HYDRAULIC PERFORMANCE OF 96-INCH REGULATING GATES IN CLOSED CONDUITS

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Summary. This paper summarizes the results of tests and observations made in the field on specially designed 96-inch gates used to regulate releases through 102-inch conduits under a head in excess of 200 feet. Test equipment installed during construction is described briefly. The results given include pressures measured in parts of the gate and in the conduit, the air demand to the flow in the conduit downstream from the gate, vibration of the gate, and other hydraulic characteristics as determined from the test program and observations which extended over a 5-year period. Where possible, comparisons are made of data obtained from the prototype and that obtained from a model of the gate. The operation of the gate was found to be satisfactory.

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Sommaire. La note suivante résume les résultats des études et observations entreprises au chantier sur les robinets-vannes de 96 inches de diamétre utilisés pour régler le débit d'eau a travers des conduites de 102 inches de diamétre, sous une pression de 200 pieds. Les appareils à mesure qui ont été utilisés durant les études seront brievement décrits. Les résultats obtenus tiennent compte, des pressions observées en plusieurs endroits de la vanne, de la conduite, de l'aération nécessaire pour l'ecoulement du débit en aval de la vanne, de la vibration de la vanne, et d'autres caractéristiques hydrauliques déterminées au cours d'un programme de 5 ans de recherches. Les comparaisons sont faites dans la mesure du possible à partir des données obtenues sur place et sur modéle réduit de vanne. Le fonctionnement de la vanne s'est avéré satisfaisant.

INTRODUCTION

Shasta Dam is a multiple-purpose structure on the Sacramento River, 9 miles above Redding, California. It is operated to regulate the flow of the river for flood control, irrigation, industrial use, municipal consumption, and power generation. Releases of stored water in excess of the capacity of the turbines in the powerhouse are made through eighteen 102-inch outlets in the spillway section of the dam, Figure 1. These outlets are placed at three elevations, four are in a lower tier at elevation 742, eight in a middle tier at elevation 842, and six in an upper tier at elevation 942, as shown in Figure 2. The maximum heads on the outlets are 323, 223, and 123 feet, respectively, for the lower, middle, and upper tiers.

The outlets, passing directly through the dam to discharge in the spillway stilling pool, have circular bellmouth entrances set flush with the upstream face of the dam. The controls are located some 3 to 4 diameters downstream. Near the exit, the conduit is turned down into a depression which fairs into the face of the dam. A cone at the end of the water passage reduces the diameter from 102 to 93 inches. This reduction of area is designed to create a back pressure to compensate for the drop in elevation between the main conduit and the exit.

The controls are installed near the entrance of the outlet tubes, primarily for economic reasons. The most important single advantage in this location is that only the portion of conduit upstream of the control is subjected to full reservoir pressure during shutoff. The downstream portion is at atmospheric pressure during periods of no flow and is under nominal pressures resulting from frictional losses and back pressures from any constriction at the end of the outlet when releases are being made.

Ring-follower gates located near the upstream ends of outlets have been used for control in some previous installations. Operation of these gates is restricted to fully open or fully closed positions. Also, they are normally used in pairs. One serves as an emergency gate and the other the service gate.

Close regulation of the river downstream from Shasta Dam required outlet controls that would operate at incremental openings. Cavitation erosion and vibration from regulating valves installed at or near the upstream end of outlets in early Bureau of Reclamation structures created serious operation and maintenance problems. Therefore, satisfactory operation required considerable improvement in design. A single control in each outlet and provision of one coaster gate for all 18 outlets were desirable at Shasta Dam. This gate could be operated down the face of the dam for emergency closure of any single outlet or for unwatering a conduit for maintenance.

Concurrent with drafting of preliminary designs of the outlets in Shasta Dam, successful efforts were being directed toward revising the shape of the flow passages through needle valves to reduce cavitation erosion. During the course of these studies, the tube valve was developed. This control is fundamentally a needle valve with the downstream tip removed. This valve, with further development, showed promise of meeting design requirements for a control that would operate satisfactorily at all openings, if the downstream conduit was adequately aerated and would have an adequate coefficient of discharge to fill the downstream portion of the conduit when the valve was in the wide-open position.

A special tube valve was developed after much study, including extensive tests on models built to scales of 1:17 and 1:5.1, Figure 3. Before the testing program was completed, construction schedules at the dam were altered. Four valves for installation in the lower outlets were urgently needed to regulate releases during filling of the reservoir; hence, the model studies were ended before a completely satisfactory design for the valve was produced. The shape of the flow passage and arrangement of air vents for relief of subatmospheric pressures, as developed, were not adequate. There were a number of combinations of valve openings and reservoir heads wherein operation should be restricted because of the cavitation erosion that would result.

A number of piezometers were placed during fabrication and construction in the bellmouth entrance, the horizontal portion of the outlet, and in the downstream elbow and cone to extend and verify the results of the model studies. In general, these piezometer openings in the outlets were placed in locations corresponding to those used in the hydraulic models. One outlet in each of the tiers, lower, middle, and upper, was fitted with piezometer connections. Similarly, one control in each level was to be equipped with piezometers. Thus, the pressure pattern of flows in the prototype could be studied throughout the conduit and control.

A number of factors delayed fabrication and installation of controls for the 14 outlets in the middle and upper tiers. Because of the high cost and the fact that the tube valves were not considered adequate to regulate flows at all openings and heads, studies were initiated to develop a different control for use in the remaining outlets. These studies were started before there was opportunity to observe the field operation of the tube valves or utilize the test equipment placed during construction and fabrication.

Because design of the outlets contemplated use of tube valves, there was installed in each of the 14 outlets in the middle and upper tiers a bell-shaped segment of conduit to connect to the upstream valve body and a torus-shaped air vent, as shown in Figure 4. For economic reasons, it was desirable that use be made of these embedded elements in the design of an improved control.

The jet flow regulating gate, shown in Figure 5, was developed from the series of analytical and model studies.2/ The control is essentially a slide gate in a special housing, having an orifice at the upstream side and, as used at Shasta, a circular opening downstream. The unique feature is the use of a carefully planned jet contraction that permits complete ventilation and eliminates flow into the gate grooves. This circumvents the very low pressure areas in the conduit downstream from the gate and vibration caused from jet impingement in the gate slots. The gate is also simple from a structural and mechanical viewpoint.

The venting system shown in Figure 5 is an adaptation to existing conditions in the outlet where the expander, vent, and conduit were already installed to accommodate a tube valve. The venting system could ordinarily be of more simple design.

At the conclusion of the development studies, it was recommended that at least one of the gates to be installed at Shasta Dam be equipped with piezometer connections placed in similar locations to those used in

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2/ The Development of High Head Outlet Valves, J. W. Ball and D. J. Hebert, International Association for Hydraulic Structures Research, Report on the Second Meeting, Stockholm, June 1948, Appendix 14, page 237.

the model. Other observations regarding general behavior of the gate were recommended. Hence, the series of prototype measurements and observations covered in this paper were carried out.

The observations and tests made in the field on the tube valves in the lower tier of outlets are first covered briefly. A more detailed description of the field tests on the jet-flow gates in the middle and upper tiers follows.

OPERATION OF TUBE VALVES IN LOWER OUTLETS

Two series of field tests and detailed observations extending over a period of time were made on the tube valves in the lower outlets at Shasta Dam.

The field tests included observation of piezometric pressures at numerous points in the conduit and in the valves, the quantity of air flowing through the valve interior and to the torus-shaped air box immediately downstream from the valve, discharge through the outlet, and general behavior of the outlet system. During the tests, the valve was opened in steps of 10 percent travel from closed to wide-open position. The tests were made with heads on the valves up to about 265 feet.

Hydraulic pressures required to open and close the tube valve were measured when the reservoir head was approximately 265 feet. Valve openings causing pressures conducive to cavitation were observed to enable verification of the boundaries of the inoperative zones previously established by model studies.

Pressure measurements and determination of air flow, which reached a maximum of some 40 percent of maximum water discharge, checked closely with the respective values predicted by the model tests. The outlet discharge was determined by reducing the river discharge as shown at an established rating station by the amount of flow through the powerhouse, by utilizing the bell entrance as a flow nozzle, and by applying the usual laws of similitude to the hydraulic model test data. The average deviation in discharge for the various valve openings and for the three means used to calculate discharges was about 1 percent. Hence, an excellent verification of the model calibration was obtained.

Observations of the valves in operation showed smooth and satisfactory operation in general. One valve showed a severe vibration in a wide-open position, but this vibration did not occur below about 98 percent opening. A noise and rumble were evident in all four valves as closure was approached. Maximum noise level was attained at openings of from 62 to 77 percent.

The discharge on the face of the dam was generally satisfactory at the small and large valve openings. However, at the intermediate openings, the spray was quite severe, extending over a large part of the powerhouse area when the outlet on that side of the spillway was operating. The bulk of the spray occurred as a result of free-falling water striking the surface of the stilling pool.

Inspections made of the interior of the outlets revealed some pitting as a result of cavitation. The areas affected were small and the holes in the metal were about 1/16 inch deep and about 1/16 inch in diameter. In all places, the damage was not great, probably because the water contained a relatively high percentage of entrained air which should inhibit cavitation erosion.

Operating experience with the valves showed that the restricted range previously mentioned could be easily circumvented and closely regulated releases maintained by using different combinations of openings of the four valves. Operation in this manner proved to be quite satisfactory.

JET-FLOW GATES IN MIDDLE AND UPPER TIERS OF OUTLETS

Description of Equipment

Because the gate design was based on studies utilizing a hydraulic model constructed to a scale of 1:17, it appeared prudent to conduct special tests and observations in the field as soon as water levels and other conditions were favorable. As previously stated, piezometer openings and suitable piping were installed during construction in one outlet in each tier for the purpose of studying the hydraulic behavior of the conduit and the control. At the time of the installation in the conduits, it was assumed that tube valves would be used for all outlets. Use of the jet-flow gates in the 14 outlets of the middle and upper tiers did not appreciably alter the basic plan. Piezometers were installed in two of these gates, one in the middle tier and one in the upper tier, during fabrication and installation.

Details of one middle and one upper outlet and the locations of the piezometers are shown in Figure 4. Access ports were also provided in the 36- and 20-inch air supply lines for insertion of a pitot tube to measure air velocity and thus obtain volume of air supplied to the outlet. The location of all piezometers installed in the gates and gate extensions are shown in Figure 5.

The testing program included pressure, discharge, and air demand measurements at gate openings of 20, 40, 60, 80, and 100 percent for heads near maximum and near minimum. Although the maximum designed reservoir elevation is 1065, the probable limit, within a reasonable number of years, was estimated to be elevation 1043, while an estimate of a similar minimum was 983. The field measurements were made with the reservoir at these elevations. Tests at an intermediate reservoir level were originally proposed. To date, these tests have not been made and will probably not be made because of the favorable operation of the outlets at the two heads tested.

Also included in the field test program was measurement of the vibration of the bonnet of the gate in one upper outlet, at various openings, and with the reservoir at elevation 1043.

Test Procedure

Pressures were measured with water and mercury manometers connected through a manifold equipped with necessary valves. This system facilitated observation of pressures from a large number of piezometer openings with a minimum of manometers, Figure 6. Subatmospheric pressures were measured with mercury U-tubes. An air line and a high pressure waterline were extended to the observation stations in galleries inside the dam. All piezometer lines were carefully purged of air immediately prior to recording pressures, except those that indicated subatmospheric pressures. These were cleared of water by allowing compressed air to flow through the lines prior to connecting the U-tubes.

The velocity of air flowing through the air supply ducts was measured with a specially constructed Prandtl-type pitot tube. The readings were taken in the pattern prescribed by the equal area method of determining the quantity of flow.

Vibration of the valve bonnet for the outlet tested in the upper tier was measured with a commercial instrument. In operation, this instrument generates a voltage proportional to the velocity of the vibrational component perpendicular to its base. This voltage is generated by the motion of a small coil mounted on the end of a pivoted shaft that is free to move in a magnetic field created by two magnets. The electricity thus generated is amplified and fed into a recording oscillograph to obtain both frequency and amplitude of vibration.

Results of Pressure Measurements

Results of the pressure measurements made at many locations in the gates and conduits are given in feet of water referenced to the piezometer orifice. This has been done because the primary interest is in pressures existing at the flow boundaries. Pressures measured at piezometers located in the flow passages are shown graphically in Figures 7 to 12. Pressures measured at piezometers in the gate bonnet, the gate slot, and in the air duct are given in Tables 1 and 2 because no particular pressure pattern was to be expected.

Locations of the piezometer orifices in the gates and conduits are shown in Figures 4 and 5. These locations are also shown on a number of the graphs for clarification.

Pressures measured in the middle and upper outlet, both upstream and downstream from the gates and gate extensions, are shown in Figures 7 and 8. All pressures shown in these figures are plotted in feet of water referenced to the center line of the conduit. Pressure readings from the four piezometers in each conduit just upstream from the gates were corrected to center line elevation.

Adequate ventilation of the flow was apparently achieved because pressures only slightly below atmospheric were observed downstream from the gate. Since the conduit in this area is not filled for most flows, there is considerable fluctuation of pressure. No unusual conditions, other than those that might be attributed to possible experimental error, were noted. Available model data do not permit direct comparison with the measured prototype pressures, and model results are not shown in these figures.

Pressures measured at the top and bottom of the elbow and exit cone of the outlets are shown in Figure 9. Observations were made in one outlet in each of the middle and upper tiers. The elbows and cones of both outlets are of the same design. Thus, it may be assumed that the same results would be obtained from one outlet operating at four different heads. The results are shown in this manner. The locations of the piezometers are given on the graphs. Severe subatmospheric pressures exist on the invert of the conduit at the upstream end of the elbow; however, physical inspections of this area have revealed no cavitation erosion. Considerable entrained air is present in the flow and would be expected to inhibit such action.

Piezometers were placed on the invert of the conduit immediately downstream from the gate to determine if aeration was effective and to obtain some indication of the behavior of the jet in this area. Pressures observed at the piezometer orifices in this group in both the middle and upper tier of outlets are shown in Figure 10. Data obtained from the model are also shown when comparable. No unusual conditions were noted. The pressure pattern changes considerably because of the altered flow conditions resulting from the different gate openings and different heads.

Pressures measured at a group of piezometers placed in the lower left quadrant of the conduit downstream from the gate slots are shown in Figure 11. Although similar installations were made in one outlet in each of the middle and upper tiers, the results are considered to be obtained from one group with four reservoir heads on the conduit. These installations were also made to study the efficiency of the aeration system and the behavior of the jet. The location is in an area of rapid pressure changes resulting from both gate movement and head change. No serious subatmospheric pressures were observed.

As previously stated, the torus-shaped air vents were placed in all outlets. Piezometers were provided in the downstream lips of the vents. The gate extension of the jet-flow gates covered the vent opening, as shown in Figure 5. One piezometer in each tier was also covered by the gate extension. Six piezometers, three in the lower left quadrant and three in the upper left quadrant, remained in these groups in each of the two test conduits. All were located in a slight depression (Figure 5). The pressures measured at these piezometers are shown in Figure 12. No adverse pressure conditions are noted as a result of the slight discontinuity in the interior surface of the conduit. The pressure pattern for all piezometers is quite similar for corresponding gate openings and heads.

Pressures observed at the piezometers located in the track for the gate and in the gate slot are given in Table 1. No dangerously low pressures were noted. No excessively high pressures, which might indicate impingement of the jet in the slot, were observed.

Table 1

SHASTA DAM--102-INCH OUTLETS--PRESSURES IN MODEL AND PROTOTYPE
IN FEET OF WATER AT PIEZOMETER OPENING
(See Figure 5 for locations of piezometers)

Piezometer No.	Tier	Head on outlet (feet of water at entrance)	Gate opening in percent				
			20	40	60	80	100
			(Pressure in feet of water at piezometer opening)				
Pressures in Roller Track of Gate							
18	Upper	40.62	-0.23	-1.02	-0.68	-0.14	-0.34
	Upper	100.71	-1.20	-2.31	-1.36	-0.61	-0.68
	Middle	140.62	-1.49	-1.76	-1.70	-0.95	-0.14
	Middle	200.16	-0.27	-2.86	-0.27	-1.09	-0.54
	Model	100 (proto)	-1.09	-1.79	+4.57	-0.97	-1.78
19	Upper	40.62	0.00	-0.27	-0.34	-0.14	0.00
	Upper	100.71	+14.78	-1.63	-1.36	-0.54	-0.27
	Middle	140.62	-0.41	-1.76	-1.97	-0.95	-0.34
	Middle	200.16	0.00	-3.40	-1.09	-1.36	-0.54
	Model	100 (proto)	-0.28	-1.01	-0.80	-0.38	-1.18
Pressures in Gate Slot							
15	Upper	40.62	-0.14	-0.41	-0.68	-0.47	-0.34
	Upper	100.71	-0.70	-1.90	-1.77	-0.82	-0.61
	Middle	140.62	-2.98	-1.49	-2.31	-8.20	-0.34
	Middle	200.16	-0.54	-2.72	-1.09	-1.09	-0.54
	Model	100 (proto)	-1.52	-1.95	-1.74	-1.32	-1.75
16	Upper	40.62	0.00	-0.41	-0.34	-0.34	-0.34
	Upper	100.71	-0.70	-1.90	-1.43	-0.75	-0.54
	Middle	140.62	-3.19	-1.15	-1.83	-0.75	-0.14
	Middle	200.61	-0.41	-2.99	-0.27	-0.95	-0.54
	Model	100 (proto)	-1.00	-1.51	-1.01	-0.60	-1.14
17	Upper	40.62	0.00	0.00	0.00	-0.34	-0.14
	Upper	100.71	+16.06	-1.09	-0.82	-0.61	-0.54
	Middle	140.62	-2.98	-0.95	-1.56	-1.22	-0.14
	Middle	200.61	-0.41	-2.31	-0.14	-1.09	-0.27
	Model	100 (proto)	-0.26	+2.55	+1.91	+0.04	-0.24
20	Upper	40.62	0.00	-0.20	-0.14	0.00	0.00
	Upper	100.71	+16.56	+12.42	-2.04	-1.16	-0.75
	Middle	140.62	-4.07	-0.41	-1.09	-1.36	-0.34
	Middle	200.61	+12.42	-1.50	-0.54	-0.54	-0.14
	Model	100 (proto)	+0.28	+14.00	+0.09	-0.09	-0.08
36	Upper	40.62	0.00	-0.54	-0.54	-0.47	-0.34
	Upper	100.71	-4.49	-1.77	-6.32	-0.95	-0.75
	Middle	140.62	0.00	-2.03	-1.22	-0.95	-0.34
	Middle	200.61	+10.55	-3.40	-0.54	-0.82	-0.68
	Model	100 (proto)	--	--	--	--	--
37	Upper	40.62	0.00	-0.14	-0.54	-0.47	-0.34
	Upper	100.71	-6.12	-1.70	-1.43	-0.82	-0.54
	Middle	140.62	--	-7.32	-3.39	-7.53	-4.47
	Middle	200.61	-0.14	-3.26	-0.82	-1.22	-0.41
	Model	100 (proto)	--	--	--	--	--
38	Upper	40.62	0.00	-0.14	-0.54	-0.41	-0.34
	Upper	100.71	-4.76	-1.16	-1.50	-0.88	-0.61
	Middle	140.62	+12.08	-4.27	-1.97	-0.75	-0.48
	Middle	200.61	+21.27	-2.72	-1.22	-1.36	-0.68
	Model	100 (proto)	--	--	--	--	--

Table 2 gives the results of pressure measurements made in the bonnet of the gate and in the air passage. The locations of the piezometers used for these measurements are given in Figure 5.

It was concluded from the results of the model studies that pressures less than 3 feet of water below atmospheric would not occur at any point in the gate or in the conduit immediately downstream.

Study of the pressure plots and tables will show that subatmospheric pressure was measured in the prototype gate at 18 different places. All except 4 of these locations produced pressures less than 3 feet below atmospheric. In the conduit immediately downstream from the valve, 9 of the 12 piezometers showed pressures less than the 3 feet below atmospheric predicted from the model studies. The minimum value obtained was 15 feet of water below atmospheric at Piezometer 31 in the conduit of the middle tier when the valve was 60 percent open and under a head of 200.2 feet. The minimum subatmospheric pressure in the control device proper was 10 feet of water at Piezometer 28 in the gate in the upper tier when the opening was 20 percent and the head was 100.7 feet.

It is significant to note that the maximum design head in the upper tier is 123 feet, and that for the middle tier is 223 feet. Pressures may be lower when the outlets are operating under the maximum head. Because the tests included measurements when the head was 80 percent of the maximum for the upper tier and nearly 90 percent of the maximum for the middle tier, no severe subatmospheric pressures are anticipated.

Results of Measurements of Air Delivered to Gate and Conduit

An air supply is provided around the jet leaving the gate and to the gate slot to relieve low pressures conducive to cavitation erosion. The

Table 2

SHASTA DAM--102-INCH OUTLETS--PRESSURES IN MODEL AND PROTOTYPE
IN FEET OF WATER AT PIEZOMETER OPENING
(See Figure 5 for locations of piezometers)

Piezometer No.	Tier	Head on outlet (feet of water at entrance)	Gate opening in percent				
			20	40	60	80	100
			(Pressure in feet of water at piezometer opening)				
Pressure in Bonnet of Gate							
12	Upper	40.62	-0.07	-0.47	-0.75	-0.34	-0.14
	Upper	100.71	-0.60	-1.12	-1.16	-0.48	-0.41
	Middle	140.62	-0.14	--	--	--	--
	Middle	200.16	0.00	-0.75	-0.27	0.00	+1.51
	Model	100 (proto)	-0.35	-0.54	-0.50	-0.12	+1.42
Pressure in Horizontal Air Passage							
13	Upper	40.62	-0.07	-0.68	-0.95	-0.61	-0.34
	Upper	100.71	-0.90	-1.90	-1.63	-0.82	-0.41
	Middle	140.62	-0.61	-1.49	-2.31	-1.76	-0.14
	Middle	200.16	-0.88	-3.13	-0.95	-1.50	-0.14
	Model	100 (proto)	-0.58	-0.90	-0.84	-0.22	+1.02
14	Upper	40.62	-0.07	-0.68	-0.95	-0.61	-0.34
	Upper	100.71	-0.80	-1.90	-1.77	-0.82	-0.27
	Middle	140.62	-0.81	-1.56	-2.31	-1.02	0.00
	Middle	200.16	-0.88	-2.86	-0.82	-0.54	-0.14
	Model	100 (proto)	--	--	--	--	--

air supply piping consists primarily of a 36-inch-diameter air duct leading from the top of the dam to a semicircular passage above the gate extension (Figure 5). This duct terminates immediately downstream from the gate leaf. In addition, there are two 20-inch-diameter air ducts that terminate in the upstream side of the lower right and left portions of the gate slot.

Velocities were measured in the 36-inch duct and in each of the 20-inch ducts for a number of gate openings and for two reservoir heads on one gate in each of the middle and upper tiers of outlets. The quantity of air being delivered through the duct system was calculated from the measured velocities.

The amount of air delivered to the control gate and conduit is shown in Figure 13. Also shown in this figure is the amount of air measured in the 6-inch model operating at a head of 100 feet (equivalent of 1,700 feet prototype). The plot merely shows the quantity of air required by the model without transfer to prototype values. This figure shows that the maximum rate of flow to the gate and conduit was nearly 2,000 cubic feet per second for the outlet in the middle tier, operating under a head of 200.2 feet at a valve opening of 45 percent. A corresponding value for the outlet in the upper tier was 1,600 cubic feet per second at an opening of 45 percent, with a head on the outlet of 100.7 feet. The maximum velocity measured in the 36-inch air duct was 286 feet per second, and in the 20-inch ducts, 81 feet per second.

Results of Vibration Measurements

Vibration of the bonnet of one gate in an outlet in the upper tier was obtained by placing an electrical pickup on one of the horizontal ribs near the center of the downstream side of the bonnet. The movement was measured in a vertical direction only when the head on the outlet was 100.7 feet. Frequency of vibration at gate openings of 20 and 40 percent varied from approximately 30 to 130 cycles per second; at openings of 60 and 100 percent, frequency variation was between 4 and 38 cycles per second. No record was obtained at an opening of 80 percent.

The magnitude of vibration at the two smaller openings was a maximum of 0.0003 inch. At the larger openings, the maximum amplitude was approximately 0.00001 inch. Each of these two numerical values was considered to be well below the accuracy of the instrument used. The measurements show that the movement was negligible. No noticeable vibration was observed during operation of the other gates. As indicated by the model studies, the vibration is less at the larger gate openings.

Figure 14 is a reproduction of portions of the vibration records made at gate openings of 40 and 100 percent. Actual movement is greatly exaggerated in the record because of amplification of the electrical current from the vibration pickup. For example, at a frequency of 22 cycles per second, an amplitude of 0.75 inch on the record is equivalent to actual movement of the gate bonnet of approximately 0.00005 inch. The model study did not include recording of vibration. Therefore, no direct comparison may be drawn.

Results of Discharge Measurements

Discharges through the outlets were determined from the differential pressures between the reservoir and a point in the outlet 19 feet 2-1/16 inches from the upstream face of the bellmouth entrance. The relationship between this differential head and the corresponding discharge was obtained from previous tests on an outlet in the lower tier when the quantity of flow was measured at a current meter gaging station a short distance downstream from the dam. Since the entrance to the outlet tested in the lower tier is identical to those in the other tiers, the same relationship between the differential head and the discharge should exist.

The coefficient of discharge of the jet-flow gate was computed from the data thus obtained for the various gate openings and heads and is shown in Figure 15. This figure also shows the values predicted from the hydraulic model. The coefficient of discharge, "C," used in the plot is defined as:

$$Q = CA \sqrt{2gh}$$

where

Q is the discharge in cubic feet per second

A is the area of the conduit in square feet

h is the total head in feet measured 1 diameter upstream from the gate

g is the acceleration of gravity (32.2 feet per second per second)

During the calibration tests on the bellmouth in the lower outlet, the current meter measurements at the gaging station included the total flow in the river; that is, the total flow through the test outlet and through the turbines. The latter discharge was calculated from scroll case pressure taps which were calibrated at the time the performance tests were made on the turbines. Thus, errors in calculating the discharge through the outlet are possible. For this reason, the data obtained at the low head of 40.62 feet on the upper outlet were not used in determining the coefficient of discharge.

The values of the discharge coefficient obtained for the other heads show good agreement, except at gate openings of 80 percent. Also, prototype values are consistently lower than those predicted from the hydraulic model. At the fully open position of the gate, the model and prototype agree within expected limits, but at an opening of 20 percent, the model discharge was approximately 1.4 times the value determined in the field. These field data are not conclusive because of the indirect procedure in obtaining the prototype discharge. It is therefore recommended that the model tests be utilized in determining the capacity of the river since such data have been found quite accurate at other installations.3/

Field Inspections and Observations

Inspection of the gates and conduits at the time of the first tests revealed no serious cavitation erosion or other incipient damage. Close observation and frequent inspection were continued over a period of years.

A report of inspection of the gates made 5 years after installation and some 2-1/2 years after the first tests states in part:

> "We are pleased to report that, during the 5 years since their installation, these gates have performed satisfactorily on all occasions and have required a minimum of maintenance. In addition, the gates are of relatively simple construction, are easily operated, and can be accurately set to any opening, making them desirable for regulating purposes. The amount of spray resulting from the discharge of these gates is generally less than from the tube valves. * * * The gates are reasonably quiet at all openings and particularly so at full opening. There is no appreciable hydraulic or mechanical vibration in the gates themselves. * * * Leakage from these gates has been

3/ "Discharge Coefficients of Gates and Valves," by Charles W. Thomas, Paper No. 746, Vol. 81, July 1955, Proceedings, American Society of Civil Engineers.

slight. There was practically no leakage after they were first placed in service, and this is still true for about half the gates. In the other cases, the leakage is generally less than 25 gallons per minute and appears to come from only one or two places on each of the gates. At the present time, there has been no occasion to dismantle any of the gates for maintenance. The downstream portions of the gates are inspected annually, since they are readily accessible through a manway while the gate is closed, without requiring use of the river outlet coaster gate. Practically the only maintenance necessary has been the repair of the interior paint on the downstream portion of the gates and conduits and protective lubrication of the surfaces of the wheels and track and the mechanical drive mechanism."

A log of operation of the control devices for a period of some 5 years after installation is given in Table 3. No. 2 outlet in the middle tier was operated the greatest length of time, a total of 1,572 hours. This gate was operated 802 hours at partial openings of 54 percent or less, while the remaining 770 hours were at fully open position. The total number of hours of service for No. 2 outlet in the upper tier was 2,336 hours, of which 22 were at an opening of 54 percent or less. The operation of the control device has been sufficient to reveal any serious deficiencies in design if such had existed.

CONCLUSIONS

Special tests, combined with experience and frequent inspections for a period of some 5 years, reveal that the gates installed in the middle and upper tiers of outlets at Shasta Dam are entirely satisfactory. The special studies were conducted when the gates were operating at various openings under heads ranging up to 90 percent of the maximum design value for the middle tier and 80 percent for the upper tier. The minimum pressure occurring in the gate proper was measured to be 10 feet of water below

Table 3

SHASTA DAM--96-INCH OUTLET GATES
Tabulation of Hours and Condition of Operation--Gates Operated at Full Opening Except as Indicated

Gate No.	Hours 4-16-48 to 7-18-48 lake elev. 1033 to 1036	Hours 12-8-50 to 12-26-50 lake elev. 1021 to 1028	Hours 2-6-51 to 2-23-51 lake elev. 1026 to 1033	Hours 2-2-52 to 2-25-52 lake elev. 1033 to 1041	Hours 4-5-52 to 5-27-52 lake elev. 1065	Hours 1-9-53 to 1-29-53 lake elev. 1018 to 1038	Summary hours: Below 54%	Summary hours: At 100%	Total
Middle Tier Elevation 842									
1		5)				78	5	78	83
2	1,350 (1)	2)				220	802	770	1,572
3	970 (2)	90) at		52		238	610	740	1,350
4	60	99) 52%	48	135		307	99	550	649
5	270 (3)	76)		116		283	82	663	745
6		77)				217	77	217	294
7						200		200	200
8		2				22		24	24
Upper Tier Elevation 942									
1		244)	180	309		377	80	1,030	1,110
2		276)	402	349	896	413	22	2,314	2,336
3		178) (4)	201	270	382	432	17	1,446	1,463
4		171)	213	190	202	421	8	1,189	1,197
5		251)	363	320	613	418	18	1,937	1,965
6		213)	192	270		322	33	964	997

(1) 730 hours at 48 percent to 54 percent; 70 hours below 48 percent.
(2) 400 hours at 48 percent to 54 percent; 120 hours below 48 percent.
(3) 6 hours below 48 percent.
(4) Below 54 percent opening for hours shown in summary.

atmospheric, about 2 feet downstream from the orifice. Immediately downstream from the control device, the minimum pressure was 15 feet of water below atmospheric at a point on the invert of the conduit approximately 9 feet 6 inches from the orifice. These subatmospheric pressures are more severe than predicted from the hydraulic model studies, but are not of sufficient magnitude to produce cavitation, as evidenced by frequent inspections.

Measured movement of one gate bonnet and continued observation have shown that there is a minimum of vibration of the gates. The gates are reasonably quiet at all openings and particularly so at full opening.

The maximum air demand for the prototype gate was found to be nearly 2,000 cubic feet per second for the outlet tested in the middle tier under a head of 200.2 feet at a valve opening of 45 percent. The corresponding value for the upper tier was 1,600 cubic feet per second at an opening of 45 percent, with a head on the outlet of 100.7 feet. The maximum velocity in the 36-inch air ducts was 286 feet per second; and in the 20-inch ducts, the largest value measured was 81 feet per second. These velocities are not of sufficient magnitude to produce objectionable noise.

The quantity of water discharged through the outlets is very close to that predicted from the model studies for the wide-open gate position, but at lesser gate openings, the difference between the predicted value and the quantity measured in the field is appreciable. However, the indirect method of obtaining the quantity of flow during the prototype studies is susceptible to considerable error, and therefore the results are not conclusive.

As a result of the comprehensive investigations at Shasta Dam, it is concluded that the gates provided for the outlets in the middle and upper tiers are entirely satisfactory for operation without limitation of opening or existing head.

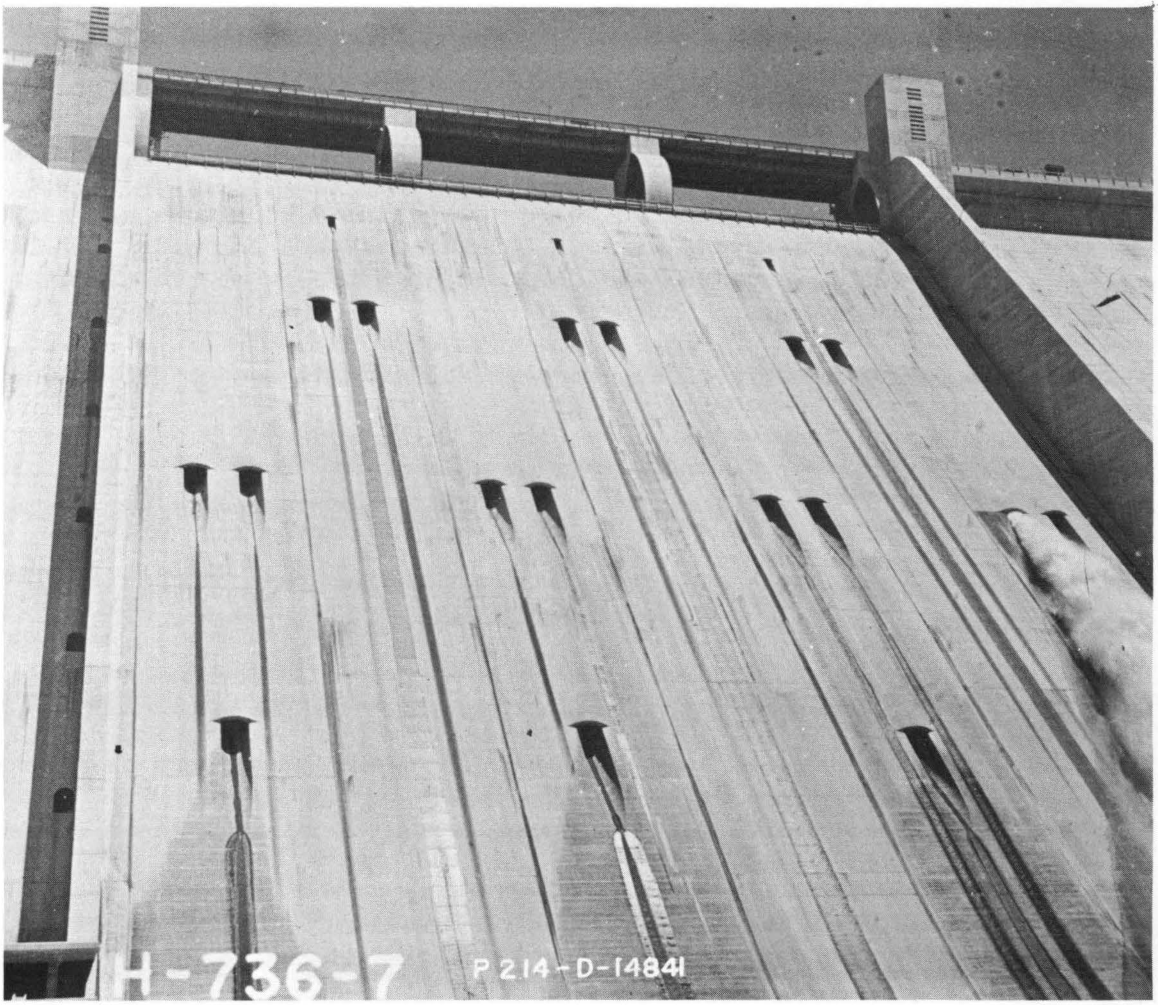


Figure 1. Shasta Dam--102-inch outlets--Spillway section

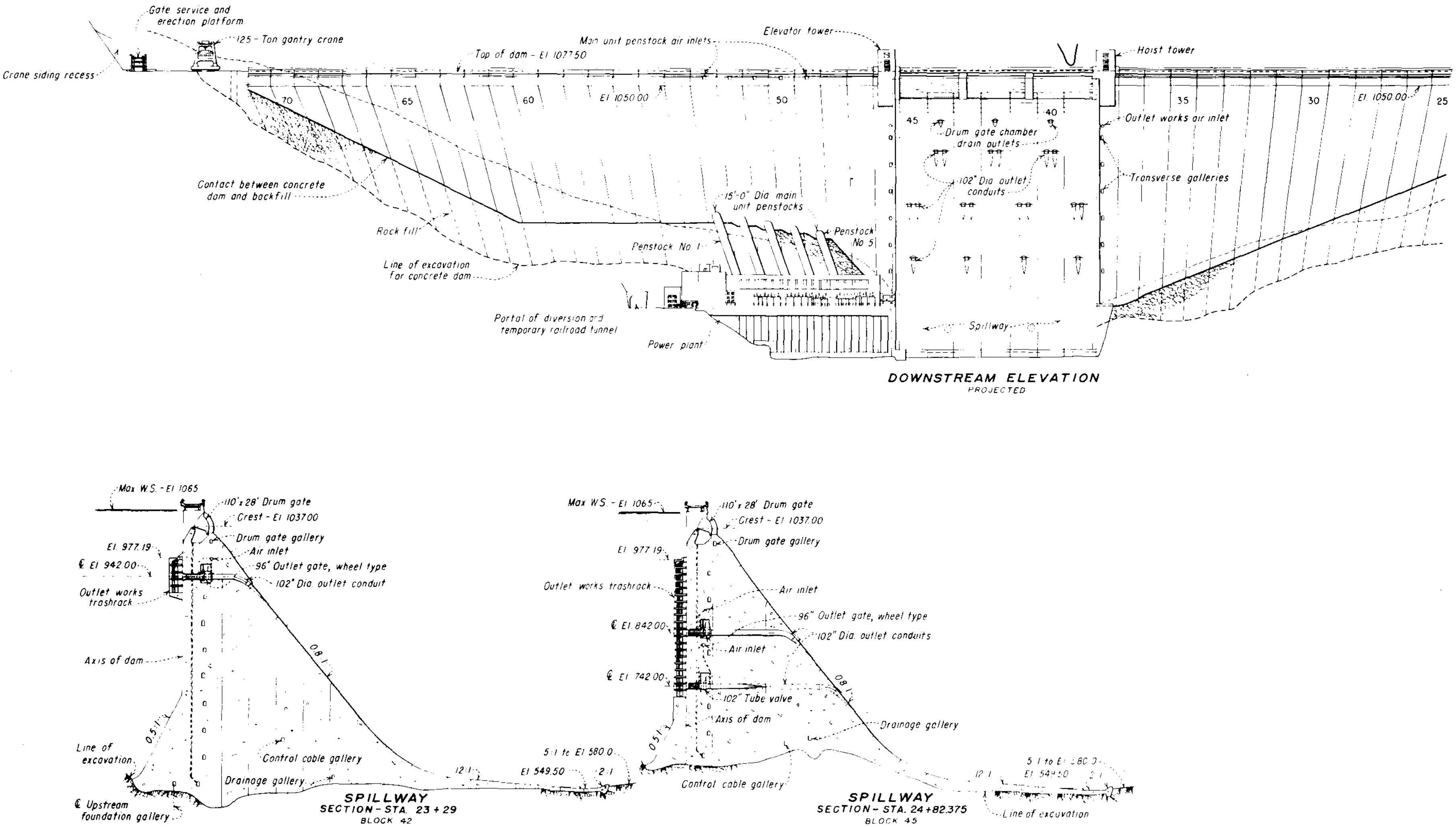


Figure 2. Shasta Dam--102-inch Outlets

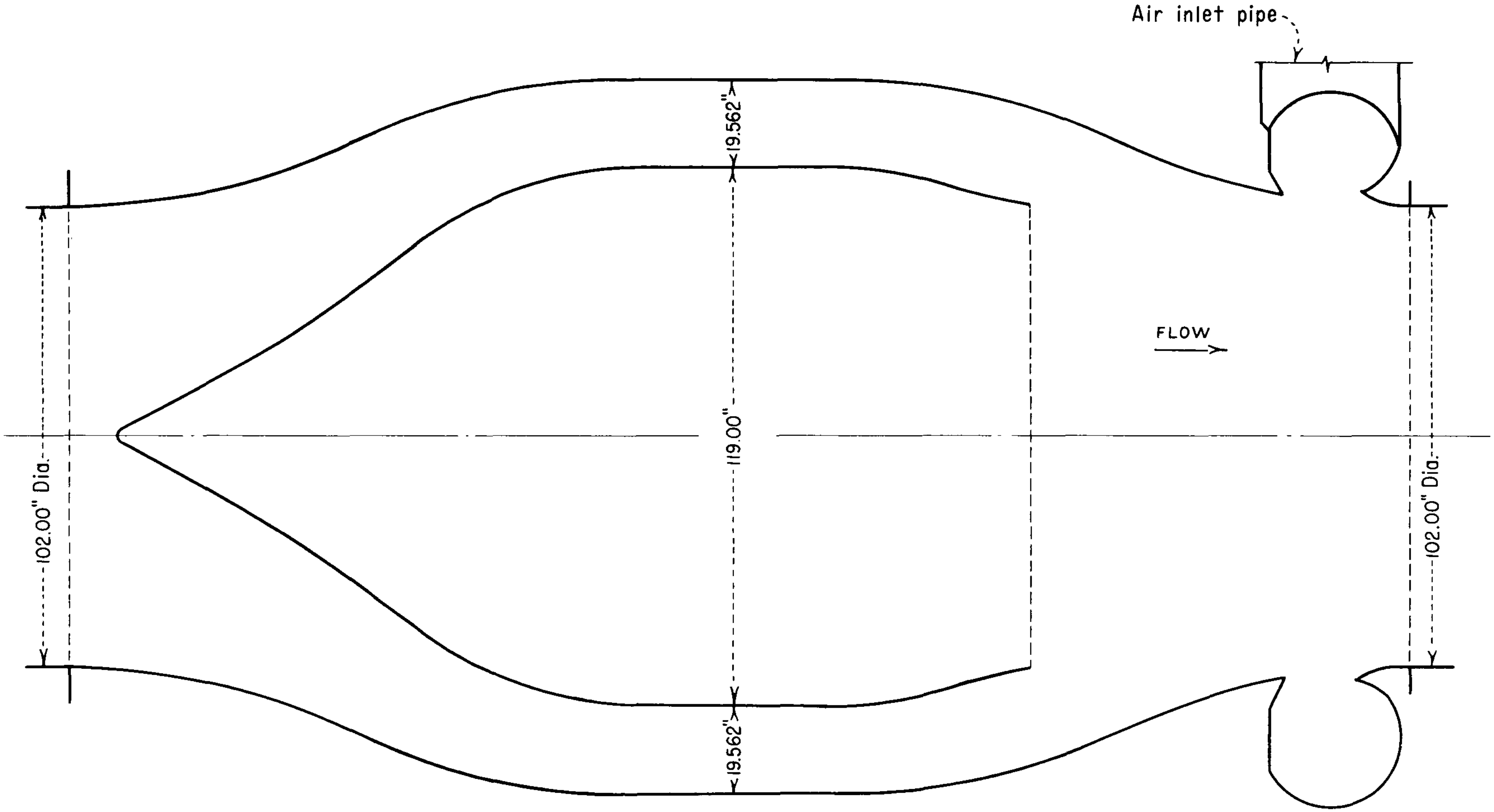


FIGURE 3
SHASTA DAM -- OUTLETS -- LOWER TIER TUBE VALVE

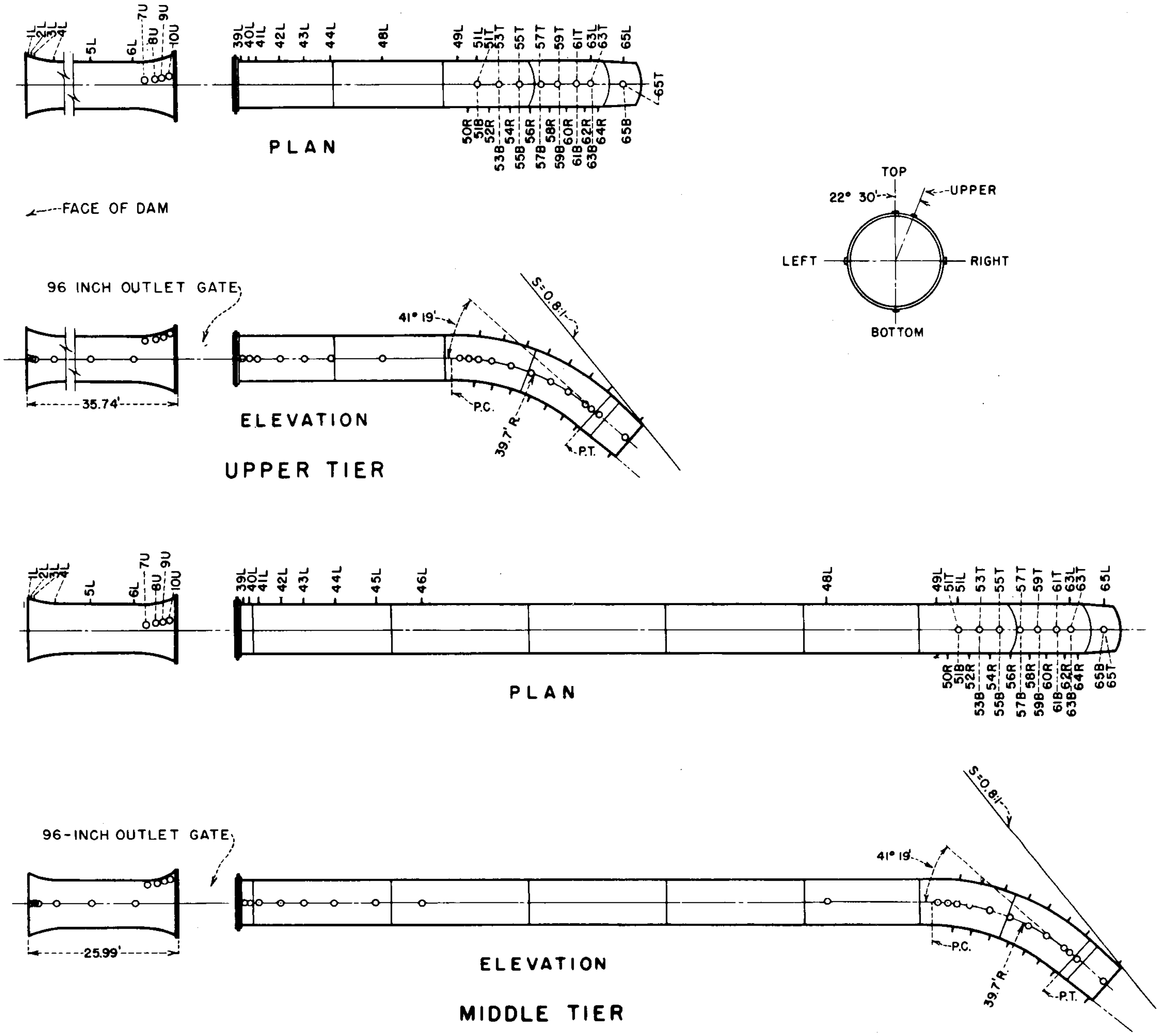


FIGURE 4
SHASTA DAM--OUTLETS--MIDDLE AND UPPER TIERS
PIEZOMETER LOCATIONS IN CONDUIT

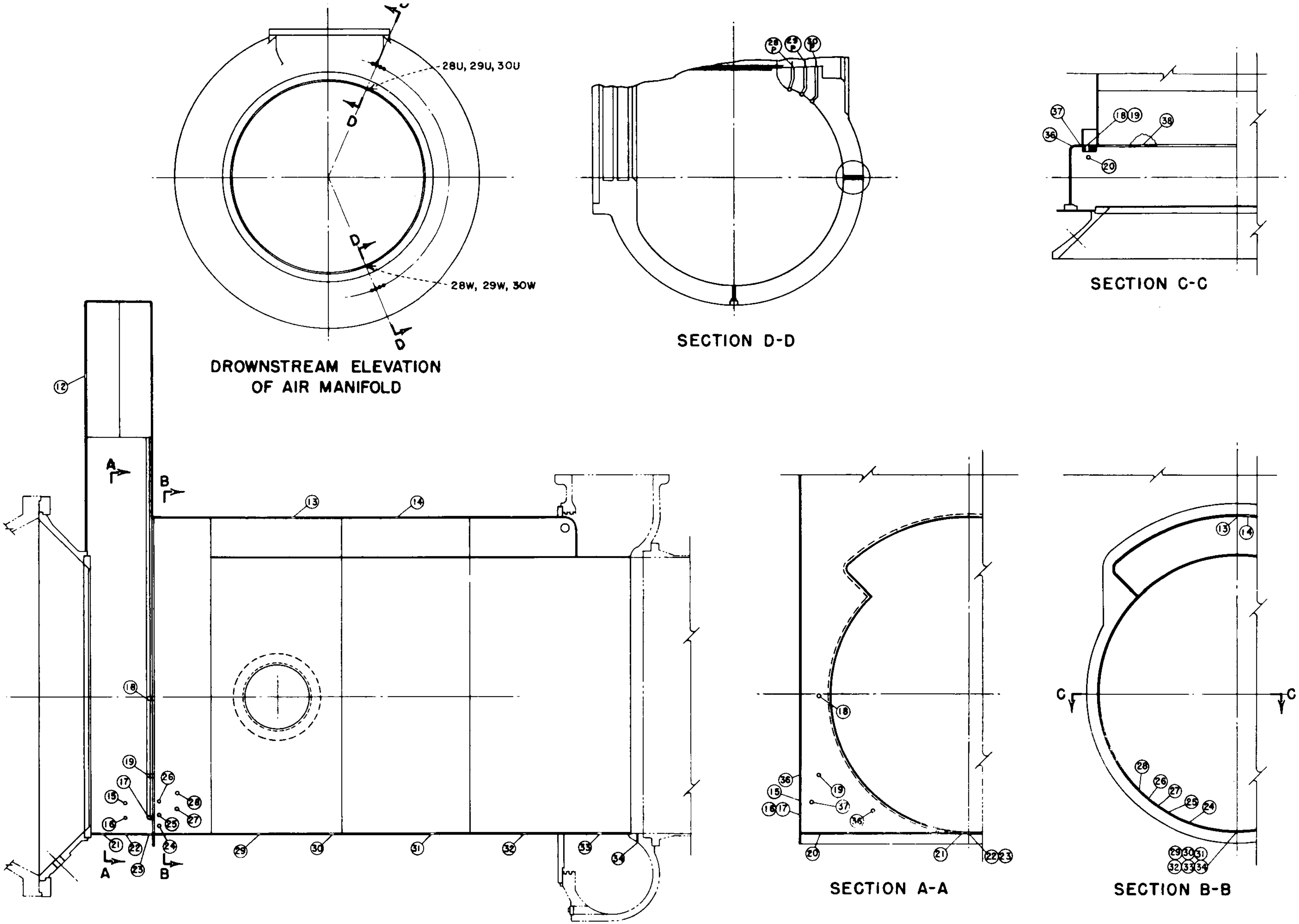


FIGURE 5
SHASTA DAM--OUTLETS--MIDDLE AND UPPER TIERS

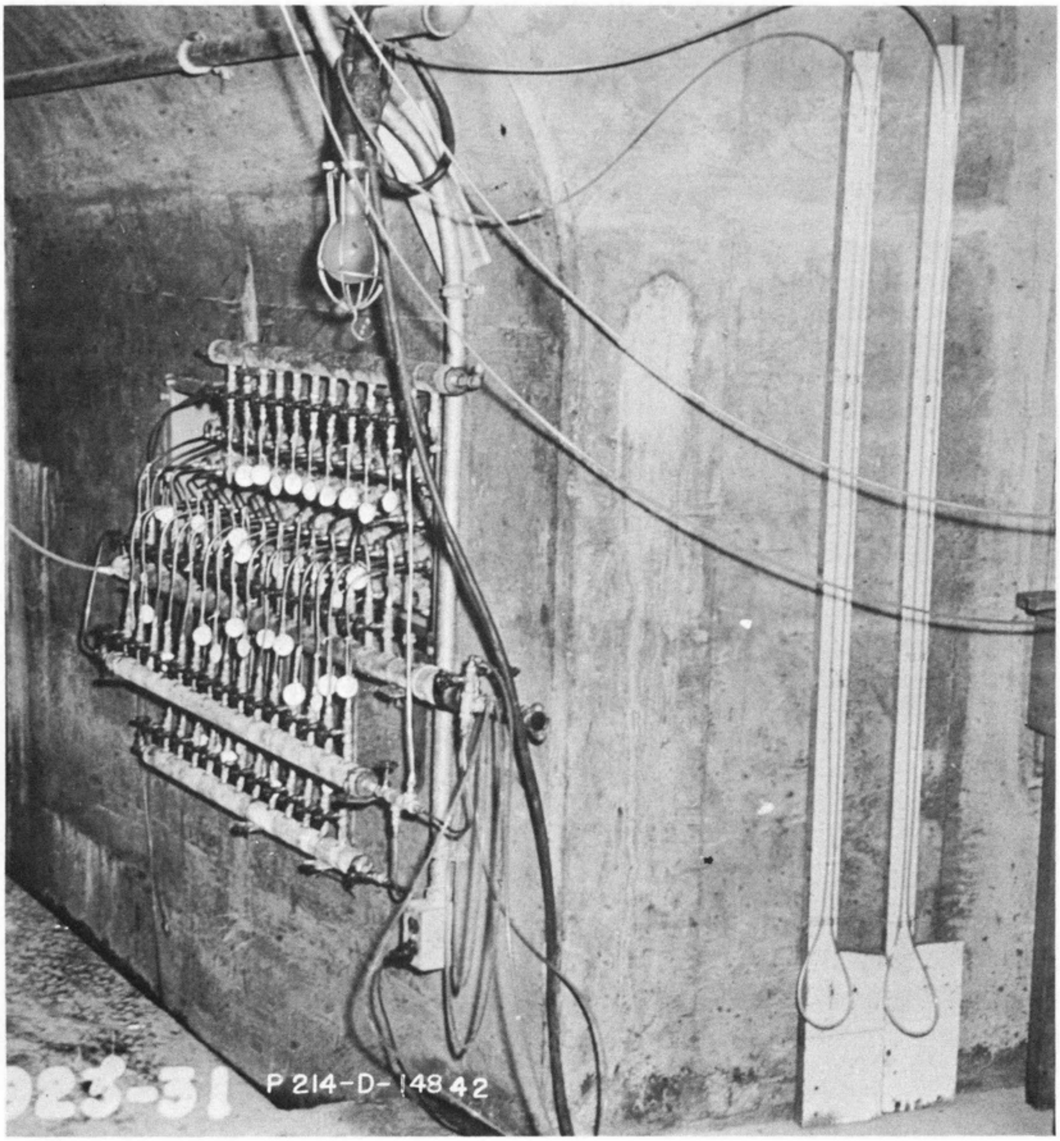


Figure 6. Shasta Dam--Field Studies on outlets--Station in gallery for observation of pressures

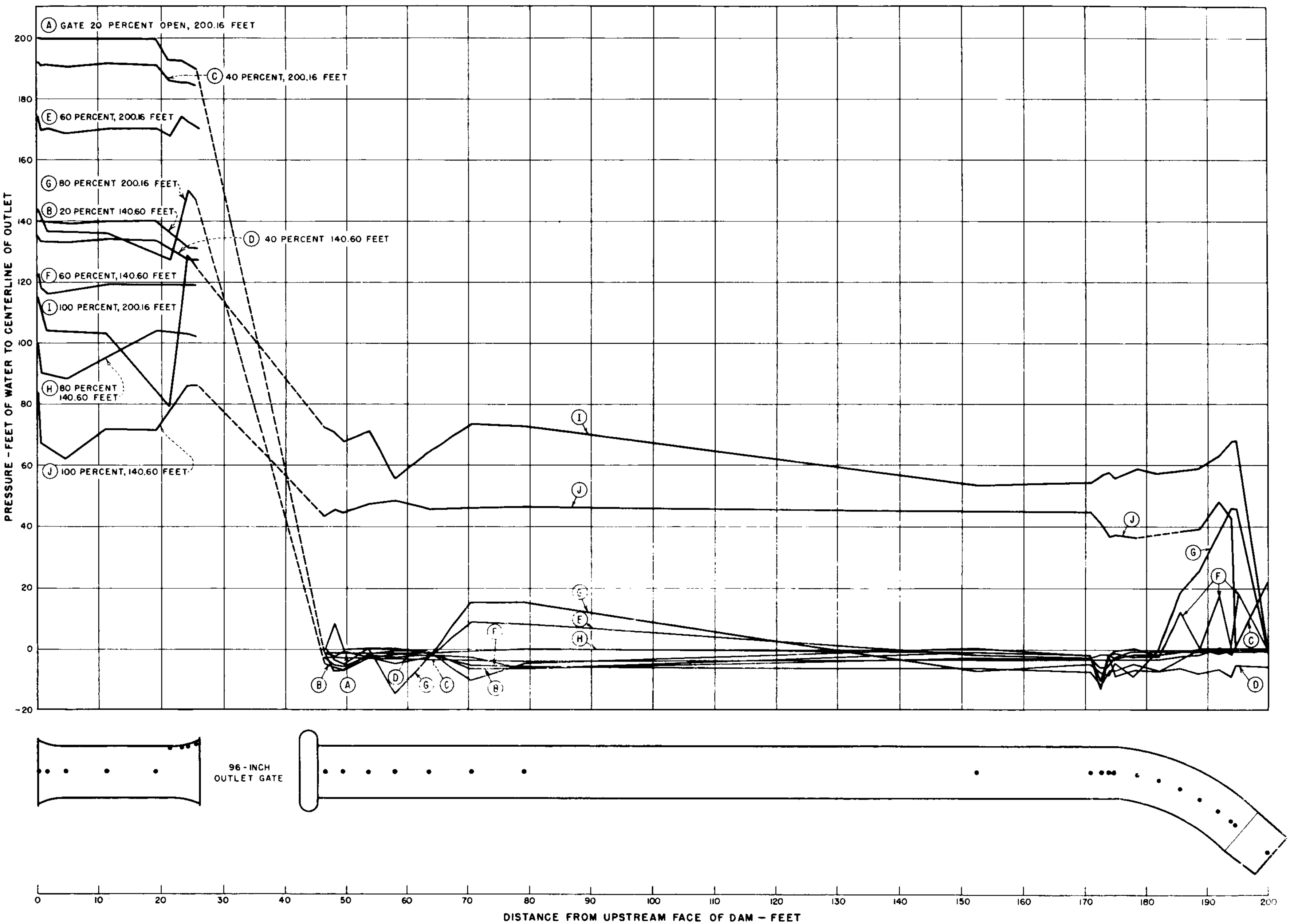


FIGURE 7

SHASTA DAM -- OUTLETS -- MIDDLE TIER

PRESSURES AT CENTERLINE OF CONDUIT

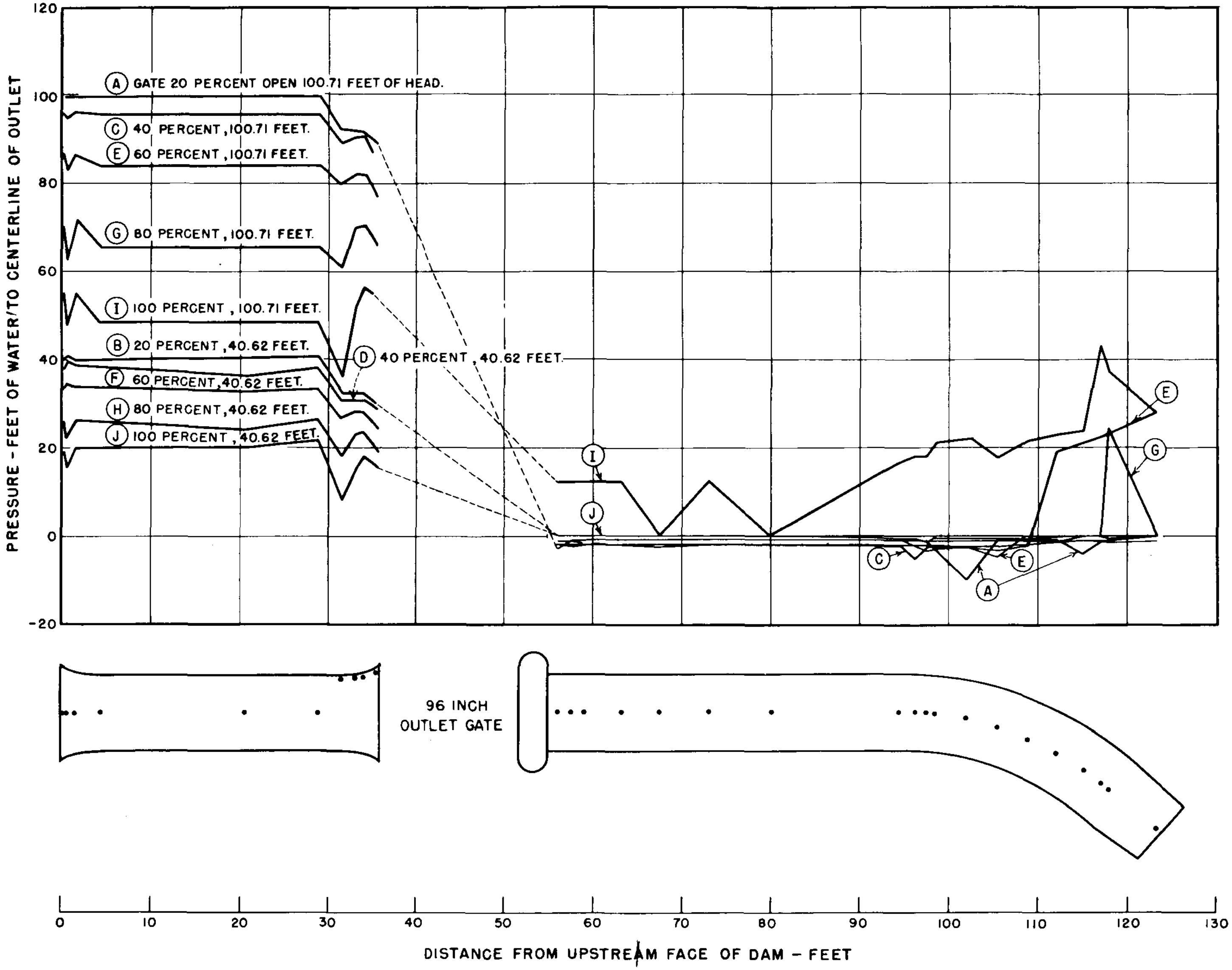


FIGURE 8
SHASTA DAM -- OUTLETS -- UPPER TIER
PRESSURES AT CENTERLINE OF CONDUIT

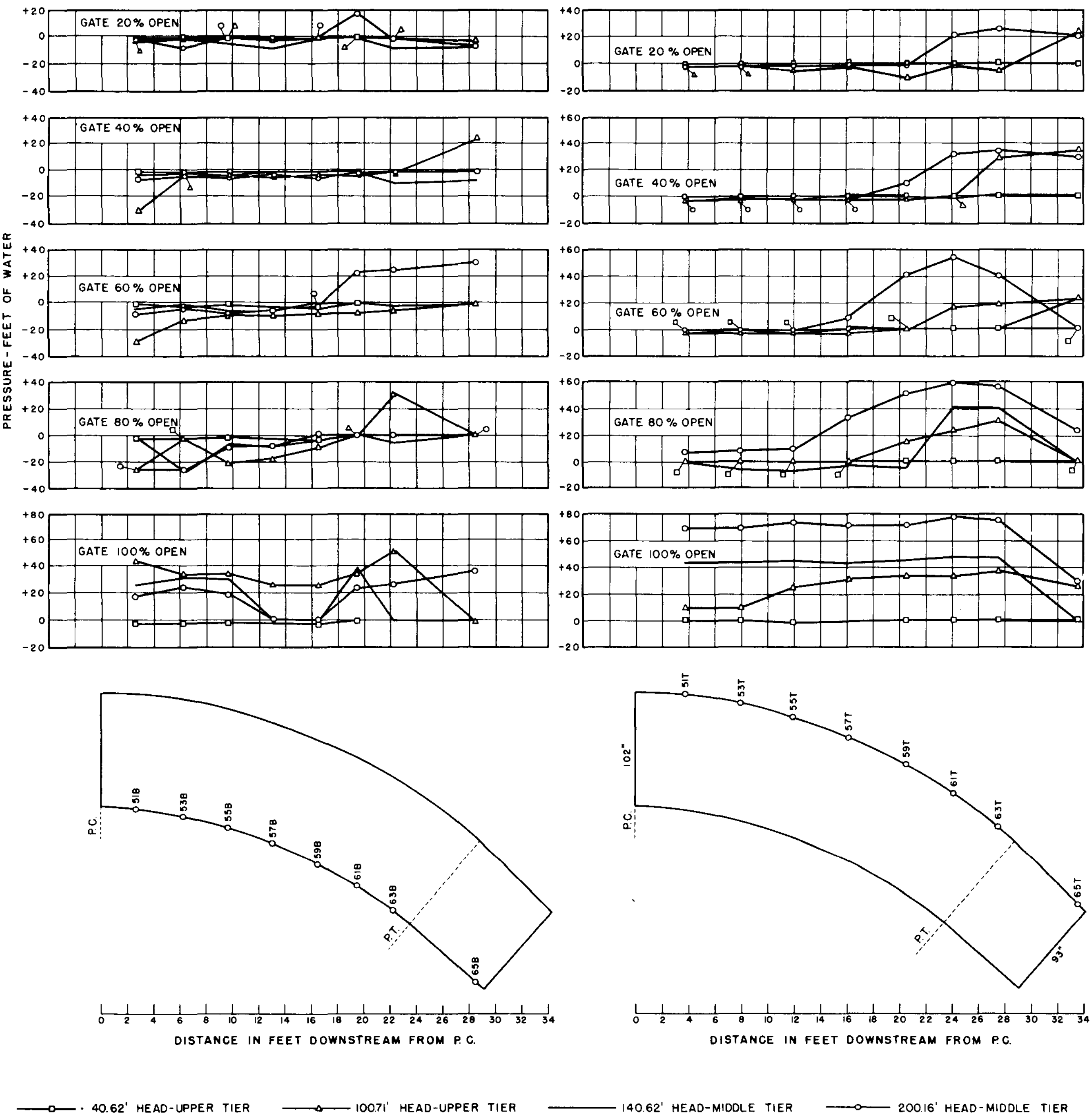


FIGURE 9
SHASTA DAM--OUTLETS--MIDDLE AND UPPER TIERS
PRESSURES TOP AND BOTTOM OF ELBOW AND EXIT CONE

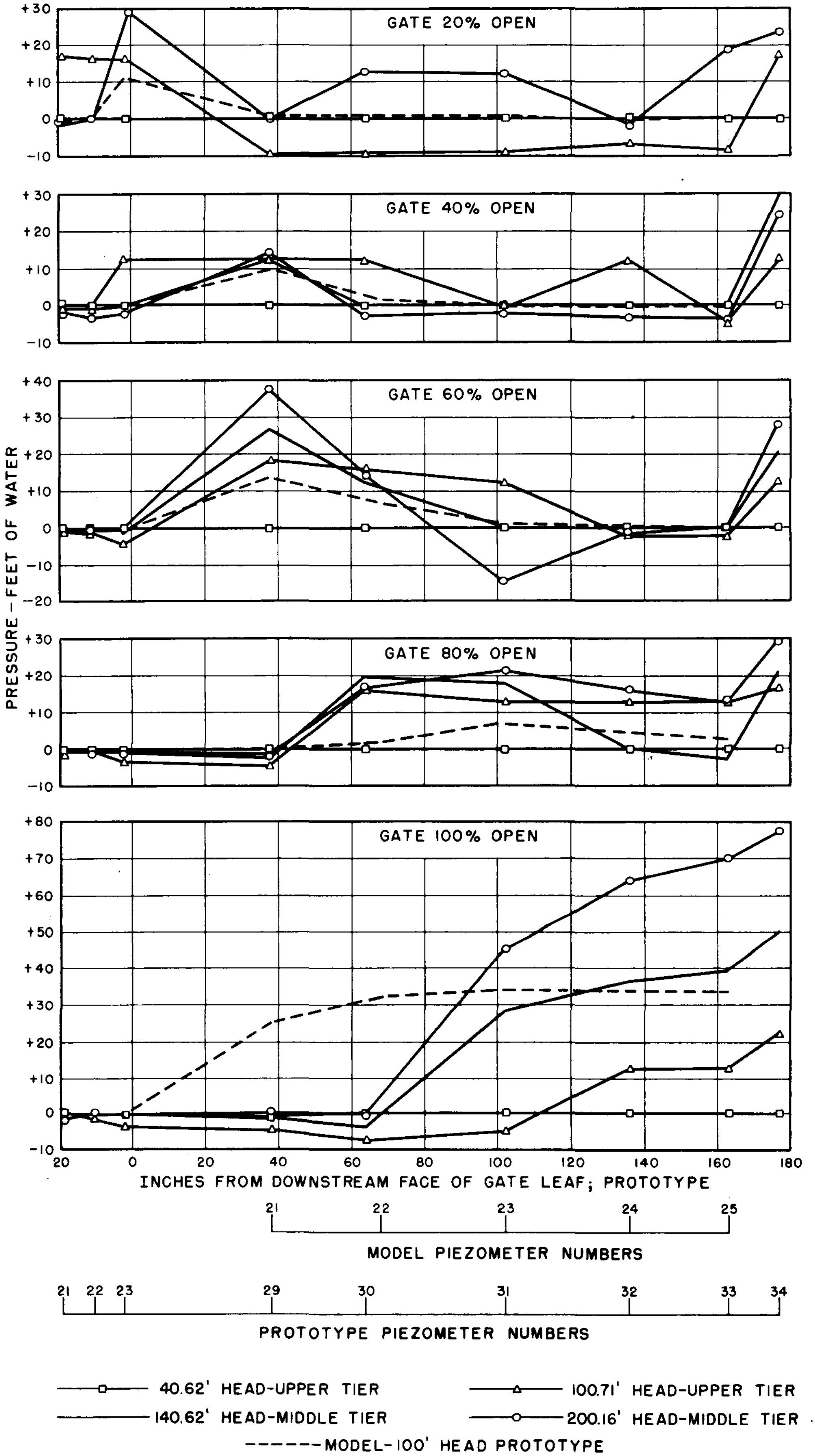


FIGURE 10

SHASTA DAM--OUTLETS--MIDDLE AND UPPER TIERS
PRESSURE BOTTOM OF CONDUIT DOWNSTREAM OF GATE

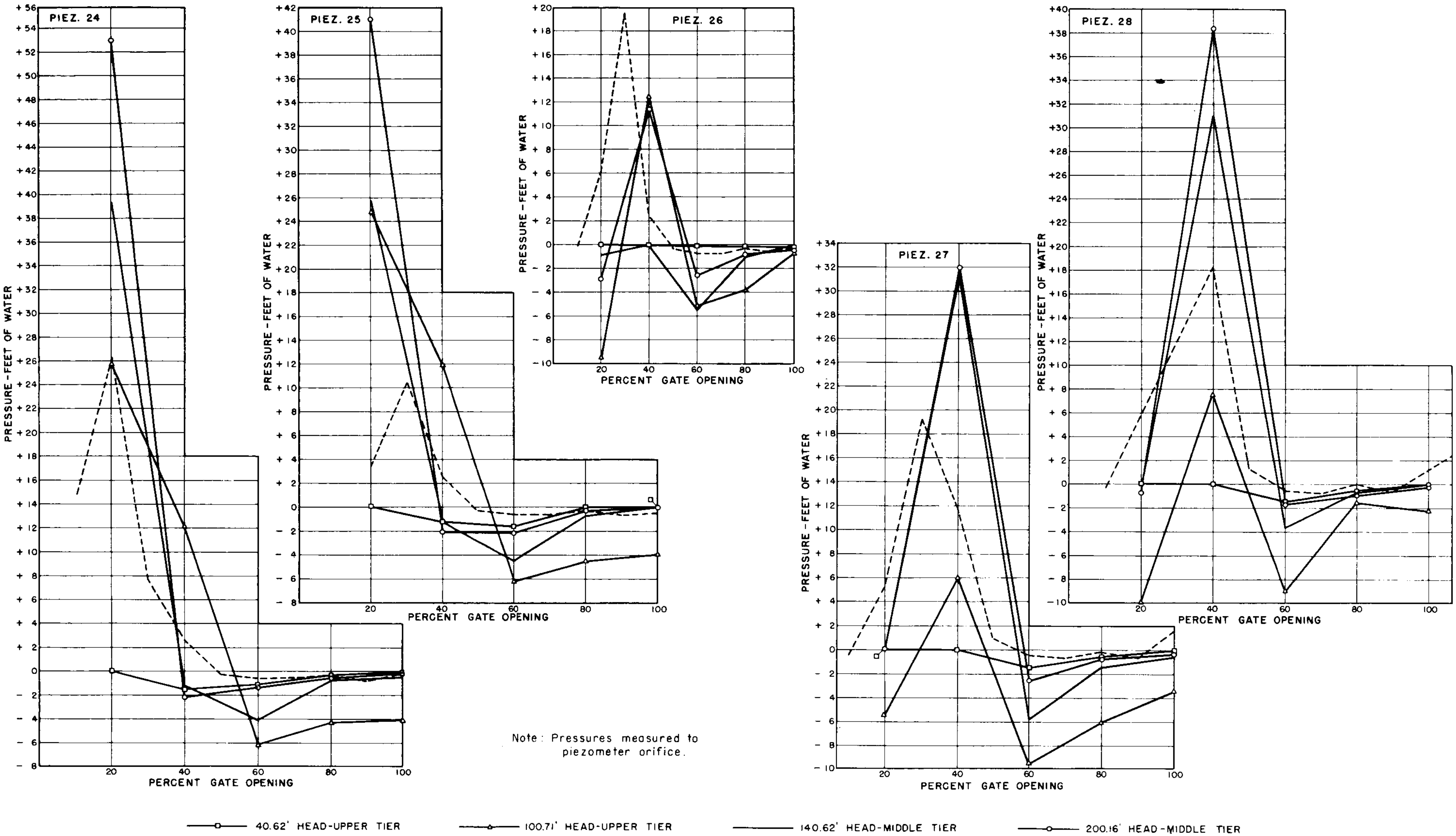


FIGURE 11
SHASTA DAM--OUTLETS--MIDDLE AND UPPER TIERS
PRESSURES IN LOWER LEFT QUADRANT OF CONDUIT DOWNSTREAM FROM GATE SLOT

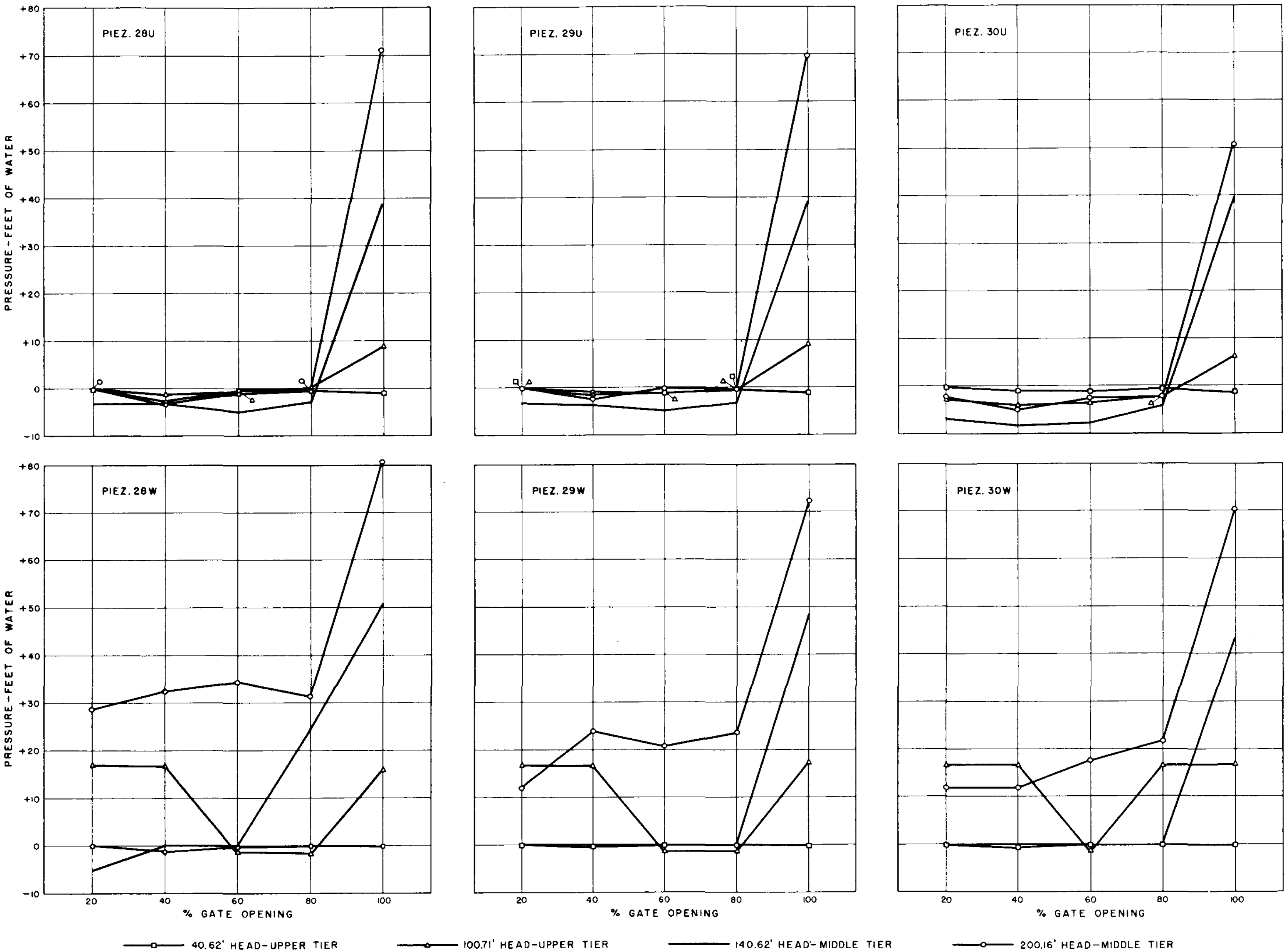


FIGURE 12
SHASTA DAM--OUTLETS--MIDDLE AND UPPER TIERS
PRESSURES IN CONDUIT AT END OF GATE EXTENSION

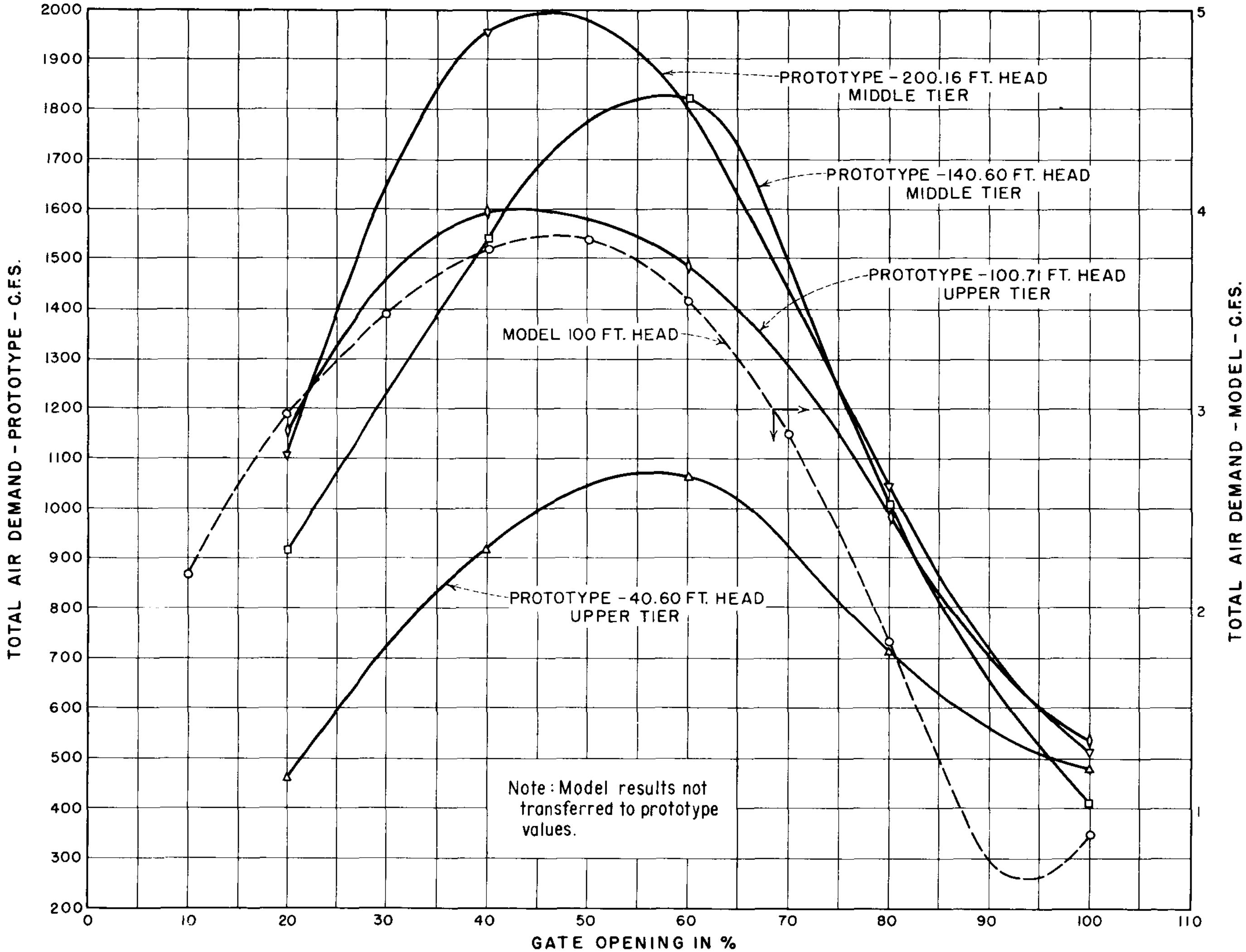
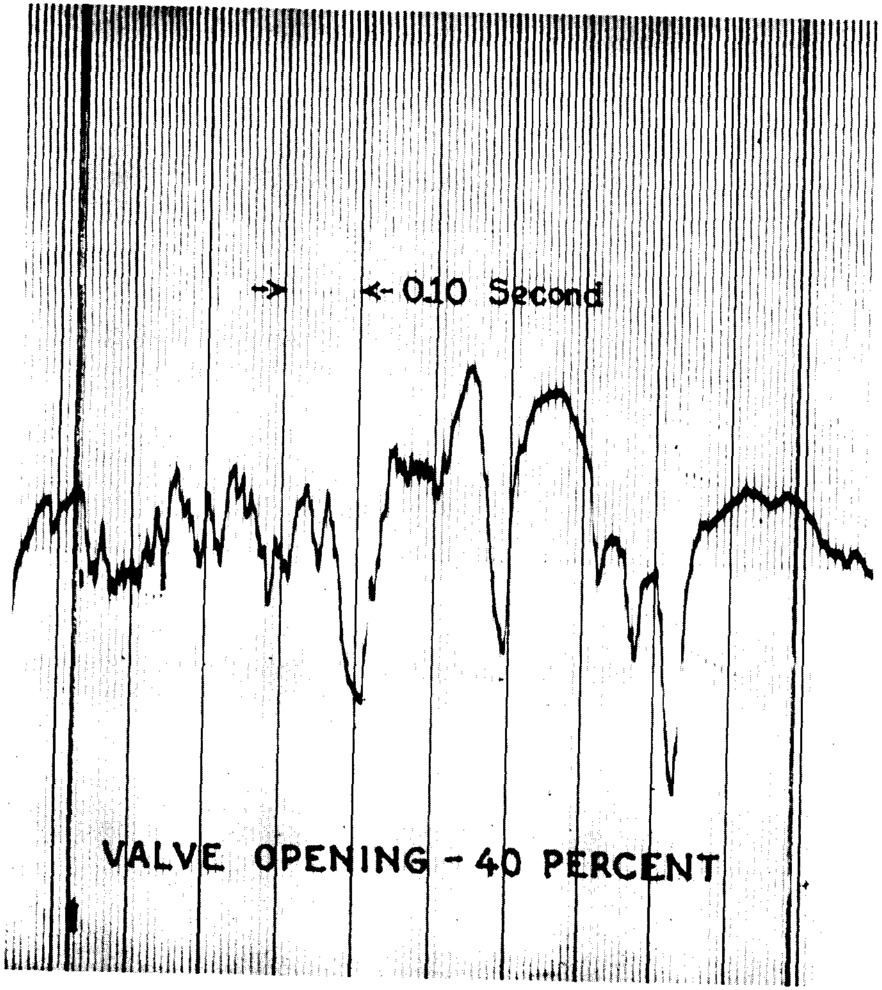


FIGURE 13
SHASTA DAM--OUTLETS--AIR DEMAND
TO GATE AND CONDUIT--MODEL AND PROTOTYPE



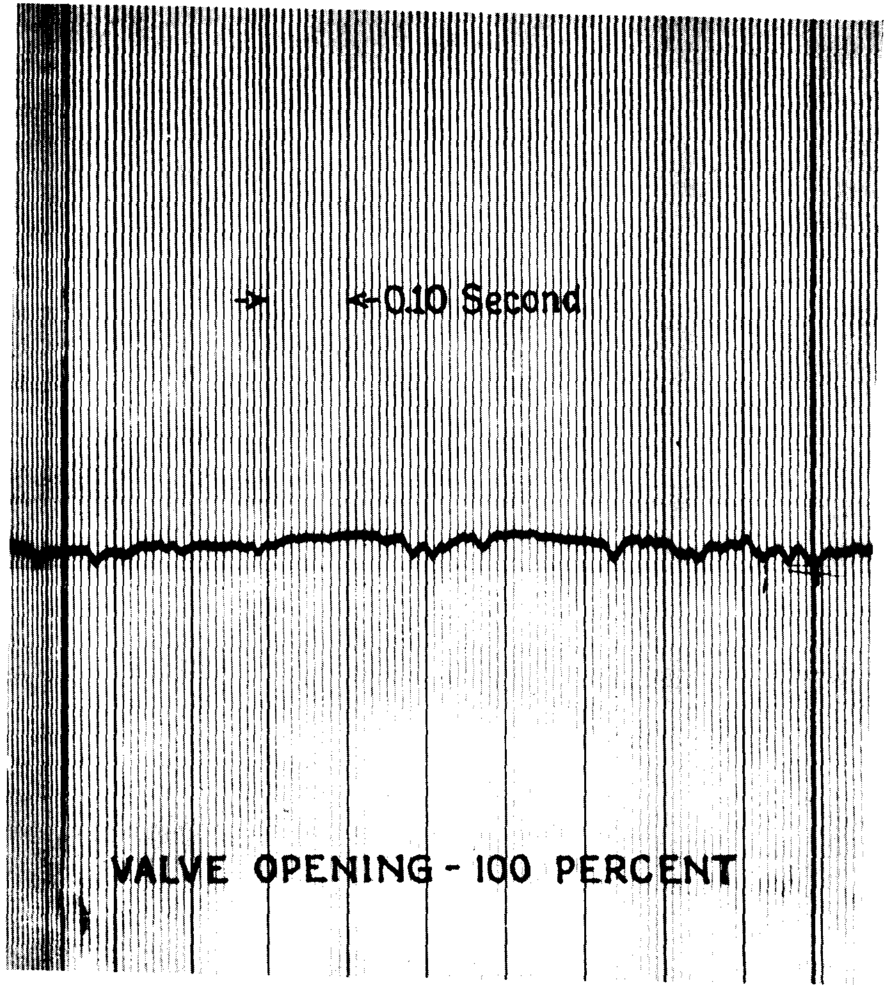


Figure 14. Shasta Dam--Outlets--Vibration of gate bonnet during operation

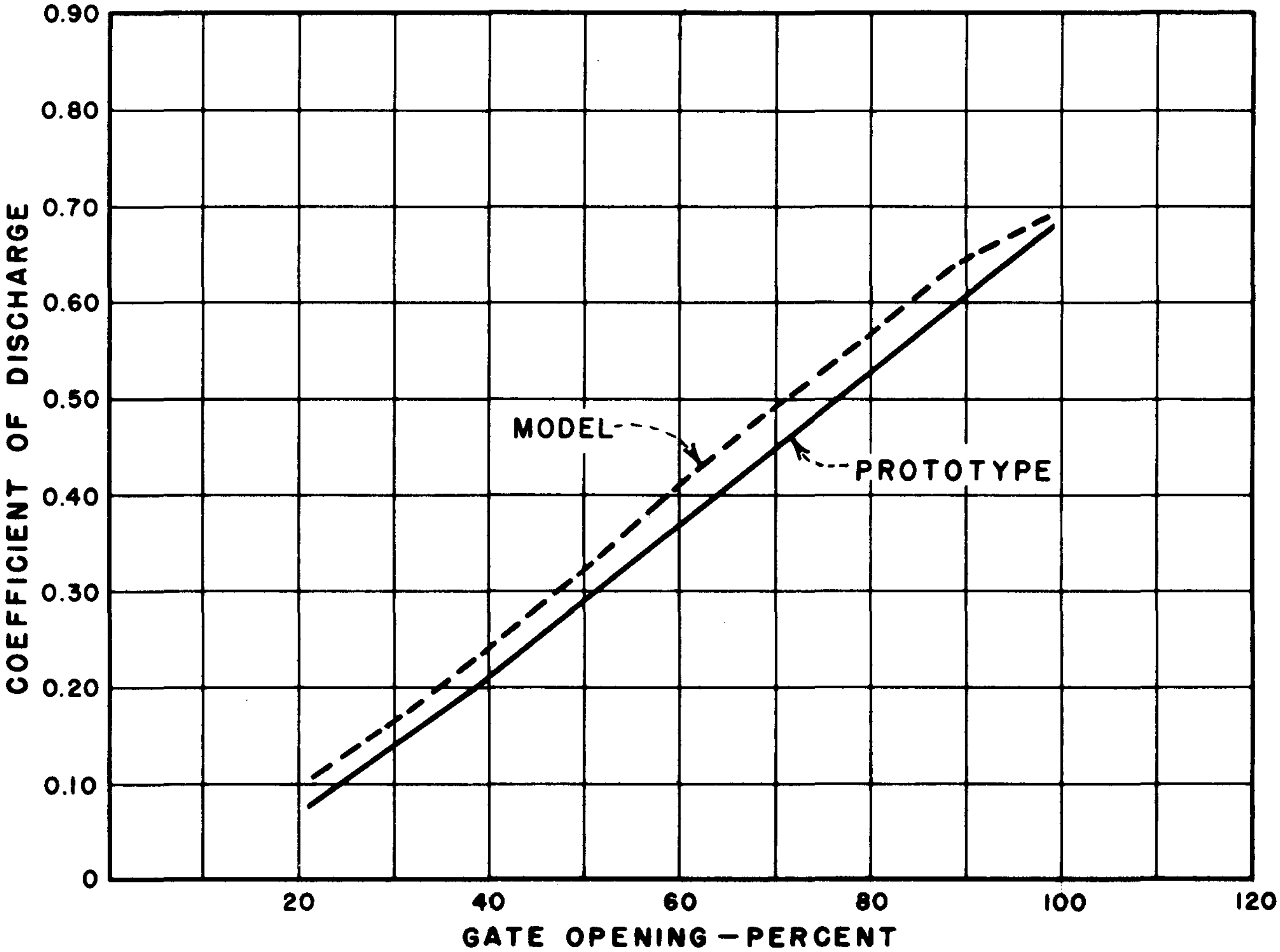


FIGURE 15
SHASTA DAM--OUTLETS
GATE COEFFICIENTS

GPO 830075