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Determination of Undernappe Over Sharp-Crested Circular Weir

By

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DETERMINATION OF THE UNDER NAPPE OVER A SHARP CRESTED WEIR, CIRCULAR IN PLAN WITH RADIAL APPROACH

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I N D E X

OBJECT OF THE INVESTIGATION

The purpose of this investigation was first, to determine the traces of the under nappe of water flowing over a sharp crested circular weir at increasing increments of head from as low a head as could be measured to the head corresponding to a flooded out condition; second, to determine the rating curve for the weir; and third, to consider the results as they may apply to morning glory spillway design.

HISTORY

Within the last twenty years the design of a number of dams having tunnel spillways with circular bellmouth inlets has required that some method be found to approximate the under nappe trace of water flowing over the bellmouth inlet so that a curve for the bellmouth may be determined which will keep the water in contact with the concrete surface.

To date this design has consisted essentially in assuming a circular weir, either vertical or sloping up stream, having a diameter sufficient to provide crest length for the required discharge. From the under nappe measurements on rectilinear weirs as determined by Bazin, the coordinates of the high point of the spillway crest are determined. The under nappe trace is then obtained by deriving from Bazin's traces an equation of the path of an assumed particle and computing the thickness of jet required to pass the flow at the available velocity.

For the assumed particle path Mr. Ford Kurtz in his design of the Pleasant Hill Dam for the Muskingum Conservancy District, chose the center line of Bazin's jet and determined the equation of this path by choosing three arbitrary points on this centerline and deriving a parabolic equation thru them.

In the Hydraulic Model Studies for the Keystone Dam by Professor George E. Barnes, the same procedure was followed except that the equation is derived for a particle path one-third the thickness of the jet from the under nappe, since the particle at this point

is stated by Bazin to have a mean velocity.

As far as actual discharge formulae for circular weirs are concerned, the only one available to the writer was Gourley's work as outlined in "Hydraulics" by F. C. Lea. Gourley's experiments were conducted with vertical metal pipes of different diameters faced off squarely on the end, thus making a weir of appreciable crest width. Experiments with this apparatus gave the following equation which was considered to be correct for head diameter ratios up to two-tenths:

$$Q = KLH^{n}$$

Where n = 1.42 and K = 2.97 for a weir 13.70 in. in diameter.

Coincident with the experiments by the writer similar experiments were conducted at the University of Iowa as student thesis work under the direction of Professor Lane. These test weirs consisted in circular sectors having radii of one, two and three feet. Under nappe trace data was not considered too reliable but the following discharge formulae were obtained:

$$Q = 3.28\ LH^{1.5}$$

for head diameter ratios from zero to two-tenths.

$$Q = 3.18\ LH^{1.5}$$

for head diameter ratios two-tenths to flood out.

Although neither of the above experiments were performed under conditions quite comparable to those of the writer, their resulting equations were used as standards of comparison in these tests.

DESCRIPTION OF APPARATUS

Path of Water. Water for this investigation was drawn from a 50,000 gallon reservoir beneath the floor of the laboratory by one of three centrifugal pumps and discharged into a constantlevel or orifice tank on the second floor. The constant level tank discharged thru a 12 x 7 inch venturi meter in a 12 in. line into an 8 in. line controlled by a valve at the end, and thence to a 3 x 3 ft. flume which discharged thru a 10 in. line joined by a 6 in. line from a weir box receiving the discharge from the orifice tank to two connected volumetric tanks on the first floor. After rising in both tanks to the level required for constant flow, discharge took place over the weir directly into the reservoir beneath the floor.

Flow Measuring Equipment. Flow for these tests was measured by venturi meter and orifice. The 12 x 7 in. venturi meter on the second floor is connected by copper pipe to a carbon tetrachloride U-tube manometer on the first floor. For very low flows a two-inch sharp edged circular orifice mounted in the side of a circular tank five feet in diameter and ten feet high was used.

Circular Weir Setup. The circular weir (plates 1 and 2) used for these tests consists in a ten-gallon cylindrical glass gasoline measuring bell of the short type from a Standard Oil Company gasoline pump. This glass cylinder is surmounted by a rolled copper ring one inch high beveled at an angle of 60 degrees on the inside face and machined to an outside diameter of 13 26/48 [13.54"] [1.128'] in. and an edge width of 1/64 inch. The foregoing assembly is mounted on a 12 in. steel pipe

which is in turn welded to the bottom of a volumetric tank concentric with the outlet valve at the bottom.

Aeration pipes consisting in four 4-inch steel pipes were mounted horizontally at the top of the 12-inch steel pipe just below the glass weir and extend radially on two diameters 90 degrees apart thru the sides of the volumetric tank.

Extremely important in the maintenance of smooth flow was a conical 16 mesh screen covering the entire approach area and mounted above the aeration pipes at the base of the glass weir.

Immediately above the feeder pipe from the first volumetric tank was placed an eight-inch sand and gravel bed supported on 1/4 in. mesh galvanized screen attached with staples to a 2 x 4 in. wood ring fastened at six points around the volumetric tank and attached in the same manner to a 2 x 2 in. wood ring surrounding the 12 in. steel pipe and supported on three 2 x 2 in. wood columns extending to the bottom of the tank.

For first runs, a vacuum manometer consisting in a water filled U-tube was mounted on the outside of the tank and connected by rubber and copper tubing to a fitting on the 12-inch pipe just beneath the glass weir. (See copper tube on Plate 2 inside left under nappe gage support angle.)

Under Nappe Gage. The under nappe gage (Plates 1, 3, 4) consists in a fixed horizontal bar mounted on 2 x 3 in. angles by a thumbscrew arrangement permitting adjustment in all planes. On the horizontal bar is mounted a rider geared to a rack on the under side of the bar carrying verniers to read the divisions on the horizontal and vertical bars. Mounted vertically on the rider and moving in guides adjusted by cap screws is a stream-lined bar of lens cross section which pierces the flow on one diameter and carries a steel ring nine inches in diameter in a horizontal plane axial with the cross section of the vertical bar. The motion of this bar is actuated by a fixed gear contacting a movable rack clamped to the vertical bar at any desired point. On the opposite diameter of the horizontal steel ring from the vertical bar is the pointer mechanism (Plates 1 and 4) consisting in a short brass rod slotted at the base to clamp on the horizontal ring and fitted with a hollow wrist pin and toggle spring assembly at the upper end which actuates a short rod carried by the wrist pin. On the end of the rod is a 1/4 in. brass spear which touches the under nappe. In order to cover the entire range of flows it was necessary to have three positions of the pointer which are maintained by positive stops as shown in the drawing.

<u>Gage for Joining of Under Nappes.</u> This gage is an ordinary point gage moving in a vertical plane over the center of the weir and moving horizontally on a rider sliding on a horizontal wood beam.

METHOD OF WORK

<u>Zeroing of Gages.</u> Before any data was recorded, the zero readings for the hook and under nappe gages were determined. In the case of the hook gage, zeroing consisted in projecting the horizontal plane of the weir to the hook gage by means of a straight wood board laid across the weir and touched by the hook gage. Contact with the point of the gage was determined by noting that a piece of thin paper just would or would not slide between the board and the point. To remove any error due to misalignment of the board the procedure was repeated with the board inverted and the results averaged.

The zero point for the under nappe gage was chosen as the nappe gage readings for each pointer position when the center of the sphere was in the plane of the weir crest at the outer edge of the weir and in the operating plane of the nappe gage on a diameter of the weir. Before these zero readings were determined, the gage assembly was placed in a vertical plane thru the center of the weir crest by means of plumb bobs. The vertical coordinates were then determined by touching a steel bar laid across the weir crest in the same manner as used for the hook gage. The horizontal coordinates were finally determined by placing the steel bar on the weir crest perpendicular to the operating plane of the nappe gage. (Plate 5) The bar was then touched by the sphere in the three positions and the horizontal reading of the nappe gage recorded. (Plate 6). The distance from the face of the bar to the edge of the weir was then measured with a make-shift dial gage micrometer which was zeroed on standard gage blocks. (Plate 7).

As a check, the entire above procedure was repeated at the end of the tests.

Interval of Under Nappe Traces. The interval of head for each under nappe trace as indicated by the hook gage was arbitrarily chosen as 0.01 foot beginning at the least head which the mechanics of the nappe gage permitted records to be taken and ending when the weir flooded out as indicated by the rising of the joining of the upper nappes to the weir crest.

Operation of Under Nappe Gage. Readings on the under nappe gage were made by noting the coordinates when the sphere, for a given pointer position, just did or did not touch the under water surface. Plate 8 shows this touch to be very definite. As the joining of the upper nappes rose the point of contact of the sphere with the under nappe was entirely obscured. Contact was then determined by looking thru the side of the weir with the aid of a small mirror held in the water at a distance sufficiently far removed to cause no interference with the flow.

Check of Data as Taken. To be sure that all under nappe data was substantially correct, readings at one pointer position were lapped with those in the next wherever possible and the locus of the center line of the spheres was then plotted for each run before the flow was changed.

Final Method of Plotting Data. The actual traces as recorded on plates differ from the above mentioned check traces by the radius

of the spherical brass pointer. At each point determined by coordinates to the center sphere a circular arc having the radius of the sphere was drawn with a compass. A smooth curve was then drawn thru the points of tangency to the arcs.

Flow Manometer Readings. For each increment of head for which an under nappe trace was made flow manometer readings were recorded. Subsequent attempts to plot a rating curve from this data resulted, however, in an illogical curve. After several attempts to correct this curve the data was abandoned and a separate rating curve was determined on the basis of a new calibration of the venturi meter.

Vacuum Manometer Readings. For the first run, the water flowing over the weir was allowed to fall directly into the reservoir. This created a venturi action as the falling jet passed the valve in the bottom of the tank and tended to remove the air from the under side of the jet in spite of the liberal aeration pipes. It was therefore considered advisable to record this negative head by the deflection of the above described water manometer. The resulting flow was, however, so unstable that an artificial pool was created in the 12-inch vertical pipe by closing the valve at the bottom of the tank until the pipe filled to a depth of about four feet. The vacuum manometer then failed to record any negative head and the readings were abandoned.

Maintenance of Steady and Smooth Flow. Theoretically, since all points of control on the flow line from the flume on the second floor are orifices, flow should have been very stable over slight changes in discharge from the constant level tank. Actually, however, the pipe from the flume did not discharge steadily but alternately discharged as an orifice, then filled to discharge as a siphon thus creating a very unsteady discharge at the higher flows. This condition was practically eliminated by maintaining a high head in the flume thus preventing the pipe from drawing air.

Previous to the placing of the above mentioned conical screen in the apparatus setup, discharge over the weir was marred by deep standing ridges. The screen removed these ridges fully; however, it was necessary to keep the screen clear of air bubbles which rose thru the sand at the bottom of the tank when flow was first started at the beginning of any set of runs previous to which the tanks had been drained.

Elevation of Joining of Upper Nappes. To determine the approximate joining elevation of the upper nappes, point gage readings were taken at several points on the joining surface with the lip of the weir as the zero point. Since this elevation was not looked upon to have any definite bearing on the results these readings were taken purely on the basis of the appearance of the joining surface.

Venturi Meter Calibration. As mentioned above, failure of the rating curve data taken in conjunction with the under nappe traces to plot necessitated recalibration of the venturi meter. The procedure for this calibration consisted in recording manometer deflections and actual flow as determined by volumetric tank readings. Nine points between a low readable deflection (0.006 ft.) and a deflection corresponding approximately to two second feet were used, four determinations being made for each point with the flow both increasing and decreasing

from point to point.

Rating Curve Runs. Following the venturi meter calibration it was considered advisable to repeat the rating curve data proceeding in the manner indicated above, since it was found that a logical curve could not be plotted from the former data on the basis of the new venturi meter calibration.

UNDER NAPPE DATA

Gage Zeroes

Hook gage at lip of weir = 1.3835 ft.

Under nappe gage at lip of weir

Pointer position	Coordinates Horizontal	Vertical
1	0.7245	1.412
2	0.899	1.4175
3	1.0445	1.4945

Trace Data

Hook gage = 1.4385 Head = 0.055 Head/Diam. = 0.049 Run No. 1

Reading number	Pointer position	Coordinates Horizontal	Vertical
1	1	0.6975	1.400
2	-	0.6735	1.380
3	-	0.6485	1.350
4	-	0.6195	1.300
5	-	0.596	1.250
6	-	0.5595	1.150
7	2	0.6855	1.000
8	-	0.6355	0.800
9	-	0.593	0.600
10	-	0.556	0.400
11	3	0.6525	0.200

Trace Data - continued

Hook gage = 1.448 Head = 0.0645 Head/Diam. = 0.0572 Run No. 2

Reading number	Pointer position	Coordinates Horizontal	Vertical
1	1	0.704	1.4045
2	-	0.694	1.400
3	-	0.6775	1.390
4	-	0.6665	1.380
5	-	0.648	1.360
6	-	0.633	1.340
7	-	0.620	1.370
8	-	0.608	1.300
9	-	0.583	1.250
10	-	0.562	1.200
11	-	0.543	1.150
12	2	0.7385	1.210
13	-	0.727	1.180
14	-	0.720	1.160
15	-	0.698	1.100
16	-	0.682	1.058
17	-	0.6525	0.950
18	-	0.6140	0.800
19	-	0.569	0.600
20	-	0.548	0.500
21	3	0.7295	0.790
22	-	0.709	0.650
23	-	0.680	0.500
24	-	0.6425	0.300
25	-	0.6125	0.110

Hook gage = 1.460 Head = 0.0765 Head/Diam. = 0.0679 Run No. 3

Reading number	Pointer position	Coordinates Horizontal	Vertical
1	1	0.703	1.406
2	-	0.685	1.400
3	-	0.658	1.380
4	-	0.6375	1.360
5	-	0.6230	1.340
6	-	0.5950	1.300
7	-	0.5685	1.250
8	-	0.545	1.200
9	2	0.225	1.220
10	-	0.699	1.150
11	-	0.681	1.100
12	-	0.6315	0.950
13	-	0.5885	0.800
14	3	0.733	0.875
15	-	0.690	0.700
16	-	0.649	0.500
17	-	0.613	0.300
18	-	0.592	0.110

Trace Data - continued

Hook gage = 1.470 Head = 0.0865 Head/Diam. = 0.0767 Run No. 4

Reading number	Pointer position	Coordinates Horizontal	Vertical
1	1	0.702	1.4075
2	-	0.682	1.400
3	-	0.6515	1.380
4	-	0.623	1.350
5	-	0.5855	1.300
6	-	0.557	1.250
7	2	0.731	1.250
8	-	0.684	1.150
9	-	0.631	1.000
10	-	0.569	0.800
11	3	0.722	0.900
12	-	0.671	0.700
13	-	0.629	0.500
14	-	0.603	0.300
15	-	0.600	0.110

Hook gage = 1.480 Head = 0.0965 Head/Diam. = 0.0856 Run No. 5

1	1	0.702	1.408
2	-	0.6755	1.400
3	-	0.6455	1.380
4	-	0.614	1.350
5	-	0.577	1.300
6	2	0.736	1.280
7	-	0.719	1.250
8	-	0.670	1.150
9	-	0.613	1.000
10	-	0.5515	0.800
11	3	0.705	0.900
12	-	0.656	0.700
13	-	0.619	0.500
14	-	0.610	0.300
15	-	0.606	0.110

Trace Data - continued

Hook gage = 1.490 Head = 0.1065 Head/Diam. = 0.0944 Run No. 6

Reading number	Pointer position	Coordinates Horizontal	Vertical
1	1	0.704	1.408
2	-	0.671	1.400
3	-	0.640	1.380
4	-	0.609	1.350
5	-	0.5705	1.300
6	2	0.737	1.290
7	-	0.7125	1.250
8	-	0.6625	1.150
9	-	0.603	1.000
10	-	0.539	0.800
11	3	0.692	0.900
12	-	0.643	0.700
13	-	0.623	0.500
14	-	0.617	0.300
15	-	0.615	0.140

Hook gage = 1.500 Head = 0.1165 Head/Diam. = 0.103 Run No. 7

1	1	0.7035	1.409
2	-	0.6685	1.400
3	-	0.6355	1.380
4	-	0.6035	1.350
5	-	0.5630	1.300
6	2	0.7210	1.280
7	-	0.703	1.250
8	-	0.6505	1.150
9	-	0.5905	1.000
10	-	0.542	0.850
11	3	0.6935	0.950
12	-	0.6405	0.700
13	-	0.6305	0.500
14	-	0.6265	0.300
15	-	0.6255	0.140

Trace Data - continued

Hook gage = 1.510 Head = 0.1265 Head/Diam. = 0.112 Run No. 8

Reading number	Pointer position	Coordinates Horizontal	Vertical
1	1	0.700	1.410
2	-	0.6625	1.400
3	-	0.631	1.380
4	-	0.5975	1.350
5	-	0.556	1.300
6	2	0.7285	1.300
7	-	0.696	1.250
8	-	0.6435	1.150
9	-	0.581	1.000
10	3	0.7345	1.100
11	-	0.671	0.900
12	-	0.645	0.700
13	-	0.6395	0.500
14	-	0.635	0.300
15	-	0.6325	0.140

Hook gage = 1.520 Head = 0.1365 Head/Diam. = 0.121 Run No. 9

1	1	0.698	1.411
2	-	0.6585	1.400
3	-	0.6255	1.380
4	-	0.593	1.350
5	-	0.550	1.300
6	2	0.723	1.300
7	-	0.689	1.250
8	-	0.6355	1.150
9	-	0.5735	1.000
10	3	0.726	1.100
11	-	0.671	0.900
12	-	0.6525	0.700
13	-	0.648	0.500
14	-	0.6435	0.300
15	-	0.640	0.140

Trace Data - continued

Hook gage = 1.530 Head = 0.1465 Head/Diam. = 0.130 Run No. 10

Reading number	Pointer position	Coordinates Horizontal	Vertical
1	1	0.697	1.412
2	-	0.656	1.400
3	-	0.623	1.380
4	-	0.588	1.350
5	-	0.595	1.300
6	2	0.717	1.300
7	-	0.6835	1.250
8	-	0.6275	1.150
9	-	0.5670	1.000
10	3	0.720	1.100
11	-	0.674	0.900
12	-	0.661	0.700
13	-	0.6555	0.500
14	-	0.6515	0.300
15	-	0.648	0.140

Hook gage = 1.540 Head = 0.1565 Head/Diam. = 0.139 Run No. 11

1	1	0.695	1.4125
2	-	0.651	1.400
3	-	0.618	1.380
4	-	0.584	1.350
5	-	0.5405	1.300
6	2	0.712	1.300
7	-	0.677	1.250
8	-	0.622	1.150
9	-	0.564	1.000
10	3	0.7165	1.100
11	-	0.6805	0.900
12	-	0.6685	0.700
13	-	0.6625	0.500
14	-	0.658	0.300
15	-	0.6545	0.140

Trace Data - continued

Hook gage = 1.550 Head = 0.1665 Head/Diam. = 0.148 Run No. 12

Reading number	Pointer position	Coordinates Horizontal	Coordinates Vertical
1	1	0.684	1.413
2	-	0.647	1.400
3	-	0.614	1.380
4	-	0.5795	1.350
5	2	0.706	1.300
6	-	0.673	1.250
7	-	0.6165	1.150
8	-	0.5655	1.000
9	3	0.716	1.100
10	-	0.657	0.900
11	-	0.675	0.700
12	-	0.6675	0.500
13	-	0.6625	0.300
14	-	0.6605	0.140

Hook gage = 1.560 Head = 0.1765 Head/Diam. = 0.1565 Run No. 13

Reading number	Pointer position	Coordinates Horizontal	Coordinates Vertical
1	1	0.6945	1.414
2	-	0.705	1.4125
3	-	0.677	1.4125
4	-	0.643	1.400
5	-	0.611	1.380
6	-	0.576	1.350
7	2	0.7045	1.300
8	-	0.670	1.250
9	-	0.6165	1.150
10	-	0.570	1.000
11	3	0.719	1.100
12	-	0.694	0.900
13	-	0.6825	0.700
14	-	0.676	0.500
15	-	0.671	0.300

Trace Data - continued

Hook gage = 1.570 Head = 0.1865 Head/Diam. = 0.165 Run No. 14

Reading number	Pointer position	Coordinates Horizontal	Coordinates Vertical
1	1	0.6865	1.415
2	-	0.703	1.413
3	-	0.675	1.413
4	-	0.639	1.400
5	-	0.6065	1.380
6	-	0.572	1.350
7	2	0.6965	1.300
8	-	0.6635	1.250
9	-	0.641	1.150
10	-	0.5745	1.000
11	3	0.7245	1.100
12	-	0.702	0.900
13	-	0.691	0.700
14	-	0.683	0.500
15	-	0.6785	0.300
16	-	0.676	0.140

Hook gage = 1.580 Head = 0.1965 Head/Diam. - 0.174 Run No. 15

Reading number	Pointer position	Coordinates Horizontal	Coordinates Vertical
1	1	0.687	1.416
2	-	0.7045	1.413
3	-	0.671	1.413
4	-	0.6360	1.400
5	-	0.604	1.380
6	-	0.569	1.350
7	2	0.6965	1.300
8	-	0.6635	1.250
9	-	0.615	1.150
10	-	0.560	1.000
11	3	0.720	1.100
12	-	0.708	0.900
13	-	0.697	0.700
14	-	0.689	0.500
15	-	0.682	0.300
16	-	0.6775	0.140

Trace Data - continued

Hook gage = 1.590 Head = 0.2065 Head/Diam. = 0.1835 Run No. 16

Reading number	Pointer position	Coordinates Horizontal	Vertical
1	1	0.685	1.416
2	-	0.705	1.413
3	-	0.668	1.413
4	-	0.633	1.400
5	-	0.601	1.380
6	-	0.565	1.350
7	2	0.6945	1.300
8	-	0.667	1.250
9	-	0.6175	1.150
10	-	0.5865	1.000
11	3	0.7355	1.100
12	-	0.715	0.900
13	-	0.705	0.700
14	-	0.696	0.500
15	-	0.6915	0.300
16	-	0.688	0.140

Hook gage = 1.600 Head = 0.2165 Head/Diam. = 0.192 Run No. 17

Reading number	Pointer position	Horizontal	Vertical
1	1	0.683	1.4165
2	-	0.703	1.414
3	-	0.667	1.414
4	-	0.630	1.400
5	-	0.5985	1.380
6	-	0.563	1.350
7	2	0.693	1.300
8	-	0.663	1.250
9	-	0.6215	1.150
10	-	0.593	1.000
11	3	0.734	1.050
12	-	0.7215	0.900
13	-	0.709	0.700
14	-	0.701	0.500
15	-	0.695	0.300
16	-	0.692	0.140

Trace Data - continued

Hook gage = 1.650 Head = 0.2665 Head/Diam. = 0.236 Run No. 18

Reading number	Pointer position	Coordinates Horizontal	Vertical
1	1	0.675	1.418
2	-	0.705	1.415
3	-	0.659	1.415
4	-	0.625	1.400
5	-	0.595	1.360
6	-	0.565	1.350
7	2	0.702	1.300
8	-	0.678	1.250
9	-	0.649	1.150
10	-	0.624	1.000
11	-	0.6035	0.800
12	-	0.591	0.600
13	-	0.582	0.400
14	-	0.5745	0.140

ELEVATION OF JOINING UPPER NAPPES

Point gage at lip of weir= 1.967

Run No.	Point gage readings: Center readings, Low point	Center readings, High point	Intersection of upper nappe with mushroom	Average elevation below crest
1	0.032			1.935
	Joining concave upward with fine spray of air bubbles in jet			
2	0.328			1.639
3	0.621			1.346
4	0.847			1.120
5	0.979			0.988
6	1.143			0.824
7	1.264			0.703
	Joining concave upward with fewer and larger bubbles			
8	1.363			0.604
	Joining almost flat with few bubbles			
9	1.465	1.565		0.452
	Further reduction in bubbles with more or less solid jet rising to convex surface at center			
10	1.558	1.681	1.614	0.349
11		1.762	1.701	0.235
	Concave surface gone with few bubbles entering jet			
12		1.780	1.726	0.214
13		1.865	1.796	0.136
14		1.921	1.858	0.077
	Standing convex mushroom with occasional bubble entering jet			
15		1.947	1.903	0.042
16		1.997	1.941	0.002
17		2.030	1.971	0.034
18		2.165	2.136	0.184

COMPUTATION OF GAGE ZEROES

Computation at beginning of Tests

Hook gage = 1.3835 ft, read directly

Under Nappe Gage Zeroes

Radius of contact sphere = 1/4 in. = 0.0104 ft

Pointer position	Coordinates: Horizontal	Coordinates: Vertical	Micrometer reading	Gage block length	Micrometer zero
1	0.5575	1.4015	0.108 in.	2 in.	2.000
	0.1566	0.0104			-0.229
	0.0104	1.4119			1.771
	0.7245				+0.108
					1.879 in = 0.1566 ft
2	0.732	1.4070	0.108 in.	2 in.	Same as above
	0.1566	0.0104			
	0.0104	1.4174			
	0.8990				
3	0.6955	1.484	0.090 in.	4 in.	4.000
	0.3385	0.0104			-0.031
	0.0104	1.4944			3.969
	1.0444				+0.090
					4.059 in = 0.3385 ft

Computation at End of Tests

Hook gage = 1.3835 ft, read directly

Under Nappe Gage Zeroes

Pointer position	Coordinates: Horizontal	Coordinates: Vertical	Micrometer reading	Gage block length	Micrometer zero
1	0.5395	1.402	0.122 in.	2 in.	2.000
	0.1738	0.0104			-0.037
	0.0104	1.4124			1.963
	0.7237				+0.122
					2.085 in = 0.1738 ft
2	0.5565	1.4065	0.023 in.	4 in.	4.000
	0.3323	0.0104			-0.034
	0.0104	1.4169			3.966
	0.8992				+0.023
					3.989 in = 0.3323 ft
3	0.6995	1.484	0.051 in.	4 in.	4.000
	0.3350	0.0104			-0.031
	0.0104	1.4944			3.969
	1.0449				+0.051
					4.020 in = 0.3350 ft

CALIBRATION OF VENTURI METER
(See Plate 9 for plot of variable coefficient)

No.	Volumetric tank Readings ft & in. Initial	Final	Difference ft & in.	ft	Actual flow cfs	Manom. dfl.	c
1	2 4.98	2 6.42	0 1.44	0.120	0.057	0.006	0.429
2	2 11.77	3 4.43	0 4.66	0.388	0.183	0.017	0.824
3	5 2.37	5 11.47	0 9.10	0.758	0.357	0.099	0.921
4	2 5.56	3 8.70	1 3.14	1.262	0.595	0.126	0.966
5	5 8.39	7 5.30	1 8.91	1.743	0.822	0.241	0.984
6	4 2.81	6 5.46	2 2.65	2.205	1.040	0.390	0.978
7	2 0.07	7 5.71	5 5.64	5.470	1.228	0.595	0.980
8	5 5.41	8 10.71	3 5.30	3.442	1.623	0.946	0.981
9	2 0.72	6 1.73	4 1.01	4.084	1.928	1.330	0.982
10	2 0.00	5 5.21	3 5.21	3.434	1.620	0.956	0.974
11	7 6.54	10 3.08	2 8.54	2.711	1.280	0.595	0.975
12	2 0.61	4 3.13	2 2.52	2.210	1.042	0.397	0.973
13	3 9.59	5 6.73	1 9.14	1.762	0.830	0.251	0.973
14	9 1.75	10 3.88	1 2.13	1.177	0.555	0.116	0.958
15	6 8.56	7 5.87	0 9.31	0.776	0.366	0.051	0.952
16	3 2.51	3 7.35	0 4.84	0.404	0.190	0.017	0.856
17	2 4.49	2 6.65	0 2.16	0.180	0.085	0.006	0.643
18	2 6.10	2 11.09	0 4.99	0.416	0.196	0.018	0.859
19	4 2.92	4 11.88	0 8.96	0.746	0.352	0.049	0.935
20	2 0.86	3 3.07	1 2.21	1.184	0.559	0.117	0.960
21	2 0.23	3 9.61	1 9.38	1.782	0.840	0.258	0.971
22	4 3.52	6 6.07	2 2.55	2.212	1.043	0.390	0.983
23	7 6.03	10 2.88	2 8.85	2.738	1.291	0.603	0.976
24	5 6.73	8 11.81	3 5.08	3.424	1.618	0.957	0.972
25	2 1.52	6 1.95	4 0.43	4.036	1.908	1.313	0.979
26	6 4.04	10 4.87	4 0.83	4.069	1.922	1.328	0.979
27	5 6.48	8 11.30	3 4.82	3.401	1.606	0.928	0.979
28	2 0.82	4 8.83	2 8.01	2.667	1.257	0.573	0.974
29	4 2.32	6 4.23	2 1.91	2.159	1.018	0.376	0.975
30	5 6.35	7 3.22	1 8.87	1.740	0.820	0.249	0.966
31	8 2.35	9 4.87	1 2.52	1.210	0.570	0.123	0.956
32	4 5.10	5 2.53	0 9.43	0.786	0.370	0.051	0.961
33	2 11.40	3 4.67	0 5.27	0.440	0.208	0.020	0.863
34	2 0.36	2 2.81	0 2.45	0.204	0.096	0.006	0.721

The value of c in the above computation is the variable coefficient of discharge for any given meter depending on the rate of flow when discharge is expressed by the following formula:

CALIBRATION OF VENTURI METER continued

$$Q = cK_2^{\,2}((s - 1)D)^{1/2}$$

Where Q = Flow in cfs
c = Variable coefficient

$$K = \pi/4 \sqrt{\frac{2g}{1 - (d_2/d_1)^4}}$$

d_1 = Diam. of pipe
d_2 = Diam. at throat
s = Sg of manom. fluid
D = Defl. of manom. in ft

For the meter used in these tests:

K = 6.68 d_1 = 12 in. d_2 = 6.915 in. s = 1.588

Then

$$Q = c\ 6.68 \times 0.576^2 \times 0.588^{1/2} D^{1/2}$$

$$= c\ 1.706\ D^{1/2}$$

$$c = Q/1.706\ D^{1/2}$$

VENTURI METER PORTION OF RATING CURVE

Hook gage zero = 1.3835 ft

Run No.	Hook gage	Head	Manom. dfl.	c	Q cfs
1	1.440	0.0565	0.012	1.370	0.150
2	1.449	0.0655	0.018	1.460	0.196
3	1,458	0.0745	0.025	1.522	0.241
4	1.475	0.0915	0.642	1.605	0.329
5	1.489	0.1055	0.063	1.622	0.407
6	1.501	0.1175	0.085	1.629	0.475
7	1.514	0.1305	0.115	1.638	0.555
8	1.527	0.1435	0.149	1.640	0.633
9	1.530	0.1465	0.158	1.644	0.654
10	1.5385	0.155	0.187	1.648	0.712
11	1.541	0.1575	0.190	1.651	0.718
12	1.5475	0.164	0.218	1.655	0.774
13	1.5615	0.178	0.274	1.658	0.867
14	1.571	0.1875	0.320	1.622	0.940
15	1.5825	0.199	0.376	1.665	1.020
16	1.594	0.2105	0.443	1.667	1.108
17	1.605	0.2215	0.508	1.669	1.187
18	1.615	0.2315	0.576	1.670	1.263
19	1.625	0.2415	0.650	1.670	1.341
20	1.635	0.2515	0.719	1.670	1.411
21	1.645	0.2615	0.804	1.670	1.491
22	1.6545	0.271	0.888	1.670	1.570
23	1.665	0.2815	0.982	1.670	1.650
24	1.687	0.3035	1.184	1.670	1.810
25	1.707	0.3235	1.356	1.670	1.937
26	1.731	0.3475	1.575	1.670	2.087

There is Calibration of weir Data.

ORIFICE PORTION OF RATING CURVE

Hook gage on weir = 1.3835 Zero reading on orifice tank 3' 0.10"

Run No.	Hook gage	Head	Head gage ft & in	Head on orifice actual head ft	Q cfs
1	1.450	0.0665	9 8.50	6.70	0.198
2	1.4445	0.061	8 2.26	5.18	0.174
3	1.4405	0.057	6 11.98	3.99	0.153
4	1.434	0.050	5 6.94	2.57	0.123
5	1.4295	0.046	5 0.46	2.03	0.109
6	1.425	.0415 0.415	4 7.24	1.60	0.097
7	1.423	.0395 0.395	4 4.36	1.35	0.089
8	1.419	.0355 0.355	4 0.25	1.01	0.077

Note:- On Run No. 8 under nappe failed to break clear all the way around the weir.

To avoid confusion of points, only Runs Nos. 2 and 8 were enclosed with circles on rating curve plot.

Determination of K for orifice.

Run No.	Head on weir	Q by venturi meter	Head on orifice H_o	$H_o^{1/2}$	$K = Q/H_o^{1/2}$
1	0.0665	0.198	6.70	2.59	0.765
2	0.061	0.174	5.18	2.275	0.765
3	0.057	0.153	3.99	1.999	0.765

Further subdivision of K obtains the following:

$Q = CA\ 8.02\ H^{1/2}$

$C = Q/A\ 8.02\ H^{1/2}$

Where Q = Discharge in cfs
C = Orifice coefficient
A = Area of orifice in sq ft
H = Head on center of orifice

For the 2 in. orifice used A = 0.0218 sq ft

Then substituting in any of the above runs:

$C = 0.198/0.0218 \times 8.02 \times 2.59 = 0.427$

MATHEMATICAL FORM OF RATING CURVE

To determine the mathematical form of the rating curve log-rithims of the head and corresponding flow taken from the rating curve were plotted on graph paper (Plate 10). If a curve of the form $Q = KLH^n$ is assumed, the slope of the average line thru the points is the value of n, while the intersection of this line with the Q axis is the value of log K + log L.

Now from the upper portion of the graphical solution:

$$n = 1.412$$

$\log K + \log L = 0.996$ Circumference of weir = 3.545 ft

$$\log L = 0.550$$

$$\log K = 0.446$$

$$K = 2.79$$

Then

$$Q = 2.79\ LH^{1.412}$$

from the lower portion of the graphical solution it is evident that the values of n and K are different from the upper portion. The value of n = 1.57, as shown on Plate 10, is, however, illogical, since in the case of a straight weir n = 1.5 is the highest obtainable value. The equation for the lower portion of the rating curve was determined by assuming the maximum value of n (1.5) and computing the value of K to give the rated discharge under a head of 0.14 ft (H/D = 0.1241) which value is shown by the graphical solution to closely approximate the point of mathematical change in form of the rating curve.

$$Q = KLH^{1.5}$$

$$K = \frac{Q}{LH^{1.5}}$$

MATHEMATICAL FORM OF RATING CURVE continued

Substituting Q = 0.615 $H^{1.5} = 0.0524$ and L = 3.545

$$K = 3.31$$

Then

$$Q = 3.31\ LH^{1.5}$$

Point number	H	Q	Log H	Log Q
1	0.04	0.091	-1.398	-1.041
2	0.06	0.167	-1.222	-0.777
3	0.08	0.267	-1.097	-0.573
4	0.10	0.375	-1.000	-0.426
5	0.12	0.491	-0.921	-0.309
6	0.14	0.615	-0.854	-0.211
7	0.16	0.744	-0.796	-0.128
8	0.18	0.889	-0.745	-0.054
9	0.20	1.026	-0.699	- 0.011
10	0.22	1.178	-0.658	0.071
11	0.24	1.328	-0.620	0.123
12	0.26	1.482	-0.585	0.171
13	0.28	1.639	-0.553	0.215

COMPARISON OF RATING CURVE FORMULAE

	(1)	(1)	(1)	(2)	(2)	(5)	(3)	(5)	(4)	(4)	(5)
No.	Head	Head Diam.	Q actual	$3.31LH^{1.5}$	$2.79LH^{1.412}$	Percent error	$2.97LH^{1.42}$	Percent error	$3.28LH^{1.5}$	$3.18LH^{1.5}$	Percent error
1	0.04	0.0354	0.091	0.094		+3.3	0.109	+19.8	0.093		+2.1
2	0.06	0.0532	0.167	0.173		+3.6	0.200	+19.7	0.171		+2.4
3	0.08	0.0708	0.267	0.266		-0.4	0.292	+-9.4	0.263		-1.5
4	0.10	0.0886	0.375	0.371		-1.1	0.400	+ 6.7	0.368		-1.9
5	0.12	0.1063	0.491	0.489		-0.4	0.520	+ 5.7	0.484		-1.4
6	0.14	0.1241	0.615	0.615	0.615	0.0	0.644	+ 4.7	0.609		-1.0
7	0.16	0.1418	0.744		0.744	0.0	0.780	+ 4.8	0.744		0.0
8	0.18	0.1595	0.884		0.882	-0.2	0.922	+ 4.3	0.889		+0.6
9	0.20	0.1773	1.026		1.029	-0.3	1.068	+ 4.1	1.040		+1.4
10	0.22	0.1915	1.178		1.178	0.0	1.222 (6)	+ 3.7	1.200		+1.2
11	0.24	0.2125	1.328		1.325	-0.2	1.387	+ 4.4		1.327	-0.1
12	0.26	0.2305	1.482		1.480	-0.1	1.554	+ 4.9		1.495	+0.9
13	0.28	0.2480	1.639		1.641	-0.1	1.726	+ 5.3		1.672	+2.0

(1) The figures in these columns were obtained from coordinates read directly from the rating curve as determined in these tests (Plate 11).

(2) Formulae for rating curve derived from these tests.

(3) Formulae for rating curve as determined by Gourley.

(4) Formulae for rating curves as determined by the University of Iowa.

(5) Percent error refers to rating curve as determined in this investigation.

(6) Formula not supposed to be reliable beyond this point.

DISCUSSION

Accuracy of Measurements. Since this investigation was essentially new and original and there was no definite procedure established for acquiring the contemplated results it is necessary to show that the measurements taken have a sufficiently accurate basis to be used in further investigations.

In view of the accurate calibration of the venturi meter and the use of the so determined coefficient to determine the discharge at all rates of flow, the venturi meter determined portion of the rating curve should be accurate within the least reading of the manometer, which is two percent for the lowest deflection used and less than three-tenths percent for the highest deflection.

For the computation of the orifice coefficient c, an extreme-low value of c (c = 0.437) was obtained. No explanation of this value is offered except that it gave results consistent with the venturi determined portion of the rating curve.

Head determinations with the apparatus described above were probably accurate within the least division of the hook gage (0.001 ft.) although by careful manipulation the gage could be read accurately to 0.00025 feet. Slight periodic variations in head, however, made necessary averaging of hook gage readings for a mean value. In no case was data recorded with hook gage readings varying more than 0.001 feet.

The mechanism of the under nappe gage made possible measurements within 0.0005 feet. This value was considerably less than the stability of the water surface warranted, since the slight variation in head gave alternate contact and free periods between the sphere and the water surface.

The interference of the under nappe gage vertical motion (Plate 3) was negligible since the ridges created did not extend more than 180 degrees around the nappe at any flow.

Contact of the spherical pointer with the under nappe (Plate 8) was very definite for the positions which could be observed directly from above. When the mirror was used the ridges were viewed from the side and appeared as streaks of light which were as readily discernible as in the case of the directly viewed contact.

Discrepancies in Data. Referring to the under nappe traces (Plates 12 and 13) discrepancies in the data were noted as indicated by the discontinuous increments of increase or decrease in departure of the traces from the zero coordinates. As mentioned above, these discrepancies were seen to exist at the time the data was taken, but repetition of the data failed to produce traces differing from those plotted by more than 0.001 feet. In the opinion of the writer these discrepancies may be attributed to slight changes in crest conditions for different flows and failure to attain equal increments of head by less than observable hook gage readings.

Discontinuity of Nappe Plot at Crest of Weir. Plate 13 shows a discontinuity in the under nappe traces between the weir crest and the beginning of the traces. The point closest to the

crest represents the last point which could be read with the sphere without interference with the lip of the weir. Traces Numbers 1 and 18 were arbitrarily extended to the weir crest for the sake of appearance, and do not represent actual traces beyond adjacent points on the trace. immediately following.

Velocity of Approach. In all computations the velocity of approach created by vertical flow thru the test tank was disregarded, since the corresponding velocity head amounted to but 0.0006 feet at the highest rate of discharge used.

It was also logical to assume that the size of the test tank was sufficient to cause no appreciable interference with the drawdown curve to the weir, since it was noted that particles on the surface of the water close to the test tank required fifteen minutes to reach a zone of rapid acceleration toward the weir.

Comparison of Under Nappe Traces. To show the degree of consistency between the under nappe traces as determined by these experiments and the computed traces used in the design of morning glory spillways at the present time, the traces on Plate 14 were drawn by scaling coordinates from Plates 12 and 13, and from the drawing of the computed under nappe trace corresponding to a vertical weir in the Hydraulic Model Studies for the Keystone Dam. The head diameter ratio for the Keystone Dam was found to agree closely with that for run 16 of these tests, so that no interpolation between traces was attempted.

CONCLUSIONS

Under Nappe Traces. The under nappe traces as determined in these experiments are sufficiently accurate to serve as a basis for further investigation.

In the case of circular weirs the departure of the under nappe from the face of the weir is not a progressive function of the head as in the case of rectilinear weirs.

The portion of the under nappe trace close to the weir crest should be investigated further to check against Bazin's curves for rectilinear weirs.

Rating Curve. The equation of the rating curve as determined by these tests disagrees sufficiently with the equations resulting from the investigations of Gourley and the University of Iowa to merit further tests on weirs of varying diameter and sharpness of crest.

The rating curve for circular weirs consists in three parts if expressed by an equation of the form $Q = KLH^n$. The first part varies in both K and n and extends to a head diameter ratio of about 0.125 for this investigation. The second part is constant in K and n, the value of n being less than three halves. The third part consists in a portion of reversal in which n becomes less than unity. This point occurs above the point of apparent flood out as indicated by the rising of the joining of the upper nappes. This third portion

of the curve is of no value in spillway design and may be neglected, since pipe friction would then be in control.

Application of this Investigation to Morning Glory Spillway Design. In the design of morning glory spillways for the proper curvature to keep the water against the concrete face the trace for discharge at maximum head should not be used and expected to satisfy conditions at lower heads without producing negative pressure. ??

Rating curve formulae for rectilinear weirs should not be used to determine crest length requirements for circular spillway design.

Under nappe traces for circular weirs computed on the basis of similar traces for rectilinear weirs are radically dissimilar to actual traces for head diameter ratios of the order of two tenths, and are therefore wholly inaccurate when used to design spillways of the morning glory type.

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P L A T E S

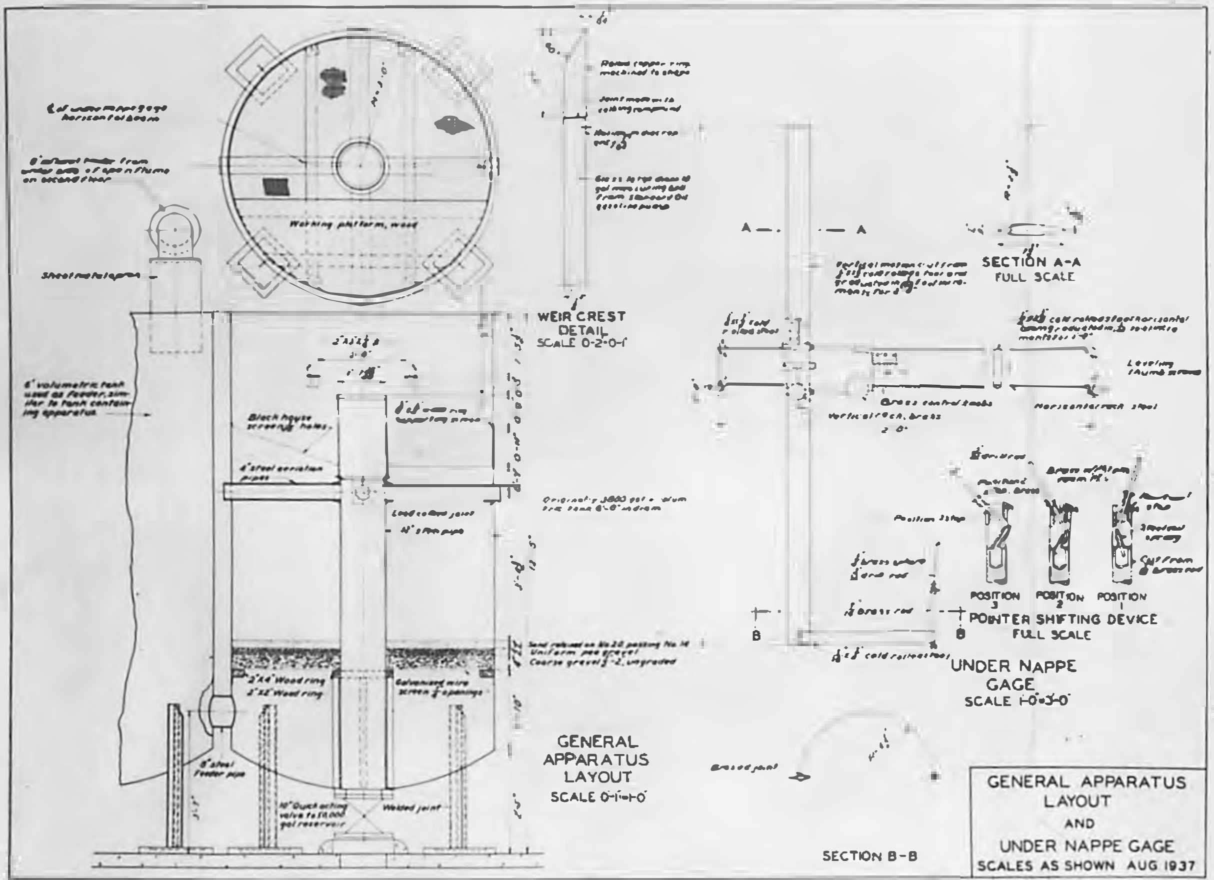
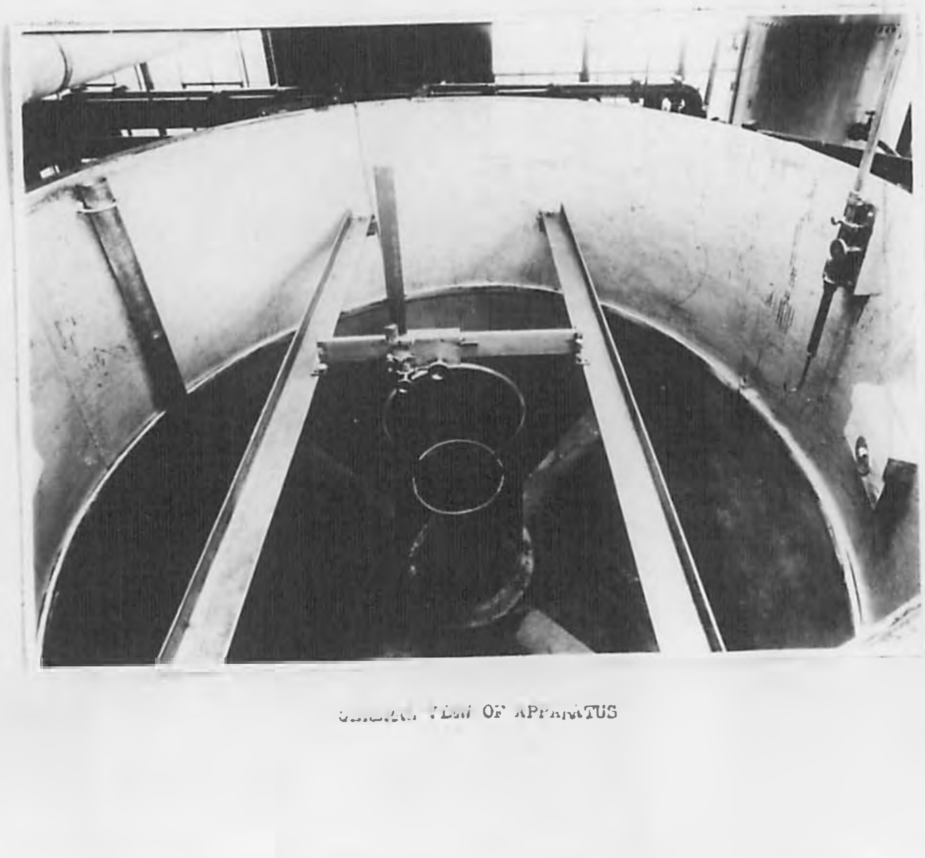
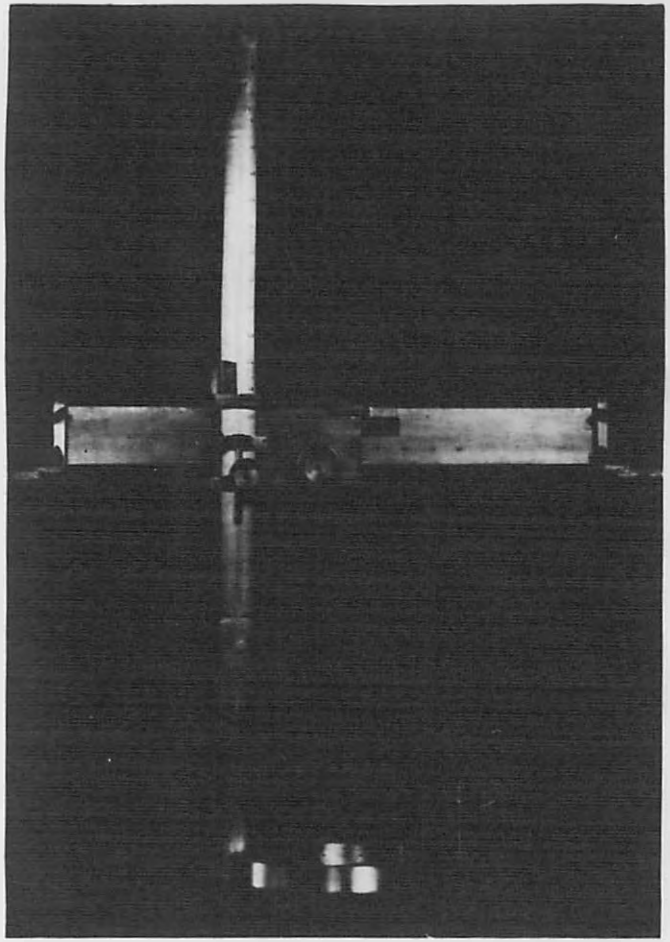


PLATE 1



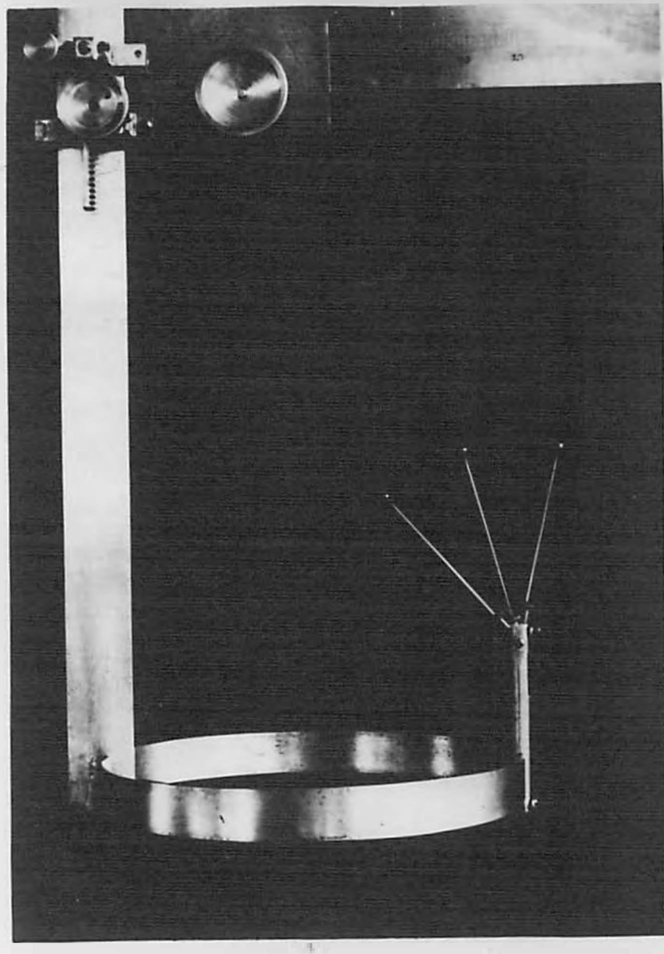
GENERAL VIEW OF APPARATUS

PLATE 2



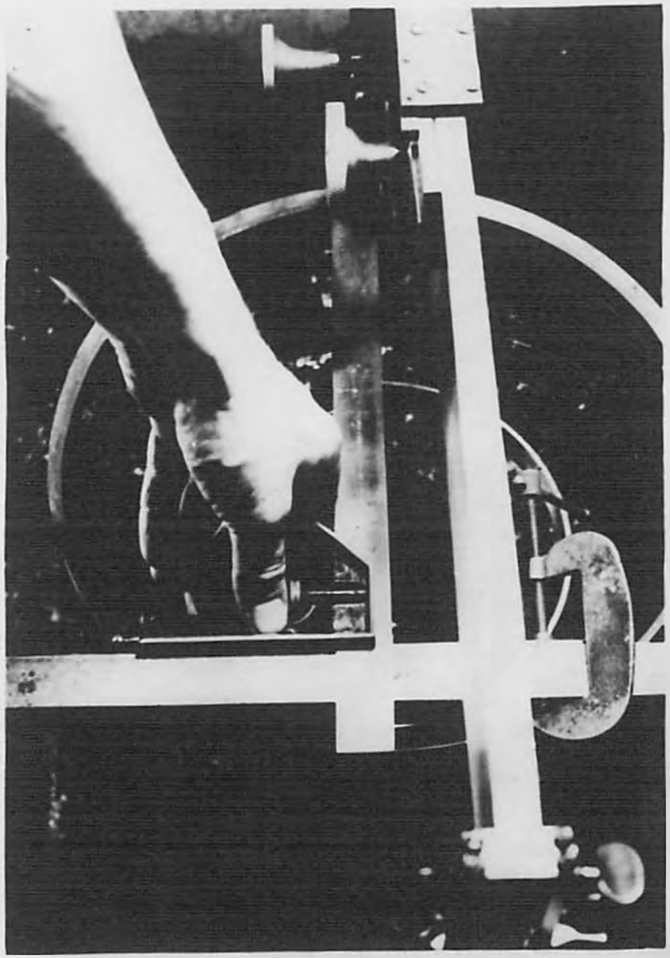
UNDER NAPPE GAGE COMPLETE

PLATE 3



POINTER POSITIONS OF UNDER NAPPE GAGE

PLATE 4

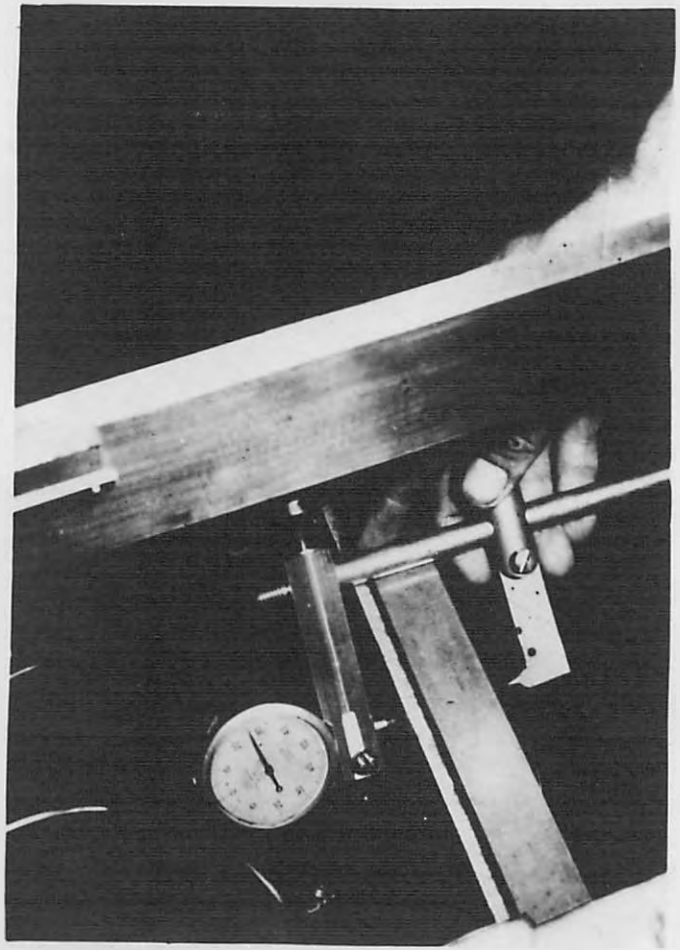


ZEROING UNDER NAPPE GAGE

PLATE 5

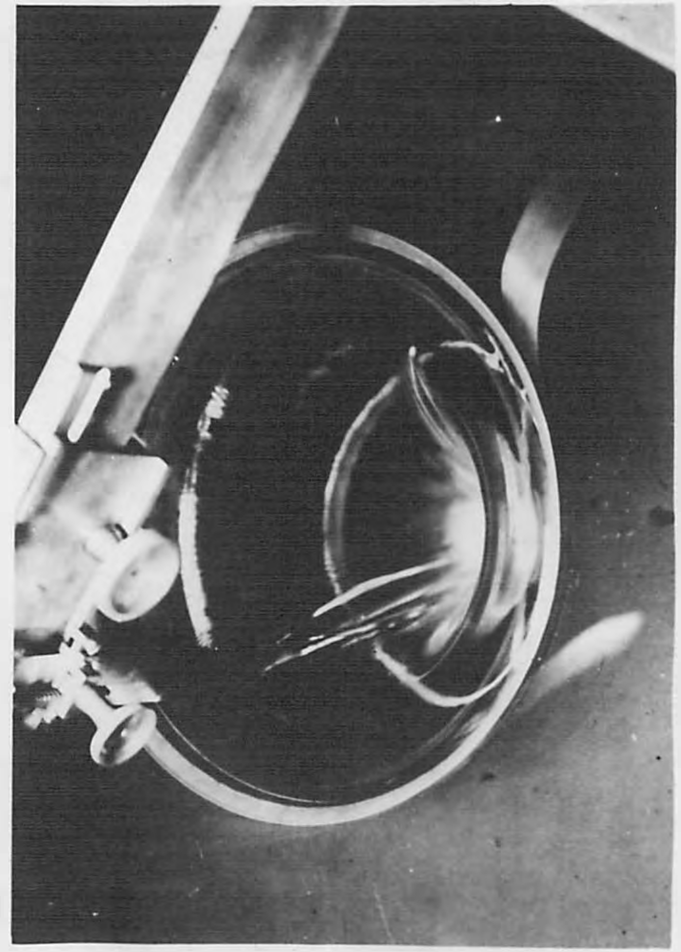
ZEROING UNDER NAPPE GAGE

PLATE 6



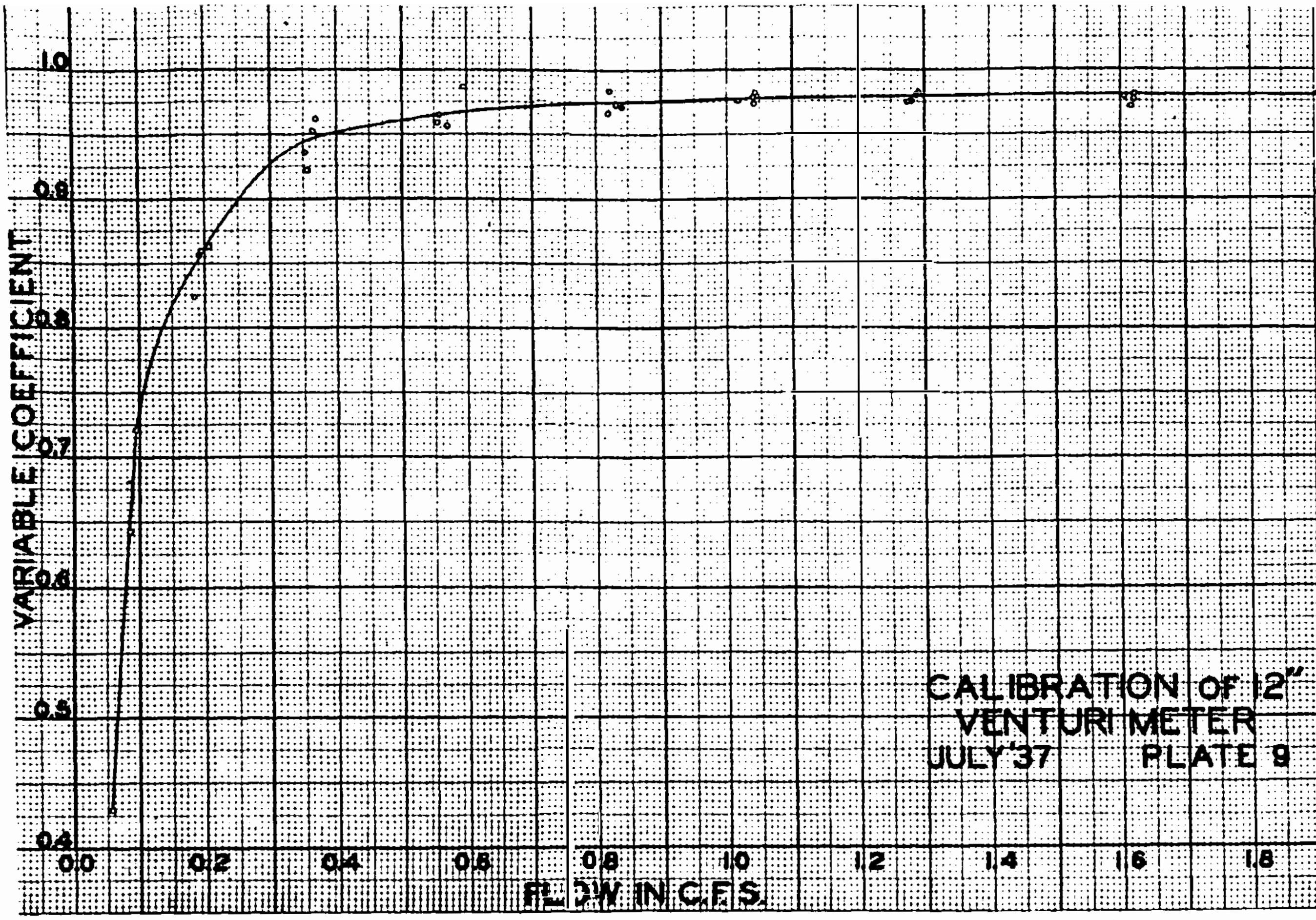
ZEROING UNDER NAPPE GAGE

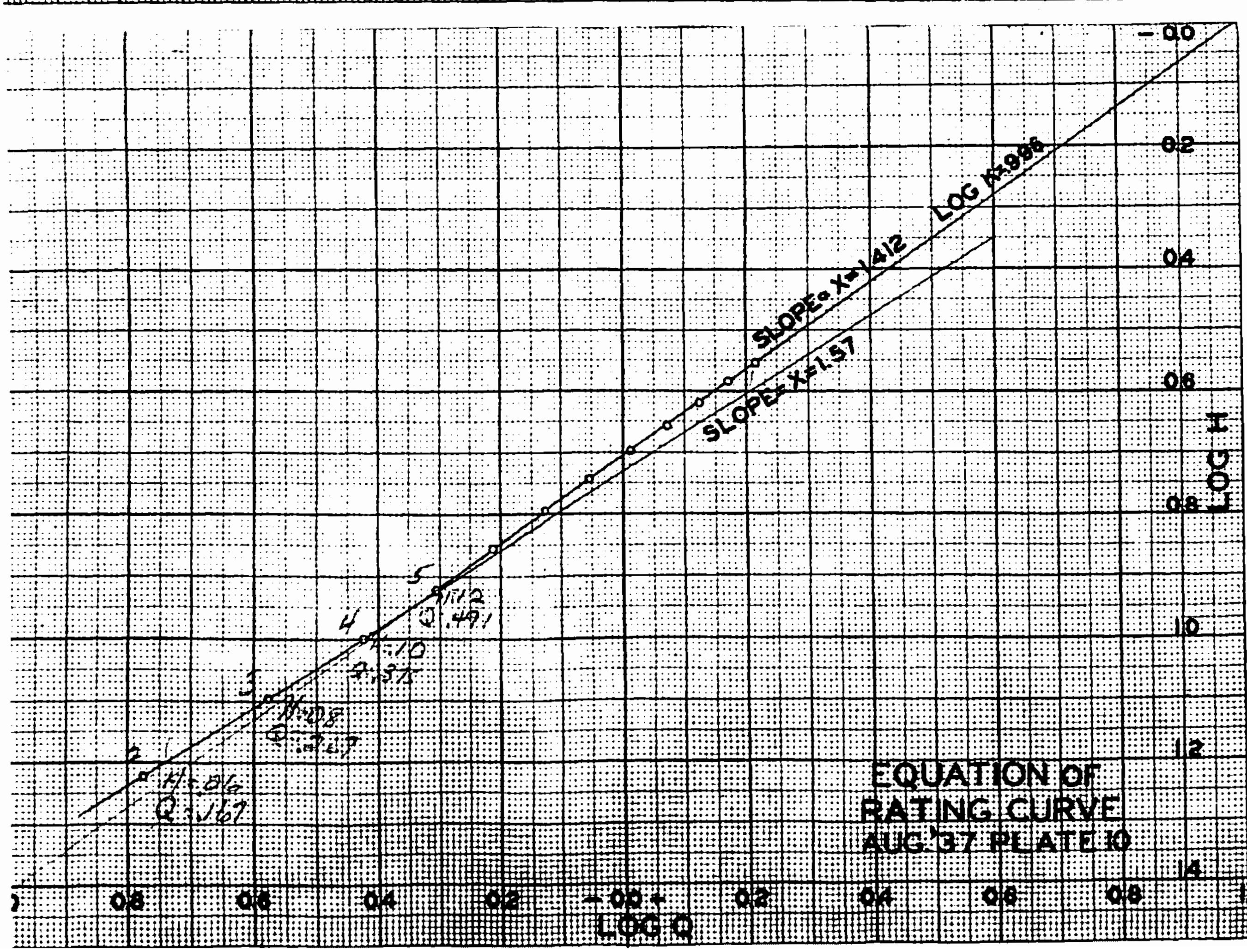
PLATE 7

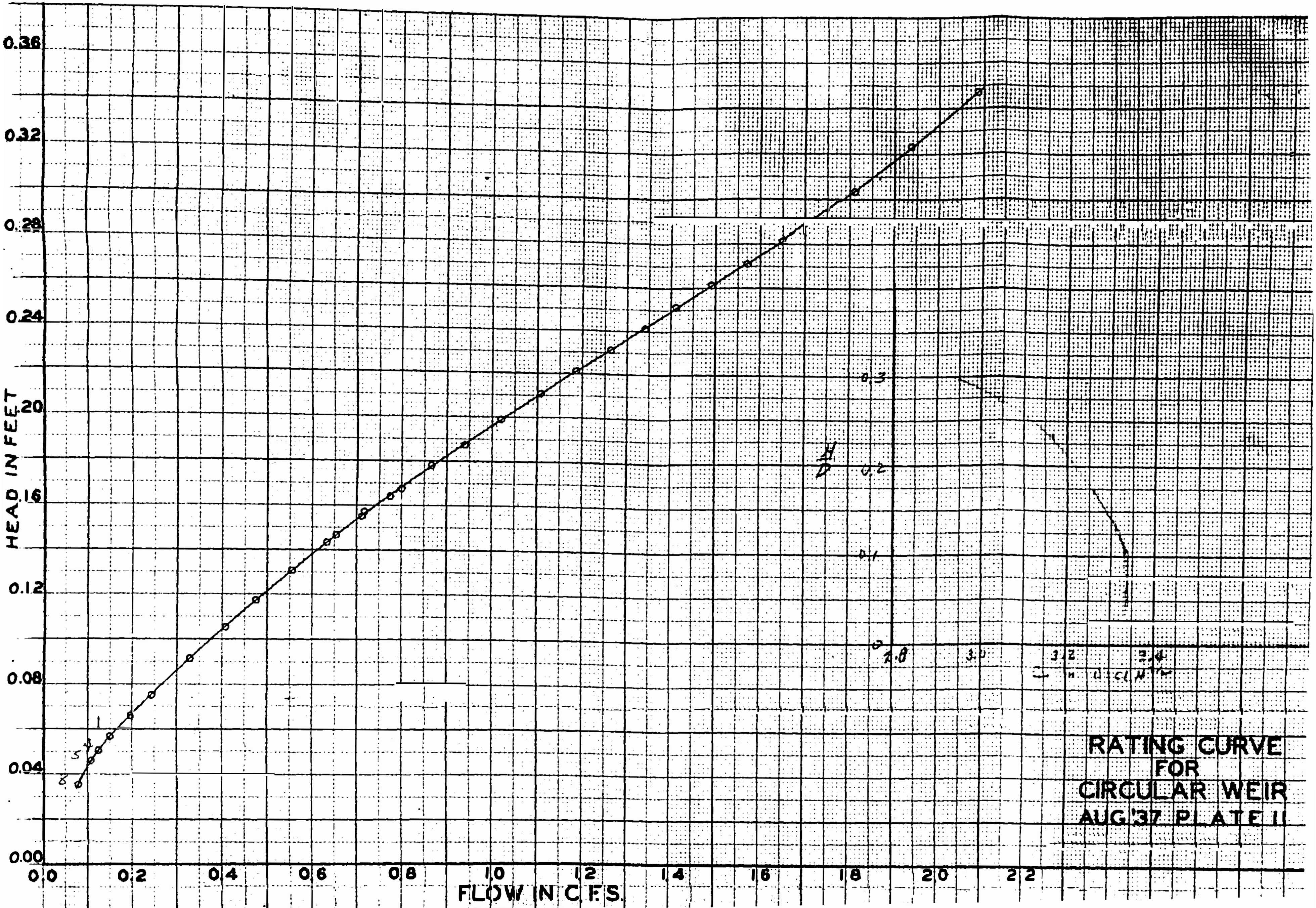


UNDER NAPPE GAGE INTERFERENCE WITH FLOW

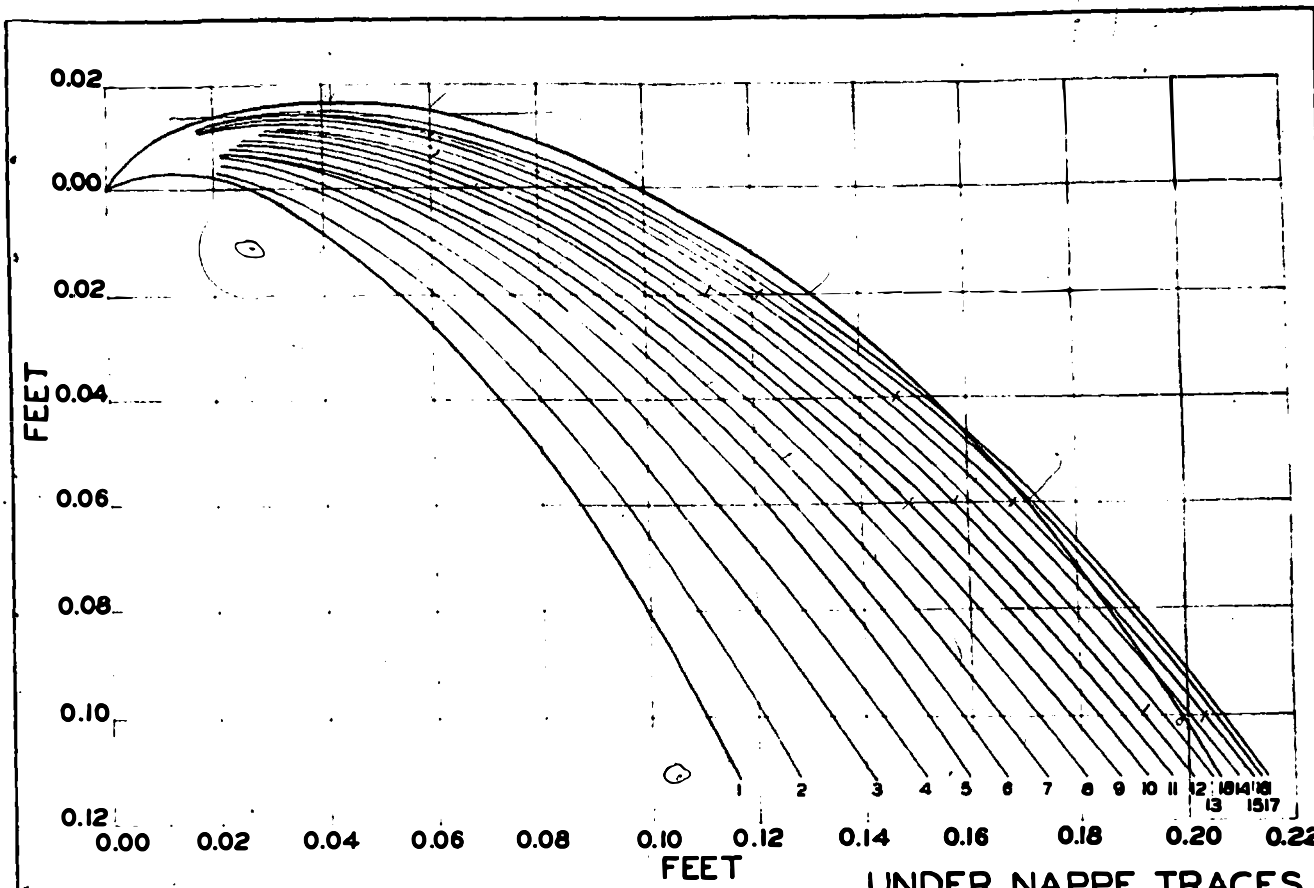
PLATE 8


CALIBRATION OF 12"
VENTURI METER
JULY '37 PLATE 9
VARIABLE COEFFICIENT
FLOW IN C.F.S.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

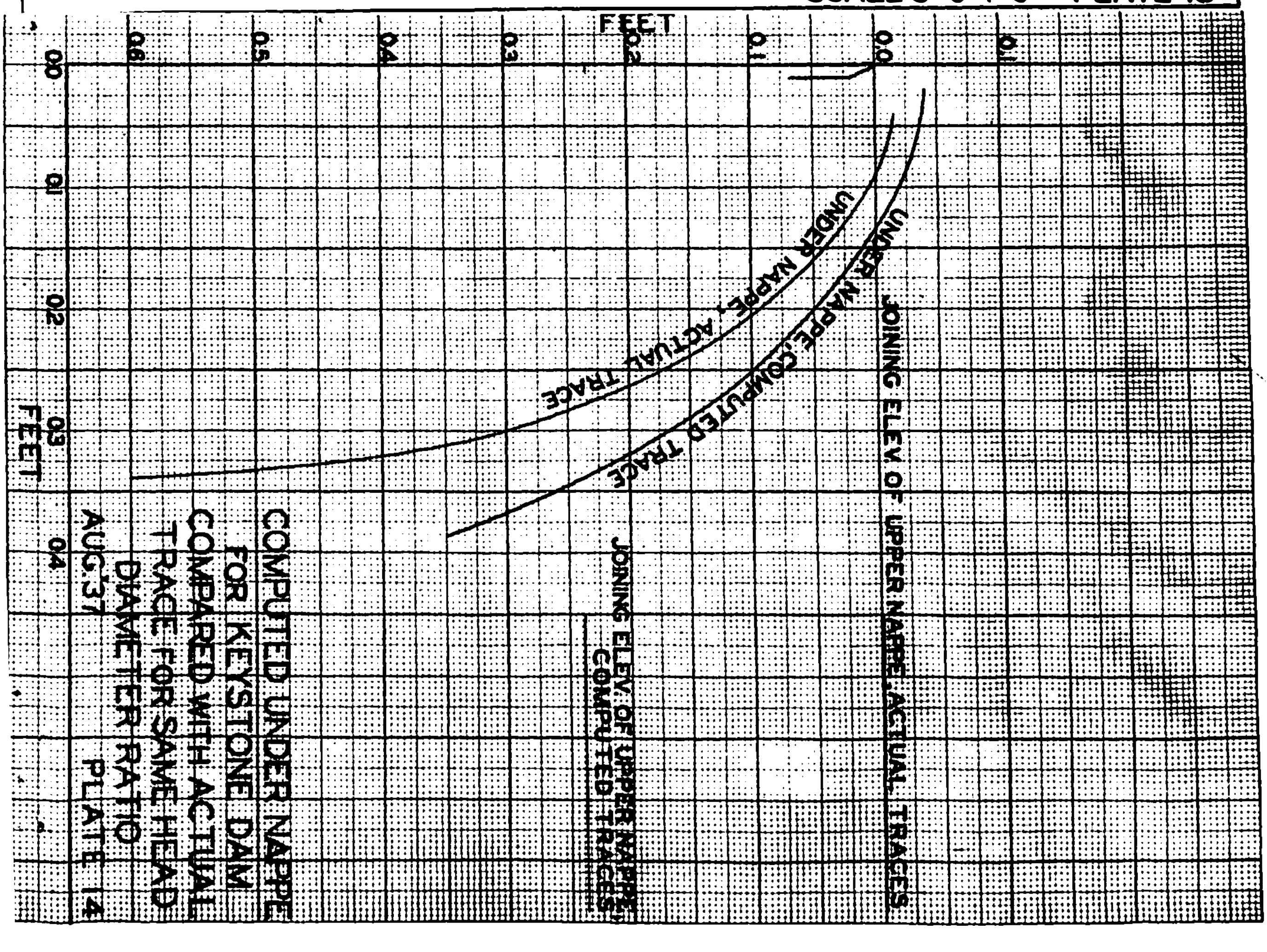

EQUATION OF
RATING CURVE
AUG '37 PLATE 10
LOG Q
LOG H
SLOPE = X = 1.412
SLOPE = X = 1.57
LOG K = .996
5
H: 1.12
Q: .491
4
H: 1.10
Q: .373
3
H: .98
Q: .217
2
H: .86
Q: .161



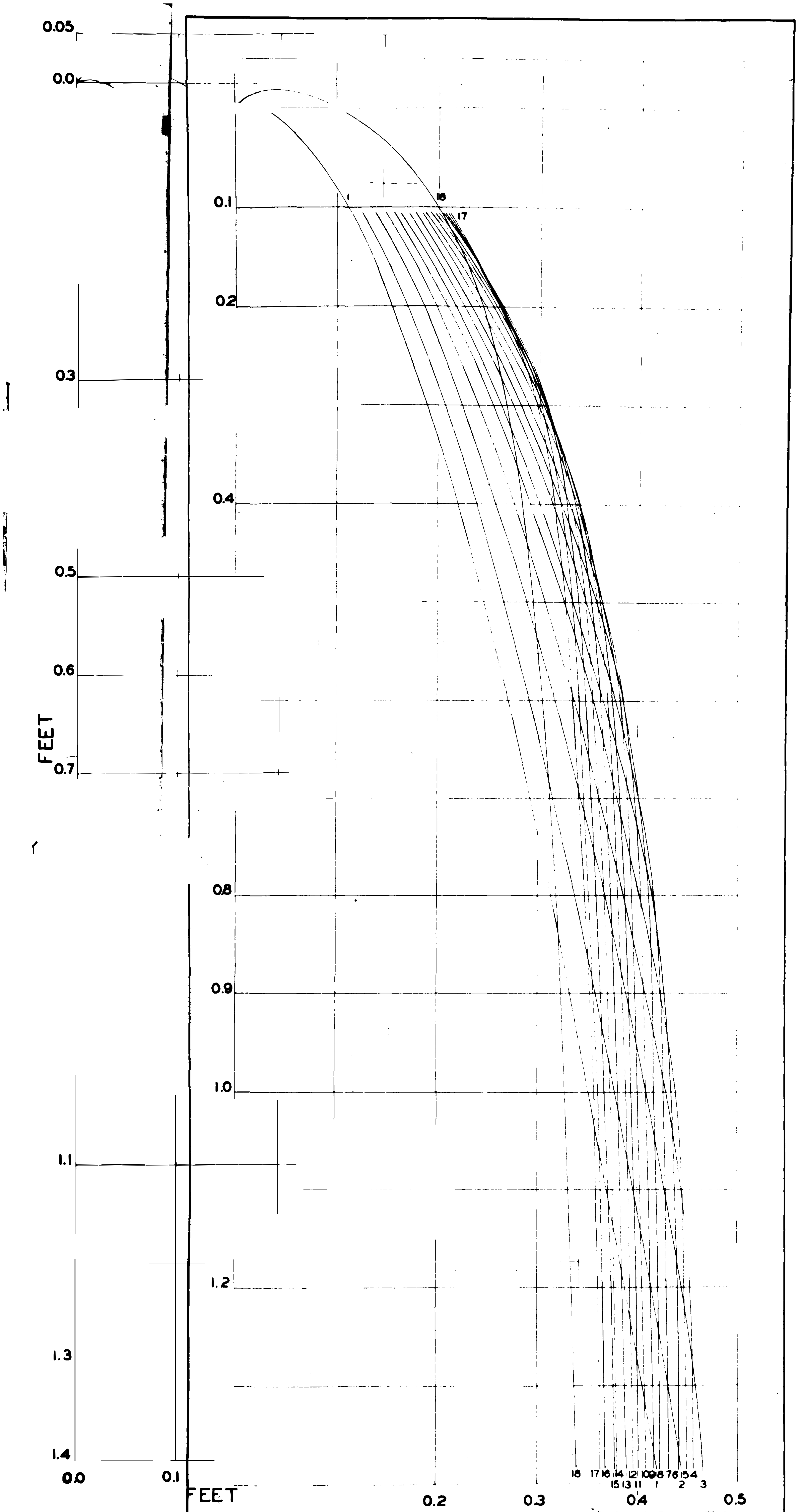
HEAD IN FEET
0.36
0.32
0.28
0.24
.20
.16
0.12
0.08
0.04
0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
FLOW IN C.F.S.
RATING CURVE
FOR
CIRCULAR WEIR
AUG '37 PLATE II



UNDER NAPPE TRACES
CREST PORTION
SCALE 3'-0" 1'-0" PLATE 13



COMPUTED UNDER NAPPE
FOR KEYSTONE DAM
COMPARED WITH ACTUAL
TRACE FOR SAME HEAD
DIAMETER RATIO
AUG 37 PLATE 14



UNDER NAPPE TRACES
LOWER PORTION

PLATE 12