UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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HYDRAULIC LABORATORY REPORT NO. 66

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Hydraulic model studies for the design of sluice entrances for Grand Coulee Dam

by

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- - -

Denver, Colorado

September 15, 1939

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Branch of Design and Construction
Engineering and Geological Control
and Research Division
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Laboratory Report No. 66
Hydraulic Laboratory
Compiled by: L. Reid

Reviewed by: D. J. Hebert

Subject: Hydraulic model studies for the design of sluice entrances for Grand Coulee Dam.

SUMMARY

A bellmouth entrance was developed which it is believed will completely eliminate the danger of cavitation. This entrance is formed by rotating an ellipse about the axis of the opening. The equation of the ellipse expressed in terms of the conduit diameter is $x^2/(0.50D)^2 + y^2/(0.15D)^2 = 1$. Therefore the length of the bellmouth is 0.50D and the contraction is 2(0.15D) or 0.30D. In order to lessen the tendency for lowered pressures along the inner radius of the elbow a converging elbow immediately downstream from the entrance is recommended. The desirability of constructing the intermediate and upper sluices to the shape of a trajectory is highly questionable and further studies are recommended regarding this point. The studies described in this report were completed in the early part of 1937.

Purpose of Studies

It has been demonstrated that sluice entrances in high dams are prone to cavitate unless the proper precautions are taken to insure against it by proper design. Since there is a lack of accurate design information for this purpose, these tests were conducted to supply this need.

While these studies are concerned specifically with Grand Coulee Dam, it is expected that the results will be applicable to the general case.

Experimental Apparatus

The objective set was that the pressures along the surface of the circular sluice entrance should not fall below atmospheric under the most severe operating conditions. In order to accomplish this objective it was necessary to know the exact shape of a jet issuing from a circular sharp-edged orifice.

Having installed a 12-inch pump capable of delivering the necessary discharge over a wide range of heads, it was necessary to construct a pressure tank which would allow the water to approach the sluice entrance in a manner as nearly similar to prototype conditions as practicable. Accordingly, a cylindrical tank 3 feet in diameter and 5 feet long was constructed.

The water entered at one end of this tank through a series of concentric distributing cones, passed through a specially constructed checkered rack designed to produce an even distribution of flow, and thence out through the orifice in the opposite end of the tank.

As the Grand Coulee sluices are to be circular in cross-section, the orifice was made circular. It was made of brass and set in a floating steel plate which was designed to remain always in a plane regardless of bulging of the tank head due to high water pressures inside the tank.

In order to determine the shape of the jet issuing from the 3-inch sharp-edged orifice and the position of the vena contracta, it was necessary to design and construct a special measuring device. This device is capable of measuring the diameter of the jet and the distance along the axis to one thousandth of an inch and the arc around the circumference of any section in degrees.

A photograph of this device is shown on Plate 1 and a section through the entire test apparatus is shown in Figure 1.

Test Program

The first tests consisted of measurements of the jet from a 3-inch sharp-edged orifice under various heads from 10 to 95 feet. A profile of the jet was taken in longitudinal planes inclined 0, 30, and 60 degrees from the vertical. The profile for the range of available heads is shown on Figure 3a. The complete test data are shown on Figure 2.

The contraction factor of the jet, or the ratio of the area of the minimum section to the area of the orifice, was found to be 0.598. This figure is close to the value of 0.611 which was used by Professor Chas. Harris in some work on orifices performed at the University of Washington. Harris attempted to prove that by rounding the entrance with a radius sufficient to reduce the area by the ratio 0.611 the problem of contracting the jet could be accomplished quite simply. This design was tried but proved to be undesirable because of the low pressures set up in the entrance. As it was evident that this method of approach was in error, it was abandoned.

Former tests at the Fort Collins laboratory had shown that an elliptical profile defined by the equation $\frac{X^2}{(1.846)^2} + \frac{Y^2}{(0.404)^2} = 1$ in the sluice entrance gave promising results. This model which had been tested at Fort Collins was then installed and tested under high heads. Negative pressures were measured near the beginning of the entrance. Upon examination of the model built at Fort Collins it was observed that the elliptical profile did not end tangent to the face of the orifice. A new entrance (called Model A) built according to the same equation, satisfied the condition of tangency. Tests showed this entrance to be no improvement over the former one (see Figure 5).

Model "A" was then used in connection with various elbows which would turn the water through 8 degrees 32 minutes. This was necessary because the face of the dam has a slope of 0.15 and the axis of the sluice entrance is set normal to this face. Two elbows were tested, one with a radius of 4D and one with a radius of 9.270D, the former called the short radius elbow, the latter called the long radius elbow (see Figure 4).

The tests on these two elbows showed that a negative pressure existed along the inner surface of the bend which was caused by the centrifugal action of the water passing around the bend. The magnitude of this decrease in pressure at the inner radius as well as the excess of pressure at the outer radius is shown on Figure 6. It can be seen that the drawdown of pressure was less in the long radius elbow.

Since it was decided to neglect the back pressure which would be present in the prototype due to frictional loss in the pipe beyond the entrance, the arrangements tested up to this point can be classified as unsatisfactory.

It appeared that the surest way to accomplish a condition of positive pressure throughout the sluice entrance and elbow was to set up a positive pressure gradient by coverging the conduit through the elbow in the direction of flow. This method of attack necessitated a widening of the opening in the plane of the face of the dam. In a conference with the mechanical section it was found permissible to increase the diameter from 132 inches to 138 inches (prototype). From this diameter the new entrance called Model "F" was formed by revolving the ellipse $\frac{X^2}{(1.50)^2} + \frac{Y^2}{(0.45)^2} = 1$, which gives at every point a slightly smaller diameter than the measured profile of the jet, until the horizontal tangent is reached (see Figure 3(b)). The ratio of the area of the jet at the final diameter of 106 inches (prototype) to the area of the orifice was made equal to 0.590 as against 0.598 for the free jet. The decrease from this diameter to the final diameter of 102 inches was accomplished by means of a converging elbow. In order to retain the initial lengths of the section of steel liners, it was necessary to insert a short tangent length between the discharge end of the elliptical entrance and the beginning of the elbow. A short length of horizontal pipe was attached to the end of the converging elbow so that any tendency of the reduced pressure to carry through the elbow could be observed.

The test results for this combination are shown on Figure 5. It is evident from the figure that no negative pressures exist under a head of 10.6 feet model. This head is more than the head corresponding to 355 feet in the prototype. Under a head of 65 feet model (see Figure 7), a negative pressure is set up showing that with no back pressure it would be possible, in the prototype, to set up a negative pressure in the elbow by running the head up to 800 feet or more.

A piece of pipe of sufficient length to insure an appreciable frictional resistance was attached to the end of the setup in order to observe the effect of back-pressure on the pressure conditions in the entrance. It can be seen (Figure 7) that the pressure at any point in the entrance is raised by the amount of the back-pressure. It will be noted, that even at the distorted head of 65 feet in the model the pressures are now entirely positive.

Since the effect of back-pressure has now been established, the frictional loss computed for the prototype can be applied to the model pressures which have been scaled up to prototype dimensions.

Bottom Sluice

The sluice downstream from the entrance and converging elbow consists of 43.5 feet of steel-lined conduit, which includes two ring-follower gates, followed by 62.70 feet of straight concrete pipe and 230.8 feet of concrete pipe laid according to the parabola $x^2 = -1085.0236y$. The total head loss from headwater to tailwater consists of the velocity head, the loss in the entrance, and the frictional loss in the pipe. Assuming that the loss in the entrance and elbow is equal to 10 percent of $V^2/2g$ and that the coefficient of friction for the concrete pipe at a Reynolds number of $70 \times (10)^6$ is equal to 0.006, the losses can be computed as follows:

Maximum headwater elevation	1290 feet
Minimum tailwater elevation	935 feet
Maximum difference in head =	355 feet

Total pressure drop is computed as follows:

$$V^2/2g + 0.1V^2/2g + 0.006 \times \frac{337}{8.5} V^2/2g = 1.338V^2/2g$$

$$1.338V^2/2g = 355 \text{ feet}$$

$$\frac{V^2}{2g} = 265.32 \text{ feet}$$

$$V = 130.65 \text{ feet per second}$$

The loss in the pipe will be

$$0.006 \times \frac{337}{8.5} \times 265.32 = 63.15 \text{ feet}$$

The drop in pressure to the end of the converging elbow =

$$1.1 \times 265.32 = 355 - 63.15 = 291.85 \text{ feet}$$

A model test was run with the pressure at the end of the elbow approximately equal to the pipe resistance of the prototype scaled down to model dimensions which computes as

$\frac{63.15}{35.4536} = 1.78$ feet. Actually this back pressure could not be accomplished at the proper head of 355/35.4536 = 10.01 feet, so the head was raised to 10.03 feet, which gave a back-pressure from the pipe resistance of 1.789 feet. In order to adjust this back-pressure to 1.78, it was necessary to subtract 0.009 from the observed pressures. This subtraction results in a head of 10.03 - 0.009 = 10.021 feet. That this figure is very close can be most clearly seen by comparing its scaled-up valve of (10.021 x 35.4536) or 355.28 feet with 355 feet.

Effect of Placing Sluices in Pairs

The tests described in the preceding pages were concerned only with a single entrance, having undisturbed approach conditions and so the results are not directly applicable to the double sluices in the Grand Coulee Dam. The single opening was treated first because it was felt that it represented the fundamental case which could be modified by the various conditions which comprise a particular case.

With a knowledge of the flow through the single sluice it would have been possible to modify the results by theoretical means and make them apply to the Grand Coulee sluiceways which are in pairs surrounded by a trashrack structure. However, the unusually high head on the dam makes any source of error intolerable and so it was decided that a model of the sluiceways be built and tested.

Due to the limitation of the experimental setup it was necessary to reduce the scale ratio from 1:35.454 to 1:54.4. The entrance was made to the same elliptical curve of the Model "F" which gave satisfactory results for the single sluice. Instead of the converging elbow used in the former case, the same convergence was accomplished by a straight tapering cone. As in the former case, the back-pressure due to the frictional loss in the conduit was neglected and the jet discharged under atmospheric pressure at the end of the cone. This setup represents the actual conditions existing in the prototype entrance excepting only the trashrack, the elbow, and the back-pressure. The location of piezometers and the results of the test are shown on Figure 8. The most important change in the pressure condition occurred at the side of the sluices farthest removed from the axis of symmetry. Here the pressure decreases due to the fact that there is more contraction at this side because of the removal of the balancing force from the opposite side. Despite the lowered pressure, the condition of pressure distribution can be considered satisfactory since there are no negative pressures. The presence of the cone seems to exert a stabilizing effect which equalizes the pressure before the end of the cone is reached, with the result that the double stream leaving the model had a particularly good configuration. For the first half inch the two jets were very clear and smooth as well as parallel.

Effect of Trashrack

A model of the trashrack structure was then installed in such a manner that it could be moved vertically through a distance equal to the spacing of the horizontal ribs. This was done in order to study the effect of the location of the ribs relative to the center-line of the sluice entrance.

The tests with the trashrack in place indicated that the position of the bottom was the most effective feature. As the bottom moved closer to the opening, the pressure along the top of the entrance decreased. The trashrack was moved to a position one-half the rib spacing above and one-half the same spacing below the designed position to show that at the designed position the bottom did influence the pressure along the top of the sluice entrance. Moving the rack through this distance caused the pressure at a selected piezometer (located along the top surface of the entrance) to change by approximately two feet of water prototype. In other words, moving the rack to a position below the designed position by one-half the rib spacing raises the pressure at a point along the top of the entrance by approximately one foot of water prototype. The effect of rib placement was very small and can safely be neglected. With the trashrack in place as designed, the pressures throughout the entrance were all positive and the discharge conditions were such that no trouble is expected downstream due to poor velocity distribution. It should be remembered that all these pressures will be increased by the amount of back-pressure.

Intermediate Sluices

The intermediate sluices differ from the bottom sluices only in the curve to which the conduits are laid downstream from the gates. The conditions under which they operate, however, are different in that the exit of the intermediate sluice may or may not be submerged by the tailwater. It is necessary, therefore, to study the intermediate sluice for various conditions of tailwater.

Maximum headwater elevation.......1290.00
Invert at exit elevation...........973.37
Maximum tailwater elevation.......1011.00
Minimum tailwater elevation........933.00
Elevation tailwater to seal exit...986.87

Take the condition of headwater at elevation 1290 and tailwater at elevation 987, (see Figure 9, Sketch "a"). The total head will be 1,290 - 987 = 303 feet.

Assume losses as follows:

Loss in entrance and elbow...0.10 $V^2/2g$
Velocity head at entrance....$V^2/2g$

Loss due to friction.........$0.0075 \frac{L}{D} V^2/2g$

To derive the expression for the length of a parabola take the general form equation:

$$X^2 = -Cy$$

$$L = \int dL = \frac{2}{C} \int_0^{X_1} \sqrt{\frac{C^2}{4} + X^2}\, dX$$

$$L = \frac{2}{C} \left[\frac{X_1}{2} \sqrt{\frac{C^2}{4} + X_1^2} + \frac{C^2}{8} \log_e \frac{X_1 + \sqrt{\frac{C^2}{4} + X_1^2}}{\sqrt{C^2/4}} \right.$$

Using the mean value of "X_1" of 208.3 feet, the length is 217 feet. The total length of conduit is 217 + 55.11 or approximately 272 feet, so:

$$1.1\, V^2/2g + 0.0075 \times \frac{272.1}{8.5} V^2/2g = 303 \text{ feet}$$

$$1.340\, V^2/2g = 303 \text{ feet}$$

$$V^2/2g = 226.1 \text{ feet}$$

$$V = 120.5 \text{ feet per second}$$

Head lost due to friction is:

$$0.243 \times 226.1 = 55 \text{ feet}$$

Drop in pipe from centerline at origin to elevation of tailwater is 1034 - 987 = 45 feet

The head loss from origin of parabola to exit is:

$$0.0075 \times \frac{217}{8.5} \times 226.1 = 43.3 \text{ feet}$$

Therefore the pressure gradient is:

47 - 43.3 = 3.7 feet below the centerline at the section where the trajectory begins.

A sketch of the pressure distribution is shown on Figure 9, Sketch "b". The assumption is made that the gradient is a straight line, which is very nearly correct as seen from the small difference between the horizontal distance and the length of the conduit. The distance "P" from the gradient to the centerline of the conduit will vary thus:

$$P = \frac{43.3X}{202} + 3.7 - \frac{X^2}{816}$$

$$\frac{dP}{dX} = \frac{43.3}{202} - \frac{X}{408}$$

setting $\frac{dP}{dX} = 0$ for maximum

$$X = \frac{43.3 \times 408}{202} = 86.4 \text{ feet}$$

and $P\ (\text{at } X = 86.4) = 13.06$ feet

The distance "P" represents the pressure in feet of water below atmospheric so the pressure on the centerline at a distance from the origin of 86.4 feet is (-13.1) feet of water gage. The negative pressure at the top of the conduit, Point A, at a section through Point B perpendicular to the centerline will be 13.1 plus a component of the radius of the pipe. The slope of the conduit at X = 86.4 feet is:

$$\frac{dy}{dx} = \frac{-86.4}{408} = \tan \emptyset = -0.212$$

so "Ø", the angle between the normal to the curve and the vertical is $\tan^{-1} 0.212$ = 12 degrees. The vertical component of the radius is then equal to 4.25 cosine 12 degrees = 4.25 x 0.978 = 4.15 feet. The pressure at "A" will then be -(4.15 + 13.1) = - 17.25 feet.

It has been shown in the foregoing computation that a negative pressure of appreciable magnitude exists. If the headwater is lowered this condition becomes worse because the head lost in overcoming friction decreases while the drop in elevation of the conduit remains the same. In view of this consideration it would seem that a further investigation, and perhaps a model study, is indicated.

Top Sluice

In the case of the top sluice, a situation similar to that of the intermediate is encountered with the exception that the end is never sealed. Assuming that the conduit flows full, the friction loss is computed as follows:

Headwater elevation..................	1290.0
Elevation invert at exit elevation..	1103.8
Head on sluice	186.2 feet

Lenght of conduit 169 feet

$$1.1V^2/2_g + 0.0075 \times \frac{169}{8.5} V^2/2g = 186.2$$

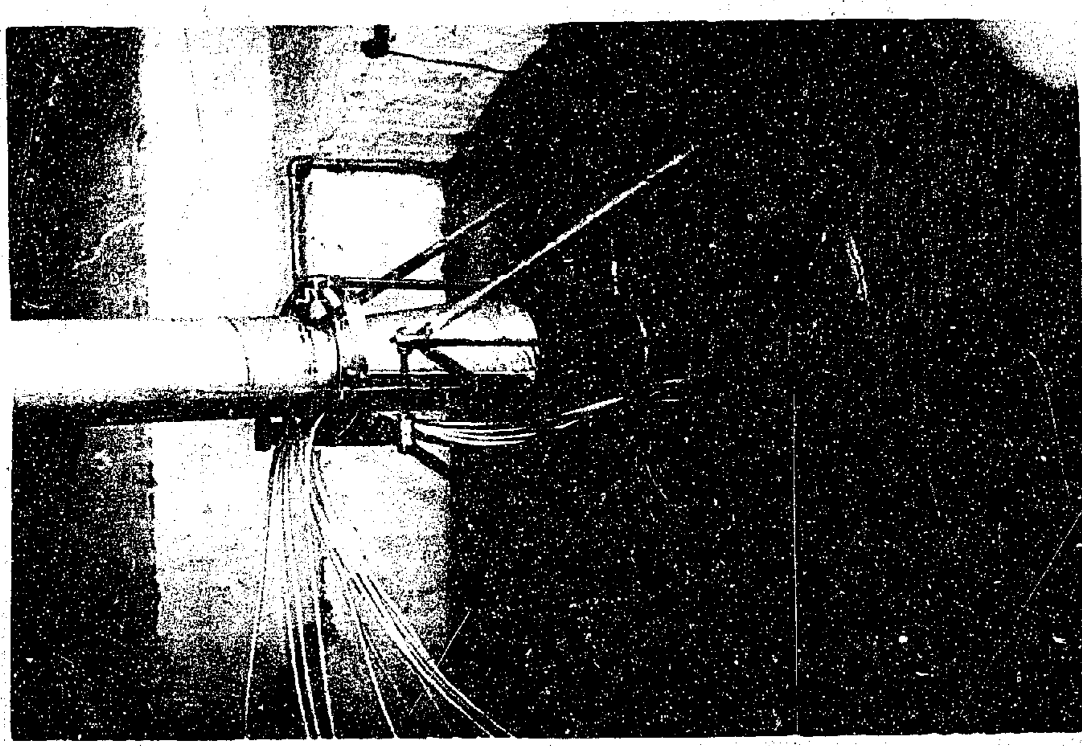
$$1.249\ V^2/2_g = 186.2$$

$$V^2/2_g = 149.0 \text{ feet}$$

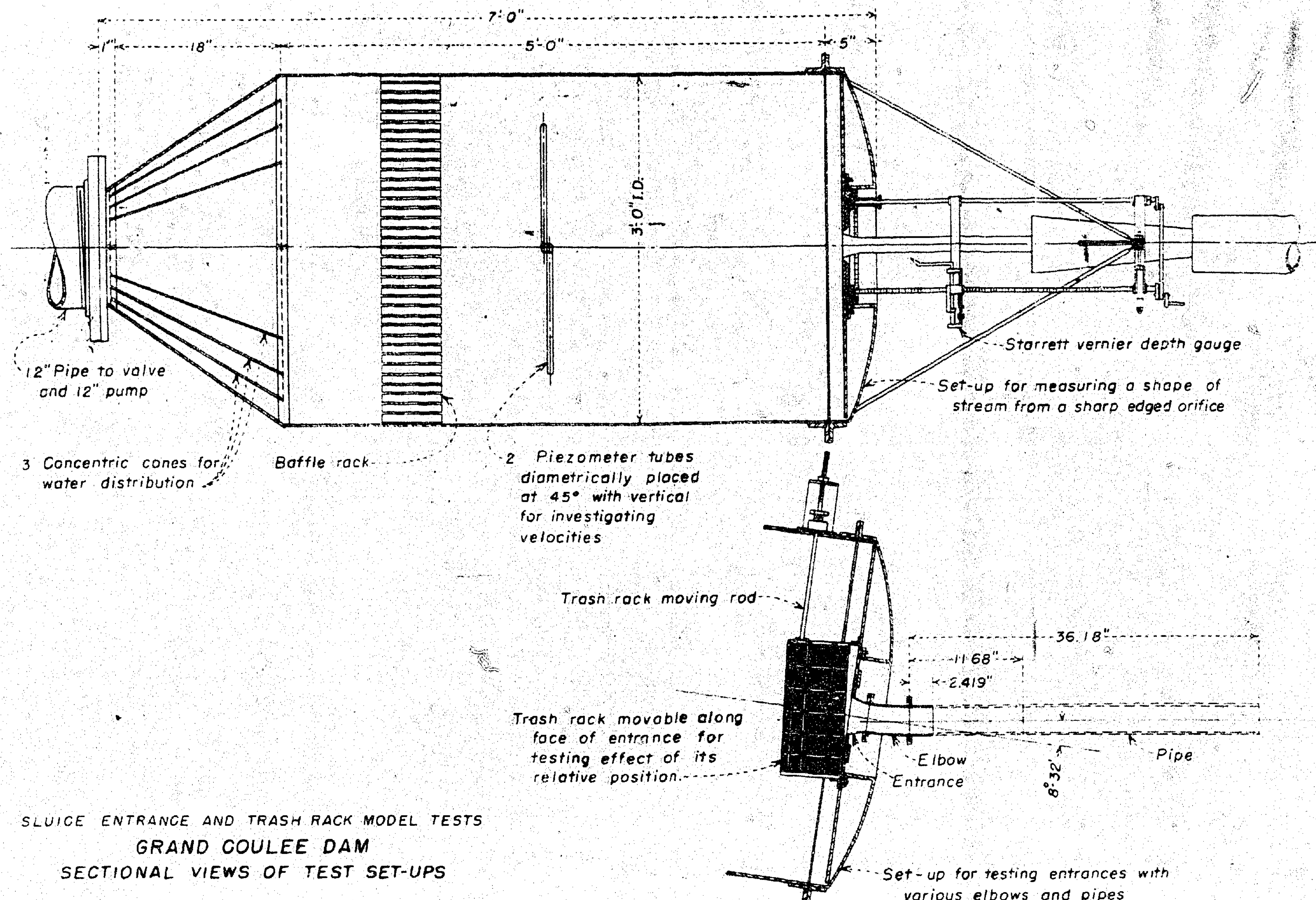
$$V = 98.0 \text{ feet per second}$$

Friction loss = 0.149 x 149.0 = 22.2 feet
Drop in parabola = 26.0 feet

Since the drop exceeds the friction loss, there will be an accelerating force and when the end is open this force will tend towards making the water break away from the sides of the conduit and admit atmospheric pressure from the discharge end. This point would also bear further investigation.



TEST APPARATUS - CALIBRATION OF FREE JET



SLUICE ENTRANCE AND TRASH RACK MODEL TESTS

GRAND COULEE DAM

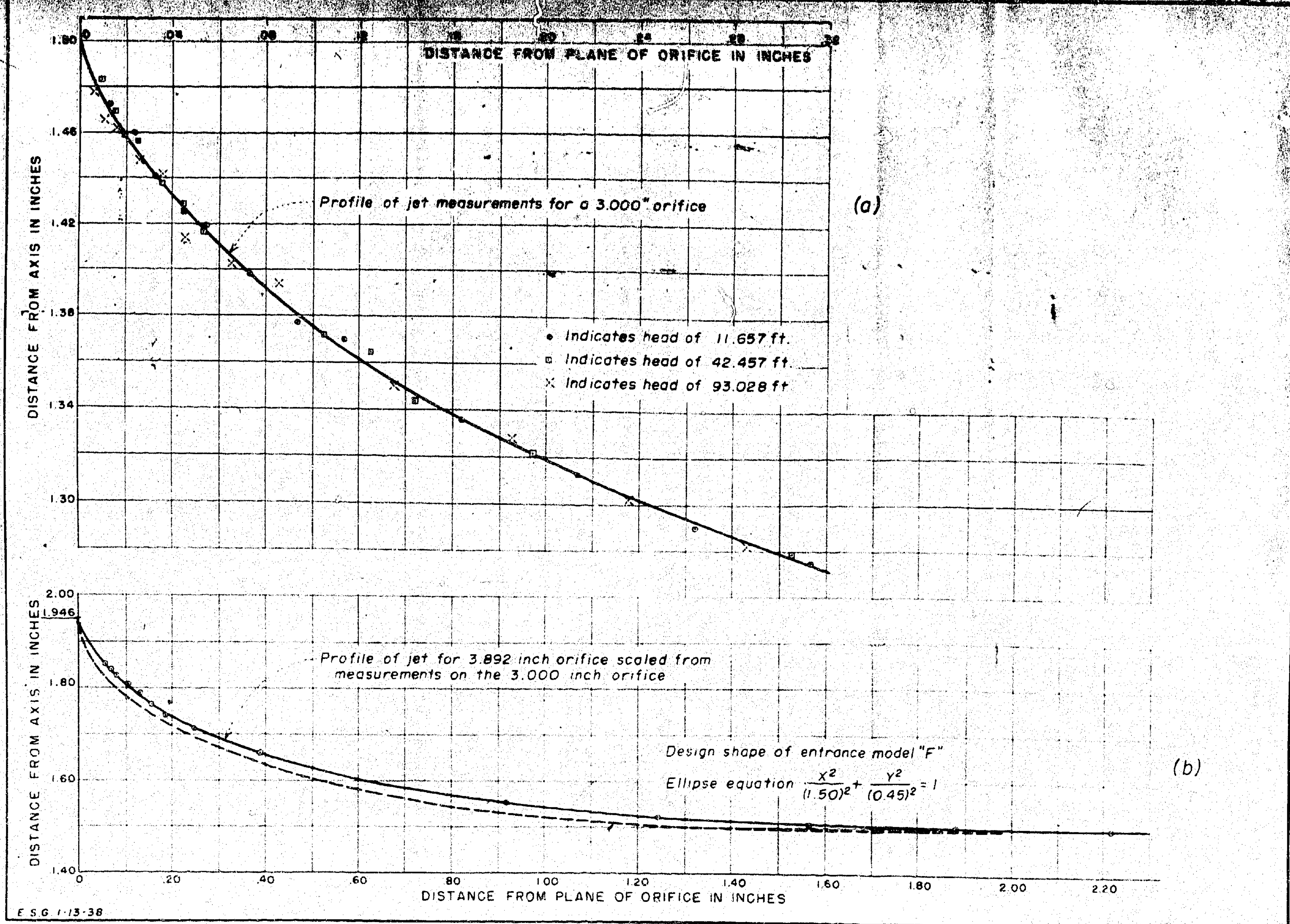
SECTIONAL VIEWS OF TEST SET-UPS

E.S.G. 1-26-38

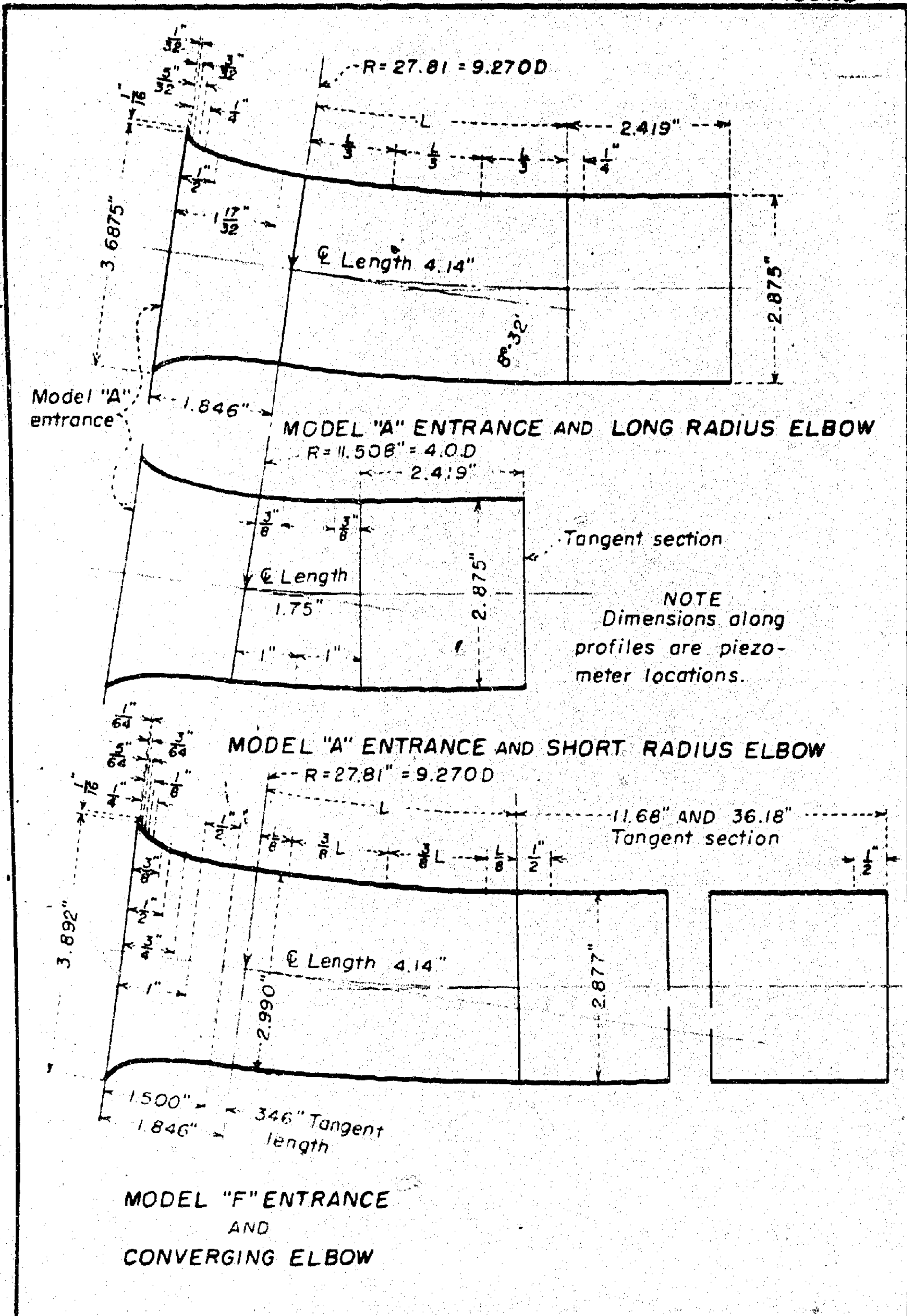
CALIBRATION OF JET FROM 3" ORIFICE DIAMETERS AT VARIOUS HEADS

HEAD 11.657 FT.				HEAD 42.457 FT.		HEAD 92.746 FT.	
DISTANCE FROM PLANE OF ORIFICE INCHES	DIAMETERS IN VARIOUS PLANES DEGREES FROM VERTICAL			DISTANCE FROM PLANE OF ORIFICE INCHES	DIAMETERS IN PLANE 0° FROM VERTICAL	DISTANCE FROM PLANE OF ORIFICE INCHES	DIAMETERS IN PLANE 30° FROM VERTICAL
	0	30	60				
				.009	2.966	.005	2.954
.013	2.952	2.939	2.948	.014	2.940	.015	2.919
				.019	2.918		
.023	2.924	2.920	2.916	.024	2.914	.025	2.883
.033	2.890	2.883	2.874	.034	2.878		
				.044	2.858	.045	2.838
.053	2.842	2.834	2.828	.054	2.840		
.073	2.802	2.798	2.796	.064	2.822	.065	2.796
.093	2.762	2.759	2.750	.084	2.788	.085	2.773
.113	2.740	2.745	2.732	.104	2.766		
				.124	2.730		
.163	2.668	2.674	2.667	.144	2.688	.135	2.702
				.194	2.642	.185	2.654
.213	2.632	2.629	2.619			.235	2.609
.263	2.580	2.584	2.576			.285	2.564
.313	2.552	2.550	2.548	.304	2.558		
.513	2.458	2.455	2.452			.485	2.468
.713	2.406	2.400	2.392	.715	2.398	.685	2.416
.963	2.354	2.363	2.354			.935	2.36[illegible]
1.213	2.322	2.341	2.336			1.185	2.329
1.463	2.316	2.325	2.306	1.489	2.336		
1.713	2.314	2.326	2.315			.685	2.320

FIGURE 3



DISTANCE FROM PLANE OF ORIFICE IN INCHES
DISTANCE FROM AXIS IN INCHES
Profile of jet measurements for a 3.000" orifice
(a)
• Indicates head of 11.657 ft.
▫ Indicates head of 42.457 ft.
× Indicates head of 93.028 ft.
Profile of jet for 3.892 inch orifice scaled from measurements on the 3.000 inch orifice
Design shape of entrance model "F"
Ellipse equation $\frac{X^2}{(1.50)^2}+\frac{Y^2}{(0.45)^2}=1$
(b)
1.946
DISTANCE FROM AXIS IN INCHES
DISTANCE FROM PLANE OF ORIFICE IN INCHES
E.S.G. 1-13-38

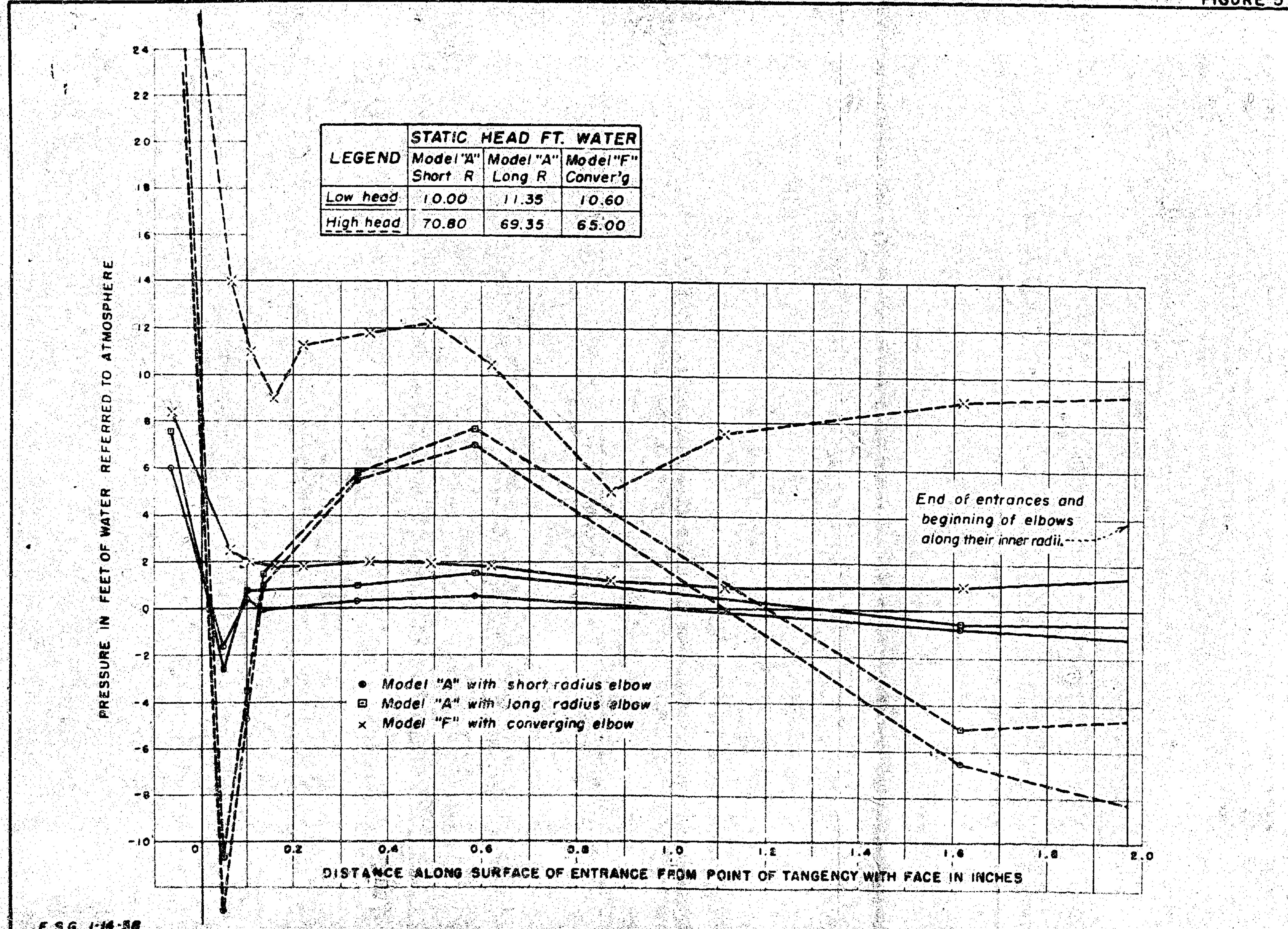


MODEL "A" ENTRANCE AND LONG RADIUS ELBOW

MODEL "A" ENTRANCE AND SHORT RADIUS ELBOW

MODEL "F" ENTRANCE AND CONVERGING ELBOW

FIGURE 5



STATIC HEAD FT. WATER
LEGEND
Model "A" Short R
Model "A" Long R
Model "F" Conver'g
Low head 10.00 11.35 10.60
High head 70.80 69.35 65.00
PRESSURE IN FEET OF WATER REFERRED TO ATMOSPHERE
DISTANCE ALONG SURFACE OF ENTRANCE FROM POINT OF TANGENCY WITH FACE IN INCHES
End of entrances and beginning of elbows along their inner radii.
● Model "A" with short radius elbow
⊡ Model "A" with long radius elbow
× Model "F" with converging elbow
E.S.G. 1-14-58

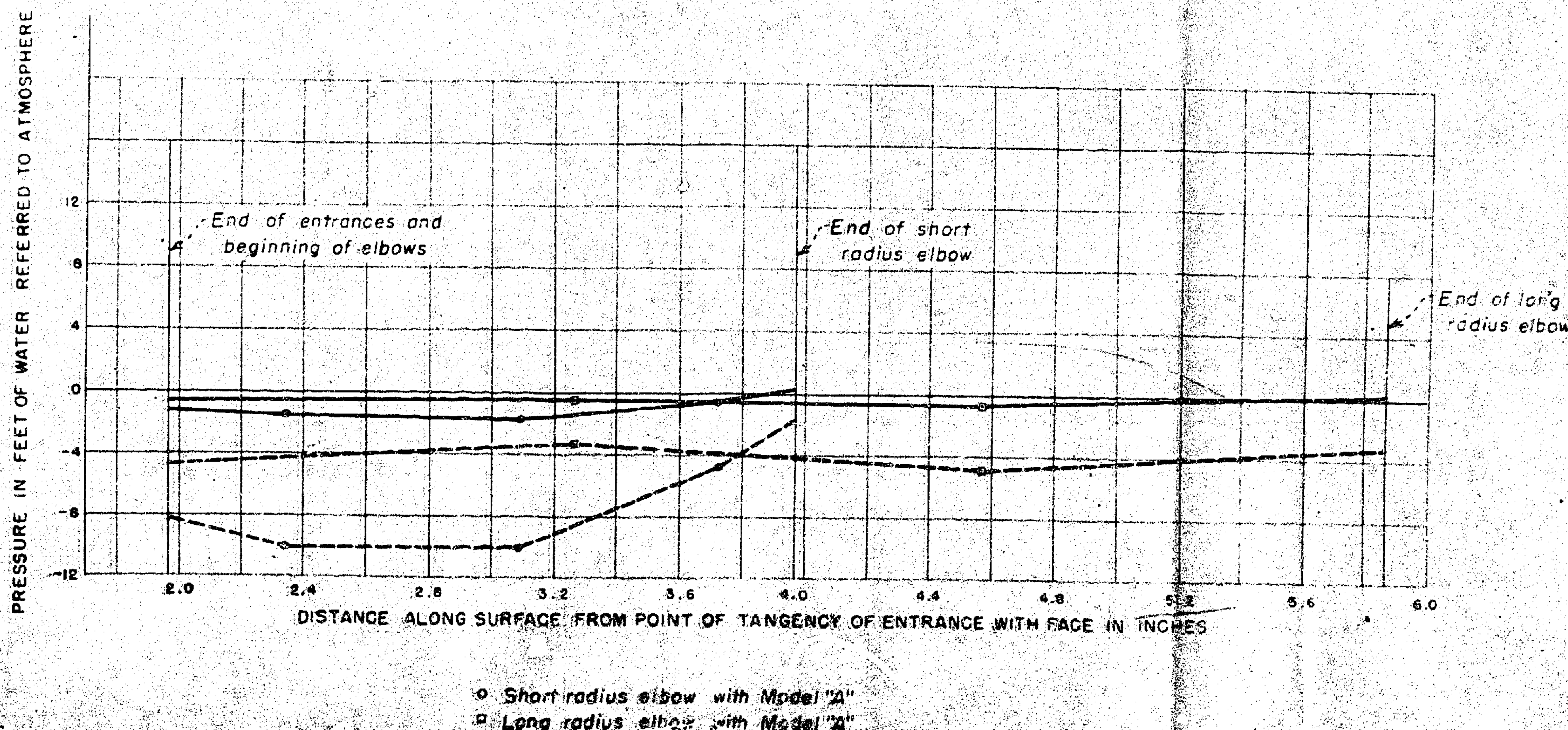
HYD-66

PRESSURES AT MIDPOINTS OF ELBOWS

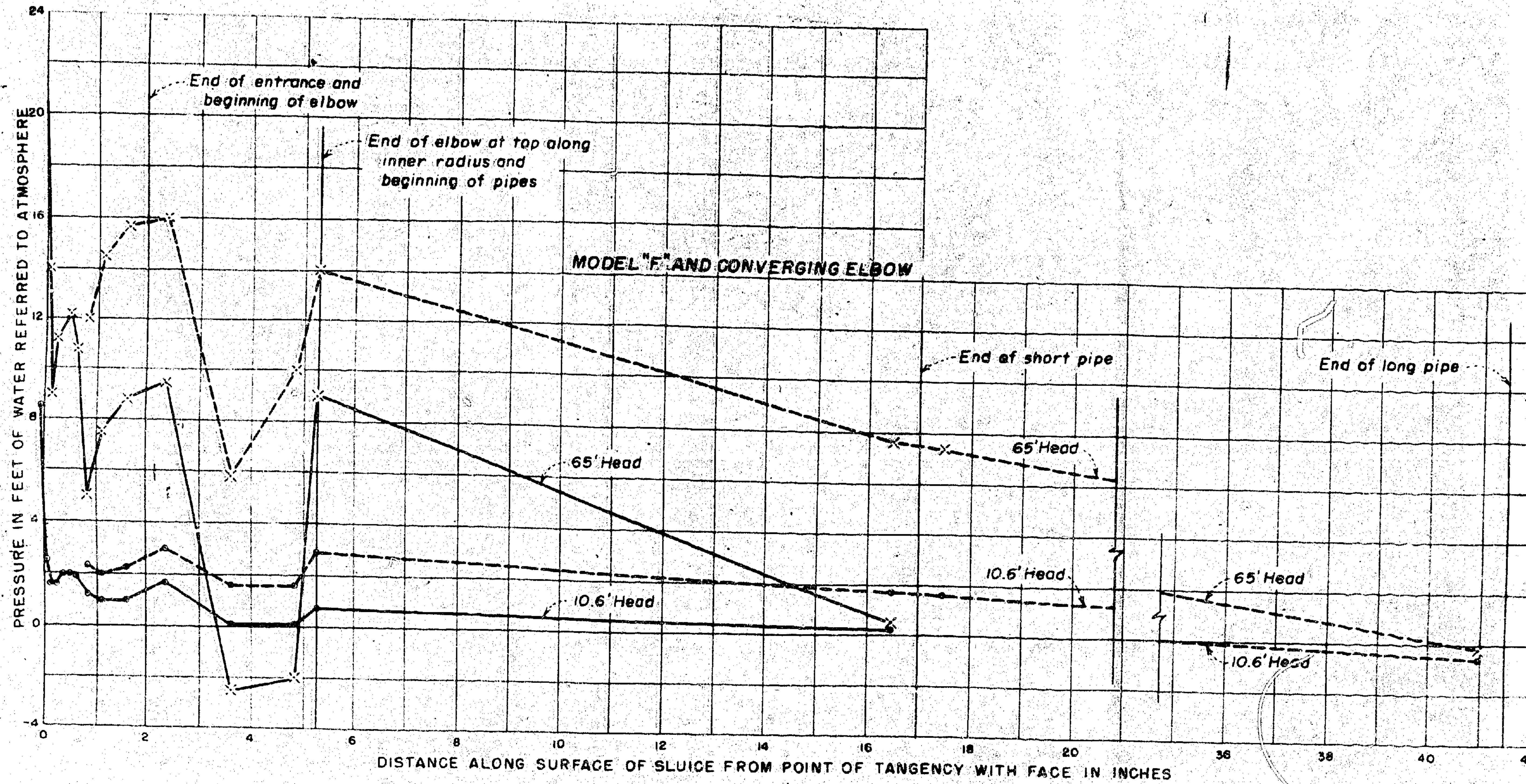
ELBOWS	HEAD IN FEET OF WATER	TOP INNER RADIUS	BOTTOM OUTER RADIUS
Short R. with Mod. "A" ℄ length 1.75"	HIGH HEAD 70.80	-10.10 *	10.90
	LOW HEAD 10.00	-1.60 *	1.50
Long R. with Mod. "A" ℄ length 4.14"	HIGH HEAD 69.35	-4.10 *	7.00 *
	LOW HEAD 11.35	-0.60 *	1.25 *

*Obtained by interpolation

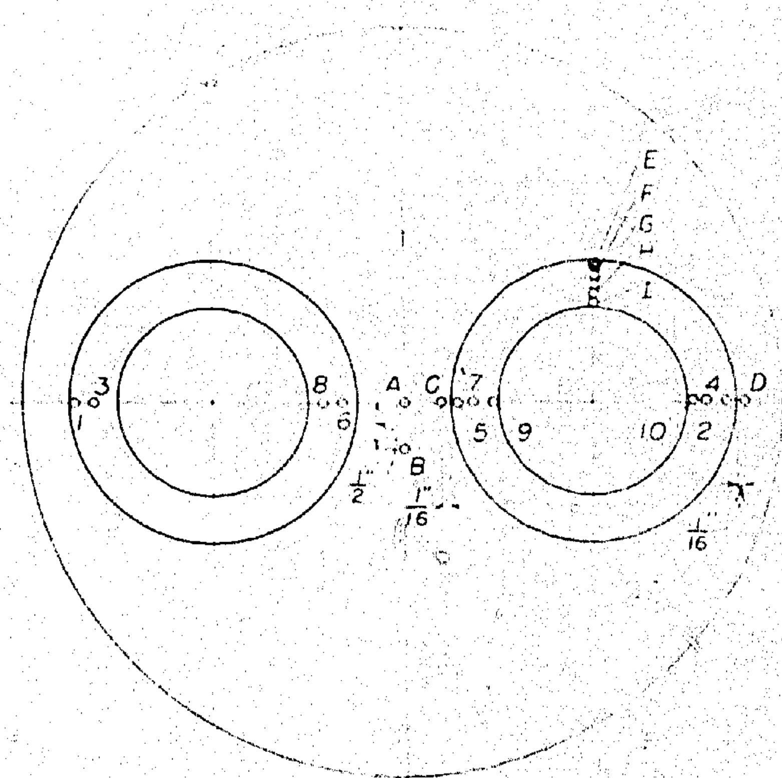
LEGEND	STATIC HEAD-FT.	
	Model "A" Short R.	Model "A" Long R.
LOW HEAD	10.00	11.35
HIGH HEAD	70.80	69.35



E.S.G. 1-14-38


MODEL "F" AND CONVERGING ELBOW
End of entrance and beginning of elbow
End of elbow at top along inner radius and beginning of pipes
End of short pipe
End of long pipe
65' Head
10.6' Head
65' Head
10.6' Head
65' Head
10.6' Head
PRESSURE IN FEET OF WATER REFERRED TO ATMOSPHERE
DISTANCE ALONG SURFACE OF SLUICE FROM POINT OF TANGENCY WITH FACE IN INCHES
24
20
16
12
8
4
0
-4
0
2
4
6
8
10
12
14
16
18
20
36
38
40
42

E.S.G. 1-15-38



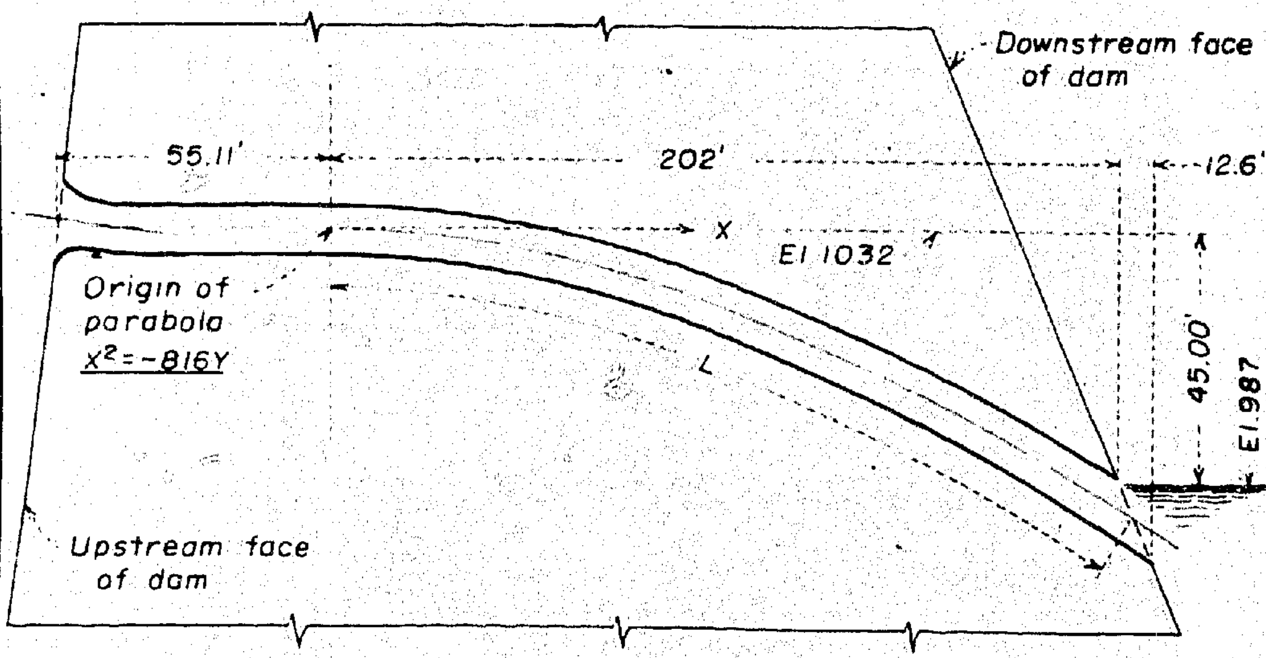
PIEZOMETER NUMBERS	DISTANCE FROM FACE
1, 5, E	1/64"
2, 6, F	1/16"
3, 7, G	5/32"
4, 8, H	31/64"
9, 10, I	0.977

TABLE I
PRESSURE DISTRIBUTION IN ENTRANCE

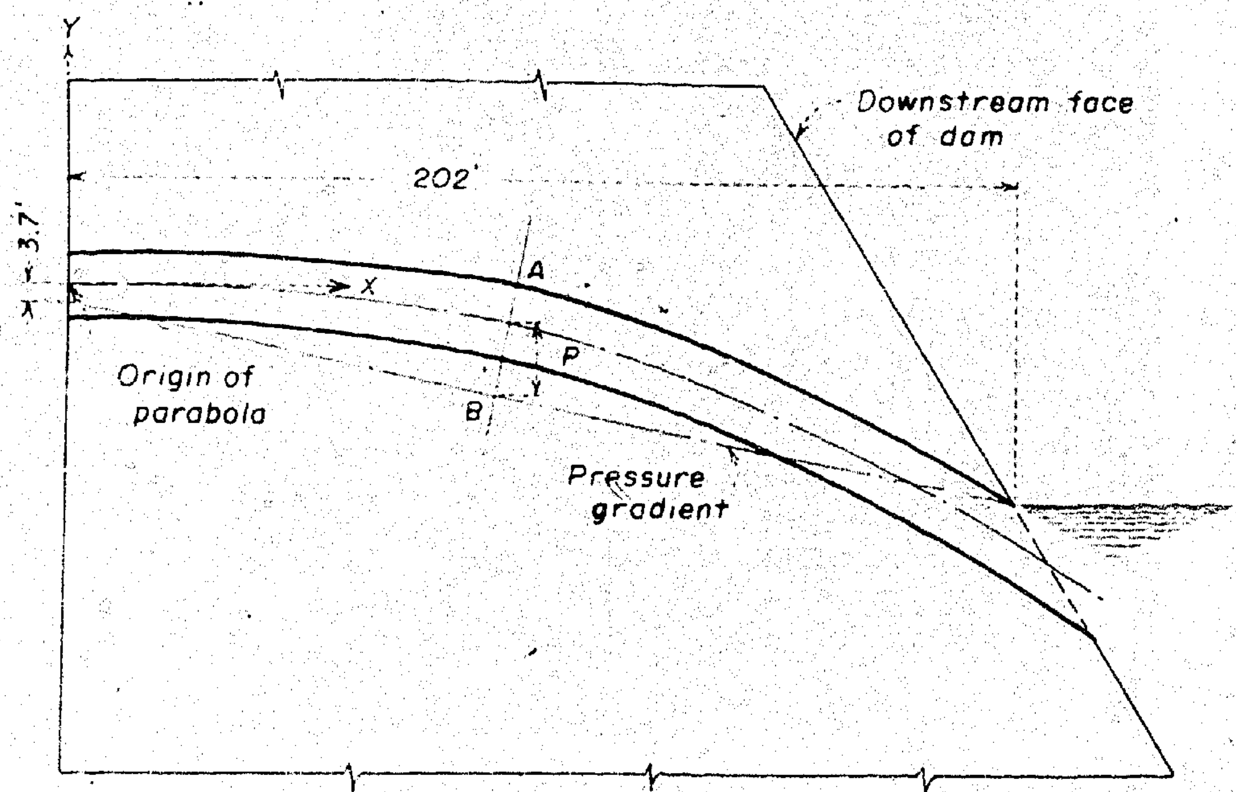
PIEZOMETER NUMBER	PRESSURE IN FEET OF WATER					
	WITHOUT TRASH-RACK	WITH RACK, RIB OPPOSITE ℄	WITH RACK, SPACE OPPOSITE ℄	RACK AT TOP POSITION	RACK AT DESIGNED POSITION	RACK AT BOTTOM POSITION
1	2.444	4.079	4.079			
2	0.610	1.988	1.920			
3	0.658	2.774	2.706			
4	1.789	2.051	2.039			
10	1.920	1.789	1.844			
D	15.136	15.398	15.791			
E						
F	1.794	1.026	0.856	0.064	0.986	1.067
G	2.837	2.233	2.098			
H	1.920	1.779	1.736			
I	1.265	1.224	1.196			
C	19.847	19.847	19.784			
7	7.941	7.548	7.679			

E.S.S. 1-13-39

FIGURE 9



SKETCH "a"



SKETCH "b"

E.S.G. 1-10-39