HYDRAULIC AND AERODYNAMIC EXPERIMENTS TO ELIMINATE CAVITATION IN THE BALANCED OUTLET CONTROL VALVES AT SHOSHONE DAM

by

James Wesley Ball

B.S.M.E., Colorado State College of Agriculture and Mechanic Arts, 1930

A Thesis submitted to the Faculty of the Graduate School of the University of Colorado in partial fulfillment of the requirements for the Degree Master of Science

Department of Civil Engineering

1944

This Thesis for the M. S. degree, by

James Wesley Ball

not proof-read, has been approved for the

Department of

Civil Engineering

by

Roderick L. Downing
____

Warren Raeder
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Date June 9, 1944

FOREWORD

The need for water in excess of the natural stream flow in dry seasons was created during the latter part of the nineteenth and the early part of the twentieth centuries by the founding of cities and the development of lands along the streams of the United States. Many storage reservoirs, where water could be impounded during freshet-flow and released to augment the natural flow in the low-water season, were provided to meet this need.

As the height of the dams forming these reservoirs increased and the conservation of the impounded water became more important, the problem of controlling the rate of outflow increased in complexity. Non-regulating gates and valves were placed in parallel in some instances to acquire closer regulation, but this practice often proved unsatisfactory. Either the regulation was not as close as required or the installation was too costly to operate or maintain, factors which prompted the development of control valves for high-head outlets. Among the first of these new valves, used extensively by the Bureau of Reclamation in the outlet structures of dams constructed in the early part of the present century, was the Ensign balanced valve, named after O. H. Ensign, a prominent engineer who contributed much to its development.

By strict definition, a balanced valve is one in which the hydraulic thrust on the regulating plunger is capable of being balanced at all openings of the valve by pressures from the fluid being discharged, making it necessary only to overcome the friction between the stationary and moving parts to attain different degrees of regulation. From this definition it is evident that the term "balanced valve" does not define a particular type, such as, a cylinder, gate, globe, plug, tube, needle or hollow-jet valve, but signifies a condition of design which might be contained in certain of the various types. A valve is considered to be balanced partially when the pressures from the discharging fluid do not counteract completely the hydraulic thrust on the shut-off plunger. Many valves are of this type.

The Ensign valve has been considered a balanced valve by strict definition. It consists essentially of; a body, made up of a stationary bull ring cylinder of iron with V-guides for supporting a sliding cylindrical plunger; a hollow cylindrical plunger of steel having a bull ring at one end and a needle tip and bronze seat-ring at the other; a support ring of cast iron with ribs to support the body of the valve and a bronze sealing-ring to prevent leakage when the plunger is in the closed position; and a discharge throat of cast iron with a steel liner and a steel or concrete discharge conduit.

Usually the valve is mounted on the reservoir face of a dam with the throat embedded in concrete and the discharge conduit extending to the downstream side, but may be encased, receiving water from a large pipe or tunnel. In either case the water surrounding the valve flows between the support ribs, past the seat, support and sealing rings, onto the needle tip surface where it is directed axially through the throat into the discharge conduit. Different degrees of regulation are attained a pitting action damaging the outlets severely; explains why early attempts to correct the condition failed and maintenance costs remained high; tells how and why the problem remained unsolved until recently when two of the valves received extensive damage by cavitation after prolonged operation; relates how the problem of correcting the conditions inducing cavitation became assigned to the laboratory, describes the laboratory investigations which were made initially on a model representing a one-eighth sector through the valve, using air as a fluid and then on a complete model of the valve and outlet conduit, using water as the flow medium; compares and summarizes the results of both investigations; explains why it was not possible to make immediate use of the most satisfactory solution evolved from the studies; and describes the temporary measures adopted, using model tests as a guide, and the conditions existing after a season's operation of the field structure.

The experiments described in this thesis were performed by the author in the hydraulic laboratory of the Bureau of Reclamation of the United States Department of Interior in Denver, Colorado under the supervision of J. E. Warnock, Senior Engineer in charge of the laboratory. All laboratories of the Bureau of Reclamation in Denver, Colorado are in the Materials Testing and Control Division, under R. F. Blanks, Senior Engineer. All design work is under J. L. Savage, Chief Designing Engineer and W. H. Nalder, Assistant Chief Designing Engineer, and all engineering work of the Bureau is directed by S. O. Harper, Chief Engineer and W. R. Young, Assistant Chief Engineer. The activities of the Bureau are directed by H. W. Bashore, Commissioner.

The author is indebted to the Bureau of Reclamation for granting permission to use the material obtained in these experiments for a graduate thesis and also for the illustrative figures.

The statements and opinions advanced in this thesis are to be understood as individual expressions of the author and as such do not necessarily represent those of the Bureau.

Ball, James Wesley (M.S., Civil Engineering)

Hydraulic and Aerodynamic Experiments to Eliminate Cavitation in the Balanced Outlet Control Valves at Shoshone Dam

A comprehensive study of the pressure distribution in aerodynamic and hydraulic models of the Ensign balanced valves in the outlets of the Shoshone Dam in Wyoming made it possible to ascertain the source of cavitation causing a destructive pitting of the valve needles and throats and to show that a redesign of certain parts would eliminate the cavitation-erosion.

The aerodynamic model served as an expedient to ascertain the feasibility of changes considered necessary to attain satisfactory conditions, while the hydraulic model verified the results from the air tests and furnished information beneficial to the interpretation of the air model data.

Tests on the hydraulic model, dealing with the pressure distribution in the outlets in particular, gave information which made possible a program of operation for limiting the range of openings to minimize the cavitation-erosion when the urgency of conserving strategic war material prevented the purchase of the castings required in the redesign installation. From the experiments it was shown that the cavitation to the valve needles could not be eliminated by minor changes to the existing design but that the action could be confined to a very small range of valve opening. The elimination of cavitation in the valve throats by proper aeration was indicated also.

Good agreement between the model and prototype was noted when discharge measurements on the existing structure were compared with the model calibration and when the results of operating the outlets at the non-critical openings indicated by the model tests were reported at the end of the 1943 season.

This abstract of about 260 words is approved as to form and content. I recommend its publication.

Signed Roderick L. Downing
Instructor in charge of dissertation

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I - INTRODUCTION

Structures Using the Balanced Outlet Valve

Several high-pressure outlet structures, designed in the early part of the twentieth century, employed the Ensign balanced valve for flow regulation. The outlets at the Roosevelt, Pathfinder, Arrowrock, Elephant Butte, and Shoshone Dams were typical installations (figure 1). The structures were similarly arranged, and, in all except the Shoshone and the Elephant Butte installations, the valves were placed on the upstream faces of the dams where they were subjected to full reservoir head. At Elephant Butte Dam the valves were placed in wells near the upstream face of the dam with the water reaching them through passages from the reservoir, while at Shoshone Dam they were placed in a tunnel bypassing the left end of the dam. Except for the 60-inch valves at Elephant Butte Dam, all were of the 58-inch size. Flow from the valves discharged into conduits downstream. Though the lengths of these conduits varied in the different structures and numerous details were dissimilar, the installations were sufficiently alike to possess similar operating characteristics, even to the mechanical and physical difficulties. The mechanical problems were usually of a nature easily overcome by small changes in design, while those of a physical nature, mainly damage to the valve needles and discharge conduits by a destructive pitting action, were more troublesome. Although similar, the damage at the different structures varied in severity, due probably to the different operating conditions.

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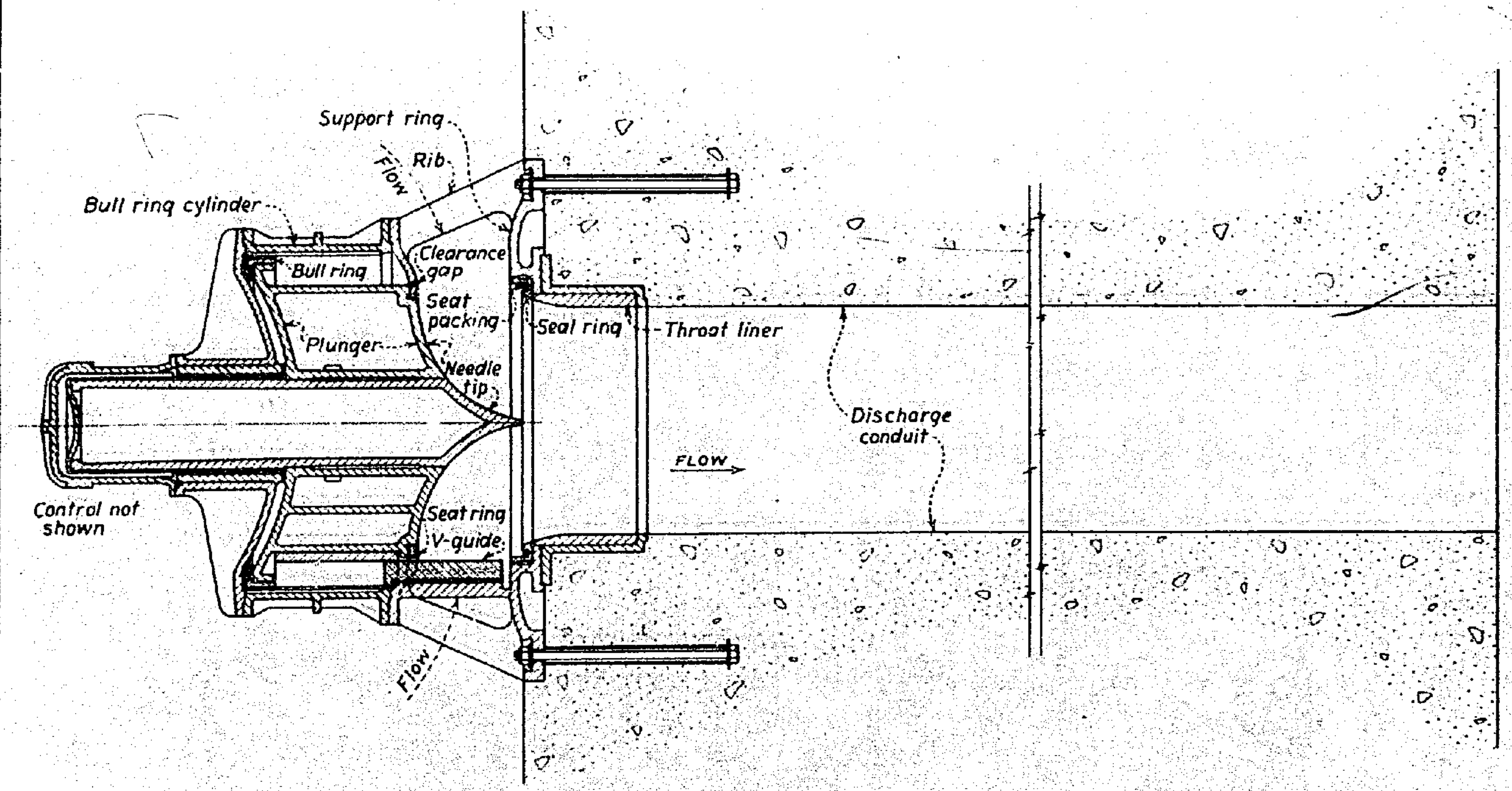

TYPICAL BALANCED VALVE INSTALLATION

FIGURE 1

Operating Difficulties at the Balanced-Valve Installations

A report[1] on the various installations, published in 1923, describes the outlet structures in detail and recounts the difficulties experienced at each. It directs attention to the seriousness of the damages resulting from the operation of the outlet and discusses measures taken to repair or eliminate them.

The major difficulties encountered in all these structures, namely, the pitting of the valve needles and discharge conduits, are discussed in detail in the report, which, on page 8, summarizes them as follows:

"...Most of the difficulties with the outlets built by the Bureau of Reclamation can be attributed to the effect of vacuum in the conduits below the regulating devices. Generally the damage to the conduits has been more serious than to the valves, although under extreme conditions the valves have also been seriously damaged.

"In valves and conduits carrying water at high velocities an irregular pitting or cavitation of the lining is often observed. This appears first as a slight blemish on the surface, but if allowed to continue, the material becomes honeycombed to a considerable depth and is ultimately destroyed. The surface is not worn away by attrition or sandblast action, but is roughened as though attacked by chemical action."

The report contains only limited discussion of the Shoshone installation since it was one of the last using the balanced-type valve and had not been required to release large quantities under high heads for prolonged periods; thus the destructive action had not developed to the critical stage. However, the nature and extent of the damage to this structure during subsequent seasonal operation are clearly depicted by the following excerpts concerning the other installations.

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[1] References are listed in numerical order of occurrence in the bibliography in the appendix.

On page 59, extracts from a project report concerning the inspection of the 58-inch balanced-valve installation at the Roosevelt Dam, are, in part:

"We found the tire steel seats of the valves in bad shape, and the first section of the discharge pipe, which is bolted to the grillage frame, is also deteriorating very fast. ... The seats and pipes are going the same way rapidly. The seats are in bad shape. In some places they are cut so that the retaining ring for the packing is half gone. ... It does not act like ordinary wear, for the metal is 'honeycombed' in peculiar shapes."

On page 60, quotations concerning the inspection of the Roosevelt outlets state:

"... The first length of pipe next the valve is very seriously pitted, and I do not think they will stand up another year without relining. ..... Two years ago these pipes showed the same pitting. At that time the abrazed part was filled with Smooth-on, leaving a satisfactory surface on the inside of the pipe. The inspection showed that this pipe was in very good condition the first of this season, but they have been discharging under such a high head that this filling seems to have worn away, and the metal itself is beginning to disappear. Where the pipes discharge into the tunnel, the No. 3 valve (the farthest from the vent in the north side) has commenced cutting into the concrete lining of the tunnel very seriously."

On pages 89 and 90, the damage by operation of the 58-inch balanced valves at the Pathfinder Dam in 1913 and 1914 is depicted as follows:

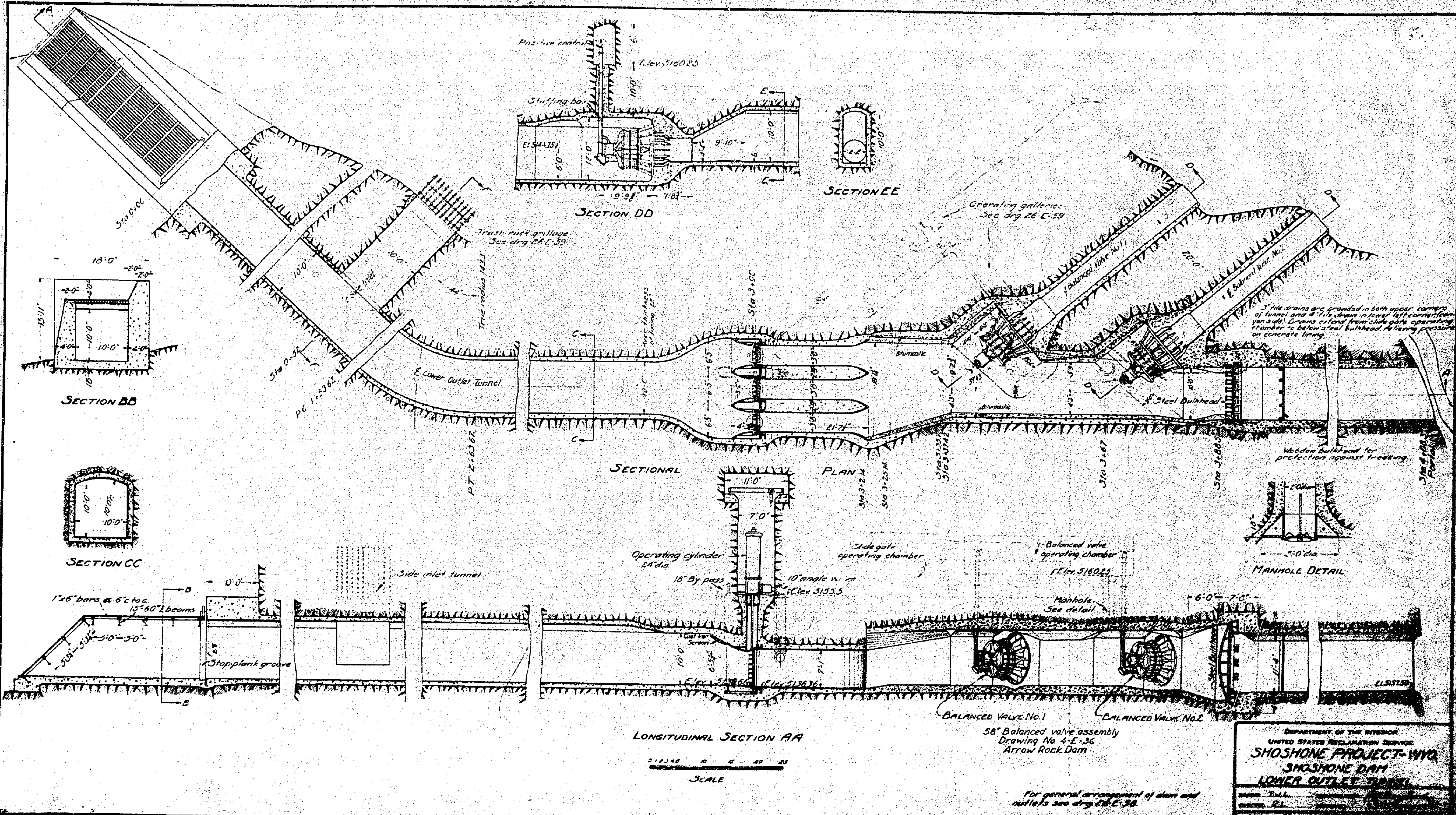
"...At the end of the season several yards of concrete were gone from the concrete conduits of Nos. 1, 4, 5, and 6. .... The damage to the concrete conduits indicated a shattering of the mass rather than an abrasion, as the concrete surfaces were jagged and rough. ....At the close of the season of 1913 it was not considered necessary to make any extensive repairs, The only work done being to plug up the holes in the concrete conduit with a rich concrete and fill the pitted places in the cast-iron linings with Smooth-on. .... After a few days operation of the balanced valves (1914) the patches in the concrete conduits began to go out, and by the end of the season there were large holes in the conduits, the damage being much greater than in the previous season, probably due to the increased use of the outlet. The damage to the cast-iron conduit linings had also increased. There were holes entirely through the $1\frac{1}{2}$-inch shell in many places, and the surface presented a spongy appearance. This damage was believed to be caused by the formation of a vacuum around the jet issuing from the valves."

The damage caused by the operation of the 58-inch balanced valves at Arrowrock Dam is described on page 112 in the following manner:

"... Annual inspections of the outlets have been made since the valves were first installed. The wear on the conduits was very slow at first, and the condition of the valves and conduits in the fall of 1920 was reported to be practically as good as when first installed. In the fall of 1921, however, the throat liners and the concrete conduits below the semisteel linings were found to be considerably worn. ..... The pitting of the throat pieces had the peculiar, rough, honey-comb appearance noted in many of the other outlets of the service and was most severe immediately below the V-guides of the balanced valves."

While the foregoing extracts do not concern the outlets at Shoshone Dam, they portray vividly the operational difficulties encountered at this project since the report was written.

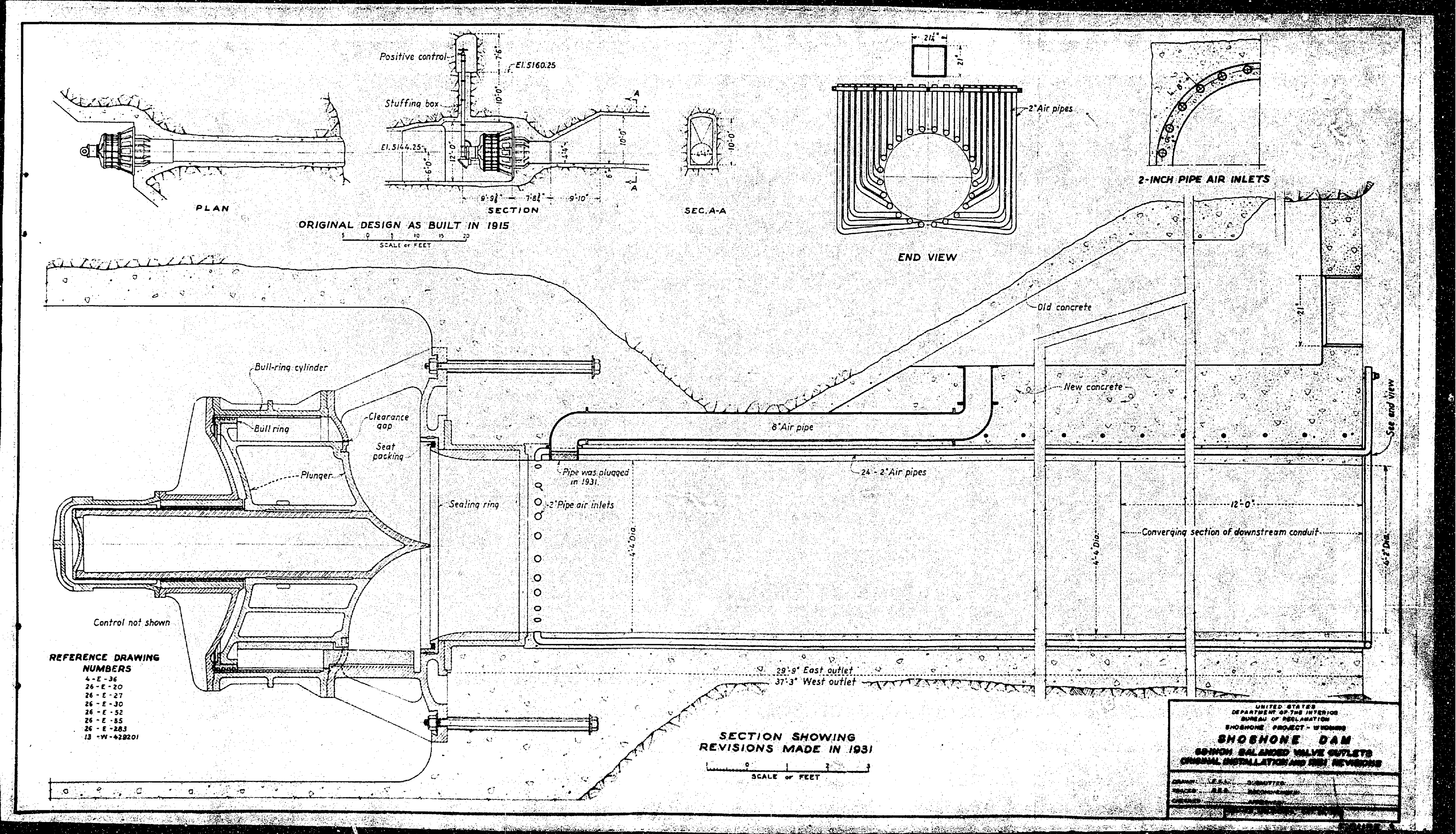
Although the theory of cavitation, as accepted by the majority of present-day hydraulicians, differs somewhat from that in the early part of the present century, the conditions described in the foregoing excerpts are still attributed to the same phenomenon. As was the case then, the most practical remedy to be applied to the discharge conduits is considered to be the introduction of air immediately below the regulating devices. The admission of air to the discharge conduit was employed in many instances during the first few years of operation, but, in view of air requirement tests made in recent years on both model and prototype structures,[2] it is doubtful if the air supply in most cases was adequate. The location of the air inlets to the conduits is often more important than the size. Thus improper location might have been one of the


Department of the Interior
United States Reclamation Service
SHOSHONE PROJECT - WYO.
SHOSHONE DAM
LOWER OUTLET TUNNEL
SECTIONAL PLAN
LONGITUDINAL SECTION AA
SECTION BB
SECTION CC
SECTION DD
SECTION EE
MANHOLE DETAIL
Positive control
Stuffing box
Elev. 5160.25
Trash rack grillage See drg. 26-E-39
Operating galleries See drg. 26-E-59
Side inlet
Side inlet tunnel
℄ Lower Outlet Tunnel
℄ Balanced Valve No. 1
℄ Balanced Valve No. 2
Steel Bulkhead
Wooden Bulkhead for protection against freezing.
3" tile drains are provided in both upper corners of tunnel and 4" tile drain in lower left corner (canyon side). Drains extend from slide gate operating chamber to below steel bulkhead relieving pressure on concrete lining.
Operating cylinder 24" dia.
18" By-pass
10" angle valve
Elev. 5155.5
Slide gate operating chamber
Balanced valve operating chamber
Elev. 5160.25
Manhole See detail
1"x6" bars @ 6" c. to c.
15"-60# I beams
Stopplank groove
Balanced Valve No. 1
Balanced Valve No. 2
58" Balanced valve assembly Drawing No. 4-E-36 Arrow Rock Dam
For general arrangement of dam and outlets see drg. 26-E-38.
Scale
20318

The bond between the new and the parent materials was none too reliable and there was always the danger that the patches would be torn out, allowing the areas to become pitted to a greater depth, possibly rendering the release system useless until extensive repairs could be made.

It was realized that the pitting was an action accompanying subatmospheric pressures, but the cause was not completely understood. At first the pitting was believed to be a direct result of the making and breaking of the vacuum in the immediate vicinity and then considered the result of cavitation, a phenomenon considered to take place when the pressure within a system approaches the vapor pressure of the flowing medium. Although opinions vary concerning the nature of the action resulting from the phenomenon, the majority[3] believe it to be the direct result of forces produced by the collapse of cavitation cavities as they pass from a zone of vapor pressure to one of greater pressure. T. C. Poulter[4] believes that other actions are involved.

An attempt was made in the winter of 1930-31 to relieve the condition at Shoshone Dam by admitting air through a system of vents to the conduits below the valves. The conduits were repaired by patching, then lengthened and provided with twenty-four 2-inch pipes and an 8-inch duct below each valve (figure 3). Each was constricted two inches in diameter at a downstream end. A marked increase in the intensity of the noise accompanying the discharging water resulted, and the experiment was considered unsuccessful. The 8-inch vents were closed with wooden plugs when investigations disclosed them to be the main source of the


Positive control
El. 5160.25
Stuffing box
El. 5144.25
A
A
PLAN
SECTION
SEC. A-A
ORIGINAL DESIGN AS BUILT IN 1915
SCALE OF FEET
2" Air pipes
END VIEW
2-INCH PIPE AIR INLETS
Old concrete
New concrete
See end view
Bull-ring cylinder
Bull ring
Clearance gap
Seat packing
Plunger
Sealing ring
8" Air pipe
Pipe was plugged in 1931
2" Pipe air inlets
24 - 2" Air pipes
12'-0"
Converging section of downstream conduit
4'-4" Dia.
4'-4" Dia.
6'-2" Dia.
29'-9" East outlet
37'-3" West outlet
Control not shown
REFERENCE DRAWING NUMBERS
4-E-36
26-E-20
26-E-27
26-E-30
26-E-52
26-E-85
26-E-283
13-W-429201
SECTION SHOWING REVISIONS MADE IN 1931
SCALE OF FEET
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
SHOSHONE DAM
BALANCED VALVE OUTLETS

increased noise. Because of the apparent failure of the vent system, resort was made to the original method of maintenance and the valves used as little as possible, being closed whenever sufficient water to meet downstream requirements passed through a notch in the spillway crest. It was realized that the pitting was serious and that repairs by the usual method were inadequate; however, a more practical method of repair was not apparent at the time. Other valves[5] in which cavitation has been eliminated are among recent developments.

The development of lands downstream and recent requests to control floods to prevent damage to crops along the river necessitated the release of more water through the outlet valves. Damage to the outlet structure was increased severely by these requirements and the problem of maintenance became critical, so much so that an inspection of the outlet structure was requested by the project engineer at the end of the 1942 season, after the valves had operated at near full capacity over an extended period to regulate flood flow. In response to this request an inspection was made in October 1942. Incurred damages (figures 4, 5 and 6) were reported as follows:[6]

"The concrete for several feet downstream from the metal lining in each conduit has been severely eroded and the majority of the twenty-four 2-inch pipes embedded in the conduit during the revision in 1931 have been torn out and washed away in the eroded areas. The leakage around the west valve in the closed position is abnormal, indicating the seat packing is missing and a leakage through the needle face on the west valve has increased in size since it was noticed in December 1941.

A. Outlets of 58-inch balanced valves in South Canyon Wall.

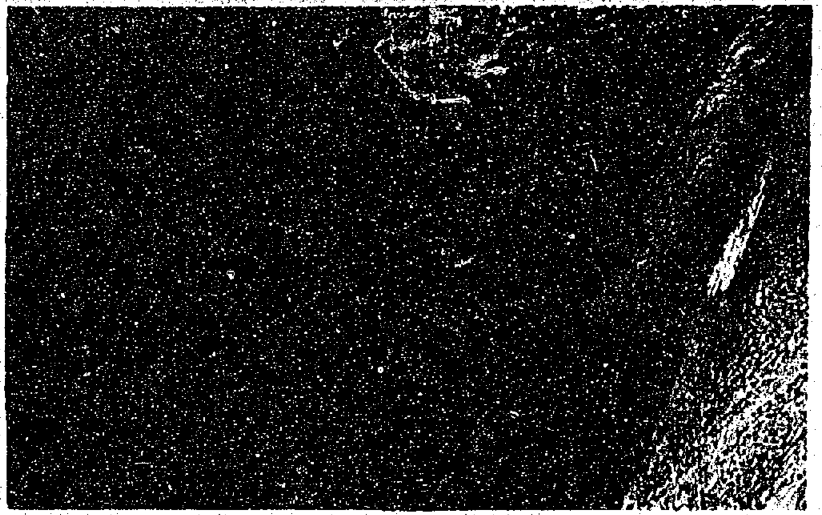
B. Remains of 2-inch air pipes in vent of 52-inch conduit looking downstream from east valve.

C. Two-inch air pipes laid bare by destruction of concrete downstream from east 58-inch balanced valve.

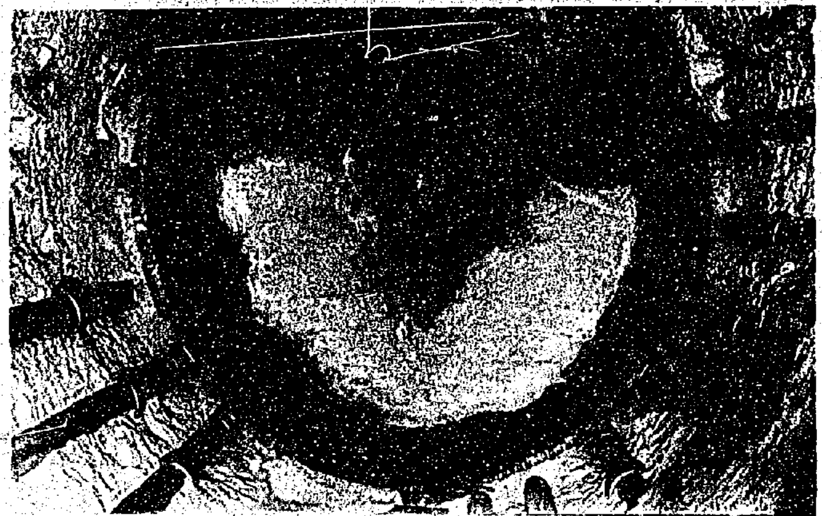
D. Severe pitting due to cavitation on conduit liner immediately below east 58-inch balanced valve.

Balanced Valves - Lower Outlet Tunnel - Shoshone Dam

FIGURE 4

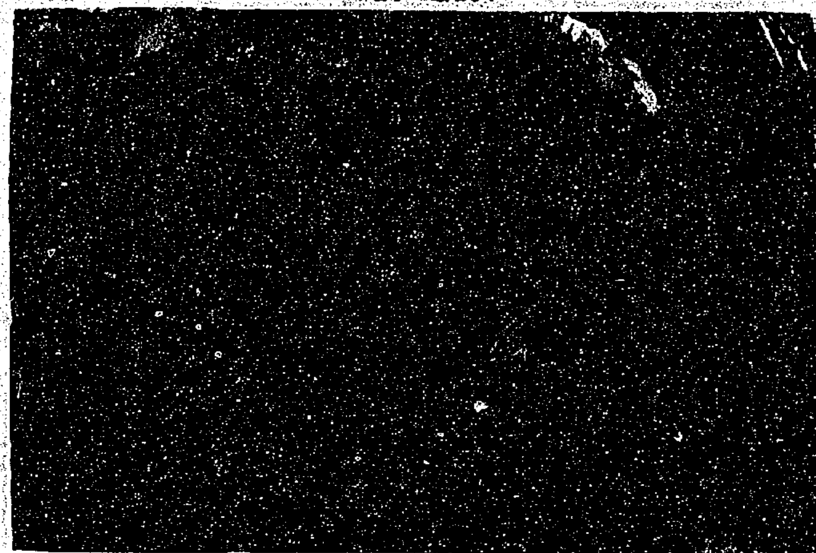


A. Pitting on metal liner near seat on east 58-inch balanced valve.



B. Remains of 2-inch air pipes in east conduit. Extensive welding on needle face is apparent. End of metal liner cut off in 1931 when present installation was made.

C. Remains of 2-inch air pipes and 8-inch vent and deep hole cut in right side of 52-inch conduit downstream from west 58-inch balanced valve.



D. Face of needle in west 58-inch valve, showing extensive welding and exposure of air vent pipes downstream from metal liner.

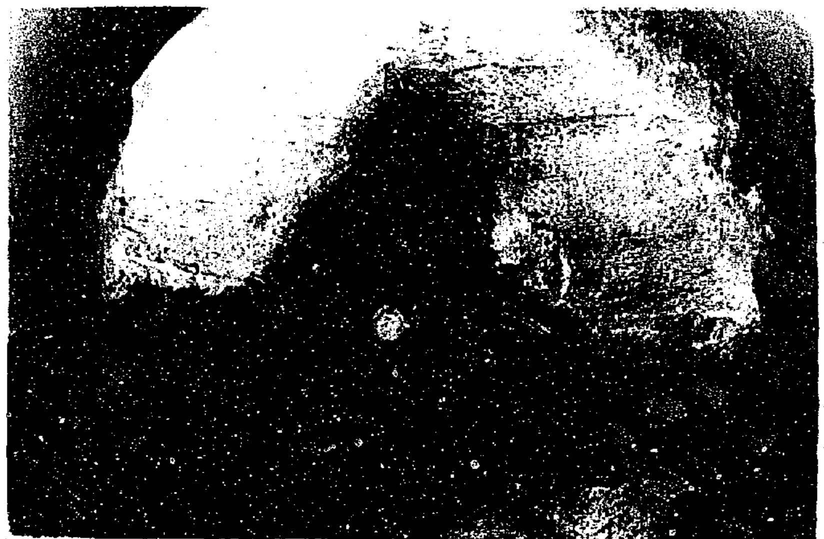
Balanced Valves - Lower Outlet Tunnel - Shoshone Dam

FIGURE 5

A. Severe pitting of metal liner and concrete in crown of conduit immediately downstream from west 58-inch balanced valve.

B. Extent of erosion in east valve of December 17 1941, showing 2-inch pipes uncovered in crown and left side of conduit.

C. Two-inch pipe openings in conduit on December 17, 1941.



D. Extensive welding on face of needle and leakage through needle - December 17, 1941.

Balanced valves - Lower Outlet - Shoshone Dam

FIGURE 6

"In the east valve conduit, seven of the twenty-four 2-inch pipes are still intact, the remainder being torn out as shown in figures 4 and 5. The concrete is stripped out from 6 to 10 feet downstream from the metal liner on the left side (figure 4) 10 feet on the bottom, and 3 to 6 feet on the right side. In the bottom, the maximum depth of erosion was 11 inches below the original invert. The 8-inch pipe in the crown, which was plugged since the trials on its effectiveness in 1931, is still intact but the concrete is torn from around it. The semisteel conduit liner below the valve is severely pitted due to cavitation as shown in figure 4. The severity of the pitting can be judged by a study of figure 5.

"The east valve closes satisfactorily, but there is an extensive pitted area on the sealing ring at the invert. The face of the needle has pitted areas on which several kinds of metal have been tried, such as Wilson 17, Airco nickel, 25-12 stainless steel and Hobart cast iron. None has been satisfactory. Figures 5 and 6 show the extensive welding on the face of the needle. The areas of greatest pitting were directly below and above the respective valve guides. In those areas only 3/4 of an inch of the original two inches of parent metal remains.

"The conduit downstream from the west valve is not as extensively eroded as the east valve but it is more severe in spots. Twelve of the twenty-four 2-inch pipes are still intact, the others being ripped from their embedment. Figure 5 shows the remains of these pipes and a hole in the concrete approximately 15 inches deep. In this conduit, the plug in the outlet of the 8-inch air pipe had been torn out."

In view of the findings of this inspection and similar previous occurrences at this and other installations, hydraulic model tests were believed to be the only practicable means of solving the problem, and a comprehensive test program was instigated immediately to enable repairs before the start of the 1943 irrigation season.

II - PURPOSE OF MODEL STUDIES

Scope of Tests

The main purpose of constructing a model of the Shoshone outlet valve was to evolve a means of minimizing or eliminating the severe damage to the outlet structure, thereby reducing the unreasonably high seasonal maintenance costs and removing the danger of a possible failure in the water release system. This problem involved an extensive study of the pressure distribution in the valves and discharge conduits, first, on a 1 to 6 scale aerodynamic model representing a one-eighth sector through a valve and discharge conduit, to expedite the redesign so that purchase of the necessary materials might be made in time for completing repairs before the 1943 irrigation season; and then on a 1 to 8 2/3 scale hydraulic model of one valve and discharge conduit to verify the air model tests, study refinements in design, and determine the adequacy of the aeration system in both the original and the proposed designs. In addition, studies concerning the actuating pressures for the valve plunger were made. After it was found impossible to obtain materials for the new needle tips and air intake manifolds required for the proposed changes, due to restrictions by the War Production Board, tests were conducted to ascertain valve-opening ranges of safe operation to minimize damage by limited operation until materials become available. Also, a study was instigated to ascertain the possibility of obtaining acceptable conditions by making minor alterations to the existing structure. The model studies included tests to determine the reliability of using air as a fluid instead of water and investigations to ascertain limitations and disadvantages of the aerodynamic model. In connection with these tests, an examination was made of hydraulic and aerodynamic equations to ascertain the error introduced when using the simpler hydraulic equation in determining the flow of air through an orifice. According to Dr. C. Keller, complete investigation of hydraulic machines is possible through aerodynamic testing. Dr. Keller's works[7] were used as a guide throughout the model study.

Summary of Results

A satisfactory solution to the problem of relieving the severe subatmospheric pressures on the valve needles and discharge conduit walls to prevent the occurrence of the cavitation phenomenon, thereby eliminating the destructive pitting action to these parts of the structure, was obtained through the model studies subsequently described.

The model tests indicated that either of two methods might be employed to give satisfactory operation. One included major changes in the valve needles and air-supply system and required the purchase of heavy metal castings, while the other involved the streamlining of the sealing edge of the existing plunger, removal of a portion of the bronze sealing ring by chipping and grinding, removal of the throat liner, and revamping the air-supply system. Aeration equivalent to three 12-inch ducts was found to be adequate in this arrangement, but slightly more area was recommended as a factor of safety because of the limited information available on the air requirement in high-velocity flow.

The model tests showed that the existing prototype vent system was inadequate to prevent cavitation for all except a very small range of valve opening. Insufficient air was supplied at openings between 23 and 70 percent, and some of the 2-inch vent pipes on the invert and crown became ineffective at openings above 85 percent, due to eddies forming immediately downstream from the V-guides. These conditions precluded safe operation of the installation at ranges of valve opening other than 70 to 85 percent.

Model studies of the existing field design indicated that the pitting of the prototype valve needles has been the result of operating at valve openings between 14 and 25 percent and that damage to the conduits resulted between 23 and 70 percent valve opening. No doubt the damage to the conduit at these openings rendered the air-supply system ineffective and aggravated the destructive action for larger valve openings. Discharge coefficients and capacity curves, which will serve to determine the flow being released by the outlet works before and after the outlets have been revised, were prepared from the model data.

The use of an aerodynamic model constructed of molding plaster proved an extremely useful expedient in determining the feasibility of the proposed redesign. The tests on aerodynamic models of the Shoshone valve and on two other small valves, using air and water as flow media, indicated that it is possible to obtain reliable pressure and calibration data from air models providing the tests are conducted carefully and proper.

interpretation of the results is made.

Investigation of hydraulic and thermodynamic equations for computing the quantity of air discharging from an orifice disclosed that the simpler hydraulic equations may be used without introducing noticeable errors only when the pressure differential through the orifice remains small.

III - INTERPRETATION OF RESULTS

Transference of Model Results to Prototype

With few exceptions, present-day hydraulicians are of the opinion that cavitation in a hydraulic passage occurs only when the pressure at some point within it approaches or 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 models was based on this concept. Because the aerodynamic tests were limited to a small range in head by the lack of air-blower capacity, the following discussion is directed principally to hydraulic models using a liquid as a test medium. However, it is applicable to air models also.

Whether or not the pressure at various points in the prototype can be accurately predicted from model results depends on the conditions existing during the operation of the prototype. If the pressures at all points within the prototype are above the vapor pressure of the fluid, the problem is simple and the usual similitude transfer relations enumerated by Chick[8] are valid. However, if the pressure at any point becomes equal 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 vapor and natural atmospheric pressures at the prototype.

If, at the scale heads, over a certain operating range, neglecting the relative difference in model and prototype friction due to different Reynolds numbers, 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

$$P_p = N P_m$$

where P_p and P_m are prototype and model pressures, respectively, and N is the model scale.

However, if the scaled value at any point extends below the vapor pressure, which condition indicates that cavitation will occur 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 the throat below the seal ring of the Shoshone valve. 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, C in the equation

$$Q = C A \sqrt{2 g h_t}$$

remains constant, the ratio of the difference in head between any points in this region to the total difference (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 must be taken to construct the model to give the correct scaled values of these pressures. Otherwise the operating characteristics of the full-sized structure may or may not be indicated by the model.

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 change of head through the 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 Reynolds 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

$$P_p = F D_t + P_c$$

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 head difference 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 the model tests.

Though the application of this method to cases where the stream tubes change appreciable with changes in head, as in the present field design of the Shoshone valve, 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 -33 feet of water, the pressures in these regions were taken as criteria in establishing the critical range of opening for the present 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.

The transference of the aerodynamic model data to prototype was made by pressure factors in a manner similar to that described previously. However, two variations of the method were employed; one, using factors based on the head on the valve, above atmosphere, expressed above or below atmosphere as indicated by the piezometer, being considered; and the other, using factors based on the total head difference but expressed above the aeration (control) pressure, obtained from the tests on the 1 to 8 2/3 scale hydraulic model. Those expressed in percent of the head above atmosphere were adequate for determining the pressures in the proposed redesign, since the aeration of the valve was sufficient to make any change from the small negative pressures at the vena contracta negligible. This is not the case in designs like the present field structure where substantial subatmospheric pressures exist.

Pressures obtained in this manner, for instances where the scaled values exceed the vapor pressure and are assumed to be equal to it, as in the redesign when unaerated, or in the present installation when partially aerated, are incorrect, the results being similar to those obtained in a hydraulic model when the familiar similitude relationship is used and the same assumption is made. Critical pressures are indicated over a greater portion of the outlet and for a wider range of valve opening than should be the case.

The second variation mentioned above was expected to give pressures more closely representing those for the prototype structure; thus it was employed in recomputing the prototype pressures in all aerodynamic tests after the aeration pressure had been determined by the hydraulic model. Excellent agreement resulted between the hydraulic and the aerodynamic data for the proposed redesign, but discrepancies of appreciable magnitude, attributed partly to different degrees of separation of the two flow media from the bounding surfaces and partly to limitations of the aerodynamic model, were noted for the present field design.

IV - SPECIAL AERODYNAMIC STUDIES

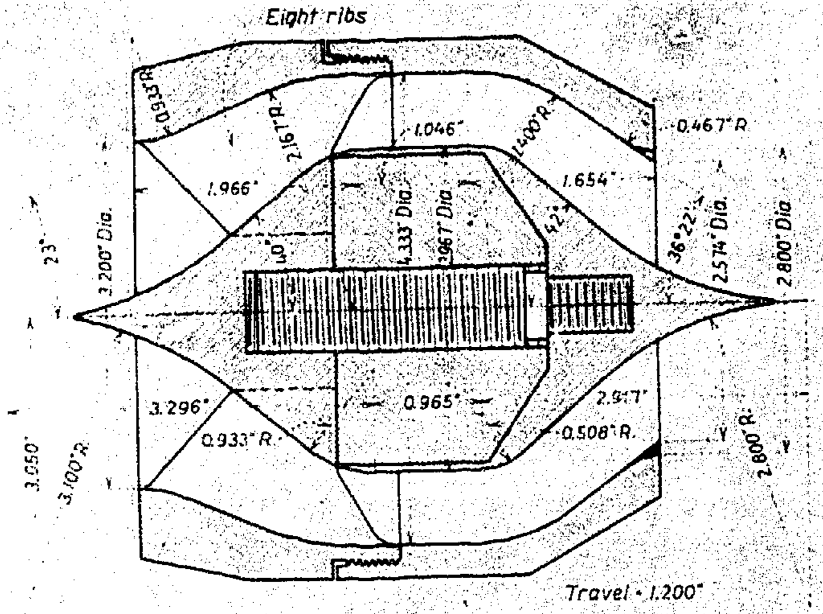
Air Versus Water as a Test Medium

The failure of discharge data taken from 45-degree sector aerodynamic models to agree within the limits of experimental error with that obtained from complete hydraulic models, in tests made previous to those on the Shoshone outlets, led to investigations to ascertain whether the difference was introduced by using air as a flow medium or by using sector models of one scale for air and complete models of another scale for water. It was concluded from the tests described subsequently that errors are more likely to result from the latter.

Two small valves (figure 7), one a 3-inch hollow-jet and the other a 2.8-inch needle, for which the laboratory air-blower capacity was sufficient to give reliable measurements, were calibrated, first with air, then with water.

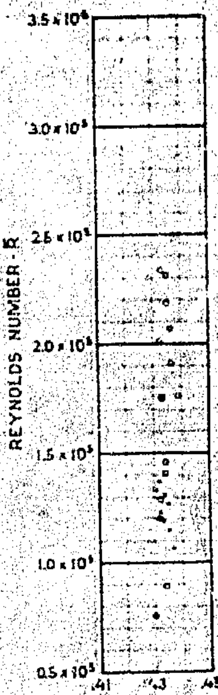
There was very poor agreement between the aerodynamic and the hydraulic data from both models when first compared. The discharge coefficients for each valve were inconsistent regardless of the medium employed, and the results obtained by using air were in poor agreement with those using water. Better comparison was obtained for the needle valve than for the hollow-jet valve.

In the initial tests on the needle valve, the exit edge of the valve was rounded similarly to the design used in the Boulder Dam outlets. Apparently this exit shape did not give constant degrees of separation at the rounded edge for a given head. It seemed that the flowing media would at times cling to the curved surface, causing a recovery of head which was not included in the reading of



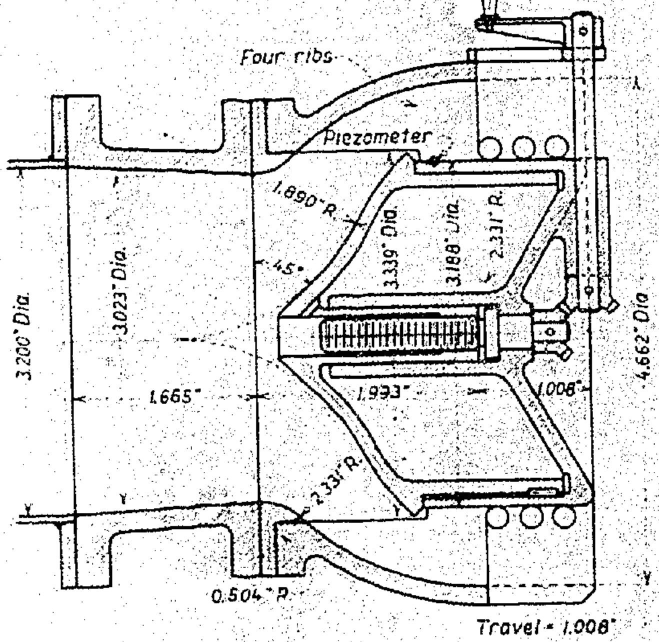
A. NEEDLE VALVE

3.200" DIA. INLET – 2.574" DIA. SHARP-EDGED EXIT



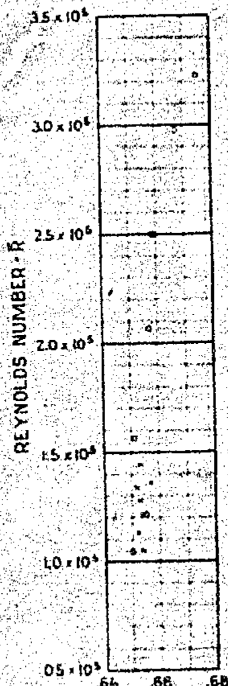
COEFFICIENT OF DISCHARGE
C in $Q = CA\sqrt{2gh_t}$

LEGEND
• AIR
○ WATER



B. HOLLOW-JET VALVE

3.023" DIA. INLET – 4.662" DIA. EXIT



COEFFICIENT OF DISCHARGE
C in $Q = CA\sqrt{2gh_t}$
h_t = static + velocity head

DISCHARGE COEFFICIENTS FOR SMALL VALVES

USING AIR AND WATER AS FLUIDS

FIGURE 7

a piezometer located one pipe diameter upstream from the valve. At other times the flow would be free from this action. To eliminate any variation from this source the valve exit was changed to the sharp-edged type. The results obtained from this arrangement were considered excellent when the discharge coefficients obtained by using the two flow media were plotted against Reynolds number based on the entrance diameter of the valve (figure 7A). The altered exit shape eliminated the abrupt changes in direction at the boundary of the flow passage and gave coefficients which did not vary with the head. Though the agreement between the aerodynamic and the hydraulic tests was good, the comparison would have been more convincing if the capacity of the air blower had been sufficient to obtain the same Reynolds number as for water, without necessitating the operation of the valve at extremely low heads where the accuracy of head and discharge measurements with water was questionable.

The first attempts to compare the aerodynamic and the hydraulic data from the 3-inch hollow-jet valve were discouraging, for the discharge coefficients obtained by using air, measuring the head on the valve with atmospheric pressure as a datum and not considering the negative pressure on the interior of the valve downstream from the outer edge of the needle, were considerably in excess of those obtained by using water. After investigating the pressures in the downstream portion of the valve near the outer edge of the needle, where appreciable subatmospheric pressures were found to exist, the disagreement was attributed to improper measurement of the head on the valve in the aerodynamic tests. At times, the subatmospheric pressure in this region was almost equal to the pressure above atmosphere recorded by the piezometer located one pipe diameter upstream from the valve. The subatmospheric pressure at the same point was negligible when water was passing through the valve; thus the head obtained for the hydraulic test had been nearer the correct value than that for the aerodynamic tests. When the head on the valve was taken as total change in pressure from a point one diameter upstream to one immediately downstream from the outer edge of the needle, very good agreement resulted between the aerodynamic and the hydraulic tests (figure 7B). These tests demonstrated that care must be exercised in conducting aerodynamic testing of hydraulic devices. Pressures bounding a jet of water may be insignificant, while those at the same boundary when air is used may represent a large percentage of the total head.

Also, it was concluded that the discharge characteristics as well as the pressure distribution for most hydraulic devices can be obtained from an aerodynamic model if the tests are made with extreme care and the results are properly interpreted. It would be practically impossible to predict pressures in the present Shoshone outlet structure by aerodynamic studies without first making hydraulic studies to obtain the aeration pressure or measuring the prototype pressures and using corresponding pressures on the model.

Even with the aeration pressures known, the problem would be a difficult one, for the abrupt changes in direction of the flow passage in this design would cause separation of the main flow from the boundary and the amount of separation would vary with the head on the valve. The difference in the physical properties of air and water would also influence the separation; thus poor agreement between tests using air and those using water as a flow medium might be expected. The difference in pressure factors obtained at various valve openings on the aerodynamic and the hydraulic models of the present field design (figure 8B) might be explained in this manner.

The pressures for the proposed design of the Shoshone outlets could be predicted accurately from the air tests, since the subatmospheric pressure at the control was negligible and sufficient aeration to obtain comparable model pressures could be provided by removing the model discharge conduit. In addition, the positive control immediately downstream from the seat assures against any appreciable change in the stream tubes to effect the pressure factors (figure 8A).

Comparison of Hydraulic and Thermodynamic Equations for Computing the Flow of Air Through an Orifice

When aerodynamic tests for the redesign of the Shoshone outlet works were instigated, it was realized that numerous computations of the air discharge through a standard intake orifice would be required during the study. This work could be facilitated if the hydraulic equation $Q = C A \sqrt{2 gh}$ was used instead of the more complex thermodynamic equation

$$Q = C A \sqrt{2 g \frac{k}{k - 1} \left[P_a V_a - P_{ds} V_{ds} \right]} .$$

Moreover, the information would be useful in future aerodynamic tests. A comprehensive comparison was made of the two equations, based on both the upstream and the downstream pressures.

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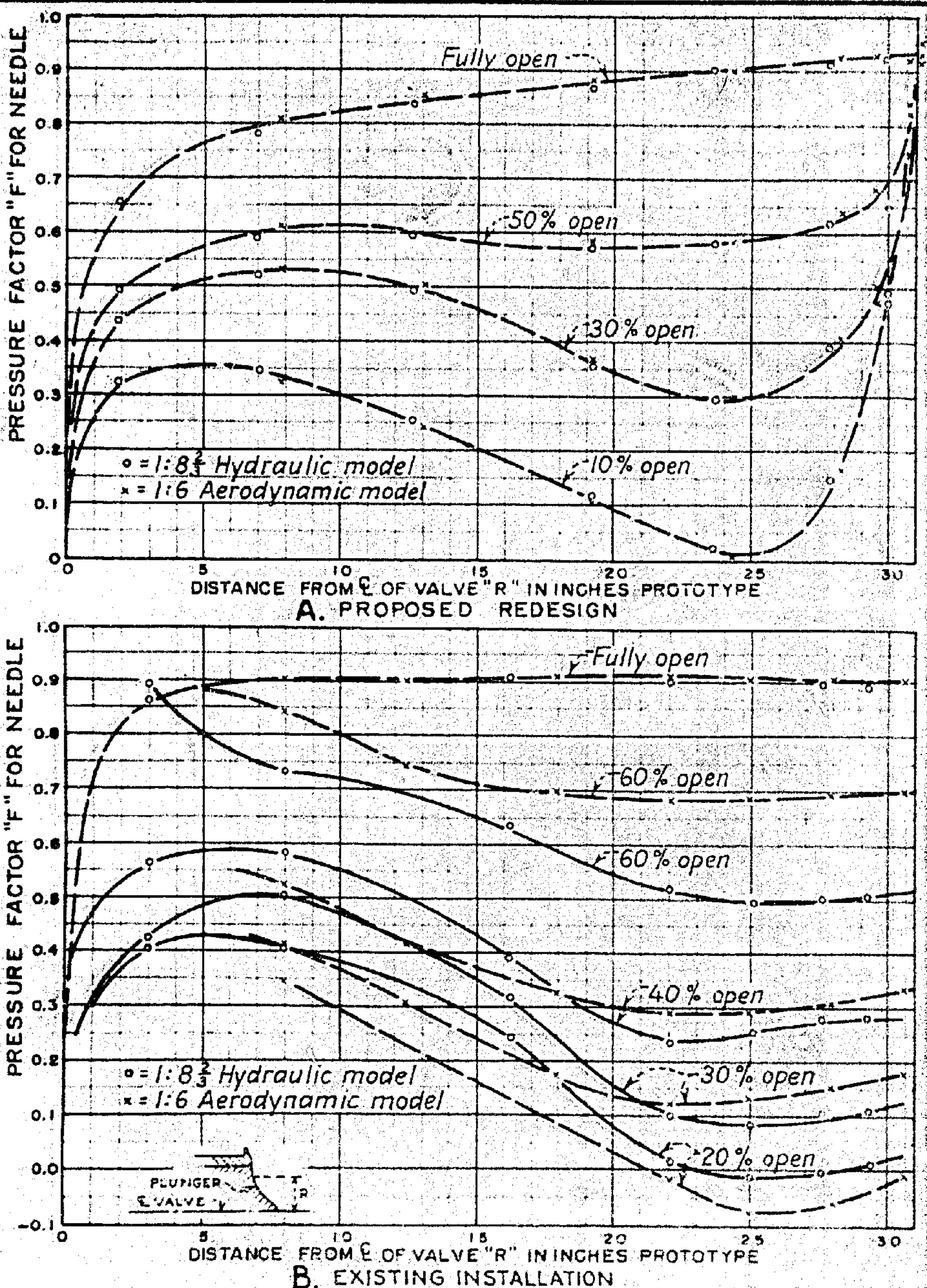

SHOSHONE DAM
COMPARISON OF PRESSURE FACTORS
PROPOSED REDESIGN AND EXISTING OUTLET
AIR VERSUS WATER

FIGURE 8

The hydraulic equation for flow through an orifice when based on atmospheric pressure may be expressed as:

$$Q_{ha} = C\,A\,\sqrt{2g}\quad\sqrt{(P_a - P_d)\,V_a}$$

and the thermodynamic equation as:

$$Q_{ta} = C\,A\,\sqrt{2g}\ \sqrt{\frac{k}{k-1}\left[P_a V_a - P_d V_d\right]\frac{V_a}{V_d}}$$

where

Q_{ha} and Q_{ta} are quantities in cubic feet per second at atmospheric pressure, obtained by the hydraulic and thermodynamic equations;

C is the discharge coefficient of the orifice;

A is the area of the orifice in square feet;

g is the acceleration due to gravity;

P_d is the downstream pressure in pounds per square inch absolute;

V_a is specific volume of the fluid at atmospheric pressure, cubic feet per pound;

V_d is specific volume at the downstream pressure; and

k, 1.405 for air, is the constant for adiabatic change of state, a change in which the system neither receives nor gives out heat.

The comparison was accomplished through the use of the ratio $\frac{Q_{ha}}{Q_{ta}}$, since it expressed the discharge obtained by using the hydraulic formula in terms of the correct amount given by the thermodynamic relationship.

From the two equations,

$$\frac{Q_{ha}}{Q_{ta}} = \frac{\sqrt{(P_a - P_d)\, V_a}}{\sqrt{\frac{k}{k-1}\left[P_a V_a - P_d V_d\right]\frac{V_a}{V_d}}} \quad \ldots\ldots(1)$$

Squaring both sides,

$$\frac{Q_{ha}^2}{Q_{ta}^2} = \frac{(P_a - P_d)\, V_a}{\frac{k}{k-1}\left[P_a V_a - P_d V_d\right]\frac{V_a^2}{V_d^2}} \quad \ldots\ldots\ldots(2)$$

Using $P_1 V_1^k = P_2 V_2^k = P_3 V_3^k$ from which $V_a = V_d\left(\frac{P_d}{P_a}\right)^{\frac{1}{k}}$

substituting for V_a in (2) and dividing both numerator and denominator by P_a, the ratio becomes

$$\frac{\left(\frac{P_d}{P_a}\right)^{\frac{1}{k}} - \left(\frac{P_d}{P_a}\right)^{\frac{k+1}{k}}}{\frac{k}{k-1}\left[\left(\frac{P_d}{P_a}\right)^{\frac{3}{k}} - \left(\frac{P_d}{P_a}\right)^{\frac{k+2}{k}}\right]}$$

Assuming values of $\frac{P_d}{P_a}$, the ratio of $\frac{Q_{ha}^2}{Q_{ta}^2}$ can be obtained.

The square root gives $\frac{Q_{ha}}{Q_{ta}}$ from which the amount Q_{ha} is greater or smaller than Q_{ta} can be determined.

When the assumed values for $\frac{P_d}{P_a}$ of 0.85, 0.90, 0.95, 0.97, 0.99 were used to obtain the ratio of quantities and the results were plotted (figure 9), it was found that substantial errors could be introduced by using the hydraulic formula; that these errors would always be positive when the hydraulic equation, based on either P_a or P_d, was used instead of the thermodynamic equation based on P_a; that they would be negative when the hydraulic equation based on P_a was used instead of the thermodynamic equation based on P_d; and that they would be positive when the hydraulic equation, based on P_d, was used instead of the thermodynamic one based on P_d.

In all cases the error was substantial for large differences in head, decreasing to a negligible amount as the difference became small and the ratio $\frac{P_d}{P_a}$ approached unity.

From this inspection it was concluded that the hydraulic equation may not be used without introducing an appreciable error unless the head differential through the orifice is small. Since the difference did not exceed 0.35 feet in the Shoshone tests, giving a value of $\frac{P_d}{P_a}$ of 0.99, and the error did not exceed 0.5 percent, the hydraulic equation based on atmospheric pressure was used in all computations to obtain the discharge of air through the standard measuring orifice attached to the intake of the blower.

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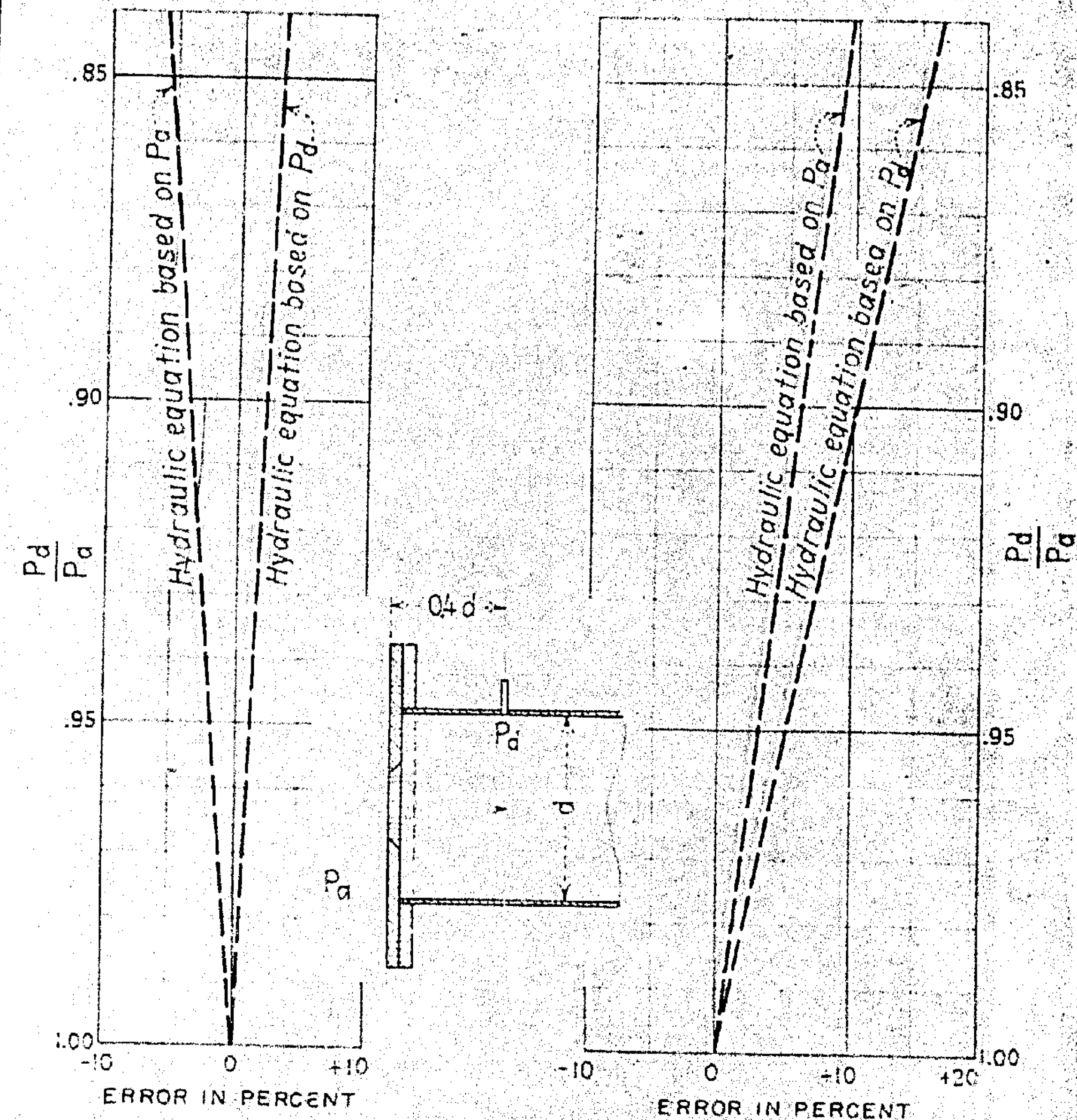


Variation from quantity obtained by Thermodynamic equation based on specific volume at P_d.

Variation from quantity obtained by Thermodynamic equation based on specific volume at P_a.

ERROR INTRODUCED BY USING HYDRAULIC INSTEAD OF THERMODYNAMIC EQUATION FOR OBTAINING FLOW OF AIR THROUGH AN INTAKE ORIFICE

FIGURE 9

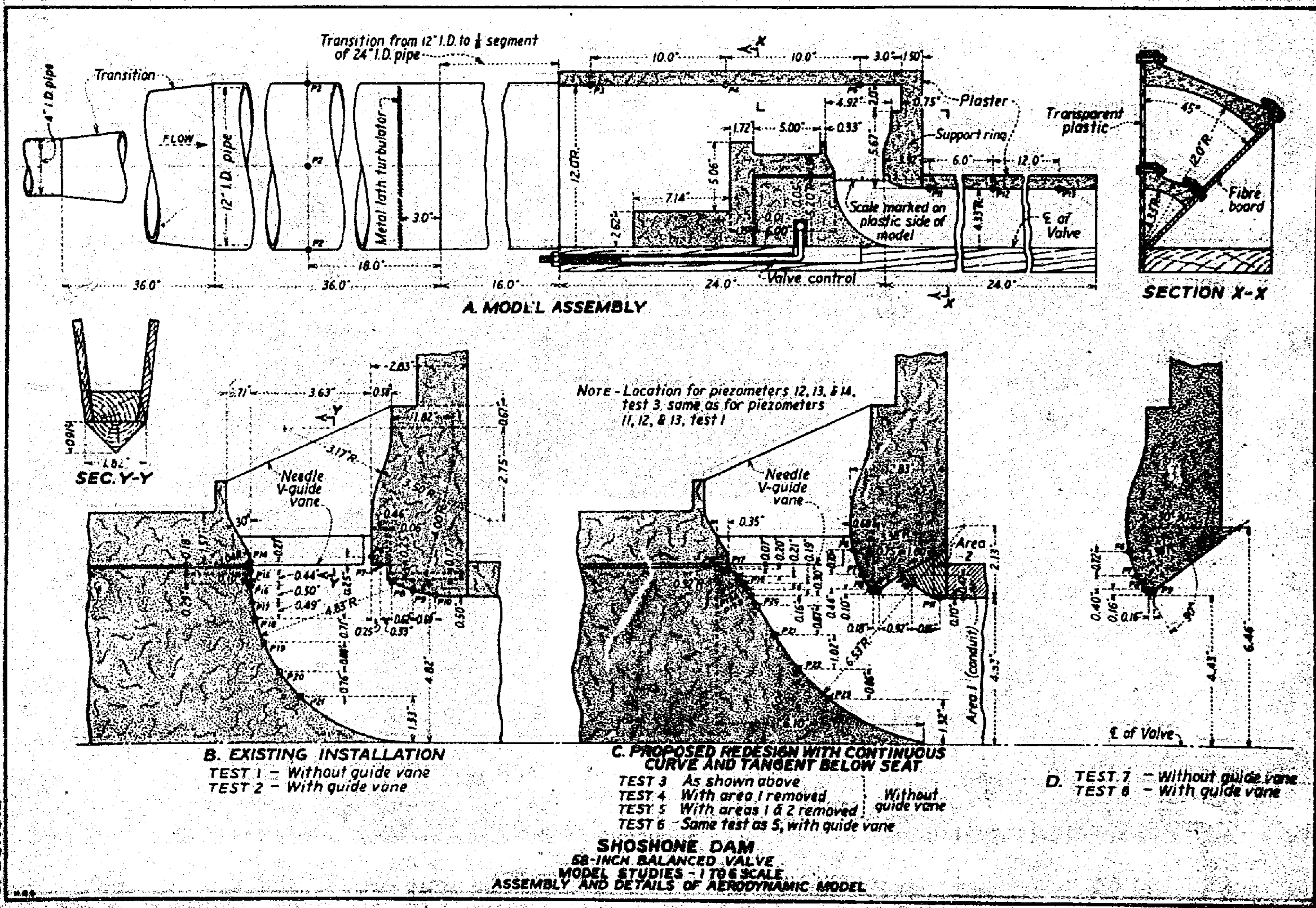
V - INVESTIGATION BY AERODYNAMIC MODEL

Description of 1 to 6 Aerodynamic Model

A model having a scale of 1 to 6, representing a one-eighth sector through the valve and discharge conduit and using air as a test medium, was employed as an expedient in determining the feasibility of proposed changes in the present field installation of the Shoshone outlet to enable the revision of the prototype structure before the start of the 1943 irrigation season. The model consisted of a section of 12-inch diameter metal pipe; a transition from 12-inch diameter to a 45-degree, 12-inch radius, circular segment; a 45-degree V-shaped channel with one side of fiber wood and the other of transparent plastic; and 45-degree plaster sectors of the valve and discharge conduit (figure 10A).

Metal templates fastened to a sliding frame fitted to the edge of a smooth flat-topped table were used in forming the sectors of the tunnel and discharge conduit. Mortar, prepared by sifting dry molding plaster into a vessel of water until it was just covered by the water and stirring it in a manner to prevent entrainment of air, was placed on the table as it reached the proper consistency, and the templates moved back and forth across it. The model segments were shaped through a process of building up and scraping off the surplus plaster as it obtained its set.

The valve needle, housing, and support ring were shaped by templates which revolved about fixed centers. The plaster mortar was placed in V-troughs with sides shaped approximately to the section profiles of the needle and housing, and the templates,



SHOSHONE DAM
58-INCH BALANCED VALVE
MODEL STUDIES - 1 TO 6 SCALE
ASSEMBLY AND DETAILS OF AERODYNAMIC MODEL

FIGURE 10

centered at the ends, swung back and forth across the troughs.

The section representing the valve support ring was constructed by a metal template revolved about a center on the flat-top table, shaping the setting plaster as explained above.

Except for the movable needle, which was controlled by an L-shaped rod with one end inserted into a metal tube installed within the needle and the other passing upstream through a groove in the bottom of the transparent-sided V-channel, all the plaster segments were fitted and bolted to the channel. Air-tight joints were obtained by placing a fillet of modeling clay along the seams inside the model. Air was supplied to the model by a 4-inch positive-displacement blower of limited capacity, a type not as well adapted to aerodynamic studies as the centrifugal or axial-flow type due to its almost constant output against various pressures.

Piezometers were installed by drilling small holes into the model segments and inserting small copper or brass tubes for attaching to a water manometer. The connections between the model and the metal tubes were made airtight by placing plaster mortar around them.

The needle actuating rod, mentioned previously, and a scale of valve openings etched on a strip of transparent plastic and cemented to the plastic wall of the V-channel, enabled accurate setting of the valve for testing.

A water manometer was used to measure the difference in piezometric pressures between the piezometer indicating the head on the valve and any particular piezometer. This procedure was followed to avoid reading extremely small differences in head when critical areas were being investigated, which would have been necessary had atmospheric pressure been selected as the datum.

Study of Proposed Redesign Outlet

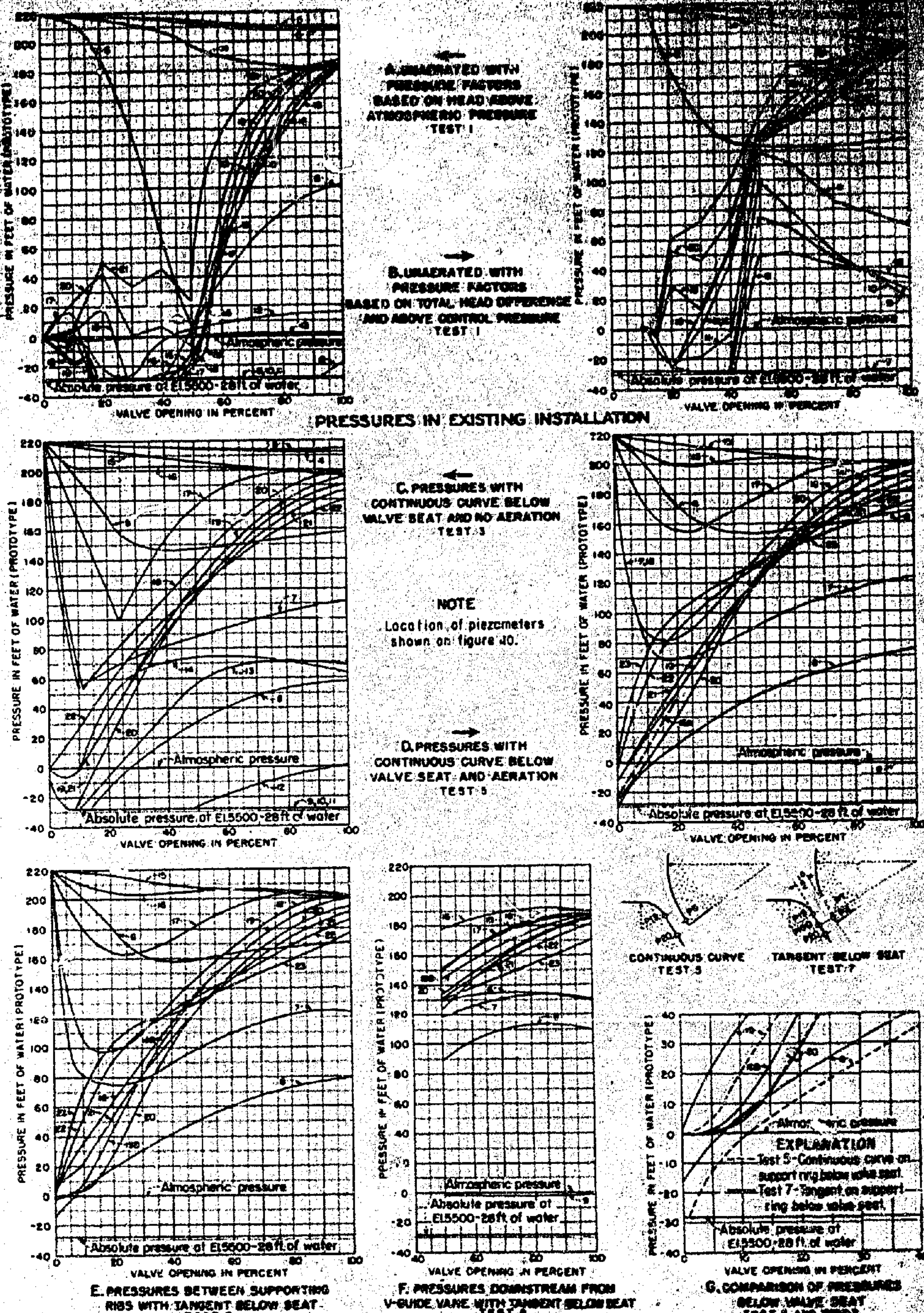
The usual procedure of first constructing and testing a model of the original design to ascertain its characteristics and then altering it to obtain improvement was not followed in this study, principally because the completion of the model tests on the proposed redesign was necessary if revision of the prototype was to be accomplished before the 1943 irrigation season. Insufficient time remained to complete both tests. Moreover, the reliability of results from air tests on a design of this type was questionable because of the magnitude of the subatmospheric pressures involved. The behavior of the model was expected to be similar to that experienced in tests conducted in the hydraulic laboratory on models of other valves. The pressures near the two zones where damage occurred on the prototype were certain to be subatmospheric sufficiently to indicate cavitation, a condition considered to exist when the scaled model pressures exceed the prototype vapor pressure.

Since subatmospheric pressures in outlet structures like those at Shoshone Dam become more severe as the head is increased, the pressures predicted from the model tests were based on the maximum prototype head, approximately 220 feet. By using the pressure factors and conducting tests to determine the variation of the control pressure with head, it would be possible to ascertain those for greater or lesser heads. The present design is an undesirable one; so an extensive program to study the variation of the control pressure with the head did not seem justified when this investigation was made.

When the proposed redesign (figure 10C) was tested without aeration and the data transferred to prototype by using pressure factors based on the static head on the valve (above atmosphere) and expressed as being above or below atmosphere, the pressures near the seat on the support ring and in the discharge conduit were severely subatmospheric (as much as 42 percent of the static head on the valve), indicating that cavitation would result to the redesign if the outlets were improperly aerated (figure 11A).

With the aeration to be provided to the prototype valve by the air-intake manifold and an air duct of approximately six square feet of area, pressures near atmosphere were expected to exist in the space surrounding the jet immediately downstream of the valve; thus the conduit sector below the model valve (area 1, figure 10C) was removed to acquire representative conditions. Tests on this arrangement disclosed that the admission of air to the region immediately below the valve was still hampered by the downstream edge of the support ring. The aeration pressure was too low so the downstream portion of the support ring (area 2, figure 11D) was negligible for all positions of the model plunger.

The clearance-gap pressure (piezometer 16, figure 11D) was equal to or greater than any on the needle, thus indicating no trouble in closing the valve from the wide-open position as had been experienced in the field installation.



PRESSURES IN PROPOSED REDESIGN OUTLET

SHOSHONE DAM
58-INCH BALANCED VALVE
AERODYNAMIC MODEL STUDIES-1:8 SCALE
PRESSURES IN VALVES AND CONDUITS

FIGURE 11

Pressure measurements for the complete range of valve opening indicated satisfactory conditions at all points in the valve except on the needle and the support-ring surfaces (piezometer 8, figure 11D) immediately below the seat where a divergent passage formed as the valve neared the closed position. To alleviate this condition, the continuous curve below the valve seat on the support ring was replaced by a short tangent, diverging one-half of one degree from the needle angle (figure 10C). Complete pressure measurements, including those downstream from the V-guides, were again taken (figures 11E and F). Though the pressures remained subatmospheric for openings of less than six percent, they were not of a magnitude indicating cavitation 11G), and the design was considered satisfactory insofar as the aerodynamic investigation was concerned. Construction drawings for the changes were prepared on the basis of these findings but it was believed advisable to corroborate the results by hydraulic tests on the 1 to 8 2/3 scale model before the plans were adopted, particularly since aerodynamic testing was comparatively new to the laboratory personnel. The aerodynamic tests later proved to be a valuable expedient when almost identical results were obtained from the hydraulic model requiring many times as long to construct.

Study of Present Outlet Installation

As the parts of the aerodynamic model were constructed easily, the model was altered to include the field design, except for the aeration system and the downstream end of the discharge conduit (figure 10B). The model was not aerated, as the prototype aeration pressures were unknown. Moreover, it would have been difficult to aerate properly the aerodynamic model to represent these pressures had their correct magnitude been known. A high-velocity air jet transports the surrounding air more readily than a water jet of the same size and velocity; thus considerable more vent area is required to obtain corresponding pressures at the vena contracta of the air jet and the area could be determined only by trial and error. The model tests indicated lower pressures at all points than would have been the case had proper aeration been supplied, a fact later verified by the hydraulic model.

The pressures in the outlet were as anticipated, severely subatmospheric on the outer edge of the plunger needle and in the conduit downstream. The pressures (figure 11A), computed by using pressure factors based on the head above atmosphere on the valve and expressed as percentages of this differential above or below atmosphere, were found to deviate markedly from those obtained subsequently from the 1 to 8 2/3 scale hydraulic model. Apparently the prototype pressures could not be predicted accurately by this procedure. Examination disclosed that the results were similar to those obtained in hydraulic models when employing the usual model-to-prototype transfer expression and assuming that all scaled values exceeding the vapor pressure were constant and equal to it. The pressures were recomputed using pressure factors based on the total change in head through the valve but expressed as a percentage of the change above the control pressure, obtained from the hydraulic tests (figure 11B). Better agreement was obtained between the aerodynamic and the hydraulic tests when the latter method was used.

The clearance-gap pressure at full opening was not subatmospheric, as had been expected, but was substantially positive, 190 feet of water or about 20 feet lower than the pressure in the tunnel immediately above the valves. Thus little would be gained to improve the operation of the valve at large openings by altering the clearance gap. Pressures on certain parts of the needle were greater than those at this point for openings above 95 percent, indicating that the valve would not be closed hydraulically from these openings by these pressures (figure 11A and B).

Although the field design was not represented correctly by the aerodynamic model, due to the short section of discharge conduit and improper aeration, the tests were believed to give some clue as to the conditions causing the damage to the outlet during the 1943 season. Moreover, the model represented the prototype structure as it existed before the discharge conduits were lengthened and the aeration systems added in 1951 and the pressures, no doubt, were closely representative of those causing considerable damage prior to that date. The tests were important in that they furnished useful information concerning aerodynamic tests and interpretation of the test data.

VI - INVESTIGATION BY HYDRAULIC MODEL

Description of the 1 to 8 2/3 Scale Hydraulic Model

The hydraulic model of one valve and discharge conduit of the Shoshone outlet works, constructed to verify the results from the 1 to 6 scale aerodynamic model, study refinements in design, investigate hydraulic operating characteristics of the valve, and determine the adequacy of the aeration system of the proposed redesign, field installation, and a modified design, consisted of a high-pressure steel head tank, a 1 to 8 2/3 scale bronze model valve, and a section of transparent plastic pipe representing the discharge conduit (figure 12A).

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 located on the needle tip and in the conduit wall immediately downstream from the valve to determine whether or not the pressures in these regions were sufficiently subatmospheric to induce cavitation. The piezometers were not installed until manual controls were provided, since their presence would interfere with the hydraulic operation of the valve. Two needle tips and two throat sections were provided. The bronze needle tips, representing those of the proposed redesign and the field design, were made removable to facilitate changing from one design to the other. The two throat sections, one representing the air-intake manifold of the proposed redesign and the other the [illegible] seal and throat liner of the field design, were machined from

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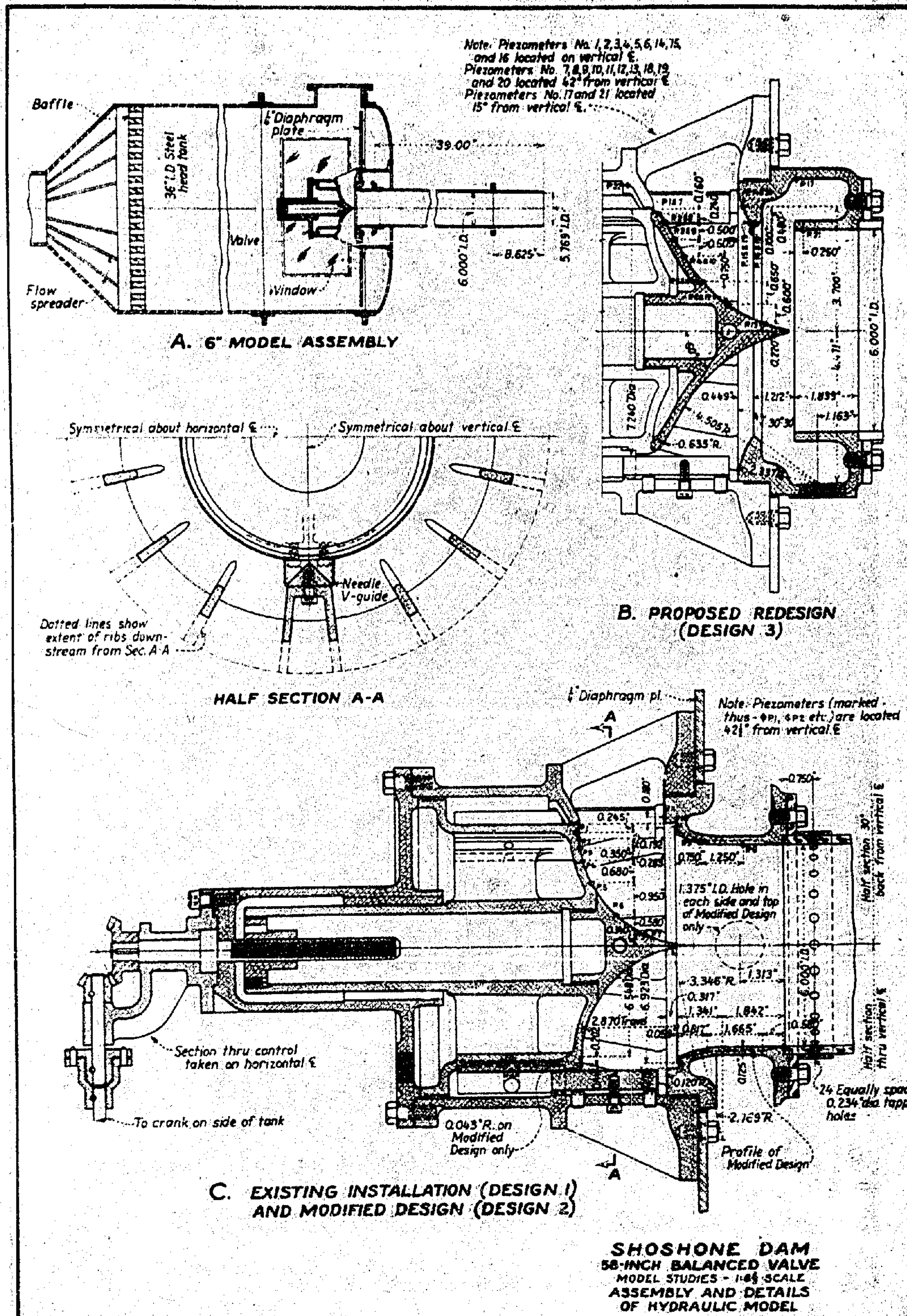

SHOSHONE DAM
58-INCH BALANCED VALVE
MODEL STUDIES - 1:8⅔ SCALE
ASSEMBLY AND DETAILS OF HYDRAULIC MODEL

FIGURE 12

bronze castings and were interchangeable. The section representing that of the field structure was remachined for tests on the modified design.

The portion of the discharge conduit beyond the throat liner of the prototype valve was represented by a length of transparent plastic pipe to permit 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 present prototype installation. Water and mercury manometers were used to record the piezometric pressures.

Hydraulic Operation of the Valve Plunger - Proposed Redesign Outlet

Tests pertaining to the hydraulic operation of the valve were made for the proposed redesign outlet (figure 18B) before piezometers were installed, since their presence would interfere with the free movement of the valve plunger, preventing a correct measurement of the friction. Moreover, they would have been of little value since the operation of the valve at definite openings would have been difficult and the data would have appeared inconsistent. The pressure tests were performed at the conclusion of this investigation after positive mechanical control of the plunger had been provided and exact openings could be established.

Initial operation of the model valve disclosed that an abnormally high pressure (about two feet of water on the model valve center line) was necessary to overcome the friction on the plunger; thus it could not be actuated by the clearance-gap pressure over much of the opening range. Changes in alinement of the V-guides reduced this value to about 0.65 foot of water. A pressure of 0.35 foot of water on the back area of the valve was required to keep the valve in motion during the closing cycle. This value was assumed to be that required to keep the plunger in motion during the opening cycle when thrust computations were made. With the reduced friction, the plunger of the proposed redesign could be operated hydraulically by pressure from the clearance gap, providing it was not allowed to reach the wide-open position. Investigation indicated that its failure to operate at this position resulted when a seal formed between the machined surfaces of the back of the plunger and the inside of the valve housing, preventing the pressure in the bull-ring cylinder from reaching the back end of the plunger. Once this seal was broken, the pressure was sufficient to actuate the valve at all openings. To ascertain if this pressure was sufficient to actuate the valve from the wide-open position and whether the failure to start closure was due entirely to the seal, grooves were cut through the bull-ring seat at the back of the plunger. The pressure transmitted to the back end of the piston through these grooves made hydraulic operation of the valve possible at all openings. Though it is not indicated by the thrust diagram (figure 13), the force to close from the wide-open position is available since the pressure on the needle surface below the V-guides at large valve openings is less than on the remaining portion of the needle and this reduction was not considered in the thrust computations. The proposed redesign of the field structure should therefore be operable at all openings by the clearance-gap pressure, providing the friction between the valve plunger and bull-ring cylinder is not too great and a seal similar to that observed on the model does not form on the prototype.

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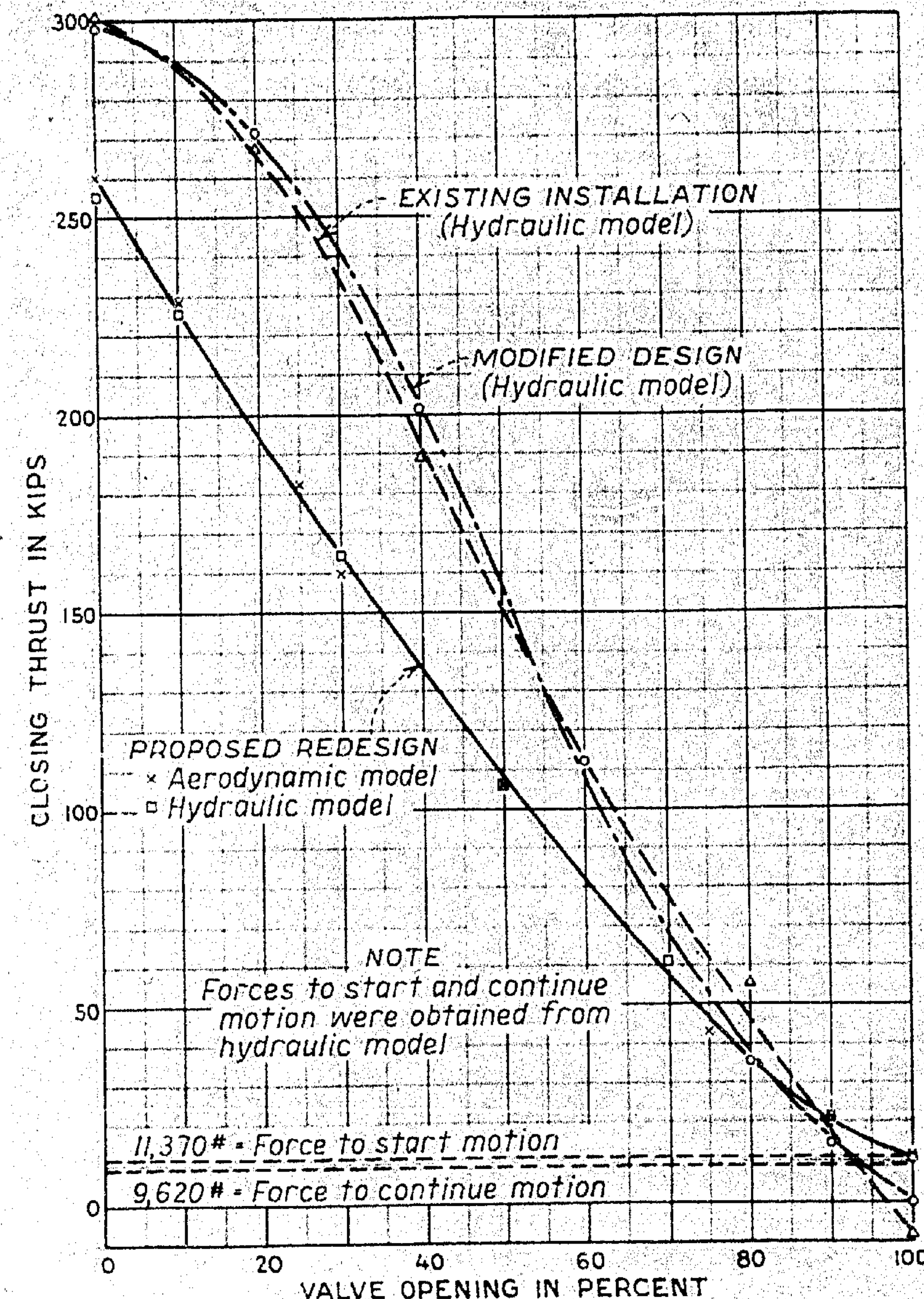

SHOSHONE DAM
58-INCH BALANCED VALVE
AERODYNAMIC - 1:6 SCALE
AND HYDRAULIC MODEL STUDIES - 1:8⅔ SCALE
UNBALANCED CLOSING THRUST FOR
EXISTING INSTALLATION, PROPOSED REDESIGN,
AND MODIFIED DESIGN

FIGURE 13

Study of Pressures in the Proposed Redesign Outlet

After the operating characteristics of the proposed redesign outlet had been studied and the clearance-gap pressure found adequate for actuating the plunger when the friction between the plunger and the bull-ring cylinder was not too great and the seal back of the bull ring was eliminated, the mechanical operating mechanism and the piezometer connections were installed. The pressures on the needle and in the conduit were recorded for small openings as well as for each 10-percent increment of valve opening and the flow conditions for each noted.

The jet from the valve was reasonably smooth with the downstream end of the discharge conduit filling and operating under pressure when the plunger neared the wide-open position.

The pressures on the needle and the support ring were positive for all except very small openings where a slightly diverging passage formed downstream from the seat causing them to become negative. Though these pressures were substantial, they were not of a magnitude indicating cavitation and the design was considered satisfactory.

The pressure in the air-intake manifold was only slightly subatmospheric over the entire range of opening, indicating adequate aeration for the design.

A comparison of these pressures with those obtained from the aerodynamic model disclosed them to be in good agreement, even to the subatmospheric pressures existing at extremely small openings (Figures 11E and 16C) and the design (Figure 15) was recommended. Invitations for bids were prepared, but due to restrictions by the

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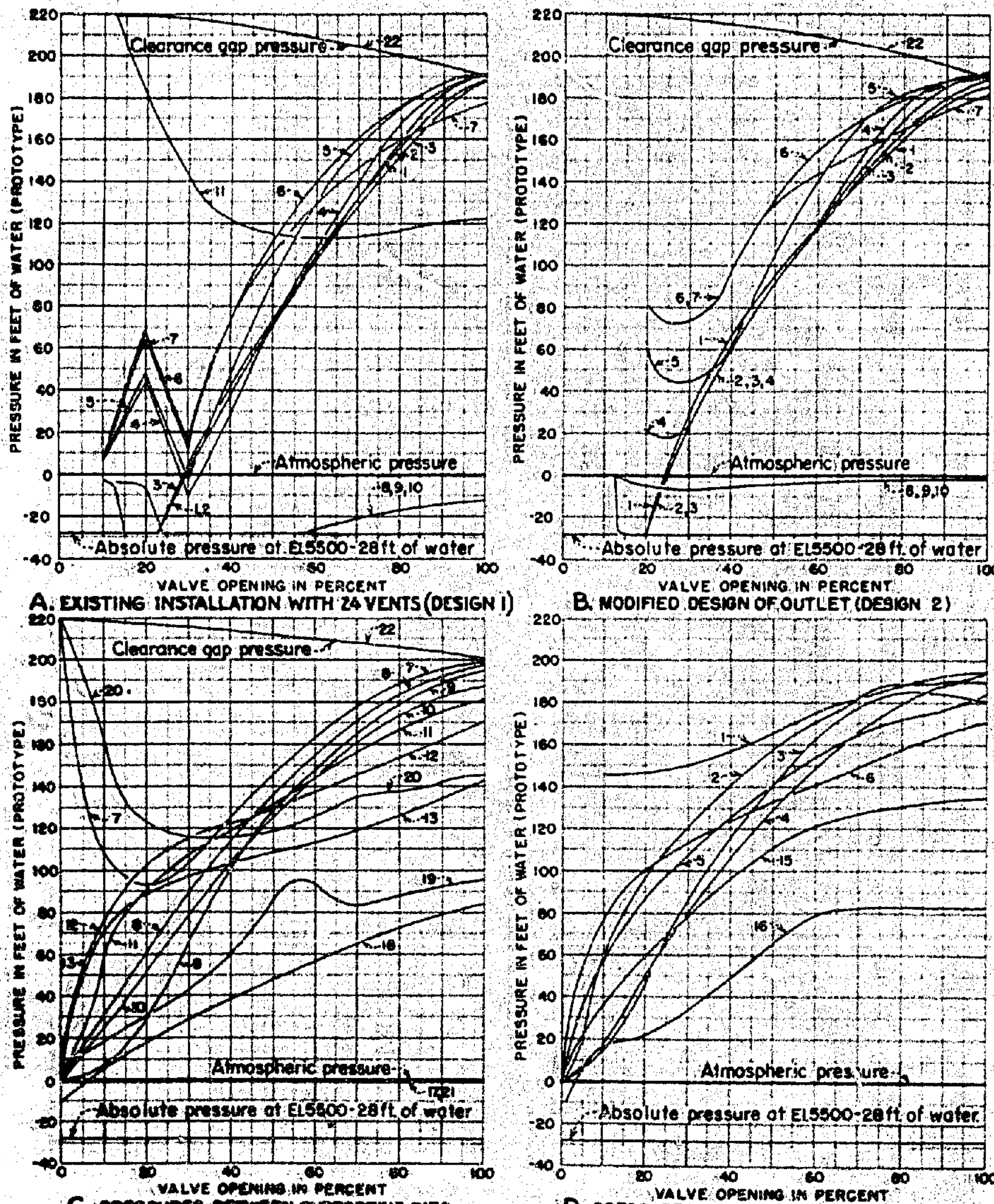


A. EXISTING INSTALLATION WITH 24 VENTS (DESIGN I)

B. MODIFIED DESIGN OF OUTLET (DESIGN 2)

C. PRESSURES BETWEEN SUPPORTING RIBS

D. PRESSURES DOWNSTREAM FROM V-GUIDE

REDESIGN OF OUTLET (DESIGN 3)

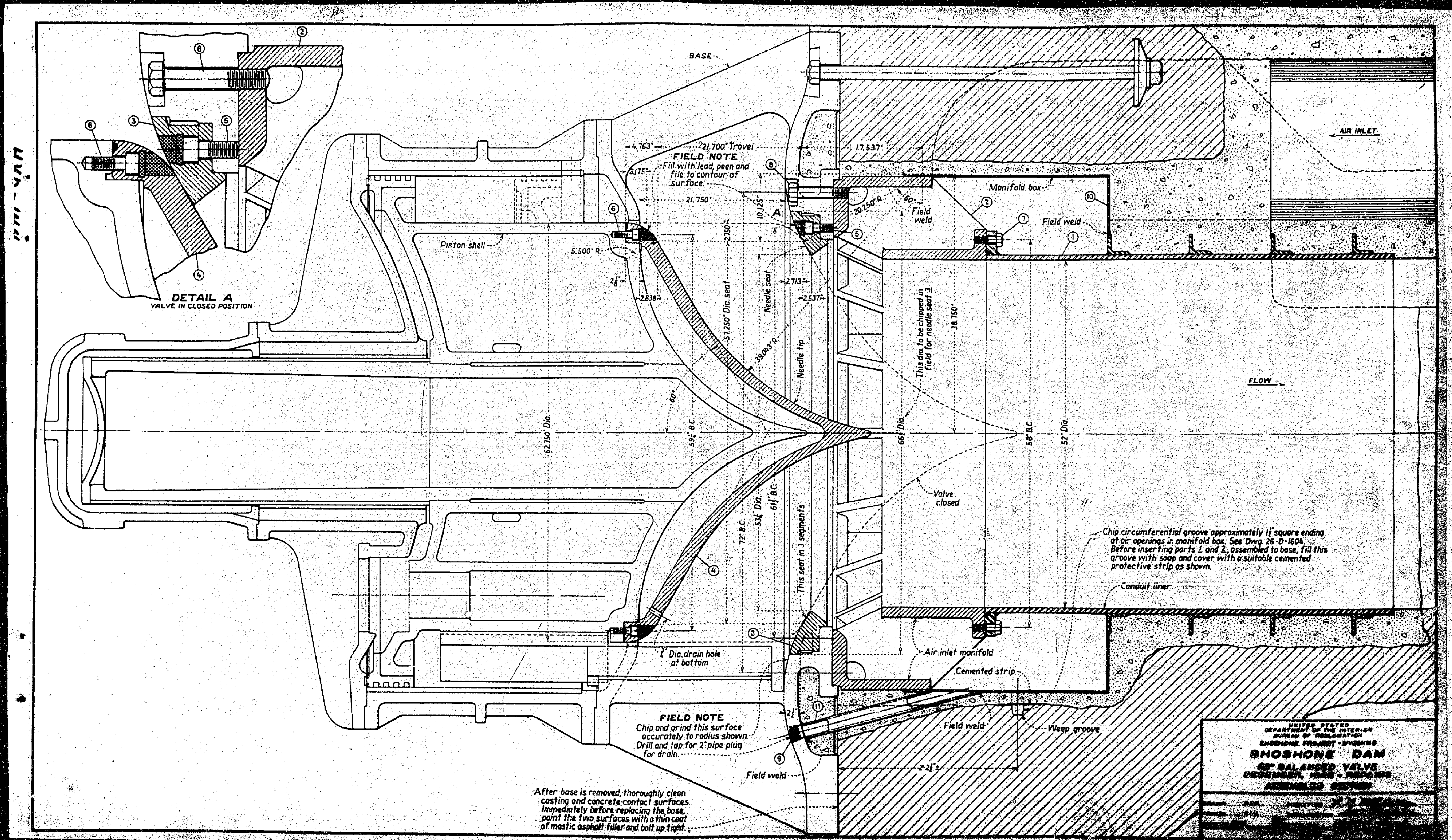
SHOSHONE DAM

58-INCH BALANCED VALVE

HYDRAULIC MODEL STUDIES - 1:8 SCALE

PRESSURES IN VALVES AND CONDUITS

FIGURE 14


DETAIL A
VALVE IN CLOSED POSITION
BASE
FIELD NOTE
Fill with lead, peen and file to contour of surface.
21.700" Travel
4.763"
3.175"
21.750"
10.125"
17.537"
20.250" R.
60°
Field weld
Manifold box
Field weld
Piston shell
5.500" R.
2.750"
2.638"
51.250" Dia. seat
Needle seat
2.713
2.537"
39.043" R.
Needle tip
This dia. to be chipped in field for needle seat 3.
38.750"
FLOW
AIR INLET
62.750" Dia.
60°
59¼" B.C.
72" B.C.
53¾" Dia.
61½" B.C.
This seat in 3 segments
66¾" Dia.
58" B.C.
52" Dia.
Valve closed
Chip circumferential groove approximately 1½" square ending at air openings in manifold box. See Dwg. 26-D-1606. Before inserting parts 1 and 2, assembled to base, fill this groove with soap and cover with a suitable cemented protective strip as shown.
Conduit liner
½" Dia. drain hole at bottom
Air inlet manifold
Cemented strip
Field weld
Weep groove
FIELD NOTE
Chip and grind this surface accurately to radius shown. Drill and tap for 2" pipe plug for drain.
Field weld
After base is removed, thoroughly clean casting and concrete contact surfaces. Immediately before replacing the base, paint the two surfaces with a thin coat of mastic asphalt filler and bolt up tight.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
SHOSHONE PROJECT - WYOMING
SHOSHONE DAM
BALANCED VALVE

War Production Board, the decision was made to repair the outlets in the usual manner and continue the test program to ascertain the feasibility of minor alterations requiring a minimum of strategic materials.

Calibration of Proposed Redesign Outlet

Prototype discharge curves (figure 16) for a single valve operating at different openings and for one valve fully open and the other at various openings was prepared from model calibration data. The curves show a substantial reduction in capacity from the present field installation--that for one valve at the maximum head being approximately 1,120 second-feet, a reduction of about 300 second-feet (figures 16 and 18).

Head losses from the reservoir to the valves were computed for various quantities flowing in the tunnel and were plotted below a horizontal line representing the reservoir elevation. The descending (loss) curve obtained in this manner represented the available head at the valves for the given reservoir elevation and various quantities of water passing through the tunnel. Plotted against discharge, the losses are the same regardless of reservoir elevation. Discharge curves for different openings of the valves, obtained from coefficients based on the total head on the valves, were plotted on the same graph. The discharge for a given valve opening and reservoir elevation is that shown by the intersection of these curves with the loss curve for the reservoir elevation. To determine the quantity of water being released when the reservoir elevation and the valve opening are known, enter the

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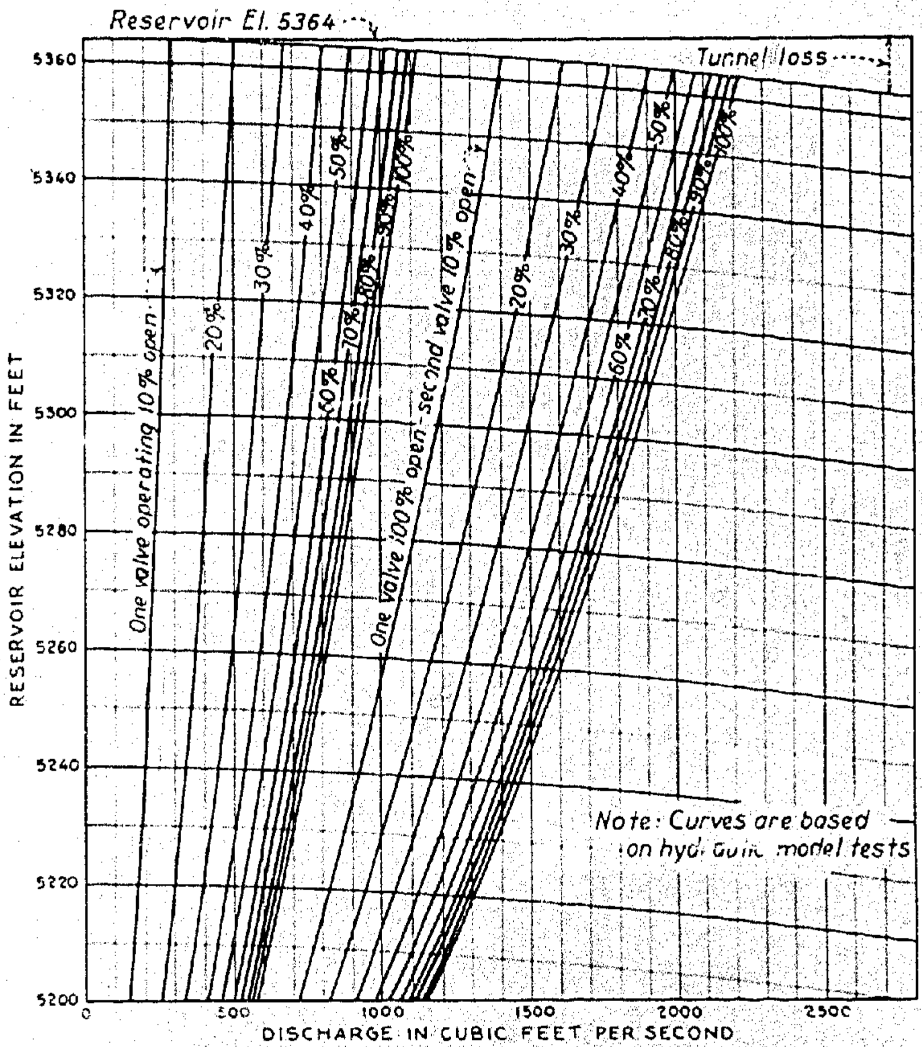
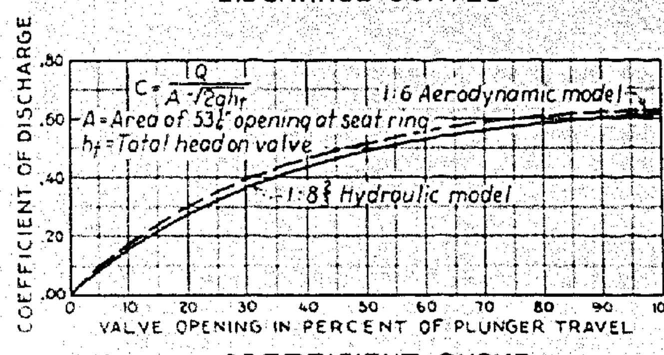


DISCHARGE CURVES



COEFFICIENT CURVE

SHOSHONE DAM

58-INCH BALANCED VALVE

HYDRAULIC MODEL STUDIES · SCALE 1 TO 8⅔

COEFFICIENT AND DISCHARGE CURVES

PROPOSED REDESIGN OUTLETS

FIGURE 16

graph on the loss curve for the known reservoir level, follow along this curve until it intersects the discharge curve for the given valve opening, and read the discharge scale vertically below this intersection. The outlet discharge for intermediate reservoir elevations may be found by interpolation.

Comparison of the discharge coefficients (figure 16) shows slightly more capacity for the air model than for the hydraulic model. The reason for this difference was not ascertained, but it might have been the result of errors inherent in constructing and assembling the V-shapes used in the aerodynamic model or the operation of the aerodynamic model at smaller Reynolds numbers. A more elaborate model than that used in the air study would have assured correct shapes and no doubt would have resulted in closer agreement.

Hydraulic Operation of the Valve Plunger of Field Installation

The pressures tending to open the model valve were greater than the clearance-gap pressure over much of the surface area of the needle tip; thus for certain openings the force exerted on the back end of the plunger by this pressure was insufficient to move it (figures 13 and 14A). This unfavorable pressure distribution existed over the range of valve opening from 95 to 100 percent and precluded successful closing of the valve by the clearance-gap pressure at these openings. This condition, which was also obtained from the aerodynamic tests, no doubt explains the difficulty experienced by the project in closing the prototype valves when they are operated near the wide-open position.

Study of Pressures in the Present Outlet Installation

As soon as it was learned that materials for the new needle tips and air-intake manifolds of the proposed redesign could not be purchased, an extensive test program was initiated to investigate: (1) the pressure conditions in the field design to ascertain the possibility of minimizing the pitting resulting from cavitation by limiting operation of the valves to noncritical openings, and (2) to attempt to discover a method for eliminating the destructive action in the present structure by minor modifications not involving the purchase of strategic war materials. Tests for comparison with those obtained from the aerodynamic model were also made.

There were two low-pressure zones in the Shoshone outlet model where the pressures at certain valve openings when transferred to the prototype reached the vapor pressure of water, about -28 feet of water. The pressures in these regions (zones A and B, figure 17) were taken as criteria in establishing the noncritical range of openings for the prototype valve. Since it was desired to determine the existence of cavitation pressures by these tests 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 simplified. However, both methods outlined previously were used and the pressure distribution for the field conditions investigated.

It was intended to use prototype measurements made in 1931 as the control pressures for the model in predicting the minimum pressures in zone A of the prototype. However, when scaled to the prototype, the model pressures in the conduit below the valve were

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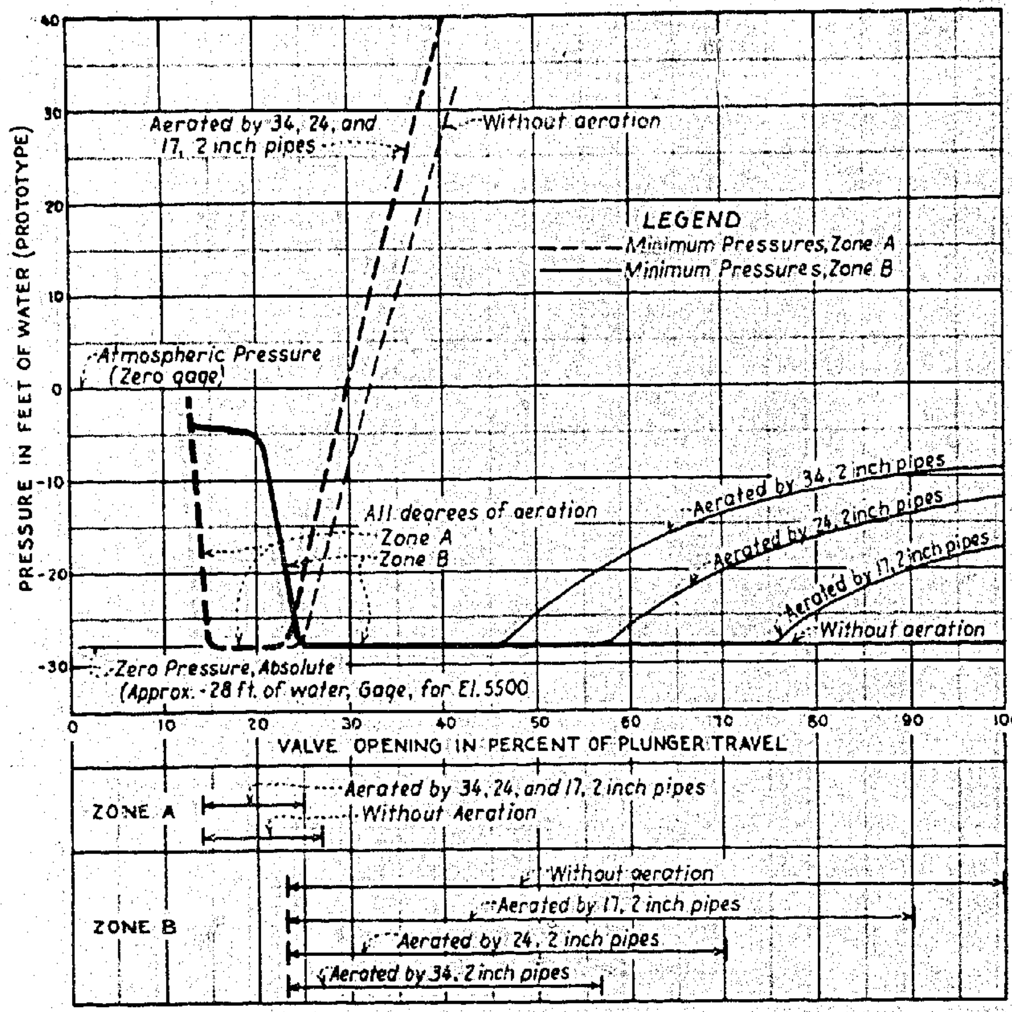
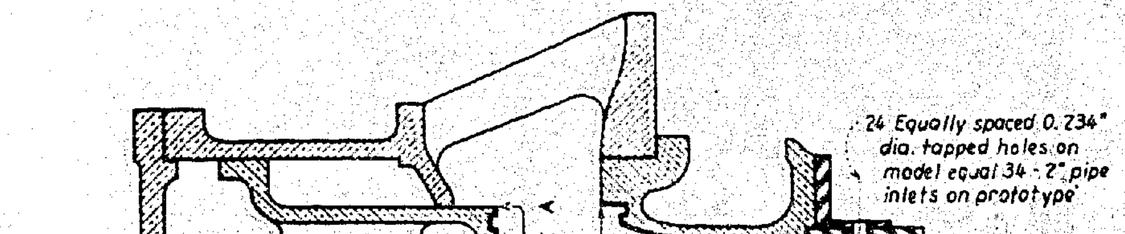


CRITICAL VALVE OPENING RANGE
Based on -20 feet of water gage pressure



SHOSHONE DAM
58" BALANCED VALVE
HYDRAULIC MODEL STUDIES – SCALE 1:8⅔
CRITICAL OPENING RANGE – VARIOUS DEGREES OF AERATION
EXISTING INSTALLATION

J.W.B.-H.R.S.

FIGURE 17

not in agreement, being nearer the vapor pressure for all valve openings than the prototype measurements, 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 by the holes instead of pipes of the same diameter and the 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, 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, for with pressures of this magnitude cavitation could not have occurred unless 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 in zone B for predicting those in other parts of the prototype were therefore obtained from scaled model pressures. The minimum pressure in zone B for each 10-percent increment of the plunger travel and maximum head was obtained and scaled to prototype by the similitude relationship,

$$P_p = N P_m.$$

When values obtained in this manner were above the vapor pressure for the prototype (about -28 feet of water 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, obtained in this manner, was added to the static head for the corresponding valve opening to obtain the total head difference 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

$$P_A = F D_t + P_B$$

Since the destructive action in the field structure indicated the subatmospheric pressures in the discharge conduit to be more severe than those measured in 1931, and since the model pressures near the vents in the crown of the discharge conduit were not in agreement with them, 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 two-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 noncritical range of valve opening. A value of -20 feet of water, above which conditions were considered satisfactory, was chosen for these studies, and the ranges of valve opening subsequently referred to as critical are based on this value.

When the model pressures in the conduit and on the needle for heads representing approximately reservoir elevation 5284 and valve openings from 20 to 100 percent were transferred to prototype, as outlined previously, 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. Only by closing the vents or by reducing the number until the hydraulic jump moved upstream to cover them was it possible to discern any change in these pressures. Even so, the change was slight, increasing by two percent the upper limit of the critical range of valve opening for the needle, making it 14 to 27 percent instead of 14 to 25 percent (figure 17). Severe subatmospheric pressures in zone A on the unaltered 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 is expected to be negligible. The different degrees of aeration produced no appreciable change in the critical range or the magnitude of the pressures in this zone. It was considered doubtful if they would become less critical even with complete aeration of zone B. Thus it might be impossible to operate the valve in this range without damaging the needle. Later tests on this valve, with minor modifications to the needle and with zone B well aerated, corroborated this belief.

Because of the peculiar expansion of the jet as it emerged from the end of the needle, the discharge conduit of the model flowed full after the valve plunger completed approximately 25 percent of its travel toward the open position. Zone B was aerated by air flowing upstream along the crown of the conduit until the needle reached this position and the pressures in this region were not severely subatmospheric for any of the degrees of aeration. As the valve approached 25 percent open and the flow of air from downstream was cut off, the pressures dropped rapidly, reaching the vapor pressure when scaled to the prototype.

When the aeration was equivalent to thirty-four 2-inch pipes, the model indicated that the minimum pressure in zone B would remain at the vapor pressure for a range of valve opening between 25 and 47 percent, then begin a gradual rise to about -8 feet of water when fully open (figure 16). 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. The upper limit of this range was increased to approximately 76 percent when the aeration was reduced to the equivalent of seventeen 2-inch pipes. The pressure at 100-percent opening reached about -18 feet of water. Without aeration, the pressure remained at the vapor pressure through the range from 23 to 100 percent. From these results it was concluded that the critical range of valve opening for the conduit in the field installation, aerated by twenty-four 2-inch pipes, based on -20 feet of water, gage pressure, would be from 23 to 70 percent open.

During operation of the model valve, with aeration representing the twenty-four 2-inch pipes, eddies were observed to form downstream from the V-guides as the valve approached 90 percent open, covering the ends of some of the air vents on the crown and the invert of the discharge conduit, thereby decreasing the amount of air reaching the throat of the discharge conduit and lowering the pressure in that region. Because of the danger of obtaining subatmospheric pressures of sufficient magnitude to cause the hydraulic jump in the pipe to move upstream and cover the remaining openings, thus producing cavitation pressures on the throat liner, a recommendation was made to limit the maximum valve opening for the installation to 85 percent.

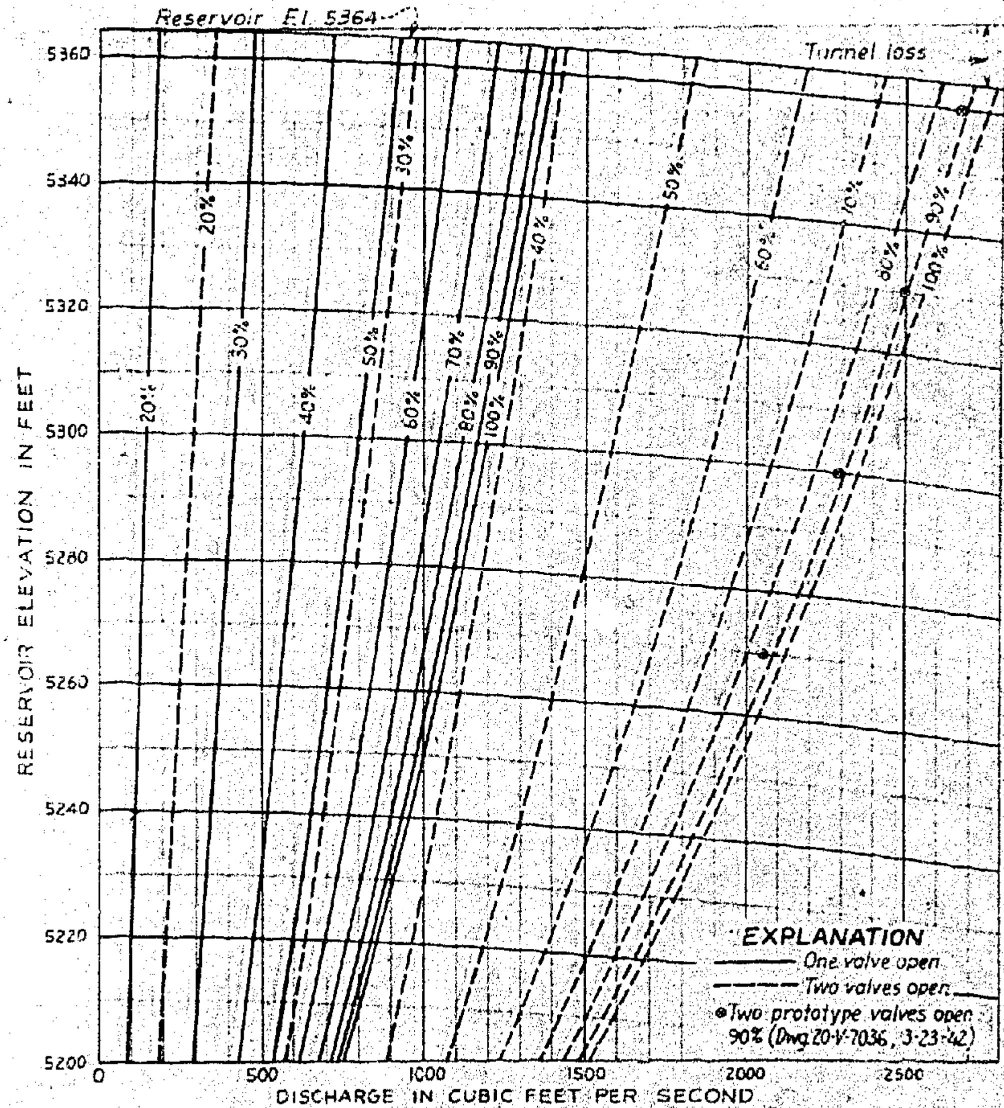
The severe subatmospheric pressures prevalent in the model of the present outlet design (figure 14A) were attributed to inadequate aeration resulting principally from improper location of the delivery ends of the air ducts, but due to the small aeration area also. The peculiar shape of the jet beyond the end of the needle tip no doubt contributed to the severity of these pressures. The stream expanded abruptly to fill the conduit at approximately 25-percent opening, with the action continuing throughout the upper range.

The model tests indicated that operation of the outlet valves to obtain any appreciable amount of flow regulation without damage to the discharge conduit was impracticable and that damage to the needle could be avoided only by limiting the valve operation to openings greater than 25 percent.

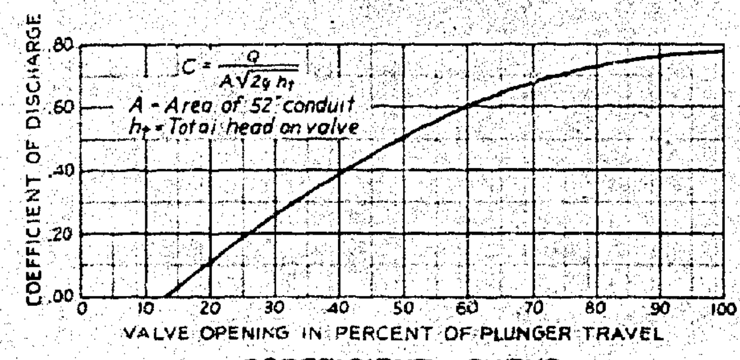
To ascertain the reliability of the aerodynamic tests on this design, the discharge conduit of the hydraulic model was shortened to correspond to that studied on the air model. Comparison of the results from the two models revealed poorer agreement than had been anticipated, but the difference was not sufficient to prove the aerodynamic tests unreliable. Part of the disagreement was attributed to the variation in the physical properties of air and water which it is believed caused different degrees of separation from the solid boundary where abrupt changes in direction of flow took place, as at the outer edge of the plunger needle when in a partially open position.

Calibration of the Field Installation

The model was calibrated to ascertain the discharge characteristics of the installation. Discharge coefficients for the various openings were obtained and capacity curves prepared in the same manner as for the proposed redesign outlet, for a single valve and for both valves operating simultaneously (figure 15). 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 2360, the increase obtained by opening the valve from 20 to 80 percent is approximately $3\frac{1}{2}$ percent of that for full opening, while that obtained by opening the valve from 80 percent to full opening is about [illegible] percent. Thus, opening the valve another 10 percent in the upper region increases the discharge only slightly. That excellent agreement exists between the model and the prototype capacity is evident [illegible] model and prototype discharges for both



DISCHARGE CURVES



COEFFICIENT CURVE

SHOSHONE DAM

58-INCH BALANCED VALVE

HYDRAULIC MODEL STUDIES - SCALE 1 TO 8⅔

COEFFICIENT AND DISCHARGE CURVES

EXISTING INSTALLATION

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

FIGURE 18

valves operating at 90 percent open (figure 18).

Study of Air Vent Size for the Modified Outlet Design

After it was found impossible to purchase materials for the revisions required in the proposed redesign outlet and pressure conditions for the field design were found to be extremely critical for practically all ranges of valve opening, it was deemed advisable to continue the model studies in an attempt to discover a satisfactory means of alleviating the condition inducing cavitation by making minor modifications requiring a minimum of strategic materials. It was believed that a solution might result from alterations consisting of streamlining the exposed corners of the bronze sealing ring in the conduit and the seat ring on the valve plunger by chipping and grinding; removing part of the throat liner; and modifying the air-vent system to provide more air to the outlet conduit at the proper location. The model was modified to include these changes (figure 18C). Aeration, equivalent to three 12-inch air ducts on the prototype, was provided. It was intended that three openings would be installed; one at the crown and two at the sides of the conduit liner in the throat. However, the openings were inadvertently placed 45 degrees counterclockwise from the intended positions. Tests were conducted on this arrangement since it was believed that the jet of water discharging from the valve would be completely surrounded by air and thus the pressure within this region would be equalized. This was found to be the case for the smaller valve openings. However, eddies forming downstream from the V-guides divided the air space into sections at the larger openings and the aeration of these two compartments was unequal.

Since the piezometers in the throat were in the section supplied by one vent and the pressures in this region were satisfactory, the arrangement was not changed. Moreover, the top vent would have been ineffective because of the eddies below the V-guides had it been placed at the crown as planned. From the model tests on the field design and this modified design, it was concluded that air vents to the balanced valve should not enter at the crown or invert of the conduit downstream from the V-guides.

Each of the vent openings on the model was provided with a 4-inch diameter by 1.5 foot long measuring section in which standard air-measuring orifices were installed for determining the air requirements and studying the air-duct size of the modified design outlet. Three orifice sizes were used, ½-, 1-, and 1½-inch diameters.

Pressures in the throat and on the needle were investigated for the three orifice sizes to ascertain the adequacy of the contemplated vent system. The three vent openings, when fitted with the ½-, 1-, or 1½-inch orifices were approximately equivalent to prototype openings of 7½, 15, and 22 inches diameter, respectively. The throat pressures were severely subatmospheric for the smallest orifice, but quite small for the other two. The maximum negative pressures in the model were -6.0, -1.4, and -0.8 feet of water for the small, medium, and large-size orifices, respectively. Air measurements for various valve openings and heads were made for all three orifices and a curve $\frac{Q_a}{Q_w}$ versus opening plotted (figure 19).

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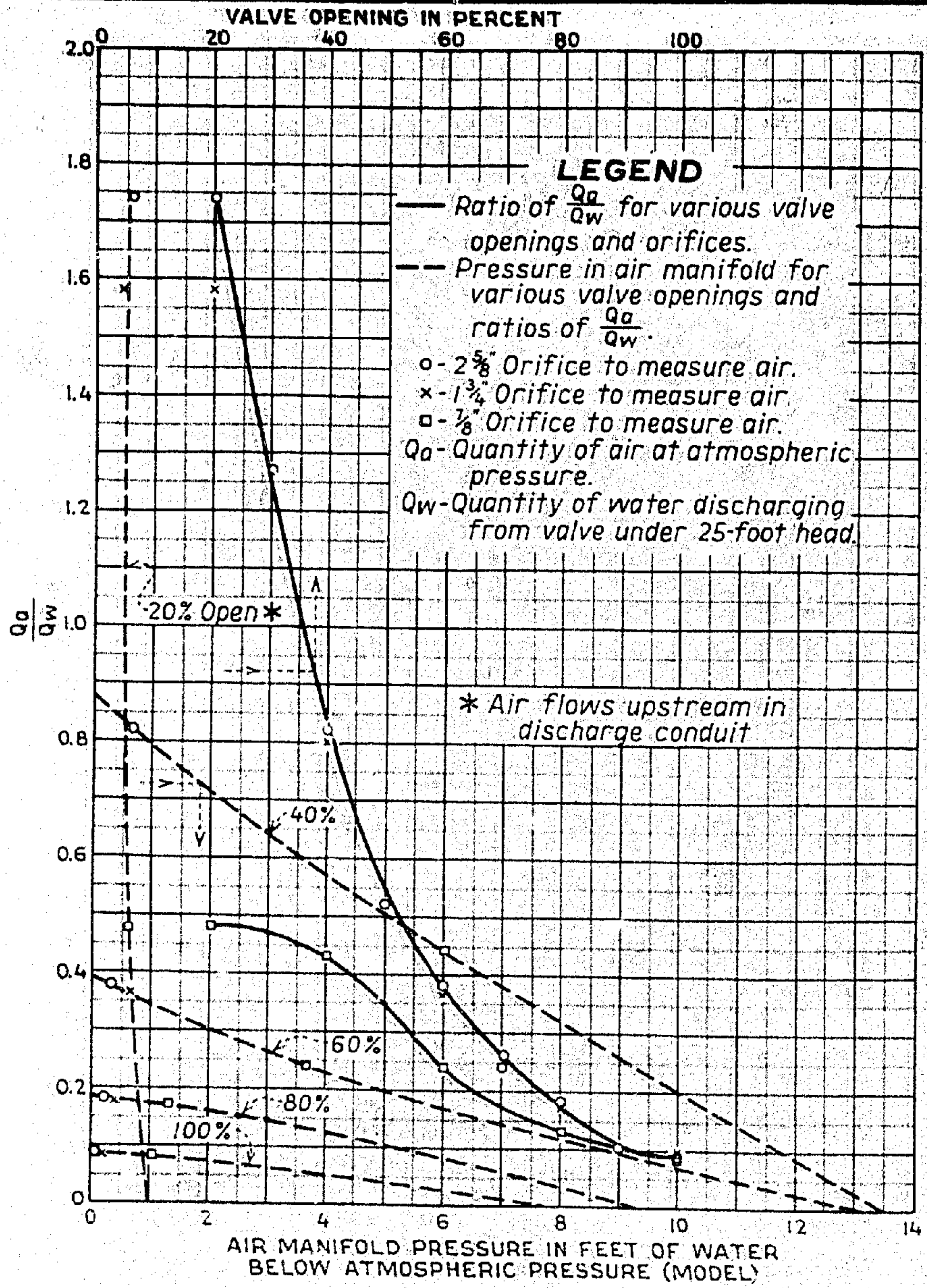


SHOSHONE DAM
58-INCH BALANCED VALVE
HYDRAULIC MODEL STUDIES - 1:8 2/3 SCALE
AIR MANIFOLD PRESSURES AND AIR DEMAND FOR MODEL OF MODIFIED DESIGN OUTLET

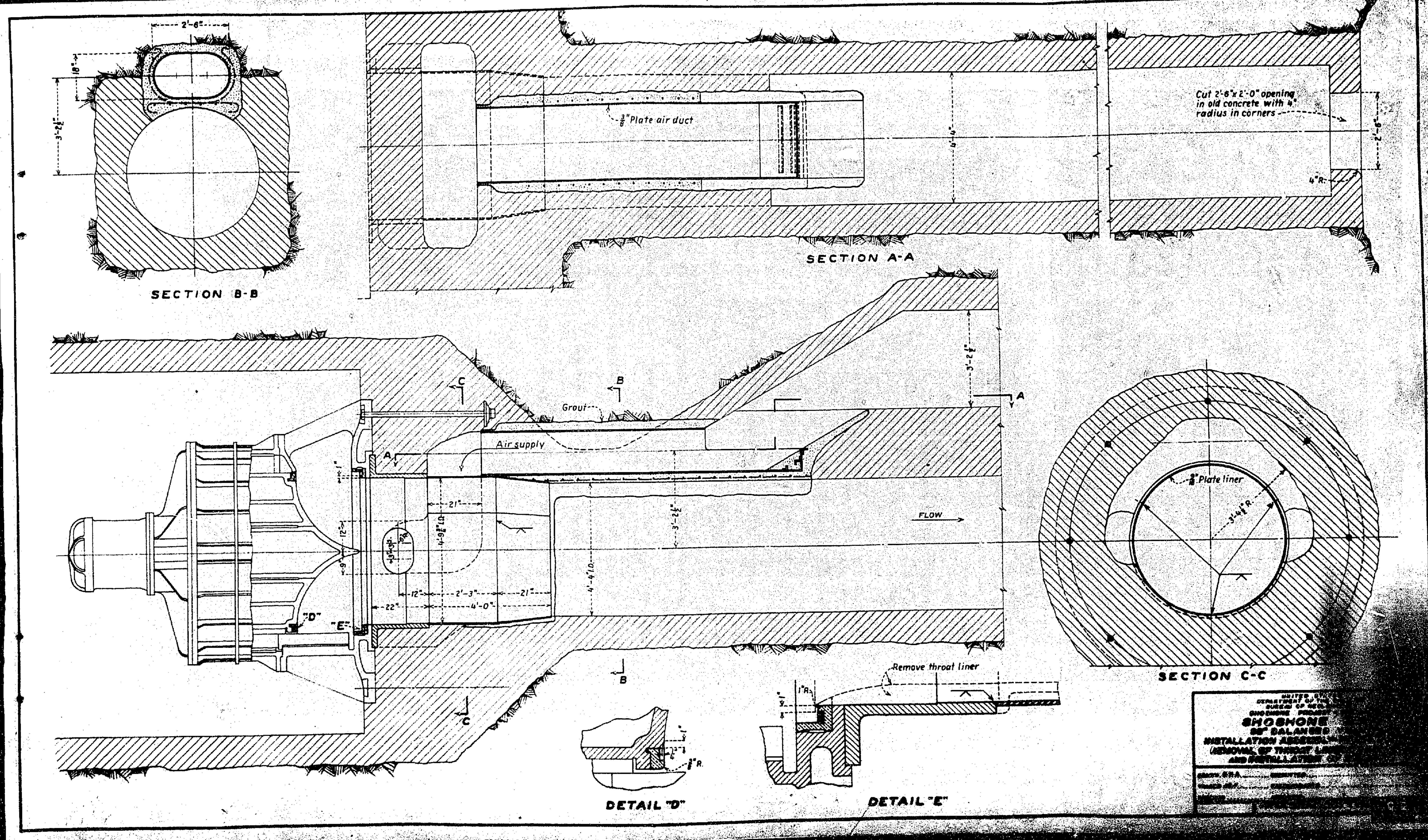
FIGURE 19

<u>Study of Pressures in the Modified Design</u>

A peculiar condition was noted on the needle during the initial tests on this modified design. The pressure at piezometer 1 was recorded as being positive, a condition not existing before the seat ring on the plunger had been streamlined. Apparently the flow did not spring free from the edge as before and the boundary layer entered the groove, producing positive pressure at piezometer 1. Piezometers 2 and 3 showed severe subatmospheric pressure, indicating this to be the case. Removal of wedge (detail D, figure 20) from the needle corrected this condition, and, although subatmospheric pressures still existed, their magnitude was decreased.

The condition of not being able to close the valves at openings above 95 percent by the clearance-gap pressure still existed, but as pointed out previously, this is not critical since the last 10 percent of opening results in an increase of discharge of less than 3 percent of the total for full opening.

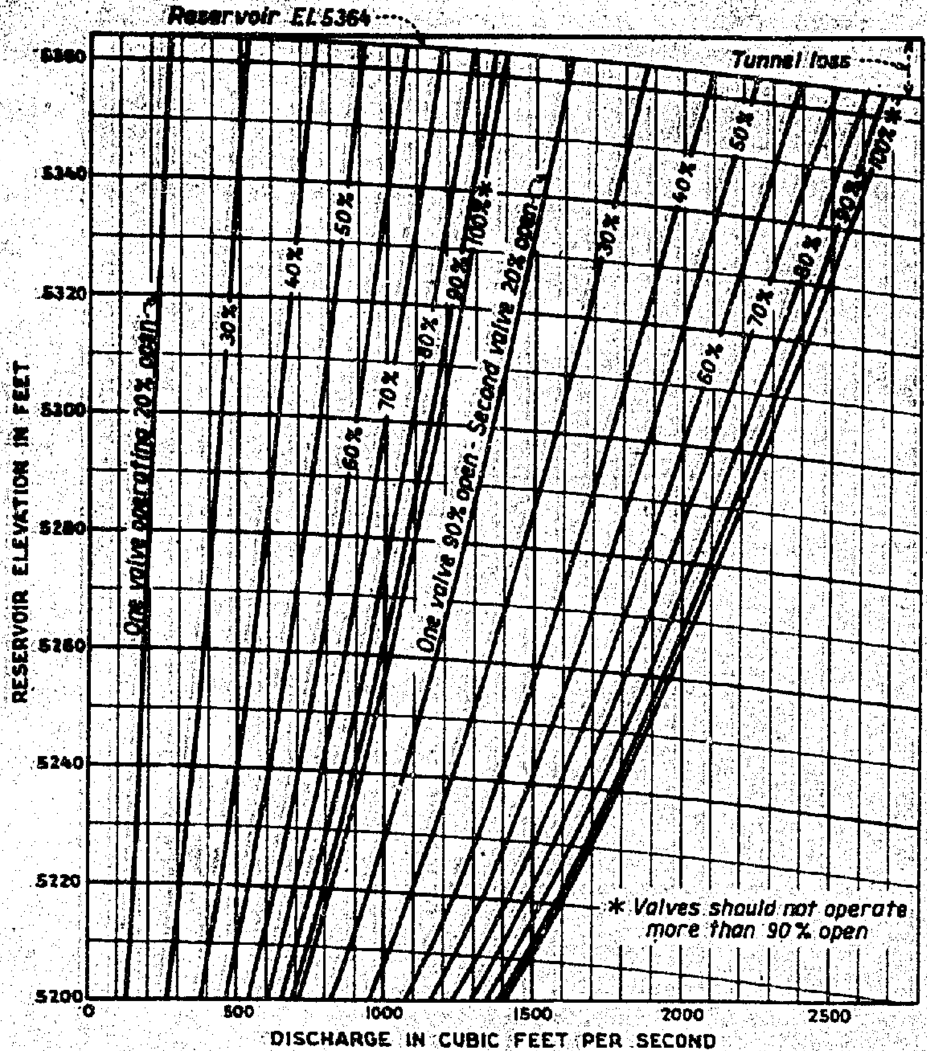
Pressures on the needle, using the $1\frac{1}{2}$-inch orifices, were found to be positive for all openings above 23 percent (figure 14B). For smaller openings the pressures on the surface of the needle near its outer edge were severely subatmospheric, indicating that cavitation would occur on the prototype. Since the critical pressure existed over such a small range of opening and damage to the needle could be eliminated by avoiding operation in this region, and since it was impossible to streamline the corner of the plunger sufficiently to relieve this condition without a major revision of the valve, it was recommended that the field structure be modified during the


SECTION B-B
2'-6"
18"
3'-2½"
SECTION A-A
3/8" Plate air duct
4'-4"
Cut 2'-6" x 2'-0" opening in old concrete with 4" radius in corners
2'-6"
4" R.
Grout
Air supply
3'-2½"
FLOW
21"
12"
2'-3"
21"
22"
4'-0"
4'-9½" I.D.
4'-4" I.D.
"D"
"E"
SECTION C-C
3/8" Plate liner
3'-4½" R.
DETAIL "D"
1/8" R.
Remove throat liner
DETAIL "E"
1" R.
SHOSHONE
INSTALLATION ASSEMBLY
REMOVAL OF THROAT LINER
AND INSTALLATION

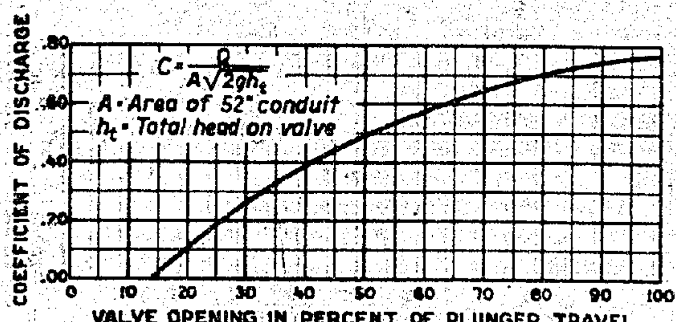
1943-44 winter season. The modification, based on the model findings, considering structural and construction difficulties, was prepared (figure 20).

Calibration of Modified Outlet Design

The outlet was calibrated and a discharge graph for various reservoir elevations prepared for one valve discharging and for both valves discharging, one at 90 percent and the other at various openings (figure 21). The graph may be used to determine water releases after the modified design is placed in operation.



DISCHARGE CURVES



COEFFICIENT CURVE

SHOSHONE DAM

58-INCH BALANCED VALVE

HYDRAULIC MODEL STUDIES - SCALE 1 TO 8⅔

COEFFICIENT AND DISCHARGE CURVES

MODIFIED DESIGN OUTLETS

FIGURE 21

VII - THE PROTOTYPE

Repairs and Alterations

The original proposal on the repairs of the 58-inch outlet valves was to so modify the design as to eliminate all of the adverse pressures which occur in the original design. Based on the results of the model studies in the hydraulic laboratory, a satisfactory design was prepared (figure 15), and invitations for bids requested. Application for Priority Assistance was made to the War Production Board for the extension of preference rating AA-2x to obtain prompt delivery of the materials covered by the specifications. Inasmuch as the extension of the rating was permissible only on qualification that the work was necessary to prevent an impending breakdown, and the model studies had shown that damage by cavitation to the existing structure could be reduced to a minimum by limiting operation to certain valve openings, the decision was made to proceed instead with the repair of the valves to permit operation during the season of 1943. The project was so informed and the suggestion made that the valves be inspected not later than July 15, 1943. If further repairs and revamping of the valves were then shown to be necessary, there would be sufficient time to obtain priority and to purchase and install these parts before the start of the 1944 irrigation season.

During the period from December 1942 to March 1943, necessary repairs were made on both valves. The east valve was dismantled except for the support ring and body cylinder; the poorly bonded weld metal on the valve needle was removed and new metal placed, using 1/8-inch "Ferroweld" arcwelding electrode; and the valve parts were cleaned and repaired. The pitted areas on the needle and throat liners on both valves were filled by welding. The 2-inch air-vent pipes and reinforcing steel in both conduits torn out during the 1942 season were replaced, and the conduits relined with concrete by pressure grouting. The damaged packing-ring seat in the west valve was replaced by a new one. The valves were under pressure and ready for operation on March 26.

Results of Inspection

In the fall of 1943, the project superintendent gave the following report on the condition of the valves and conduits:

"The 58" balanced valves and their conduits were inspected on August 7. The west valve has been operated 35 days this season at 0.75 opening. The valve itself shows no visible evidence of additional pitting. A minimum amount of pitting has occurred, however, in the extreme top of the discharge conduit. A square foot or so of concrete is gone where it covered the capped 8" air vent and lapped over onto the pitted discharge liner. This exposes part of the capped 8" air vent. Then at odd intervals of about one foot apart are pitted areas not over two inches deep which extend out the discharge conduit for about ten feet. None of the 2-inch air vent pipes are exposed. Except for the spotted pitting in the top of the discharge conduit, no other damage to the concrete lining can be observed. It is planned to patch the small damaged areas before the valve is again put in operation.

"The east valve has been operated for only 8½ hours this season at 0.30 opening. The plunger needle on this valve and the concrete lining in the discharge tunnel look the same as when repair work was completed last spring.

"The opening of the west valve so far this season has been in the non-critical range as pointed out in the Chief Engineer's letter of April 17, 1943. It appears that it will soon be necessary to use one of the valves for the release of water from the reservoir and it will probably by necessary to operate it in the critical range if stored water is to be conserved for the generation of power this winter. It is therefore probable that the greatest amount of damage to the discharge conduits, etc., this season will occur during the remainder of the irrigation season."

VIII - CONCLUSIONS

Outlet Structure

From the model studies of the Shoshone outlets, it was concluded that the damage to the structure in past years had resulted from cavitation, a phenomenon which takes place when the pressure at some point within a flow passage reaches the vapor pressure of the flowing medium. The presence of cavitation pressures in the prototype, a condition producing the damage observed on the field structure, was indicated by the subatmospheric pressures on the model whose scaled values were equal to or lower than the vapor pressure for the prototype.

Without alterations, it would be difficult to operate the valves to obtain an appreciable amount of regulation without damaging the outlet structure. Pitting of the needles is expected when the valves operate between 14 and 25 percent open and in the conduit between 25 and 70 percent open; also, there is danger at openings greater than 85 percent, since the ends of several of the 2-inch air-supply pipes will be covered by eddies forming below the V-guides. Little damage should result when the valves are operated between 70 and 85 percent open.

The severe subatmospheric pressures on the needles at small valve openings can be reduced by streamlining the outer corner of the seat ring on the plunger, but cannot be eliminated without a major revision similar to that in the proposed redesign outlet.

The existing aeration system is inadequate, as well as improperly located, to relieve the pressures inducing cavitation.

The 8-inch vents, which have been plugged in previous years, would tend to relieve the critical pressures in the conduit but would be inadequate to eliminate them, even though they do not become covered by the hydraulic jump in the conduit or by eddies downstream from the V-guides. If they were properly located, the additional air reaching the critical pressure zone in the throat would offer considerable relief.

Should the friction (by restriction or roughness) 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 8-inch vents as the valve plunger approaches the wide-open position, severe subatmospheric conditions inducing cavitation and consequently destructive pitting would result.

The damage to the needle during the 1942 season was the result of operating the valves from 82 to 48 percent open during the last few weeks of the season. The damage to the conduits first resulted from operating between 46 and 52 percent during the first one and one-half months and was then aggravated by operating at 90 percent open after the initial damage had reduced the effectiveness of the 8-inch vent pipes.

The presence of pressures on the valve needles which exceed the clearance-gap pressure at valve openings in excess of 95 percent, prevent closure by this pressure when the plungers are in this region.

Though the subatmospheric pressures tend to lessen as the head on the valves decreases, a substantial reduction would be necessary to alleviate the damaging action on the existing field structure

From model calibration data it was found that the increase in flow from the valves is small compared with the increase in the plunger movement when they operate near full opening, the increase in discharge being $3\frac{1}{2}$ percent between 80 and 90 percent and $2\frac{1}{2}$ percent between 90 and 100 percent. Since $97\frac{1}{2}$ percent of the maximum discharge through the valves can be obtained at 90 percent opening, it is not important that the valves operate beyond this point, particularly since it is difficult to close the valves when this opening is exceeded.

Damage by cavitation on the valve needles and discharge conduits can be entirely eliminated by revising the needle tips, the valve seat, the conduit throat, and the aeration system. This solution would be applicable to similar outlet installations. Maintenance cost would be reduced to a minimum by this revision and valves could be operated at any desired opening without the fear of damage due to subatmospheric pressures. The aeration system for the proposed redesign is satisfactory, probably over-adequate. The outlet capacity, however, will be substantially reduced, and consideration should be given to this fact when future revisions are planned.

Damage to the conduits can be eliminated in the existing design by streamlining the exposed edge of the bronze sealing ring, removing the throat liner, and providing an adequate air-supply system at the location as shown on figure 20. However, operation of this modified design at openings smaller than 23 percent would have to be avoided to prevent damage to the needle.

Openings into an area of low pressure, such as those to the throat of the Shoshone outlet, should not be placed too near the surface of the flowing water, for this condition constricts the flow of air and prevents complete aeration of the jet. For example, the same size opening into the outlet throat will provide more aeration when the throat liner is removed. An air-supply duct equivalent to three 12-inch diameter openings into the throat of the outlet should provide ample quantities of air at all valve openings in the modified design. The modified outlet is likely to be noisy since the air taken into the conduit via the aeration system will be under pressure when released at the conduit exit, and explosive reports may accompany its expansion.

Interpretation of Model Results and Reliability of Aerodynamic Testing

Transference of model pressures to prototype, by assuming all scaled values exceeding the vapor pressure to be equal to it, is incorrect. The pressure distribution, when such conditions exist, does not correctly represent that of the prototype, for all pressures obtained in this manner (except the control pressure) are too low. It is not possible to predict accurately the pressure distribution in cases where the scaled values exceed vapor pressure and the stream tubes change with the head unless the model is enclosed in a partial vacuum to give the proper relation between the artificial atmospheric pressure of the model and the natural atmospheric pressure of the prototype.

It is difficult, and in many cases impossible, to determine control pressures in a hydraulic structure from air tests alone. This means that the control pressures must be known or must be determined by computation or from a carefully constructed hydraulic model before the prototype pressure distribution can be predicted accurately.

Aerodynamic models are extremely useful as an expedient in testing preliminary designs of hydraulic devices with closed-conduit flow. The models can be constructed easily and quickly and the tests can be conducted rapidly and without the cumbersome piezometer boards and connections. Calibration data as well as pressure data may be obtained, providing extreme care is taken to assure that the model is being tested under comparable conditions. It is necessary to make radical alterations to the aerodynamic model in some cases to attain the required effect. The removal of the downstream portion of the model of the proposed redesign outlet to give desired pressures is an example.

The positive-displacement rotary blower used in the aerodynamic tests had insufficient capacity and was too inflexible to permit extensive tests by this method. This type of blower is not as well adapted to aerodynamic studies as the centrifugal or axial-flow types which deliver large quantities at low pressures. The 4-inch positive-type blower in the laboratory is inadequate for all except small scale models and larger scale sector models which are difficult to construct and operate.

When the difference in head across a standard air-measuring orifice is small, the hydraulic equation $Q = CA \sqrt{2gh}$ may be used, since the error introduced is negligible.

APPENDIX

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Acknowledgments

The author wishes to express his appreciation to the Bureau of Reclamation for permitting the use of the material contained in this thesis and for the illustrative figures.

Credit is extended J. E. Warnock, Senior Engineer, for his untiring efforts and interest which made possible the extensive treatment of the thesis subject.

Credit is also extended B. H. Staats, Engineer, D. J. Hebert, Associate Engineer, and Fred Locher, Assistant Engineer, who assisted in preparing the model and prototype plans, contributed to the analysis of the model data and assisted in conducting the test program.