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HYDRAULIC CHARACTERISTICS OF HOLLOW-JET VALVES

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SYNOPSIS

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.

INTRODUCTION

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 performance and economic limitations.

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 the hollow-jet valve. This type, however, is limited to use as a free discharge valve preventing its

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application in closed conduits. 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 Federal Government without payment of royalties.

Models

The design was accomplished with the aid of three models; a 45 degree segment of a 12-inch-diameter air model, a 6-inch-diameter hydraulic model tested in the Hydraulic Laboratory of the Bureau of Reclamation at Denver, and a 24-inch-diameter model tested at Hoover Dam under a high head.

The prime purpose of the 24-inch model was to ascertain the hydraulic characteristics of a hollow-jet valve constructed under prototype conditions. That is, the outer shell, the supporting vanes, and the cylinder containing the needle were cast in one piece. Machine-finished surfaces were limited to the needle and that part of the outer shell flow surface upstream from the vanes. Because the rough finish of the casting could conceivably affect boundary flow sufficiently to cause local areas of low pressures, all surfaces in the 6-inch model were machine finished.

The secondary purpose for studies with the 24-inch model was exploration of some critical areas that were too small in the 6-inch model for exploration by piezometer orifices. A few revisions were found necessary as a result of tests with the 24-inch valve. This valve was later installed permanently in a Reclamation project.

Prototype

Although hollow-jet valves have been installed at a number of structures, initial installation of large units was on the four river outlets through Friant Dam, Fig. 1. Details of this installation are shown on Fig. 2. One of the four 96-inch valves was equipped with piezometer orifices to permit performance of special tests to ascertain if this type valve possessed predicted hydraulic characteristics. Fig. 3 shows locations of piezometer orifices in the valve. Where distances between orifices were small in the direction of flow, the orifices were offset laterally. A photograph taken looking upstream at this valve is shown on Fig. 4. Performance of the large valve could conceivably differ from that predicted by the 6-inch and 24-inch hydraulic models due to roughness of the large casting and because of larger tolerances necessarily allowed for machined surfaces in the prototype valve.

A field testing program was inaugurated about a year after the valves were placed in operation. The program consisted of piezometric measurements at valve openings of 10, 20, 40, 60, 80, and 100 percent of needle travel with operating heads of 102, 180, and 223 feet. The maximum design head at this installation is 246 feet. For each test, discharge through the valve was obtained from operating records based on current meter measurements in the river channel a short distance downstream from Friant Dam. In this instance, all flow in the river passed through the valve under test. Hence, measurements of river flow were not subject to possible errors due to subtracting flow from another source such as a powerhouse.

Other field observations included general characteristics of the hollow-jet valves; such as, noise intensity and vibration, inspection of the interior of one unit, and stability of the jet.

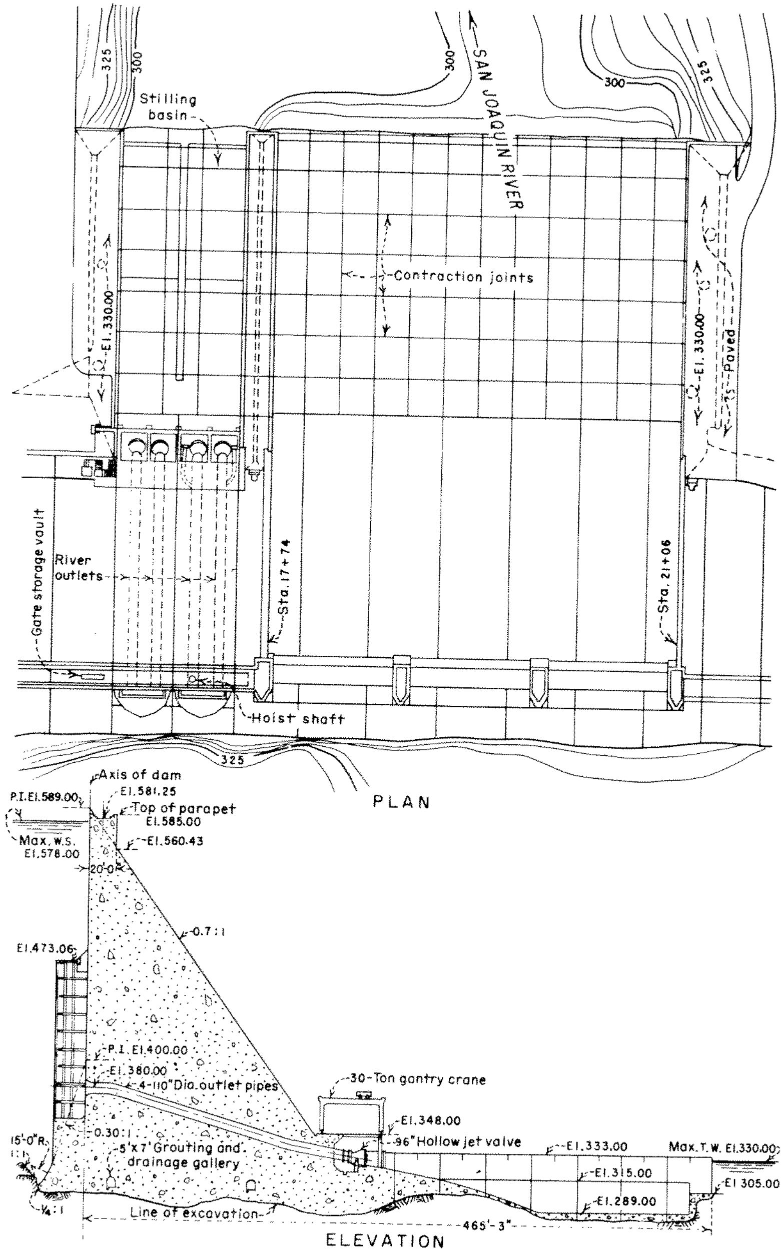


FIGURE 1 - PLAN AND ELEVATION OF RIVER OUTLETS
FRIANT DAM

Results of Pressure Measurements

Pressure measurements were obtained 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 were referred to the elevation of the center line of the upstream end of

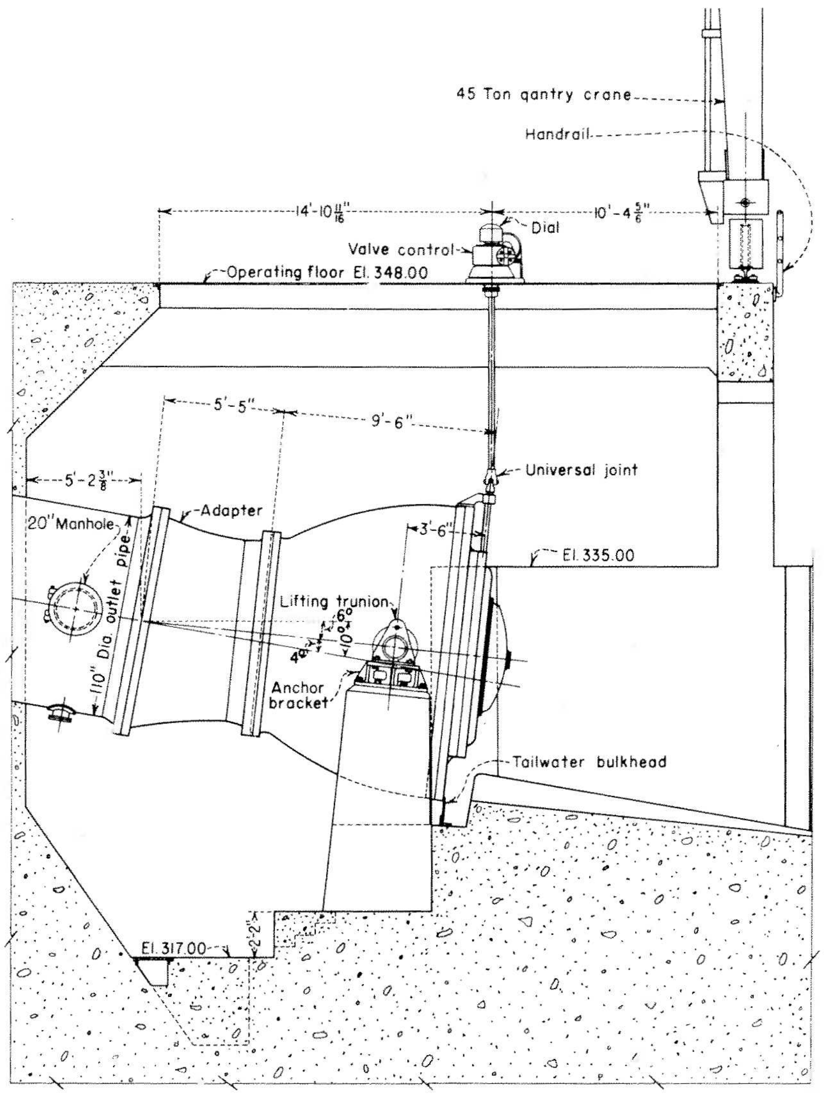


FIGURE 2 - 96-INCH HOLLOW JET VALVE INSTALLATION
FRIANT DAM RIVER OUTLETS

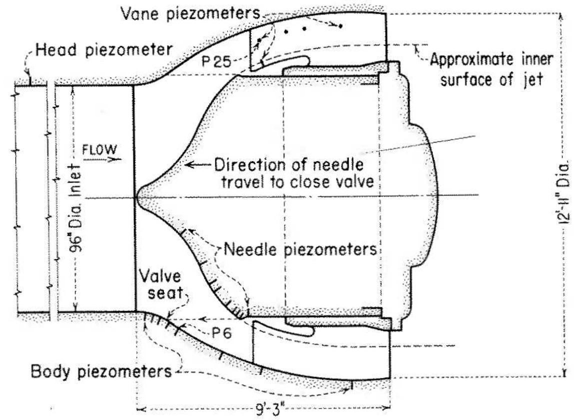


Figure 3 - Piezometer locations in 96-inch hollow-jet valve--
Friant Dam River Outlet

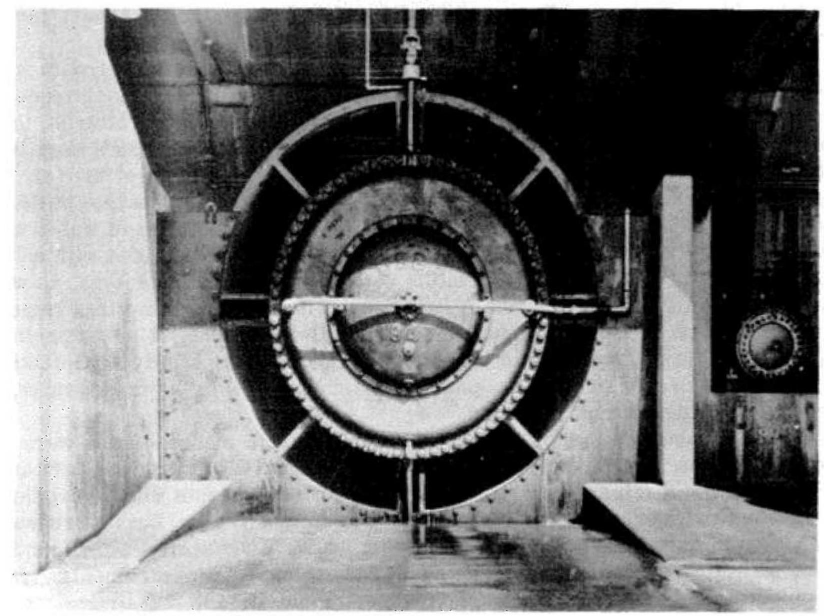


Figure 4 -Two-rack conduit (horizontal) encasing piezometer leads from interior of 96-inch hollow-jet valve--
Friant Dam River Outlet

the valve. The valve operating head was measured with a piezometer orifice one inlet diameter upstream from the valve and referred to the same elevation as the other pressures. Hence, the prototype valve was considered to have a horizontal center line that corresponded to the hydraulic models, while actually the center line of the prototype valve sloped downward as shown on Fig. 2.

Pressures were plotted against percent valve opening by utilizing a pressure factor, F, defined as the ratio of the measured piezometric head, in feet of water, to the total head (static head plus velocity head), one inlet diameter upstream from the valve, Fig. 5. This procedure reduces F to a dimensionless ratio and makes 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 one of the piezometers, for which a plot is shown on Fig. 5, when the total design head is 200 feet of water and the valve is 50 percent open, follow the 50 percent line on the plot until it intersects the curve for the particular piezometer and read the value of the pressure factor at the left. Then multiply the pressure factor by 200 to obtain the pressure at the piezometer for the case being considered. If the piezometric pressure is below atmospheric, then the F value is negative and the calculated pressure is also negative.

Plots of pressure factors versus valve openings, similar to Fig. 5, were made for all piezometer orifices installed in the 96-inch valve and in the models. The locations of Piezometers P6 and P25, for which pressure plots are shown on Fig. 5, are shown on Fig. 3.

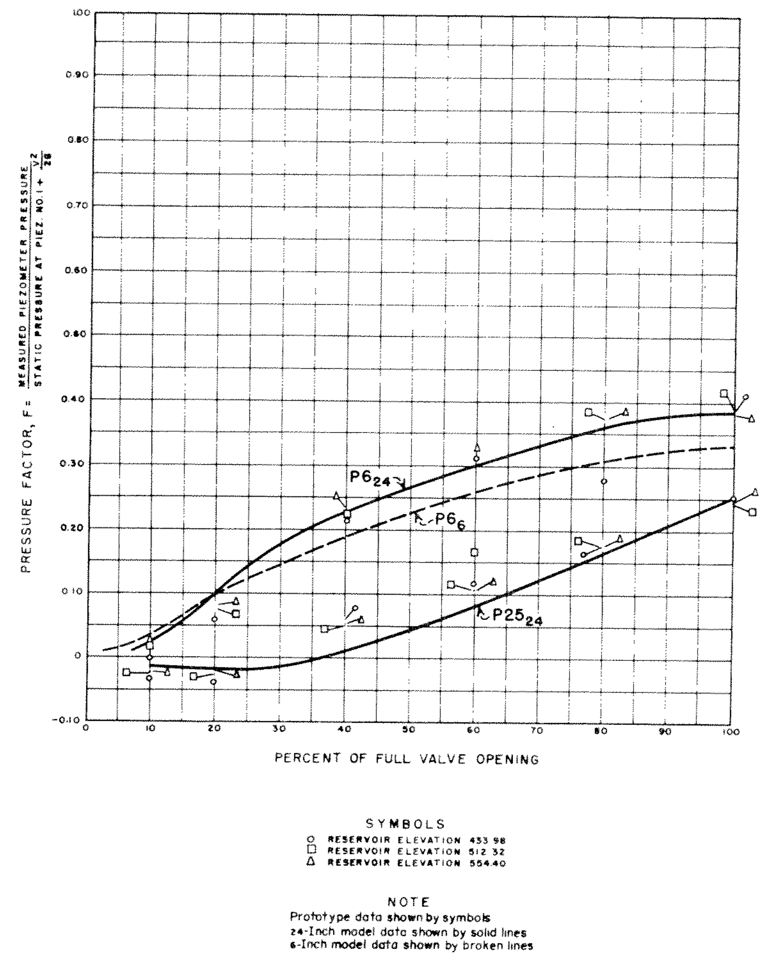
The pressure at the needle piezometer in the air space just upstream from the vanes was found to be a negative 1.22 feet of water in the 24-inch model when 100 percent open under a total head of 196.6 feet. In the prototype, the corresponding pressure when referred to the same total head was a negative 4.9 feet of water based on pressure factors obtained from tests at the two highest reservoir heads. Based on the pressure factor from the test at the lowest reservoir elevation, the pressure was a negative 9.8 feet of water when referred to the same total head. All of these values were obtained with a valve opening of 100 percent. Variation between model and prototype, as well as variation in the prototype itself, is attributable to the fact that this region is filled with an air-water mixture due to insufflation of the jet in the prototype valve. This mixture could conceivably choke the air supply sufficiently to cause an increase in subatmospheric pressure, while in 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. This conclusion was verified by the prototype tests which revealed an average pressure of minus 13 feet of water in this region, but no pressures conducive to cavitation occurred. However, negative pressures were found in other locations in the prototype valve contrary to model measurements. The magnitudes of such pressures were small and insignificant.

In general, pressures measured in the 96-inch prototype valve differed from those measured in the 24-inch model by an amount approximately equal to the difference between the values determined in the 6-inch and 24-inch models. The average deviation between model and prototype pressures were found to be less than 10 feet of water at maximum prototype test head. These

deviations can be attributed to a slightly different location of piezometer orifices, interference by a bolt head near a piezometer orifice, a slight difference in contour of the flow passages, or insufflation of portions of the prototype jet.

As previously stated, no measured pressures were sufficiently low to cause cavitation erosion. However, inspection of the tested prototype valve revealed that cavitation erosion had occurred on several localized areas of the valve body upstream from the vanes. Although erosion of the affected areas was not severe, the metal had been pitted. Since there was no established pattern or zone of cavitation damage, this condition was attributed to



PIEZOMETERS 6 AND 25

FIGURE 5 - HYDRAULIC PERFORMANCE TESTS
FRIANT DAM RIVER OUTLET VALVE

the rough surface of the casting. The fact that cavitation damage did occur exemplifies the need for specifying cast surfaces with a roughness factor held within specified limits.

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 and heads less than 200 feet.

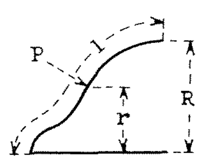
Results of Thrust Measurements

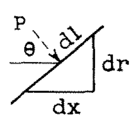
During design studies, considerable emphasis was placed on location and size of openings or ports through the needle portion of the valve to admit pressure into the interior, thereby balancing pressures so as to minimize power required to open and close the valve. Fig. 6 shows thrust on the needle in the upstream and downstream directions predicted from the 24-inch model, together with comparable information obtained from the 96-inch prototype.

For comparison purposes, the units on Fig. 6 have been reduced to those applicable to a 1-foot-diameter valve under a 1-foot head. This permits computation of thrust forces for other size hollow-jet valves operating under various heads. These computations can be made by multiplying results shown on Fig. 6 by both the desired head and the square of the diameter of the valve under consideration, these values being in feet and square feet, respectively. The results of similar data obtained on the 6-inch model are not shown since locations 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 forces predicted from the 24-inch model and those determined by field measurements on the 96-inch valve. The greatest difference between model and prototype results 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. The unbalanced force or the difference between the upstream and the downstream thrusts is the most important, and the maximum unbalance occurs at a valve opening of 100 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

Total thrust in x-direction = $2\pi \int_0^l rP \cos\theta \, dl$ and since

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

The integration was done graphically since relationship of P to r was not determinable analytically. Values of Pr as determined with piezometers on the needle were plotted against r values 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 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.

Thrust in the upstream direction is the pressure inside the needle, which was measured, multiplied by the area over which the pressure acts.

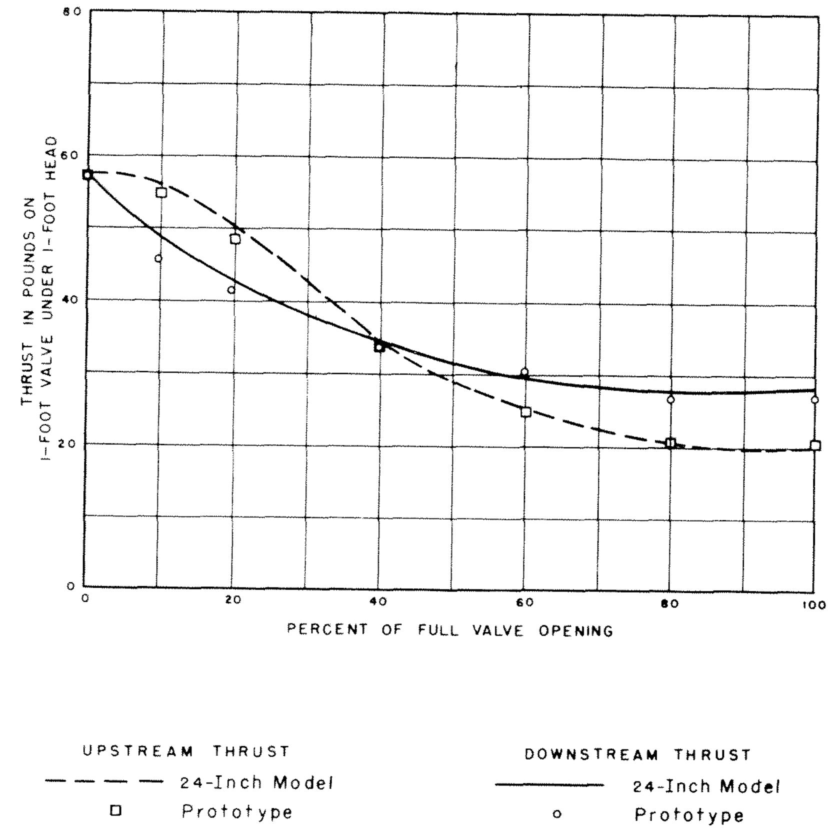


FIGURE 6 - THRUST ON HOLLOW JET VALVE NEEDLE
FRIANT DAM RIVER OUTLET

Rate of Discharge

Comparison of rates of discharge of a prototype and model valve are particularly important since they serve to evaluate discharge curves prepared from laboratory calibrations. The use of model instead of field calibrations can result in saving large amounts of money and time. The time and expense involved in performing a field calibration are demonstrated by the fact that approximately 600 current meter traverses 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 of Friant-Kern Canal, and also through needle valves at the headworks of Madera Canal. Results show that the current meter measurements could have been dispensed with since discharge curves established by model calibrations were as accurate as curves determined by field measurements.

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 flow characteristics.

Figs. 7 and 8 present data to support accuracy of the laboratory 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 and may be partly accounted for by the fact that lower discharges in the prototype were not susceptible to accurate measurements with current meters.

When using valves as metering devices extreme care is necessary to insure that position indicators accurately reveal true valve openings. The particular valves described in this paper are equipped with verniers on the

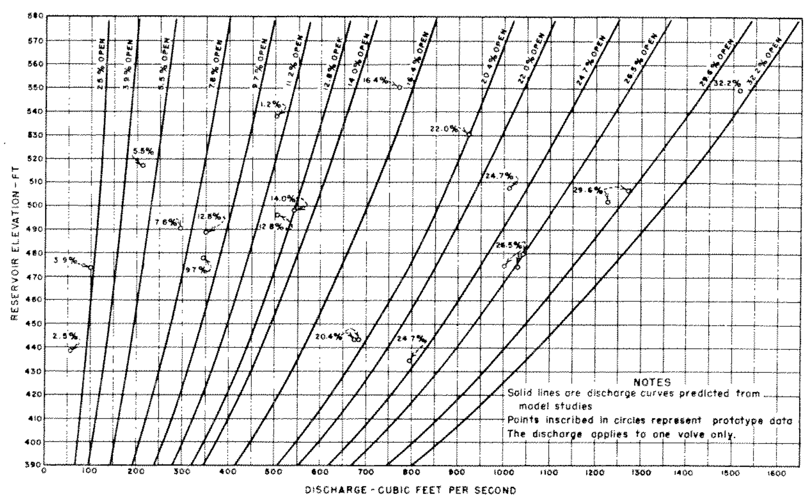


FIGURE 7 - HYDRAULIC PREFORMANCE TESTS
COMPARISON OF DISCHARGE BETWEEN MODEL AND PROTOTYPE
FRIANT DAM RIVER OUTLET

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.

General Behavior of the Valve

General behavior of the hollow-jet valves has been entirely satisfactory. This statement applies to both mechanical operation and hydraulic characteristics. Operation has been quiet, free from vibration, and the jets remain stable and well defined.

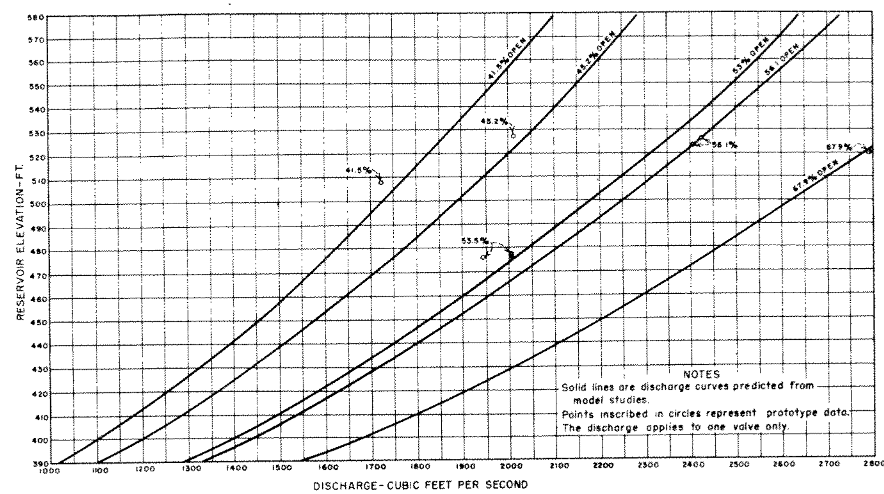


FIGURE 8 - HYDRAULIC PREFORMANCE TESTS
COMPARISON OF DISCHARGE BETWEEN MODEL AND PROTOTYPE
FRIANT DAM RIVER OUTLET