Engineering and Geological Control and Research Division
Field Trip Report No. 31

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MEMORANDUM TO CHIEF DESIGNING ENGINEER
(J. W. Ball through J. E. Warnock)

Subject: Hydraulic model studies of the 58-inch balanced valves to determine an operating schedule for minimizing damage to needle tips and discharge conduits during the 1943 season - Shoshone Dam - Shoshone project.

1. Introduction. Model studies to ascertain the feasibility of altering the 58-inch balanced valves in the lower outlet tunnel at Shoshone Dam, to prevent pitting by cavitation to the needles and discharge conduits when the valves are operated for extended periods, were instigated in October 1942, after the outlet works had incurred severe damage while operating during the summer months. (Report of October 30, 1942, from Engineer J. E. Warnock to Chief Engineer, "Repair of 58-inch balanced valves in lower outlet tunnel - Shoshone Dam - Shoshone project.") Preliminary studies were made on a 1:6 scale model constructed of molding plaster, representing a one-eighth sector through a valve and discharge conduit, using air as a test medium. The proposed alteration (design 3, figure 2C) proved practicable, but it was impossible to purchase castings for the new needle tips and air intake manifolds. As a result, repairs were made as in previous years to permit the use of the valves during the 1943 season.

Metal was arc-welded onto the pitted areas of the needle tips and ground smooth. The twenty-four 2-inch air pipes were repaired and the pitted areas in the discharge conduits patched with a high-grade concrete. Also, the east valve was dismantled, cleaned, and inspected.

It was realized that these repairs were temporary and that permanent changes would have to be made when materials become available. However, it was hoped that damage during the coming season could be held to a minimum by limiting the operation of the valves to openings where pressures on the needles and in the conduits were unlikely to result in cavitation. An operating schedule of this type, though it provides but little regulation, would be important, since it would enable release of water with minimum damage until such time as materials for the changes become available. It was believed that the feasibility of limited operation could be ascertained through hydraulic model investigations, so plans were made to conduct pertinent tests on the 1:8-2/3 scale valve, constructed when the study of the Shoshone valves was first instigated.

2. The model. The model used for these tests consisted of a high-pressure steel head tank, the 1:8-2/3 model valve, machined from brass castings, mentioned above, and a section of transparent plastic pipe (design 1, figure 1A and B).

The model valve was made geometrically similar to the prototype to permit a study of its operating characteristics, when the plunger was actuated hydraulically, and to investigate methods of increasing the effectiveness of the actuating mechanism when the valve plunger neared the open position. Piezometers were placed in the needle tip and in the wall of the conduit immediately downstream from the valve for investigating pressure conditions in these regions to ascertain over what range of opening the pressures were sufficiently subatmospheric to induce cavitation.

The portion of the discharge conduit beyond the throat liner of the prototype valve was represented by a length of transparent plastic pipe which permitted observation of the flow conditions in the conduit. Twenty-four 0.234-inch holes were provided in the wall of this pipe to represent the 2-inch vent pipes on the prototype.

3. Transference of model results to prototype. It is generally accepted by present-day hydraulicians that cavitation in a hydraulic passage occurs only when the pressure at some point within it reaches the vapor pressure of the flowing medium. In view of this concept, pressures equal to the vapor pressure of water would have to exist in the outlets at Shoshone Dam before damage to the valve needles and discharge conduits would result. Interpretation of the pressure data obtained from the 1:8-2/3 model valve was based on this concept.

Whether or not the pressure at various points in the prototype can be accurately predicted from the model results depends on the conditions obtaining for various operating schedules of the prototype. If the pressures at all points within the prototype are above the vapor pressure of the fluid the problem is easy and the usual similitude transfer relations are valid. However, if the pressure at any point becomes e ual to the vapor pressure of the fluid and cavitation is present, the problem is more involved and accurate evaluation of pressures may become impossible unless the model is enclosed in a partial vacuum such that a true scale exists between the vapor and artificial atmospheric pressures of the model and the natural vapor and atmospheric pressures at the prototype.

If at the scale heads, over a certain operating range, the scaled model pressures at any point within the valve do not extend below the vapor pressure of the prototype, the pressure at any corresponding point on the prototype may be found by the usual model-to-prototype transfer expression,

$$P_p = NP_m$$

where P_p and P_m are prototype and model pressures respectively in feet of water and N is the model scale.

However, if the scaled values at any point extend below the vapor pressure, which condition indicates cavitation on the prototype, it is not possible by this method to predict the correct pressure for any point on the prototype other than that corresponding to the lowest existing on the model, and possibly the pressure which controls the discharge, as that in zone B of the Shoshone valve (figure 2). To assume all pressures with such scaled magnitudes to be equal to the vapor pressure on the prototype (the lowest obtainable prototype pressure) is erroneous, particularly if the values are for widely separated points and both are not of the same intensity. Pressures obtained in the usual manner for any point in the prototype other than the control or lowest pressure, will, therefore, be too low and the percent of error will be proportional to the deviation of the scaled pressure from the vapor pressure. When this condition obtains another method must be employed to evaluate the prototype pressures.

If the model and prototype have definite controlling pressures at the same relative location and the boundary contour upstream from this point is sufficiently streamlined to preclude any change in the shape of the stream tubes, due to changes in head, that is, the coefficient of discharge in the equation,

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

remains constant, the ratio of drop in head between any two points in this region, to the total drop (upstream to control pressure) is constant and may be termed a pressure factor for predicting the prototype values at corresponding locations. This method of predicting prototype pressures is also applicable where the scaled model pressures are above the vapor pressure of the prototype as explained above, providing of course that the stream tubes do not change shape when the head is varied. If the model is to be used in determining the control pressures, care should be taken to construct the model to give the correct scaled values of these pressures. This is particularly important when the prototype control pressures are above the vapor pressure.

Since the pressure surrounding the vena contracta of a jet issuing from a valve influences its discharge rate and hence the pressures at all points within it, the total drop through a valve should be taken as that from the upstream side to the vena contracta. Neglecting the relative difference in model and prototype friction because of the difference in Reynold's number, the stream tubes will remain geometrically similar and the same relation will exist in the prototype as in the model. Thus knowing the control pressure on the prototype and the pressure drop ratios (pressure factors, F) for the points in

question, it is possible to predict quite accurately the pressures at these points by using the expression.

$$P_p = FD_t + P_c$$

where P_p is the prototype pressure, in feet of water, for the point in question; P_c is the prototype control pressure (negative and equal to the vapor pressure of water at the prototype, when the scaled value equals or exceeds the vapor pressure), expressed in feet of water above or below atmosphere as the case may be; D_t is the total drop in feet of water on the prototype, from the upstream side of the valve to the control pressure; and F is the factor for the point in question, obtained from model tests.

Though the application of this method to cases where the stream tubes change appreciably with changes in head, is incorrect and the model should be enclosed in a partial vacuum to give true pressure values, it may be used to a limited extent. In regions where the boundary surface of the main flow does not change appreciably the values obtained by this method will be reasonably correct, while those obtained for regions where the boundary change is considerable, as at the downstream edge of a low-pressure zone where the main flow separates from the solid boundary, will be substantially in error.

As there were two low-pressure zones in the Shoshone outlet model, where the scaled pressures for certain valve openings extended below the vapor pressure of water at the prototype structure, about -28 feet of water, the pressures in these regions (zones A and B, figure 2) were taken as criteria in establishing the critical range of opening for the prototype valve. Since it was desired to determine the existence of cavitation pressures and not the pressure distribution in the valve or the location where damage would result from the collapse of the cavities, the transfer of model data to prototype was not so involved, however, both methods outlined above were used.

At first it was intended to use the prototype pressure measurements made in 1931 as a datum to predict the minimum pressures in zone A of the prototype. However, when scaled to the prototype, the model for the pressures were not in agreement, being much nearer the vapor pressure for all valve openings than the prototype measurements indicated, even with all twenty-four 0.234-inch holes open. To ascertain whether this discrepancy was due to a deficiency of air resulting from aeration via these holes instead of pipes of the same diameter and scaled length, the capacities of the two systems were compared. Computed discharges, using the same pressure difference, showed the quantity of air from the holes to be about 1.42 times that for an equal number of pipes of the same diameter, and it was concluded that the

difference was not due to the method of aerating the model. Damage to the field structure also indicated more severe pressures than those tabulated in a report from the Project Superintendent to Chief Engineer, dated December 11, 1931, for with pressures of this magnitude cavitation could not have occurred, unless of course aeration was not effective upstream from where the pipes entered the discharge conduit, and the model studies did not indicate this to be the case. The control pressures for the prototype were therefore obtained from scaled model pressures. The minimum pressure in zone B for each 10 percent increment of the plunger travel was used as a basis for predicting the prototype pressures. The pressure in this zone was scaled to prototype by the similitude relationship,

$$P_p + NP_m.$$

When values obtained in this manner were above the vapor pressure for the prototype (about -28 feet of water-gage pressure at Shoshone Dam) they were used directly. When below this value (numerically larger) they were assumed to remain constant at -28 feet of water. The pressure in zone B for each valve opening obtained in this manner was added to the static head for the corresponding valve opening to obtain the total head across the valve. The static head was obtained from a head loss-discharge curve computed for the outlet tunnel.

The minimum pressure in zone A on the needle, for each valve opening was then obtained from the relationship,

$$P_a = FD_t + P_b.$$

4. Model tests and results. Since the destructive action in the field structure indicated the subatmospheric pressures in the discharge conduit to be more severe than those measured on the prototype in 1931, and since the model pressures near the vents in the crown of the discharge conduit were not in agreement with these pressures, it was considered necessary to determine the effect of different degrees of aeration on their magnitude. Pressures in the model were observed for four degrees of aeration, which were obtained by varying the number of open supply ports (0.234-inch holes) to the discharge conduit. The model was operated with 24, 17, and 12 of these ports open and with all of them closed. As the supply ports were approximately 1.42 times as effective as pipes of scaled length, and the same diameter, the aeration of the first three arrangements was equivalent to 34, 24, and 17 2-inch pipes.

Some criterion as to the allowable magnitude of the minimum pressures in zones A and B, to prevent cavitation, had to be adopted to establish the critical range of valve opening. A value of -20 feet of water gage, was chosen for these studies and the ranges of valve opening subsequently referred to as critical ranges, are based on this value.

When the model pressures in the conduit and on the needle for heads representing approximately reservoir elevation 5364 and valve openings from 20 to 100 percent, were transferred to prototype as outlined in the previous section of this memorandum, the results indicated that the pressures in zones A and B would reach the vapor pressure of water over certain ranges of valve opening.

There was practically no change in the minimum pressures in zone A on the needle for the different degrees of aeration tested. Only by closing the vents completely, or by reducing the number until the hydraulic jump moved upstream to cover the vents, was it possible to discern any change in these pressures. Even so, the change was only slight, increasing the upper limit of the critical range of valve opening by two percent, making the range from 14 to 27 percent instead of 14 to 25 percent (figure 2). Severe subatmospheric pressures in zone A on the present prototype design may therefore be expected over a range of opening from 14 to 25 percent. Roughness of the surface in this zone might extend the critical range, but because of the rapid rate of increase in pressure at the upper limit, any change from this source would be negligible. Although the degrees of aeration tested on the model produced no appreciable change in the critical range or the magnitude of the pressures in zone A on the needle, it is possible that the pressures would become less critical if the aeration was more complete. The negligible change observed in these tests, however, make this doubtful, thus regardless of the degree of aeration in zone B, it may be impossible to operate the valve in this range without damage to the needle.

The discharge conduit of the model did not flow full until the valve plunger had completed approximately 25 percent of its travel toward the open position. As a result, zone B was aerated by air flowing upstream along the crown of the conduit and the pressures were not severely subatmospheric for any of the degrees of aeration tested. However, in all cases, as the valve approached 25 percent open and the flow of air from downstream was reduced, the pressures dropped rapidly, reaching values that were below the vapor pressure when scaled to the prototype. This condition is not possible on the prototype since the pressures are limited by the barometric pressure and vapor tension of water to about -28 feet of water gage, at Shoshone Dam. Therefore, when scaled values were equal to or greater than -28 feet of water, they were assumed to remain constant at that value. When scaled values were numerically less, they were used directly.

When the aeration was equivalent to thirty-four 2-inch pipes, the model indicated that the pressure in zone B remained at the vapor pressure for a range of value opening between 25 and 47 percent, then began a gradual rise to about -8 feet of water at 100 percent open (figure 2). With aeration equivalent to twenty-four 2-inch pipes the range over which the pressure remained at -28 feet of water was extended to about 58 percent from where it rose to approximately -12 feet of water at 100

percent open. This range was further increased (to approximately 76 percent) when the equivalent aeration was reduced to seventeen 2-inch pipes and the pressure at 100 percent opening reached about -18 feet of water. Without aeration the pressures remained critical through a range from 23 to 100 percent open. From these results it appears that the critical range of valve opening for zone B in the present field installation, aerated by twenty-four 2-inch pipes, based on -20 feet of water-gage pressure, will be from 23 to 70 percent open.

The model was calibrated to ascertain the discharge characteristics of the balanced-type valve. Discharge coefficients for the various openings were obtained and capacity curves were prepared for a single valve, and for both valves operating simultaneously (figure 3). From these curves it may be shown that the rate of increase in discharge decreases materially as the valve plunger approaches the open position. With the reservoir at elevation 5360, the increase by opening the valve from 80 to 90 percent is about 3½ percent of that for full opening. Opening the valve from 90 to 100 percent gives an increase of 2½ percent of the total for full opening. Thus, opening the valve another 10 percent in the upper region increases the discharge only slightly. That excellent agreement existed between the model and prototype is evident from a comparison of model and prototype data for both valves operating at 90 percent open (figure 3).

5. Conclusions. The model study of the 58-inch balanced valves in the lower outlet tunnel at Shoshone Dam indicates that it will be difficult to operate them to obtain any appreciable amount of regulation during the coming season without causing some damage to the outlet structure.

Pitting of the needles is likely to occur if the valves are operated between 14 and 25 percent open.

Damage to the conduits is likely to result if operation is between 23 and 70 percent open.

Critical valve opening ranges for the two low-pressure zones overlap, thus damage to some part of the outlet structure may be expected between 14 and 70 percent open.

No damage should result to either the needle tips or the discharge conduits when the valves are operating beyond 70 percent open. However, should the friction in the downstream portion of the discharge conduit be relatively greater on the prototype than on the model and cause the hydraulic jump to move upstream over the 2-inch vents as the valve plunger approaches the wide open position, the noncritical operating range might be materially reduced. In view of this danger it seems that the maximum valve opening should be limited to 85 percent. The

increase in discharge is very small with further increase in opening, thus very little would be gained by operating beyond this point. Moreover, as the valve approaches 90 percent open, eddies forming downstream from the V-guides cause water to spout from 3 or 4 vents on the crown and invert of the discharge conduit, reducing the effective aeration and increasing the severity of the subatmospheric pressures.

The valves should not be operated in the range where pitting of the conduit in the region of the 2-inch air vents occurs, for damage to these pipes would reduce the aeration and result in more severe pressure conditions which in turn would hasten destruction of the conduit walls. If allowed to operate in this manner the conduit walls may become sufficiently rough to materially increase the friction, causing the hydraulic jump to cover the 2-inch vents and produce a severe destructive action.

To avoid damage to the outlet structure, the valves should not be operated in the critical range for any appreciable length of time, but should be opened directly to the noncritical range, 70-85 percent open. Any damage to the vent pipes will cause the pressures to approach those obtained without aeration.

From the results of this model study, it appears that the damage to the needle during the 1942 season occurred during the last few weeks of operation when the valve opening ranged from 22 to 48 percent, and that the pitting of the conduit walls occurred during the first one and one-half months' operation when the valve operated between 46 and 52 percent open. The damage, thus incurred, materially reduced the effectiveness of the 2-inch pipes and severe subatmospheric pressures resulted at 90 percent open, hastening the destruction of the conduit walls.

The admission of sufficient air at the proper location in the discharge conduits of these valves will preclude any damage by cavitation to the conduit walls. A test is to be conducted on the 1:8-2/3 hydraulic model in the near future to study the feasibility of admitting a larger quantity of air to the valve jets immediately downstream from the seat ring, figure 1D. The results will be contained in a memorandum, now being prepared, covering all tests made in connection with the Shoshone valves.

Though the subatmospheric pressures in the critical zones will tend to approach atmospheric pressure as the head on the valve decreases a substantial reduction in head would be necessary to diminish appreciably the critical valve opening range.

The 8-inch vents, which have been plugged in previous years, would help materially in relieving the critical conditions, providing the

opening is not covered by the hydraulic jump in the conduit. Though noisy, their being open should not aggrevate conditions in the conduit, instead, the additional air reaching the critical pressure zone in the conduit should offer some relief.

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J. W. Ball.

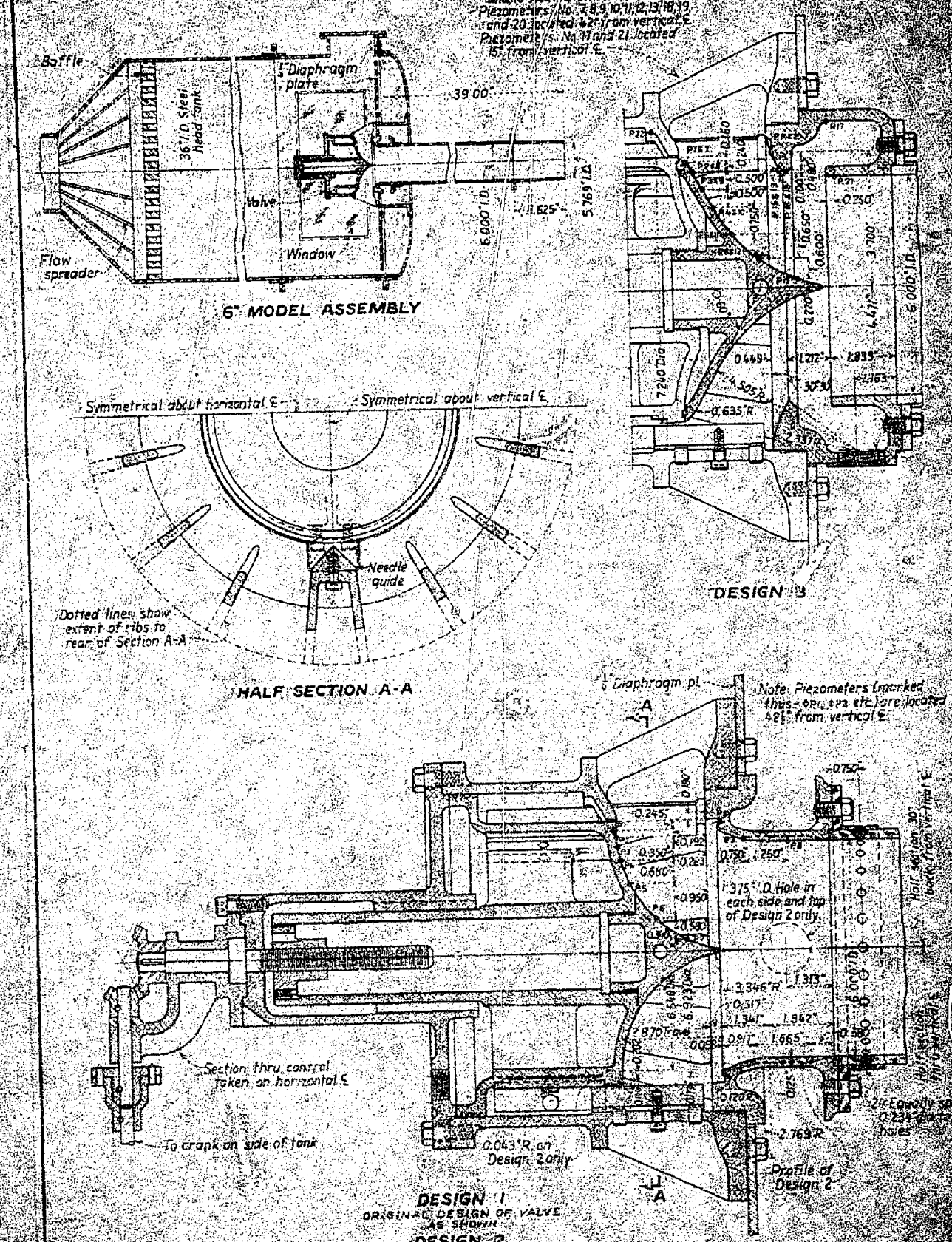
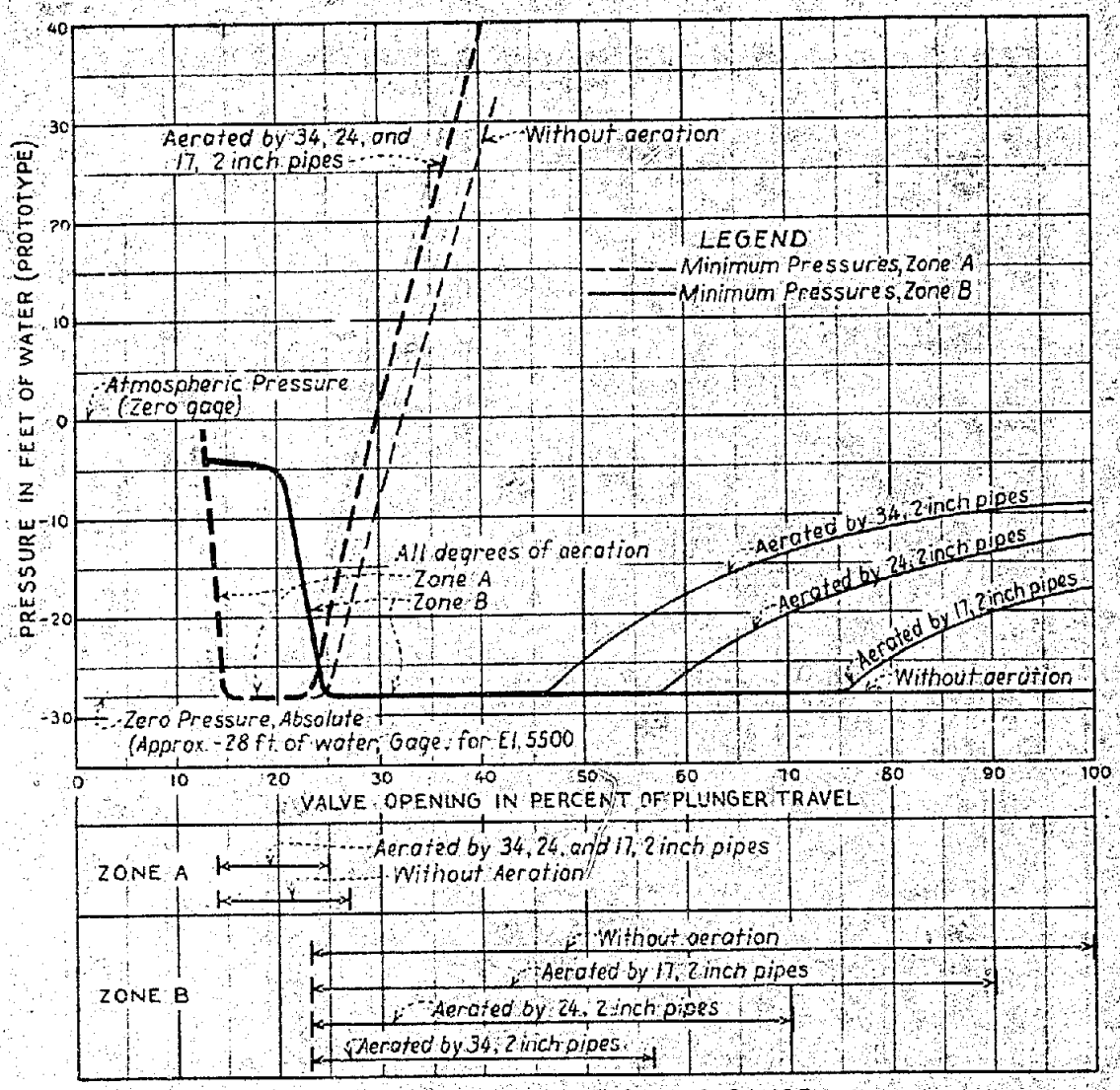
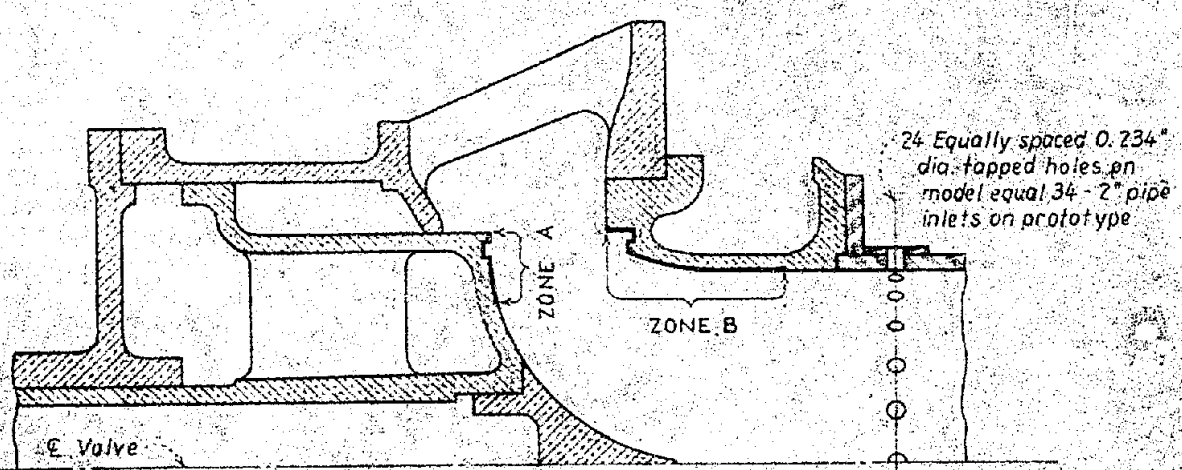

Note: Piezometers No. 1,2,3,4,5,6,14,15, and 16 located on vertical ℄
Piezometers No. 7,8,9,10,11,12,13,18,19, and 20 located 42½° from vertical ℄
Piezometers No. 17 and 21 located 15° from vertical ℄
Baffle
Diaphragm plate
36" I.D. Steel head tank
39.00"
Valve
Window
Flow spreader
6" MODEL ASSEMBLY
Symmetrical about horizontal ℄
Symmetrical about vertical ℄
Needle guide
Dotted lines show extent of ribs to rear of Section A-A
HALF SECTION A-A
DESIGN 3
Diaphragm pl.
Note: Piezometers (marked thus - ⊕P1, ⊕P2 etc.) are located 42½° from vertical ℄
.375" D. Hole in each side and top of Design 2 only.
Half section 30° back from vertical ℄
Section thru control taken on horizontal ℄
To crank on side of tank
0.043" R. on Design 2 only
Profile of Design 2
24 Equally spaced 0.231" Dia. holes
DESIGN 1
ORIGINAL DESIGN OF VALVE AS SHOWN
DESIGN 2
ALTERATION TO DESIGN 1 AS SHOWN AND NOTED
SHOSHONE DAM
58" BALANCED VALVE
6 INCH TEST MODEL - SCALE 1:8 1/2
MODEL ASSEMBLY AND DETAILS OF VALVE DESIGNS 1, 2 AND 3

FIGURE 2

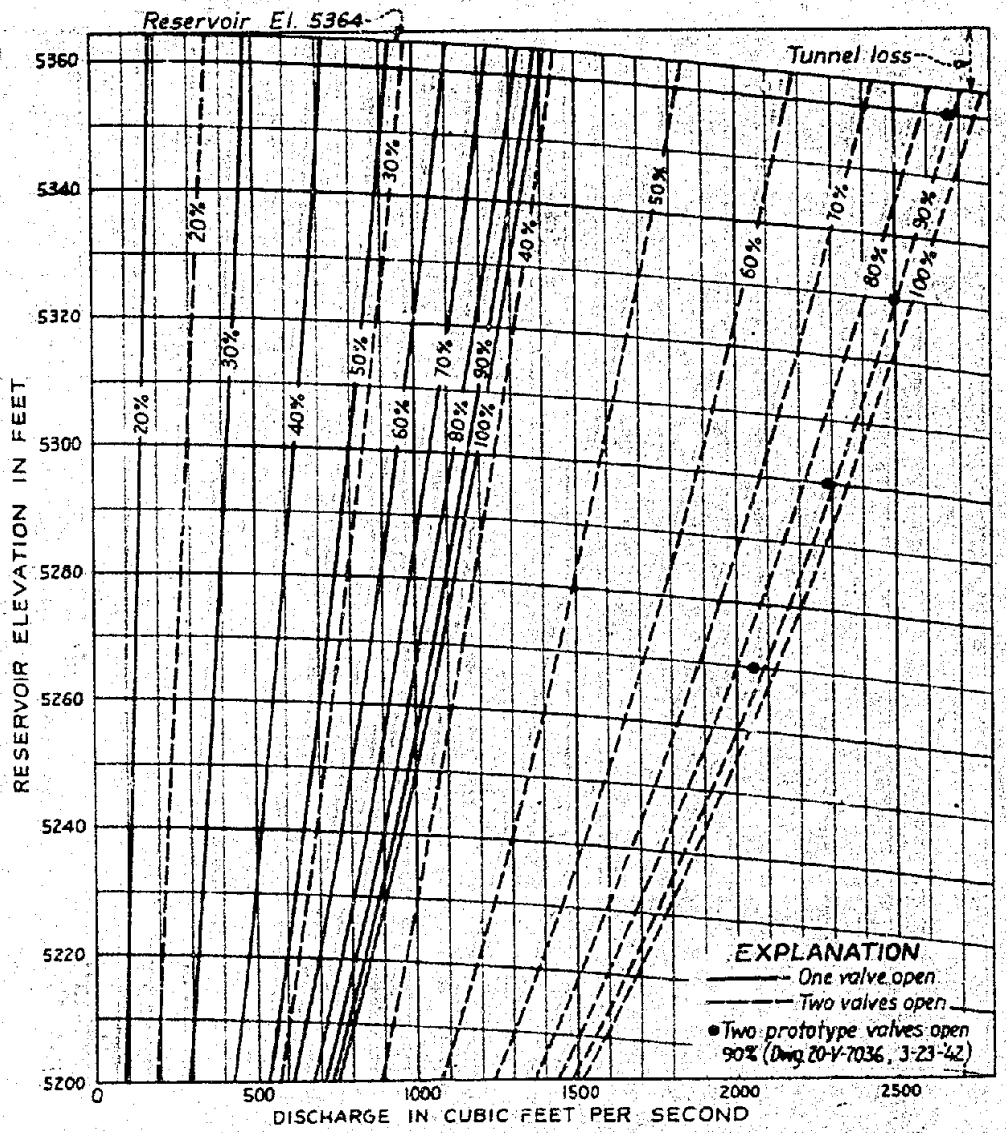


CRITICAL VALVE OPENING RANGE
Based on -20 feet of water gage pressure

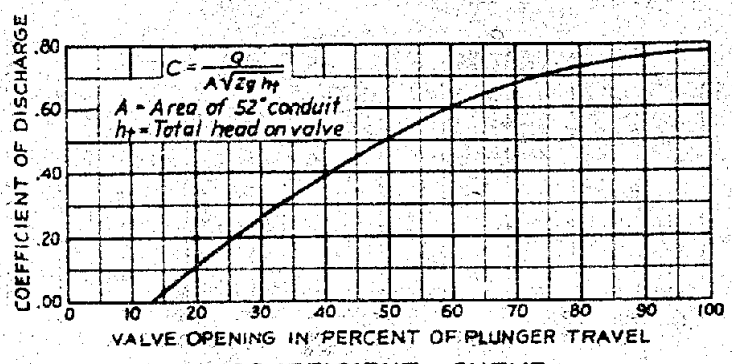


SHOSHONE DAM
58" BALANCED VALVE
HYDRAULIC MODEL STUDIES - SCALE 1:8⅔
CRITICAL OPENING RANGE - VARIOUS DEGREES OF AERATION
ORIGINAL DESIGN

FIGURE 3



DISCHARGE CURVES



COEFFICIENT CURVE

SHOSHONE DAM

58-INCH BALANCED VALVE

HYDRAULIC MODEL STUDIES - SCALE 1 TO 8⅜

COEFFICIENT AND DISCHARGE CURVES

ORIGINAL DESIGN

J.N.B.-H.R.S.-R.E.McD.