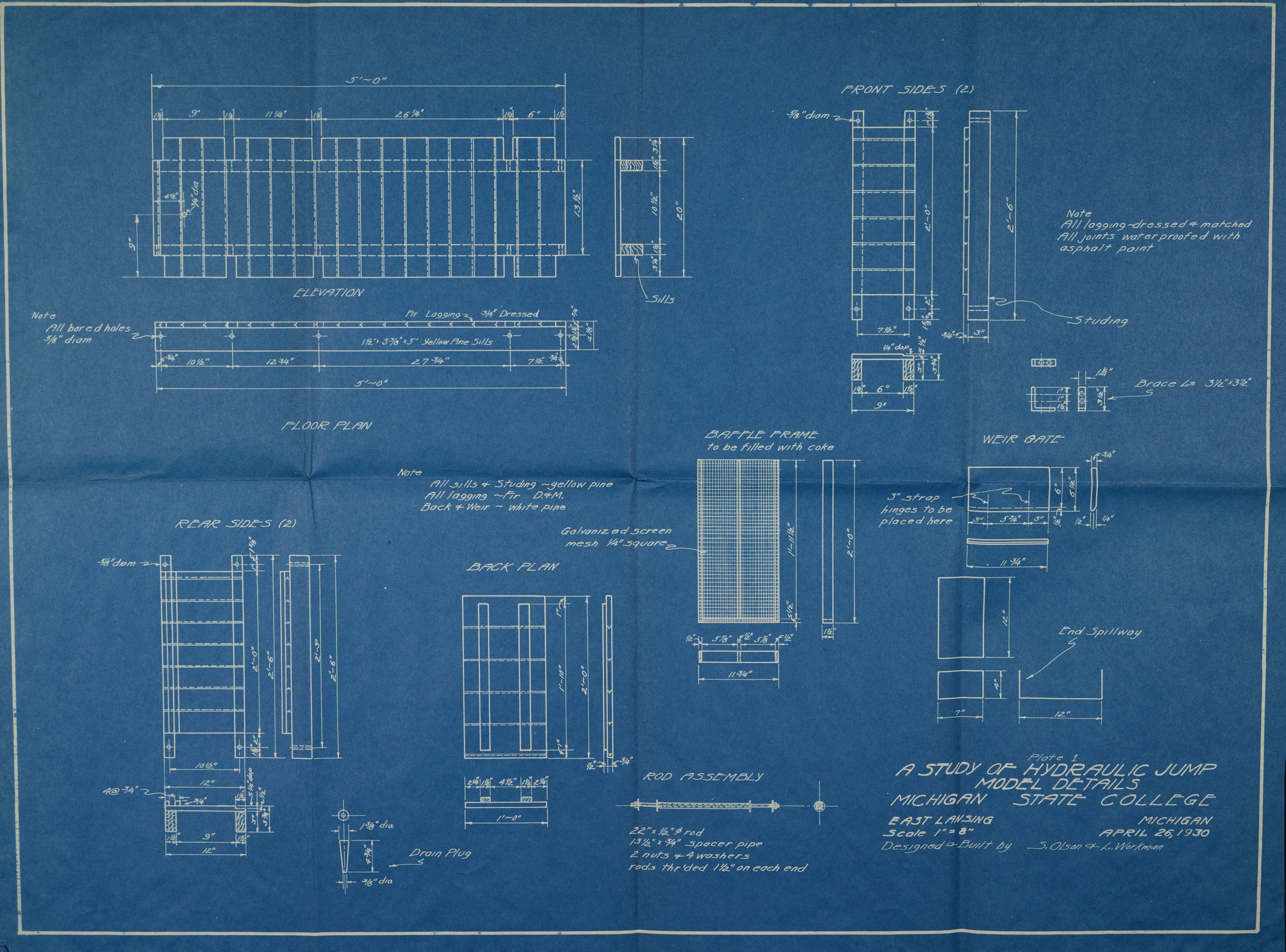
Pocket has:
3 Plans


ELEVATION
Sills
Note
All bored holes 5/8" diam
Fir Lagging 3/4" Dressed
1½" x 3⅝" x 5' Yellow Pine Sills
FLOOR PLAN
FRONT SIDES (2)
5/8" diam
Note
All lagging-dressed & matched
All joints waterproofed with asphalt paint
Studing
Brace Ls 3½" x 3½"
BAFFLE FRAME
to be filled with coke
Galvanized screen mesh ¼" square
WEIR GATE
3" strap hinges to be placed here
End Spillway
Note
All sills & Studing ~ yellow pine
All lagging ~ Fir D&M.
Back & Weir ~ white pine
REAR SIDES (2)
5/8" diam
BACK PLAN
ROD ASSEMBLY
22" x ½" φ rod
13½" x ¾" spacer pipe
2 nuts & 4 washers
rods thr'ded 1½" on each end
Drain Plug
Plate 1
A STUDY OF HYDRAULIC JUMP
MODEL DETAILS
MICHIGAN STATE COLLEGE
EAST LANSING
MICHIGAN
Scale 1" = 8"
APRIL 26, 1930
Designed & Built by S. Olsan & L. Workman

CONSTRUCTION
3/4" boards nailed together.
Finished with = 11 1/2"
Rubber gasket around outer
edge next to glass.
Surface waterproofed with paraffin

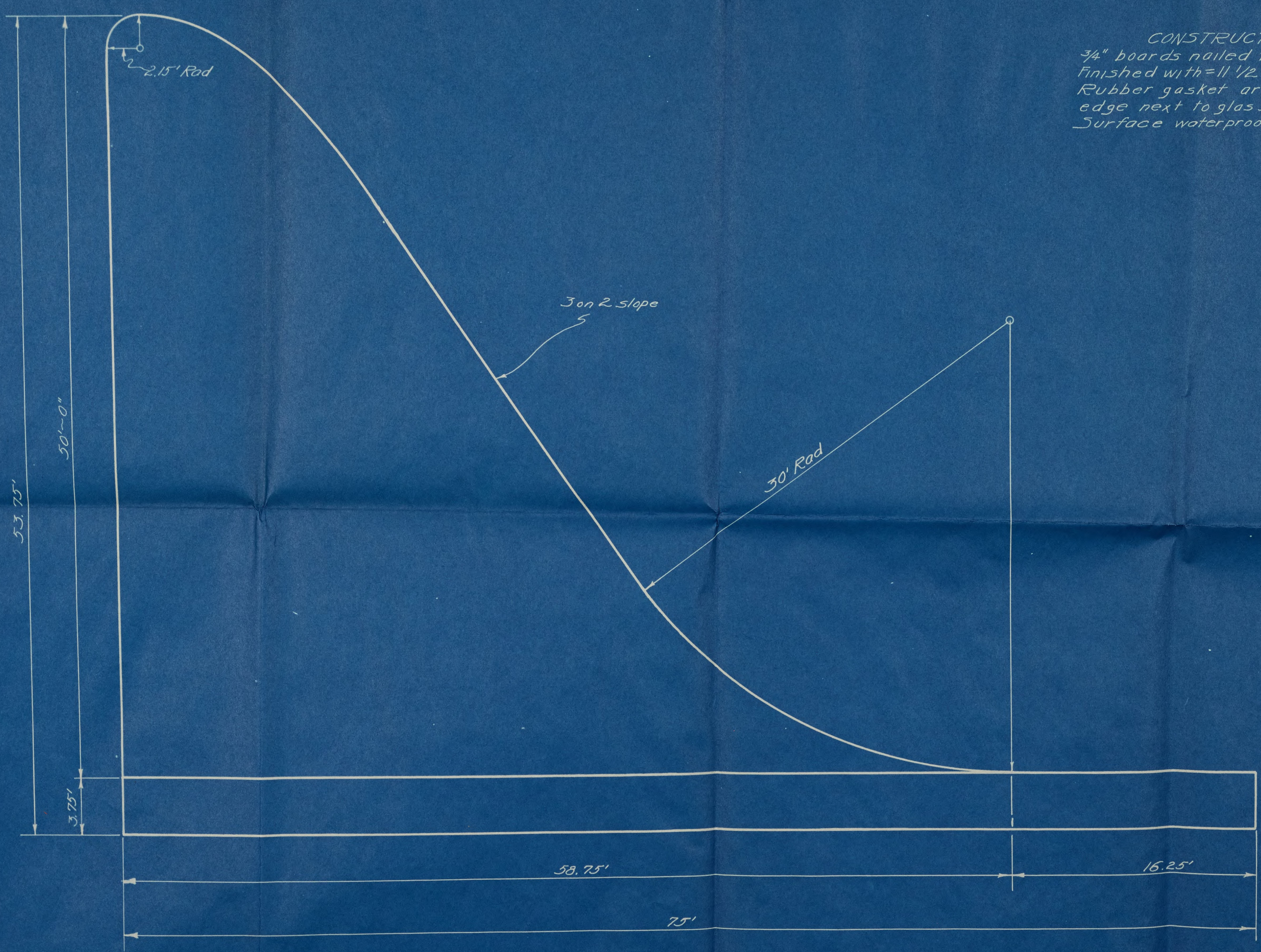
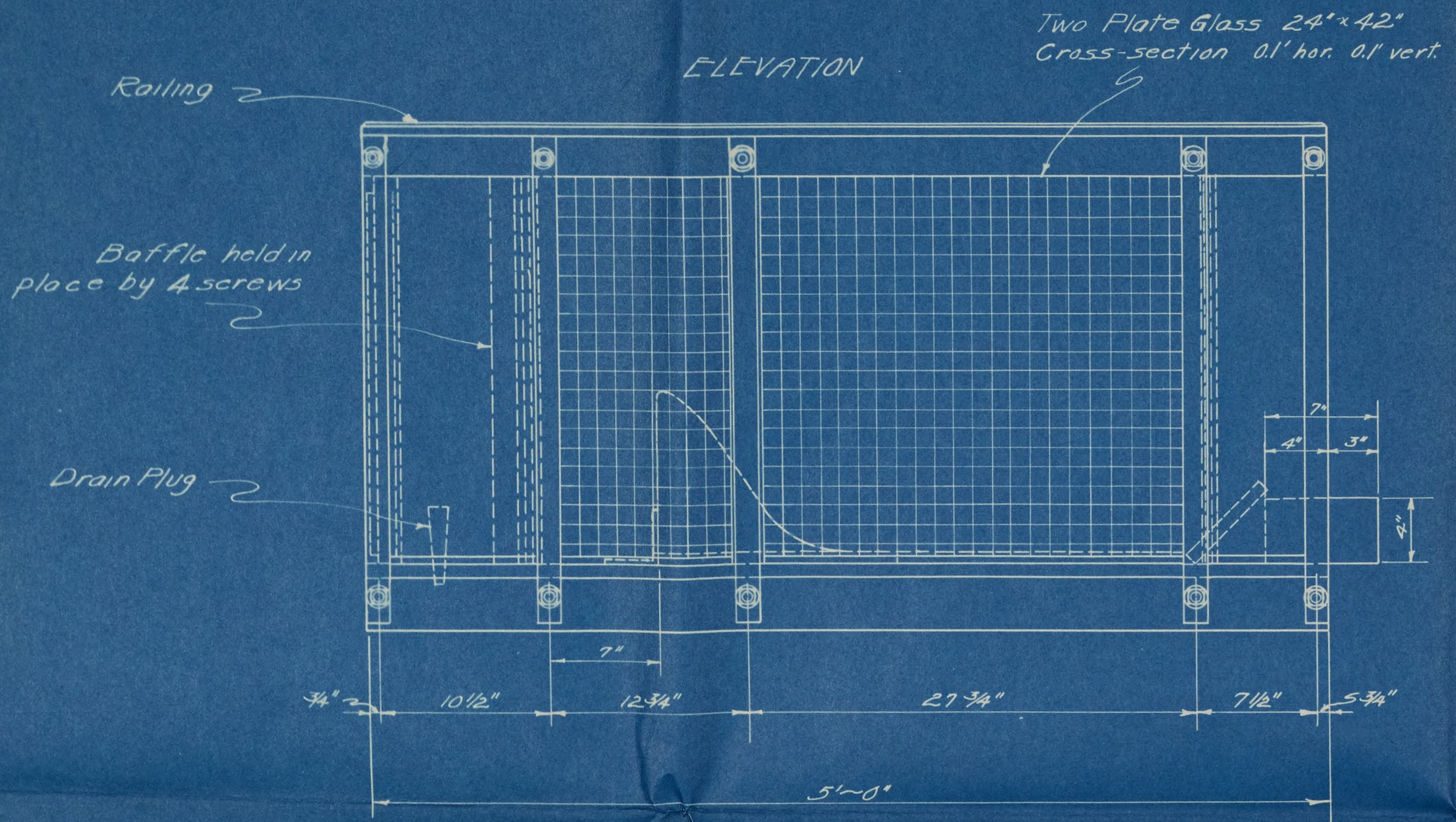


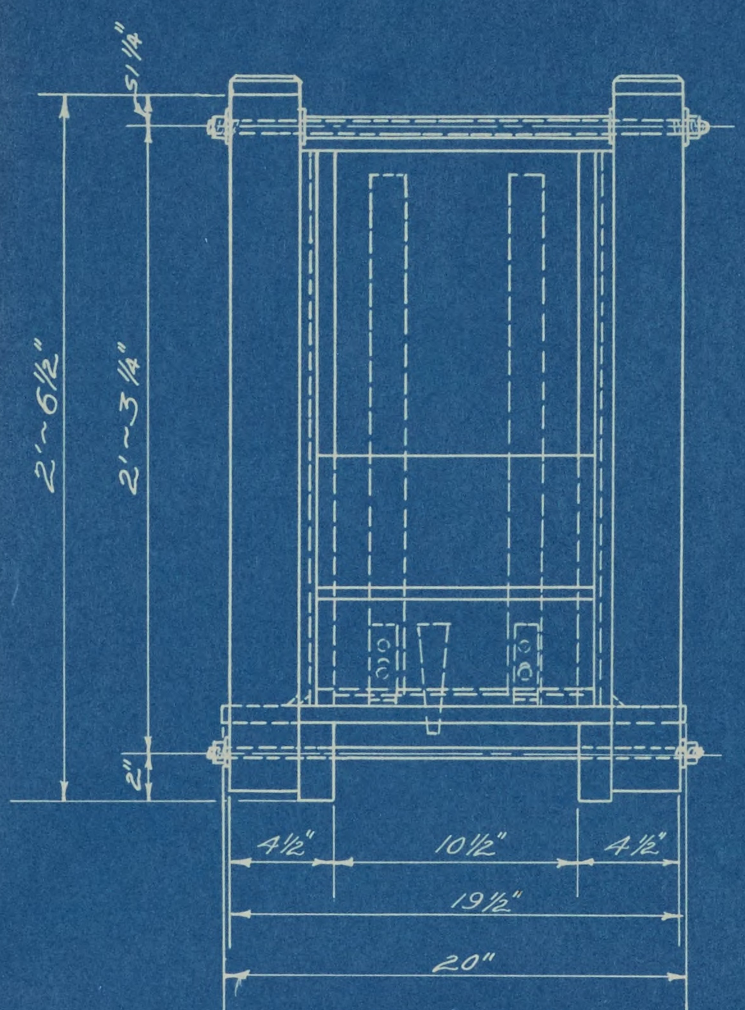
Plate 3

A STUDY OF HYDRAULIC JUMP
OGEE SPILLWAY
MICHIGAN STATE COLLEGE

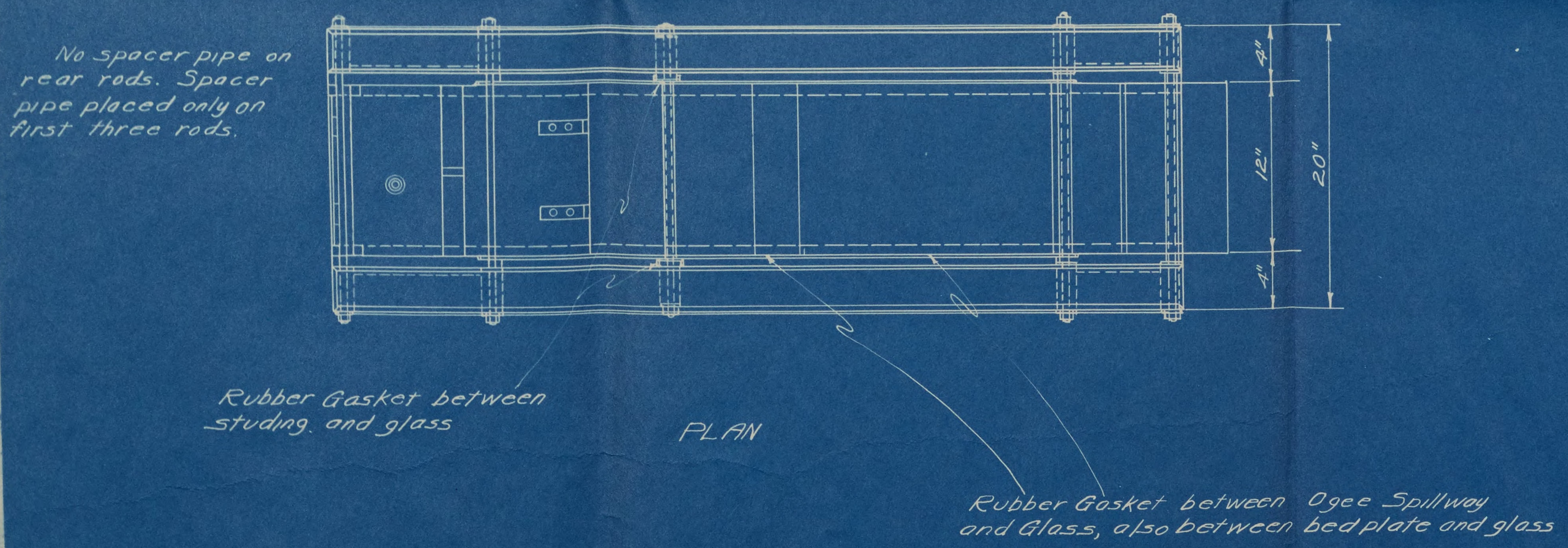
EAST LANSING MICHIGAN
Scale 1" = 5' MAY 9, 1930
Designed & Built S. Olson L. Workman



ELEVATION



END VIEW



PLAN

BILL OF MATERIAL			
Amount	Kind	Material	Size
10	Studs	Yellow Pine	1½" x 3" x 2'-6"
2	Front sides	Fir	(¾" x 4") 9" x 2'
2	Rear Sides	Fir	(¾" x 4") 12" x 2'
1	Floor	Fir	(¾" x 4") x 20" x 5'
2	Sills	Yellow Pine	3⅜" x 1½" x 5'
10	Rods	Wrought Iron	½" x 22"
26	Washers	Wrought Iron	1⅛" dia
20	Nuts	Wrought Iron	½"
1	Molding	White Pine	½" x ½" x 12'
1	Back	White Pine	(¾" x 6") x 12" x 2'
2	Back Strips	Yellow Pine	½" x 1½" x 1'-10"
4	Molding	White Pine	¾" x ¾" x 2'
3	Strips	Yellow Pine	½" x 1½" x 2'
1	Strip	Yellow Pine	½" x 1½" x 10¾"
1	Weir Board	White Pine	¾" x 6½" x 11⅞"
1	Spillway	Galvanized Tin	7" x 20"
1	Bed Plate	White Pine	¾" x 11¾" x 18"
1	Ogee Spillway	White Pine	10" x 11¾" x 12"
1	Bottom Plate	White Pine	¾" x 11¾" x 15"
2	Strap hinges	Wrought Iron	3"
2	Screens	Gal. Wire	12" x 24"
1	Drain Plug	White Pine	⅝" x 1⅜" x 4¾"
2	Ls	Struct. Steel	3½" x 3½" x 1¼"
1	Gasket	Rubber	1" x 3'
2	Railing	White Pine	¾" x 3" x 5'
3	Spacer Pipes	Iron	¾" x 13½"
2	Plate	Glass	24" x 42"
4	Strips	Gal. Metal	1" x 2'

Plate 2

A STUDY OF HYDRAULIC JUMP
MODEL ASSEMBLY

MICHIGAN STATE COLLEGE
EAST LANSING, MICHIGAN

Scale 1" = 8"

May 3, 1930

Designed & Built by S. Olson & L. Werkman