THE HYDRAULICS OF HOLLOW-JET VALVES AS DETERMINED BY FIELD AND LABORATORY TESTS

By

Dale M. Lancaster

Engineer, Public Works,
U. S. Navy

and

Robert B. Dexter

Hydraulic Engineer
Bureau of Reclamation

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PAP 74

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SUMMARY

For free discharge conditions the hollow-jet valve has proved to be a satisfactory control device for flows through large conduits operating under high heads. Results of field tests with a 96-inch hollow-jet valve have revealed close agreement with hydraulic characteristics predicted from model studies. Piezometric measurements, thrust determinations on the valve needle, and rates of discharge were included in both field and laboratory tests. The prototype valve can be used as a metering device by the employment of model calibration results provided accurate position indicators are used. The only cavitation erosion evident in the prototype valve was caused by local irregularities in the body casting, which have been alleviated in subsequent valves by careful foundry practice and inspection.

THE HYDRAULICS OF HOLLOW-JET VALVES AS DETERMINED BY FIELD AND LABORATORY TESTS

Dale M. Lancaster, Assoc. M., ASCE 1/
Robert B. Dexter 2/

The search for a satisfactory valve to operate at any opening, to control flow through large conduits discharging under high heads, has been in progress for nearly half a century. The need for such a control device was responsible for development of the Ensign valve (Arrowrock Dam), the needle valve (Alcova Dam), and the tube valve (lower outlets through Shasta Dam). Other valves have also been developed for the same purpose, but the ones named constitute those primarily used by the Bureau of Reclamation. All of these valves had certain limitations which included operation and cost.

The increasing demand for closer control of releases through modern multiple-purpose structures prompted a continuation of studies to obtain a more suitable valve and led to development of a new type, termed a hollow-jet valve. This new type, however, is limited to use as a free discharge valve preventing its application in closed conduits. For those cases where the valve must discharge in a closed conduit, a recently developed type, known as a jet-flow valve, has been proved successful.3/

The hollow-jet valve was developed by the Bureau of Reclamation and is patented (Patent No. 2,297,082) with rights reserved for use by the

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1/ Engineer, Department of Public Works, U. S. Navy, Great Lakes, Illinois.

2/ Hydraulic Engineer, Engineering Laboratories, Bureau of Reclamation, Denver, Colorado.

3/ Hydraulic Laboratory Report No. Hyd-389, "Hydraulic Performance of the Control Devices in the 102-inch River Outlets of the Middle and Upper Tiers--Shasta Dam--Central Valley Project," by Dale M. Lancaster.

Federal Government without payment of royalties. The design was accomplished with the aid of a 45° segment of a 12-inch-diameter air model and a 6-inch-diameter hydraulic model in the Hydraulic Laboratory of the Bureau of Reclamation in Denver, together with a 24-inch-diameter model tested at Hoover Dam under a high head.

The purpose of the largest model was principally to ascertain the hydraulic characteristics of the hollow-jet valve constructed under prototype conditions, that is, by casting the supporting vanes, the cylinder containing the needle, and the outer shell in one piece with a machine finish limited to the needle and that part of the outer shell upstream from the vanes. The rough finish of the casting could conceivably effect boundary flow sufficiently to cause local areas of low pressures, whereas, in the 6-inch model, all surfaces were machine finished.

A second reason for studies on the 24-inch model was that some of the critical areas were too small for exploration by piezometer orifices in the 6-inch model. A few revisions were found necessary as a result of tests of the 24-inch valve, which was later installed permanently at Jackson Gulch Dam, Mancos Project, Colorado.

Although hollow-jet valves have been installed at several structures, initial installation of large units was on the river outlets through Friant Dam, Figure 1. Details of this installation may be seen on Figure 2, while the valve proper is better displayed on Figure 3. One of the four 96-inch valves was equipped with piezometer orifices to permit performance of special tests to ascertain if this new type valve possessed the predicted hydraulic characteristics. Locations of the piezometer orifices are shown on Figure 3. The performance could conceivably be different from the hydraulic models due to roughness of the large casting as previously stated or larger tolerances necessarily allowed for machined surfaces in the prototype valve could cause difficulty. A photograph taken looking upstream at the prototype valve is shown on Figure 4.

The field testing program was inaugurated in August 1950, although the valves were placed in operation one year earlier. The program consisted of piezometric measurements at valve openings of 10, 20, 40, 60, 80, and 100 percent operating under heads of 102, 180, and 223 feet. The maximum design head is 246 feet. Discharge through the valve was obtained from operating records based on current meter measurements in the river channel a short distance downstream from the structure. In this instance, flow in the river represented only the discharge through the outlets. Hence, current meter measurements of river flow were not subject to possible errors by subtracting the flow from other sources such as a powerhouse.

Other field observations included the general behavior of the hollow-jet valves, inspection of the interior of one unit, and character of the jet.

Results of Pressure Measurements

Pressure measurements were obtained in the usual manner by connecting piezometer orifices to manifolds joined to mercury gages. A valve on each connecting line permitted determination of pressure for any particular piezometer.

All pressures have been referred to the elevation of the valve center line at the upstream end. The head was measured with a piezometer orifice one diameter upstream from the valve and referred to the same elevation as the other pressures. Hence, the outlet was considered to be on a horizontal center line to correspond to the hydraulic model, while actually the center line of the prototype valve slopes downward.

The pressures have been plotted by utilizing a pressure factor, F, defined as the ratio of the measured piezometer pressure to the total head (static head plus velocity head), one inlet diameter upstream from the valve, Figure 5. This procedure reduces F to a dimensionless ratio making it possible to obtain the pressure for any head at any piezometer in the valve by selecting from plotted pressure curves the correct value of F and multiplying it by the total design head on the valve one diameter upstream from the inlet.

As an example, to find the pressure at a piezometer when the design head is, say, 200 feet of water and the valve is 50 percent open, follow the 50 percent line on Figure 5 until it intersects the curve for the particular piezometer and read the value of the pressure factor at the left. Then multiply 200 times the pressure factor to obtain the pressure at the piezometer for the case being considered. Of course, if the piezometric pressure is below atmospheric, then the F value is negative and the calculated pressure is also negative.

The pressure in the air space just upstream from the vanes was found to be a negative 1.22 feet of water in the 24-inch valve when 100 percent open under a total head of 196.6 feet. In the prototype, the corresponding negative pressure under the same total head was found to be 4.9 feet of water based on tests at the two highest heads. Based on field test at the lowest reservoir elevation, the negative pressure was 9.8 feet under similar conditions of head and valve opening. The reason for variation between the model and prototype, as well as variation in the prototype itself, can be traced to the fact that this region is partly filled with an air-water mixture due to insufflation of the jet in the case of the full sized structure. This mixture could conceivably choke the air supply sufficiently to cause an increase in subatmospheric pressure, while in the case of the model valve, little, if any, insufflation occurred.

The only subatmospheric pressures predicted from model studies were on the large vanes, but these were not considered sufficient to produce cavitation erosion. Although prototype tests revealed a pressure of minus 13 feet of water in this region, no pressures conducive to cavitation occurred.

Negative pressures were found in other locations in the valve contrary to model predictions, but the magnitudes of such pressures were insignificant. In general, pressures measured in the field differed from those measured in either the 6-inch or 24-inch model by an amount approximately equal to the difference between the values determined in the models. The average deviation between model and prototype pressures may be considered less than 10 feet of water at maximum head. These deviations can almost invariably be attributed to a slightly different location of piezometer orifices, interference by a bolt head near a particular piezometer orifice, or a slight change in contour of the valve.

As previously stated, no pressures measured were sufficiently low to cause cavitation erosion. However, inspection of the prototype valve tested revealed that cavitation erosion had occurred on the valve body upstream from the vanes, Figure 6. The dark spots in the light portion of the valve are areas of cavitation erosion and, although not severe, have pitted the metal. This condition is unquestionably due to the rough surface of the casting.

At the time of inspection, the valve had operated for a total of 5,896 hours at openings varying from 2 to 66 percent under heads from 78 to 207 feet. Most of the operating time had been at openings less than 30 percent at heads less than 200 feet.

The fact that cavitation erosion did occur as a result of the rough surface of the casting exemplifies the need of specifying casting surfaces with a roughness factor held within limits to prevent such cavitational pressures.

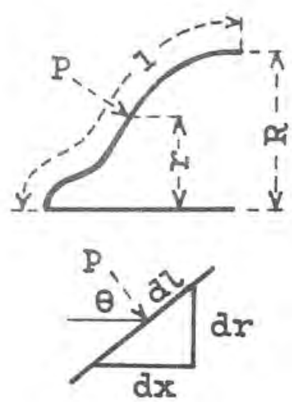
Results of Thrust Measurements

During design studies, considerable emphasis was placed on location and size of openings or ports through the needle portion of the valve to admit pressure into the interior, thereby balancing the pressure to minimize power required to open and close the valve. Figure 7 shows the thrust in the upstream and downstream directions predicted from the 24-inch model, together with comparable information obtained on the 96-inch prototype.

For the sake of simplicity, the units have been reduced to those applicable to a 1-foot valve under a 1-foot head; this permits computation of thrust forces for other size hollow-jet valves operating under various heads by multiplying results shown on Figure 7 by both the head in feet, and the square of the diameter in feet. The results of similar data obtained on the 6-inch model are not shown since the location of the balancing ports established by tests on this small model were changed after analysis of results from the 24-inch valve.

The values shown on the plot reveal very close agreement between thrust predicted from the 24-inch model and quantities determined by field measurements on the 96-inch valve. The greatest difference occurs in downstream thrust at a valve opening of 10 percent where the prototype value is approximately 94 percent of that determined in the model study. Of course, the unbalanced force or the differential between the upstream and the downstream thrusts is the most important, and the maximum unbalance occurs at a valve opening of 10 percent. This unbalanced force is 1.29 times the value predicted from the model.

The thrust on the needle in the downstream direction was computed from prototype data as follows:



Let P = measured piezometric pressure
l = length along surface of needle
r = radius to piezometer
$2\pi rPdl$ = total thrust on increment dl
$2\pi rPdl \cos\theta$ = thrust on increment dl in x - direction.

$$\text{Total thrust in x - direction} = 2\pi \int_0^l rP \cos\theta \, dl$$

and since

$$dl = \frac{dr}{\cos \theta}, \text{ then } 2\pi \int_0^R Prdr = \text{total thrust.}$$

The integration was done graphically since relationship of P to r was not known explicitly. The value of Pr was plotted against r for a valve opening of 10 percent, and the area under the curve was obtained with a planimeter to obtain $\int_0^R Prdr$ and that value of area was multiplied by 2π to obtain the total thrust on the needle in the downstream direction. The same procedure was utilized for valve openings of 20, 40, 60, 80, and 100 percent.

The thrust in the upstream direction is simply the pressure inside the needle times the area over which the pressure acts. This area is that of a 104-1/4-inch-diameter circle minus the area of a circle of 10-1/2-inch diameter, or 58.675 square feet.

Rate of Discharge

The rate of discharge of a prototype valve is particularly important for comparison with hydraulic model study since it serves to evaluate discharge curves prepared from laboratory calibrations. The advantages of dispensing with field calibrations can only be evaluated by considering the tremendous expenditures of money and time in performing field calibrations.

Once a laboratory calibration has been made of a valve, this same calibration may be utilized for all installations of the same valve except for certain situations where complicated approach conditions disrupt the flow characteristics.

A concept may be had of time and expense involved in performing a field calibration by considering the fact that approximately 600 current meter measurements were made over a period of 5 years to determine discharges through the river outlet valves at Friant Dam. At this same structure, similar current meter measurements were performed to determine discharges through the hollow-jet valves at the headworks to Friant-Kern Canal, and also through needle valves at the headworks to Madera Canal. None of the current meter measurements were necessary since discharge curves established by model calibrations were as accurate as curves determined by field measurements.

Figure 8 presents data to support accuracy of the predicted calibration curves. For valve openings greater than 15 percent, the variation between model and prototype discharges may be considered as 3 percent. For smaller valve openings the difference is greater; this does not mean that the model calibration is incorrect, but suggests inaccuracy of field data due to the fact that lower discharges are not susceptible to accurate measurements with current meters.

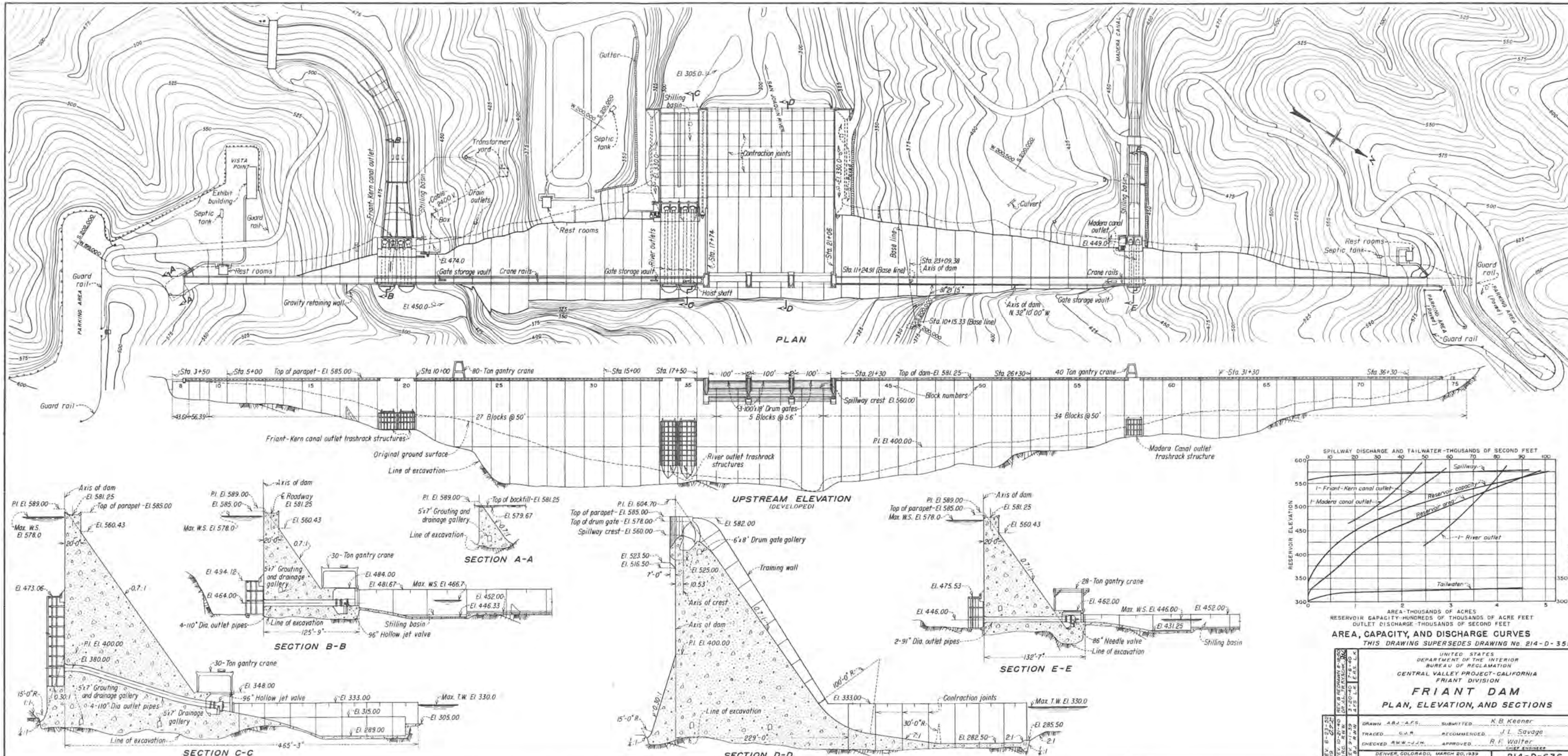
One important item when using valves as metering devices pertains to position indicators which must accurately reveal true valve opening. The particular valves being described in this paper are equipped with verniers on the position indicators to permit accurate setting of valve openings. An equally important item is that the true head on the valve must be known. Difficulties have been encountered in some instances due to an improperly operating head gage.

Other data exist to show the effectiveness of calibration curves determined from hydraulic models, but this paper is limited to the particular installation at Friant Dam.

General Behavior of the Valve

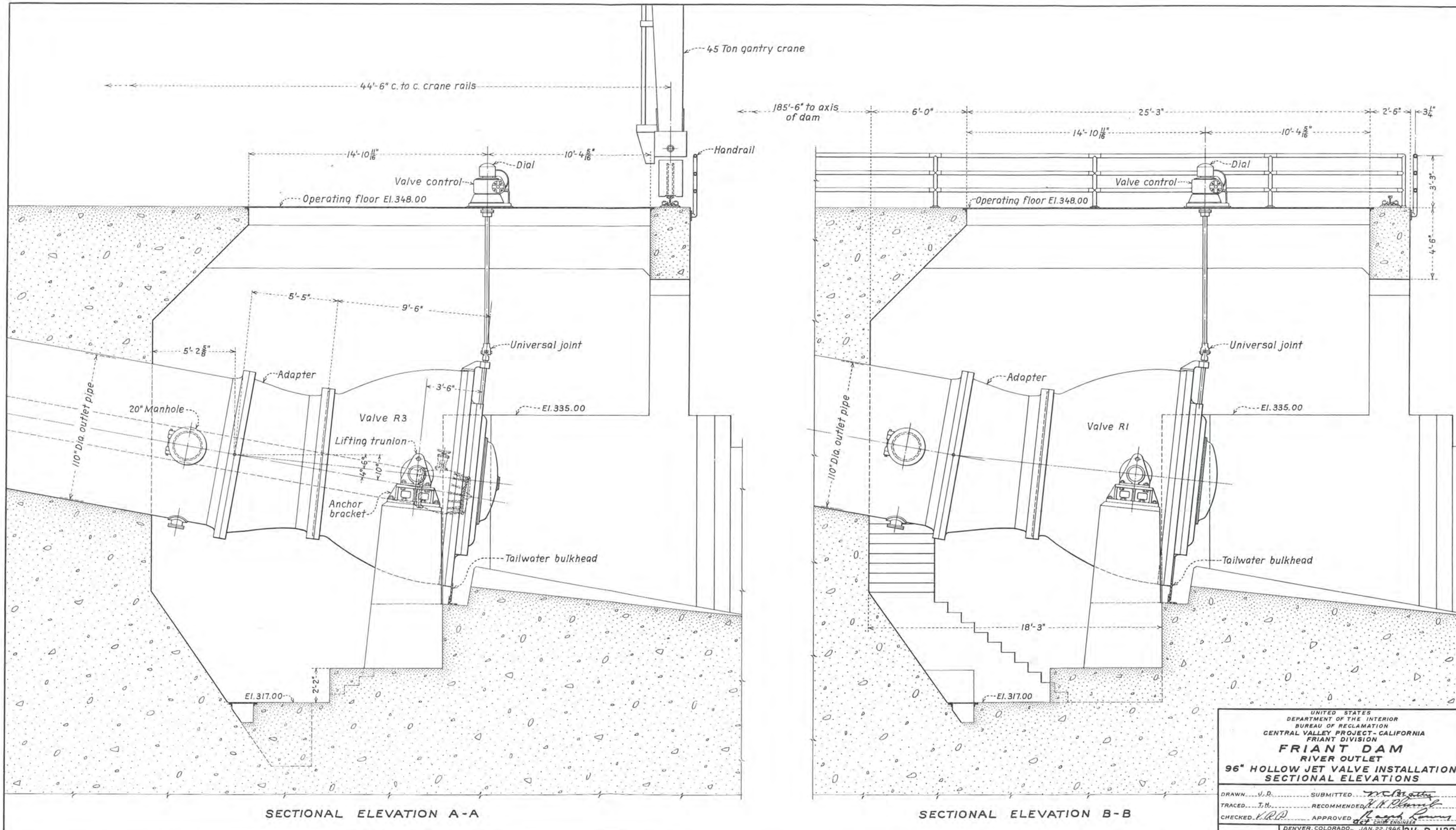
General behavior of the valve has been entirely satisfactory. Operation has been quiet and free from vibration. The jets remain stable and well defined at the exit of the valve.

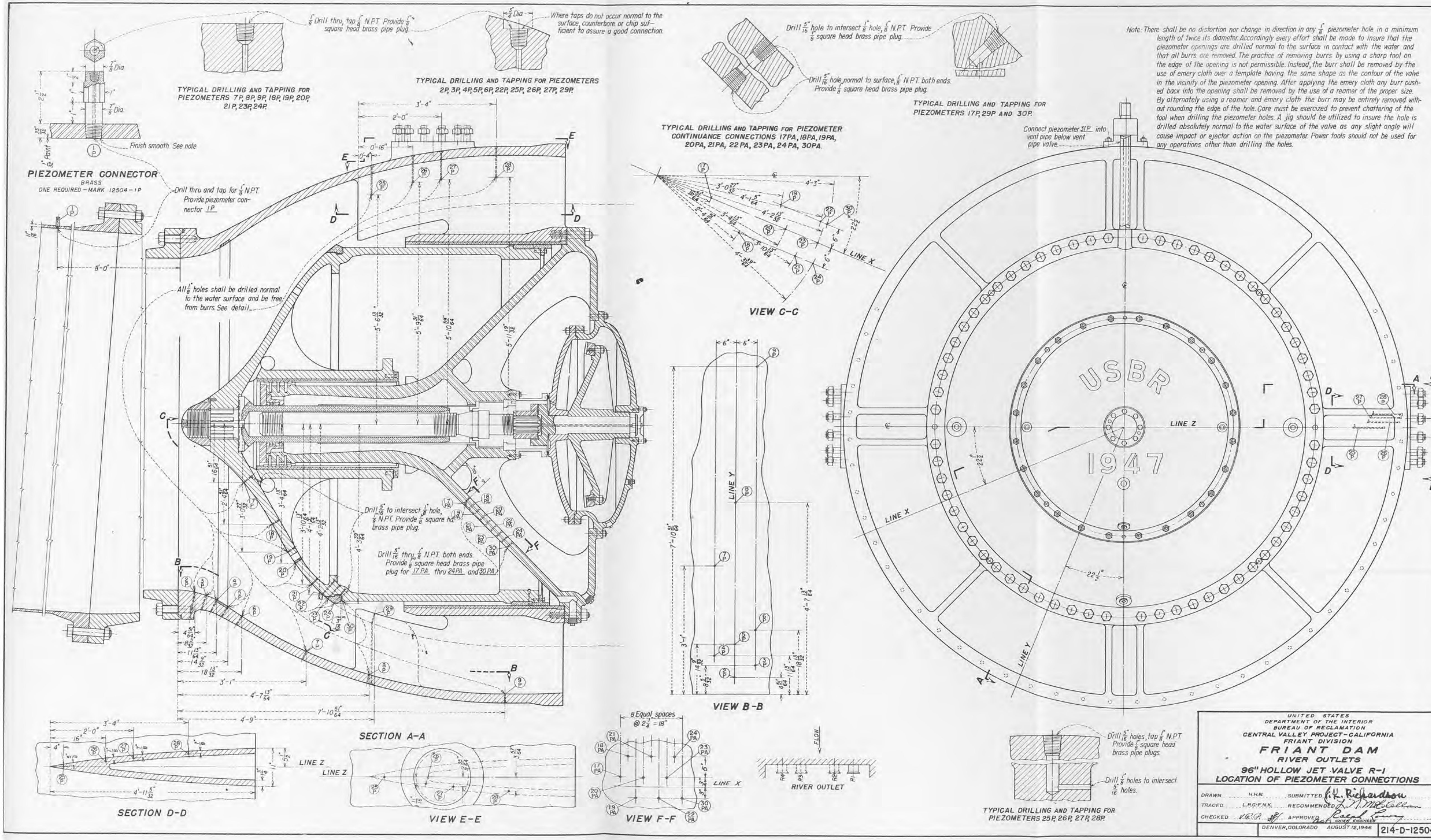
FIGURE 1

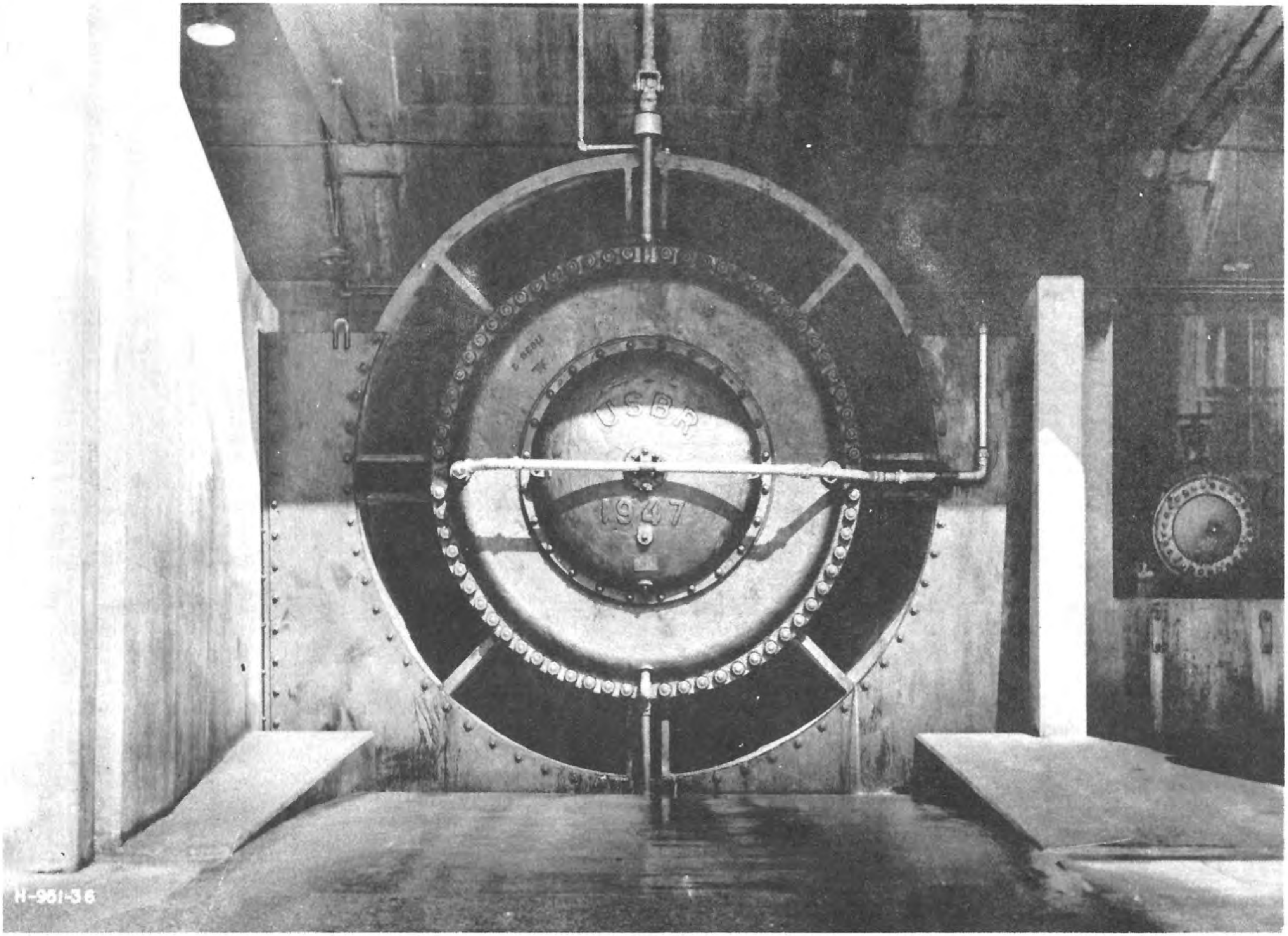


PLAN
UPSTREAM ELEVATION
(DEVELOPED)
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
Friant-Kern canal outlet
Madera canal outlet
Stilling basin
Contraction joints
River outlets
Gate storage vault
Crane rails
Rest rooms
Septic tank
Vista point
Exhibit building
Guard rail
Parking area
Transformer yard
Gravity retaining wall
Hoist shaft
Culvert
Base line
Axis of dam N. 32°10'00" W.
Sta. 23+09.38 Axis of dam
Sta. 11+24.91 (Base line)
Sta. 10+15.33 (Base line)
Top of parapet - El. 585.00
Top of dam - El. 581.25
80-Ton gantry crane
40 Ton gantry crane
3-100'x18' Drum gates - 5 Blocks @ 56'
27 Blocks @ 50'
34 Blocks @ 50'
Spillway crest El. 560.00
Block numbers
Friant-Kern canal outlet trashrack structures
Original ground surface
Line of excavation
River outlet trashrack structures
Madera Canal outlet trashrack structure
P.I. El. 400.00
30-Ton gantry crane
5'x7' Grouting and drainage gallery
4-110" Dia. outlet pipes
96" Hollow jet valve
Stilling basin
Max. W.S. El. 578.0
Max. T.W. El. 330.0
6'x8' Drum gate gallery
Training wall
Axis of crest
Axis of dam
28-Ton gantry crane
2-91" Dia. outlet pipes
86" Needle valve
SPILLWAY DISCHARGE AND TAILWATER-THOUSANDS OF SECOND FEET
RESERVOIR ELEVATION
TAILWATER ELEVATION
Spillway
Reservoir capacity
Reservoir area
1- Friant-Kern canal outlet
1- Madera canal outlet
1- River outlet
Tailwater
AREA-THOUSANDS OF ACRES
RESERVOIR CAPACITY-HUNDREDS OF THOUSANDS OF ACRE FEET
OUTLET DISCHARGE-THOUSANDS OF SECOND FEET
AREA, CAPACITY, AND DISCHARGE CURVES
THIS DRAWING SUPERSEDES DRAWING No. 214-D-355
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT-CALIFORNIA
FRIANT DIVISION
FRIANT DAM
PLAN, ELEVATION, AND SECTIONS
DRAWN A.B.J.-A.F.S. SUBMITTED K.B. Keener
TRACED C.J.R. RECOMMENDED J.L. Savage
CHECKED R.W.W.-J.J.H. APPROVED R.F. Walter
CHIEF ENGINEER
DENVER, COLORADO, MARCH 20, 1939
214-D-636

FIGURE 2

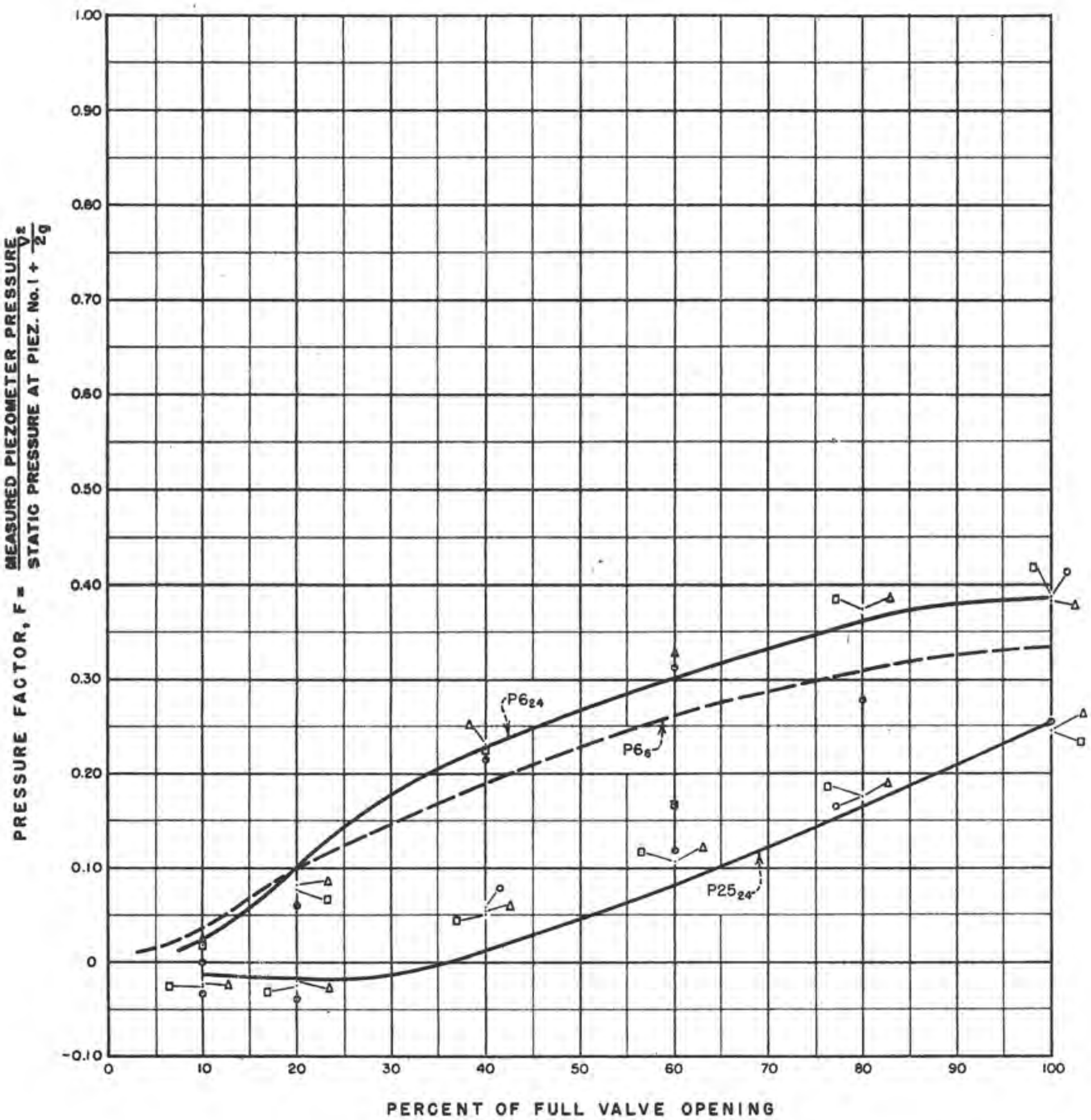

45 Ton gantry crane
44'-6" c. to c. crane rails
14'-10 11/16"
10'-4 5/16"
Handrail
Dial
Valve control
Operating floor El. 348.00
5'-5"
9'-6"
5'-2 5/8"
Universal joint
Adapter
3'-6"
El. 335.00
20" Manhole
110" Dia. outlet pipe
Valve R3
Lifting trunion
4'-6"
10"
Anchor bracket
Tailwater bulkhead
2'-2"
El. 317.00
SECTIONAL ELEVATION A-A
185'-6" to axis of dam
6'-0"
25'-3"
2'-6"
3 1/4"
14'-10 11/16"
10'-4 5/16"
Dial
Valve control
Operating floor El. 348.00
3'-3"
4'-6"
Universal joint
Adapter
El. 335.00
110" Dia. outlet pipe
Valve R1
Tailwater bulkhead
18'-3"
El. 317.00
SECTIONAL ELEVATION B-B
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT - CALIFORNIA
FRIANT DIVISION
FRIANT DAM
RIVER OUTLET
96" HOLLOW JET VALVE INSTALLATION
SECTIONAL ELEVATIONS
DRAWN J.D.
TRACED T.H.
CHECKED
SUBMITTED
RECOMMENDED
APPROVED
CHIEF ENGINEER
DENVER, COLORADO., JAN. 22, 1946.
SHEET 3 OF 3
214-D-11329


PIEZOMETER CONNECTOR
BRASS
ONE REQUIRED - MARK 12504-1P
Finish smooth. See note.
TYPICAL DRILLING AND TAPPING FOR PIEZOMETERS 7P, 8P, 9P, 18P, 19P, 20P, 21P, 23P, 24P.
TYPICAL DRILLING AND TAPPING FOR PIEZOMETERS 2P, 3P, 4P, 5P, 6P, 22P, 25P, 26P, 27P, 29P.
Where taps do not occur normal to the surface, counterbore or chip sufficient to assure a good connection.
TYPICAL DRILLING AND TAPPING FOR PIEZOMETER CONTINUANCE CONNECTIONS 17PA, 18PA, 19PA, 20PA, 21PA, 22PA, 23PA, 24PA, 30PA.
TYPICAL DRILLING AND TAPPING FOR PIEZOMETERS 17P, 29P AND 30P.
Connect piezometer 31P into vent pipe below vent pipe valve.
Note: There shall be no distortion nor change in direction in any 1/8" piezometer hole in a minimum length of twice its diameter. Accordingly every effort shall be made to insure that the piezometer openings are drilled normal to the surface in contact with the water and that all burrs are removed. The practice of removing burrs by using a sharp tool on the edge of the opening is not permissible. Instead, the burr shall be removed by the use of emery cloth over a template having the same shape as the contour of the valve in the vicinity of the piezometer opening. After applying the emery cloth any burr pushed back into the opening shall be removed by the use of a reamer of the proper size. By alternately using a reamer and emery cloth the burr may be entirely removed without rounding the edge of the hole. Care must be exercized to prevent chattering of the tool when drilling the piezometer holes. A jig should be utilized to insure the hole is drilled absolutely normal to the water surface of the valve as any slight angle will cause impact or ejector action on the piezometer. Power tools should not be used for any operations other than drilling the holes.
All 1/8" holes shall be drilled normal to the water surface and be free from burrs. See detail.
VIEW C-C
VIEW B-B
SECTION A-A
SECTION D-D
VIEW E-E
VIEW F-F
RIVER OUTLET
USBR
1947
LINE X
LINE Y
LINE Z
TYPICAL DRILLING AND TAPPING FOR PIEZOMETERS 25P, 26P, 27P, 28P.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT - CALIFORNIA
FRIANT DIVISION
FRIANT DAM
RIVER OUTLETS
96" HOLLOW JET VALVE R-1
LOCATION OF PIEZOMETER CONNECTIONS
DRAWN H.H.N. SUBMITTED
TRACED L.R.G.-F.N.K. RECOMMENDED
CHECKED APPROVED
CHIEF ENGINEER
DENVER, COLORADO AUGUST 12, 1946
214-D-12504



Friant Dam River Outlets. Two-rack conduit (horizontal) encasing piezometer leads from valve interior. September 1950.

FIGURE 4



SYMBOLS

- ● RESERVOIR ELEVATION 433.98
- ■ RESERVOIR ELEVATION 512.32
- ▲ RESERVOIR ELEVATION 554.40

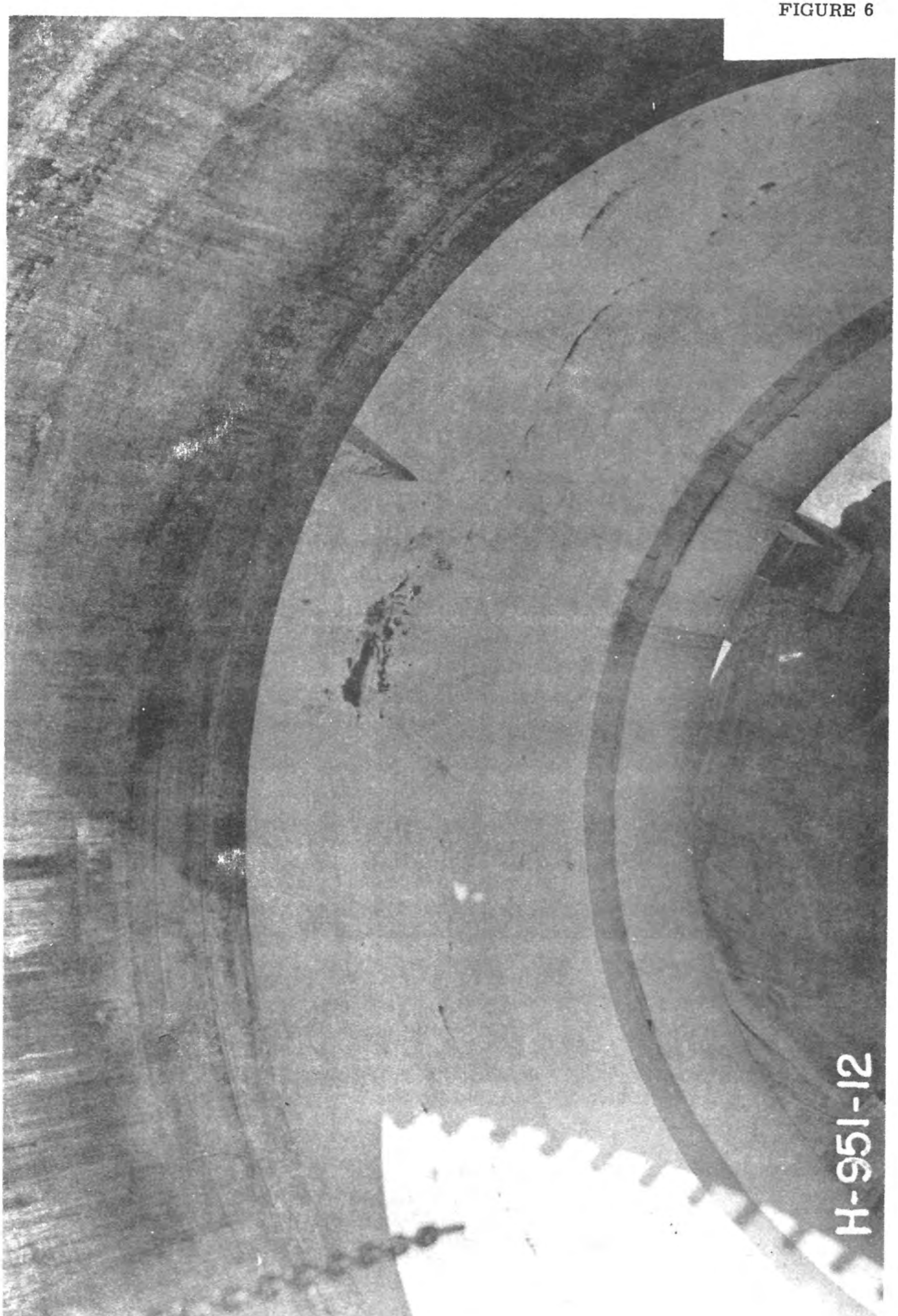
NOTE

Prototype data shown by symbols.
24-Inch model data shown by solid lines.
6-Inch model data shown by broken lines.

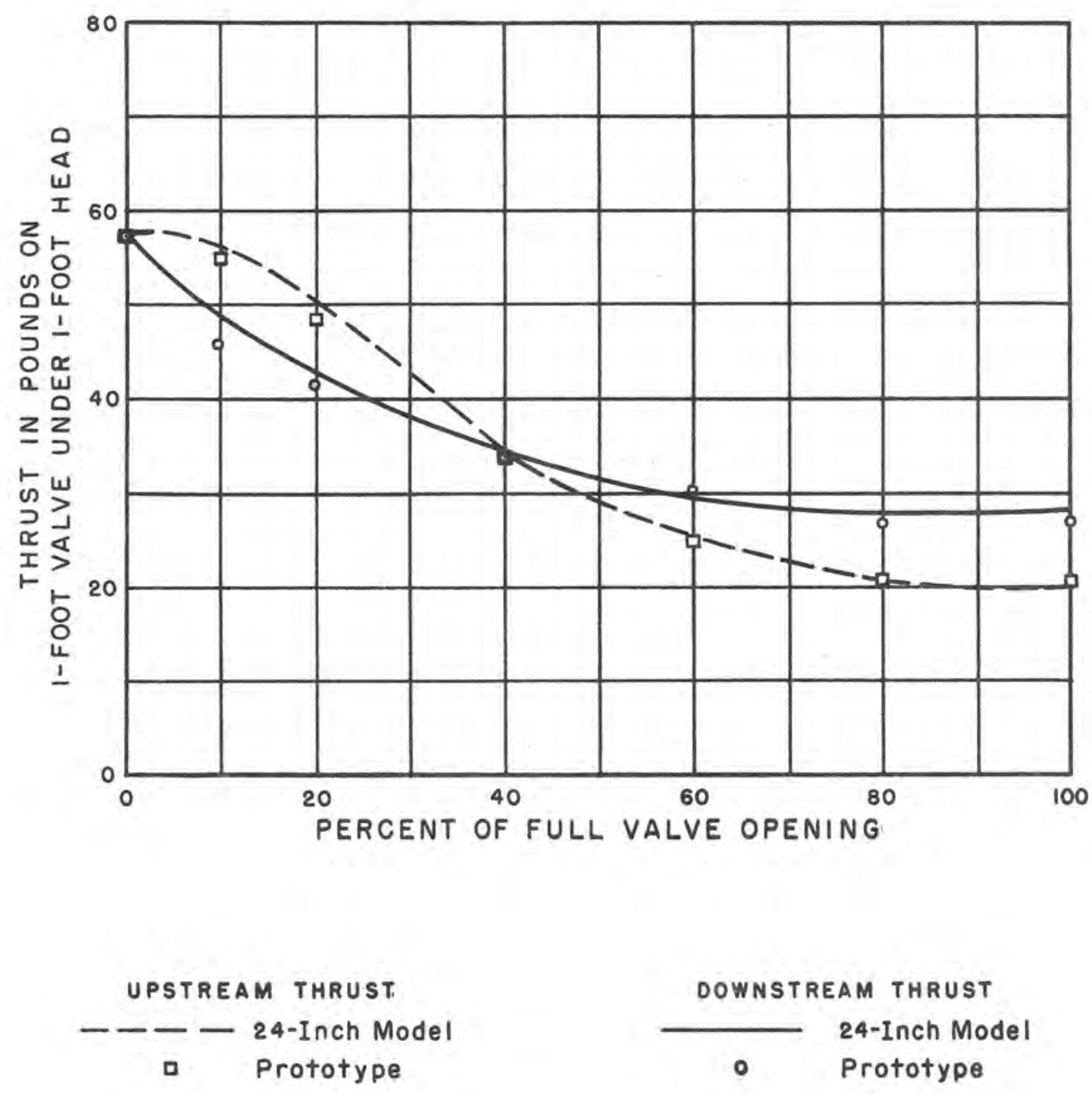
FRIANT DAM
RIVER OUTLETS
HYDRAULIC PERFORMANCE TESTS
PIEZOMETERS 6 AND 25

3-15-54 D.M.L.

FIGURE 6

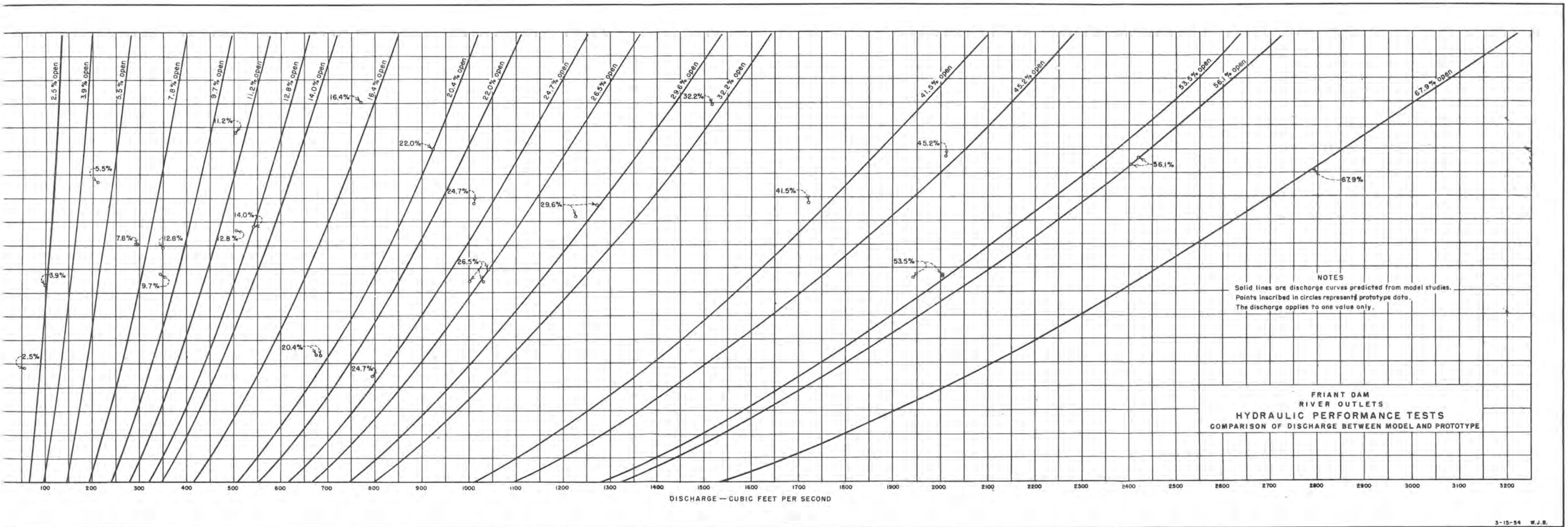


Cavitation erosion (dark spots) on body of river outlet hollow jet valve R-3, Friant Dam.



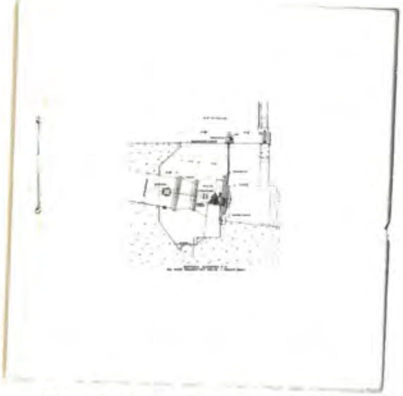
FRIANT DAM
RIVER OUTLETS
HYDRAULIC PERFORMANCE TESTS
THRUST ON NEEDLE

260 3-15-54. D.M.L.

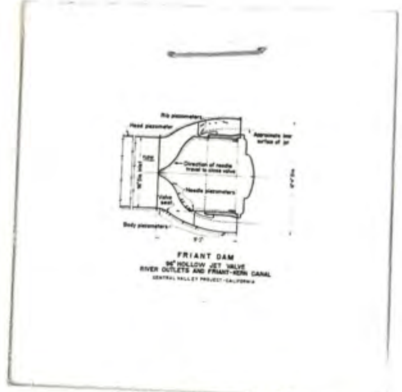

2.5% open
3.9% open
5.5% open
7.8% open
9.7% open
11.2% open
12.8% open
14.0% open
16.4% open
20.4% open
22.0% open
24.7% open
26.5% open
29.6% open
32.2% open
41.5% open
45.2% open
53.5% open
56.1% open
67.9% open
NOTES
Solid lines are discharge curves predicted from model studies.
Points inscribed in circles represent prototype data.
The discharge applies to one value only.
DISCHARGE — CUBIC FEET PER SECOND
FRIANT DAM
RIVER OUTLETS
HYDRAULIC PERFORMANCE TESTS
COMPARISON OF DISCHARGE BETWEEN MODEL AND PROTOTYPE
3-15-54 W.J.B.

Slides for ASCE Paper for Berkeley, Calif meeting, Aug. 1955
Hollow-Jet Valves, Lancaster & Dexter
Slides filed in Drawing and Data Files

PAP-74

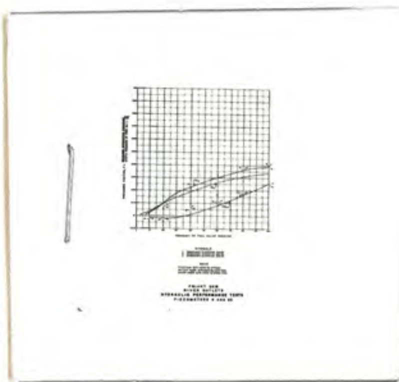


T-214-D-11329
Fig. 2 of Paper



PX-D-1311
substituted for
Fig. 3 of Paper

TH-951-36
Fig. 4 of Paper
Thomas had slide for previous use (~~No print available~~) slide returned to Thomas



PX-D-1309
Fig. 5 of Paper

H-951-12
Fig. 6 of Paper

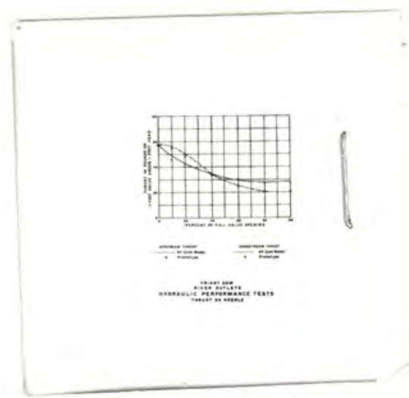


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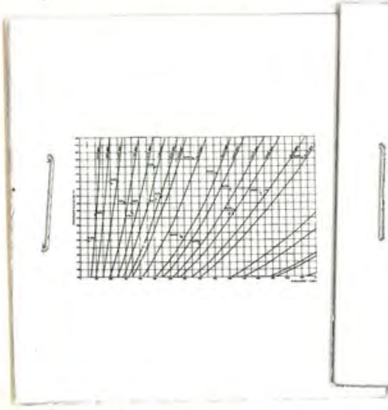
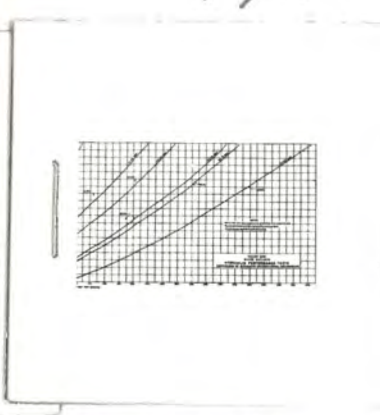
Fig. 7 of Paper





PX-D-1312A PX-D-1312B
Fig. 8 of paper (Figure divided, too long for one slide)