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HYDRAULIC LABORATORY REPORT NO. 148

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MODEL STUDIES FOR THE DEVELOPMENT OF THE HOLLOW-JET VALVE ANDERSON RANCH DAM - BOISE PROJECT, IDAHO

By

FRED LOCHER, ASSISTANT ENGINEER

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Denver, Colorado
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Under Direction of

J. E. WARNOCK, SENIOR ENGINEER
and
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- - - - -

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UNITED STATES
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Branch of Design and Construction
Engineering and Geological Control
and Research Division
Denver, Colorado
September 12, 1944

Laboratory Report No. 148
Hydraulic Laboratory

Compiled by: Fred Locher
Reviewed by: J. E. Warnock

Subject: Model studies for the development of the hollow-jet valve - Anderson Ranch Dam - Boise Project, Idaho.

INTRODUCTION

1. General. The water conservation and irrigation demands of the Bureau of Reclamation projects have required accurate regulation of flow either from the reservoirs to the various irrigation projects or for release downstream to another reservoir. The valve in earliest use for this purpose was the balanced Ensign type which was installed at Arrowrock and Shoshone dams and other of the earlier dams. This valve was very bulky, and considerable trouble was experienced with its operation (laboratory report No. 135). The Ensign valve was superseded by the needle valve which, after considerable adjustment, was found to operate satisfactorily. However, the valve was expensive, and its coefficient of discharge was low. In the search for a less costly valve, the tube valve was developed. Its design was similar to a needle valve with the major part of the downstream end of the needle removed. This arrangement was less expensive than the needle valve, but the coefficient of discharge was still low; and it had the added disadvantage of not producing a stable jet at small valve openings.

Further search for a more suitable regulating valve with high heads produced a preliminary design for the so-called hollow-jet valve, which was submitted to the hydraulic laboratory for testing in 1940.

PURPOSE OF MODEL STUDIES

2. Scope of tests. The purpose of the model tests was to investigate the feasibility of the proposed design. The investigation included a study of the valve operating mechanism, the pressure distribution on critical portions of the valve, a comprehensive calibration of the design, and a study to determine a suitable location for the balancing ports in the needle.

3. Summary of results. Pressures on the valve body and the needle of the final design of figure 4 were positive for all valve openings. Although they decreased and became small at some points as the needle approached the closed position, none became negative; and it is not anticipated that any trouble due to cavitation will be experienced with this valve. Discharge coefficients and capacity curves for the final design (figures 4, 5, and 6) show considerable improvement over the former needle and tube valve designs. The coefficient of the hollow-jet valve, based on the inlet diameter, was 0.696 at maximum opening as compared to 0.583 for the Friant Dam needle valves, and 0.52 for the tube valves. By increasing the needle travel of the hollow-jet valve to 105.5 percent of the design travel, it was possible to obtain a coefficient of 0.724 without materially affecting the pressure distribution (figure 5). On a cost basis, at the headworks of the Friant-Kern Canal it was found possible to effect a saving of approximately one hundred thousand dollars by replacing the two needle valves and the two tube valves with hollow-jet valves of the same discharge capacity, and at the same time to have valves which would operate satisfactorily over any range of head or opening.

THE INVESTIGATION

4. Description of the model. The inlet diameter of the hydraulic models was 6 inches in all cases. All parts of the valve were bronze castings carefully machined to conformity of shape and proper finish. The operating mechanism of the first valves was hydraulic. The later models were operated mechanically. Piezometer pressures were taken in practically all of the models. The locations of the piezometers are shown on drawings of the model valve and are designated by a circle and a number.

To expedite the testing and provide an inexpensive means of determining the practicability of some of the suggested designs, an aerodynamic model was constructed to provide for testing the 12-inch diameter valve segments. This model consisted of a length of 6-inch diameter metal pipe; a transition from 6-inch diameter to a 45-degree 6-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 plastic sectors of the valve body and the needle (figure 2A). The segments, except for the needle, were fitted and bolted to the sides of the V-shaped channel. The needle was made adjustable and was controlled by a rod passing through a hole in the end of the V-shaped channel. The joints were made airtight by placing fillets of molding clay along the seams inside the model. Air was supplied by a 4-inch positive displacement blower.

Piezometers were installed by drilling small holes into the model segments and inserting small copper tubes for attachment to a water

manometer. The connections between the plaster and the copper tubes were made airtight by placing plaster mortar around them.

5. Initial tests. The preliminary design of figure 1A was a 6-inch bronze model having a hydraulically operated needle. Tests with this model indicated that the operating mechanism for the needle was satisfactory and that accurate settings of the needle could be obtained with the aid of an indicator.

The coefficient of discharge, based on the inlet diameter and maximum opening was 0.607, which was considered too small in view of results obtained with the needle valves. To increase the coefficient of discharge, the needle travel was increased from 2.00 to 2.25 inches. This increased the coefficient to 0.621 and the piezometric pressures did not indicate any negative pressures on either the needle or the valve body. The coefficient of discharge was then increased to 0.692 by increasing the body radius. While this coefficient was more satisfactory, piezometric pressures on the needle indicated severe negative pressures and the needle was again changed as shown on figure 1A, revision 4. The revision reduced the coefficient to 0.629 and eliminated the negative pressures. This design was not appreciably better than the first revision of the original design, and it appeared that a complete revision of design was necessary to obtain satisfactory pressure conditions and a suitable coefficient of discharge.

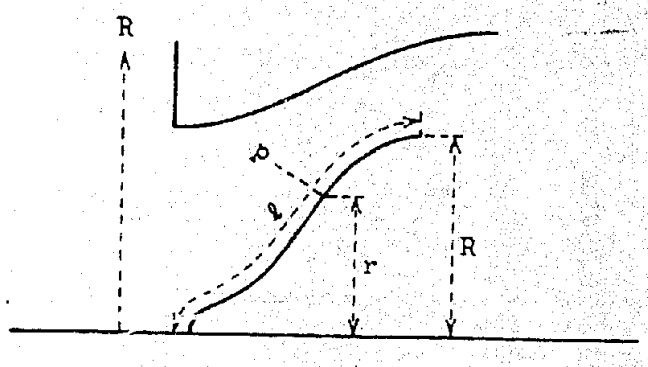
6. Tests to determine accuracy of aerodynamic models. To compare the results of a 45-degree sectional model as shown on figure 2A with the results obtained with the hydraulic model, a plaster segment of a section of valve 1, figure 2B, was constructed and tested using air as a fluid. The results of these tests indicated a coefficient of discharge of 0.716 as compared to 0.678 obtained with the hydraulic model. As no attempt was made to compensate for the absence of vanes in the air model, the results obtained were considered sufficiently accurate for preliminary testing and work was continued with this type of model to develop a design for testing in a hydraulic model.

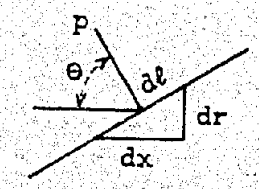
7. Aerodynamic tests leading to the design of valve 2. In view of the preceding tests, this model was constructed with an exit of smaller body diameter and with a smaller needle having more curvature at the downstream end than those used in previous models (figure 2C). The results from aerodynamic tests indicated the coefficient of discharge to be 0.677 without a vane and 0.642 when the vane was in place. The piezometric pressures were positive at all valve openings.

It appeared that considerable savings in cost could be effected in the design of the valve if the hydraulic operating mechanism were replaced by a balanced chamber and ports in the needle located so that the unbalanced pressure on the needle would be minimized for all valve openings. The locations of these ports were obtained by

integrating the measured piezometric pressures on the needle for various valve openings between the closed and the fully open position. The thrust on the needle thus obtained was plotted against valve opening. From the piezometric pressures it was possible to select a location for an opening into the balancing chamber where the balancing thrust at various valve openings did not vary greatly from the needle thrust. A location was found which limited the unbalanced thrust to approximately plus or minus 10 percent of the maximum head on the valve.

The thrust on the needle was computed from the piezometric pressures as follows:





Elements of needle

p = measured piezometric pressure,

ℓ = length along surface of needle,

r = radius to piezometer,

$2\pi r p \, d\ell$ = total thrust on the increment $d\ell$,

$2\pi r p \, d\ell \cos\theta$ = thrust, or same area in x-direction.

Then the total thrust in the x-direction is

$$2\pi \int_0^{\ell} r p \cos\theta \, d\ell,$$

but $d\ell = \dfrac{dr}{\cos\theta}$, so the total thrust reduces to

$$2\pi \int_0^{R} r p \, dr.$$

To evaluate this integral it was necessary to know p as a function of r; but, as this was not known, the integration was done graphically. The value pr was plotted against r; the area under the curve was planimetered to obtain $\int_0^R r\,p\,dr$; and that value was multiplied by 2π to obtain the total thrust on the needle for a particular position. This operation was repeated for several positions of the needle, and the results were plotted.

To find the best location for the balancing port it was necessary to plot piezometric pressure against valve opening for each piezometer on the needle, and from these curves a pressure was chosen which, when multiplied by the projected area of the balancing chamber in the R-plane, resulted in a balancing thrust that roughly approximated the needle thrust. The piezometric pressures for determining this location were obtained from the aerodynamic model and were later verified in a hydraulic model of valve 2.

8. Hydraulic performance of valve 2. The 6-inch model of valve 2 was constructed according to figure 1B. The hydraulic control on the needle of the previous design was replaced by a screw mechanism and a balancing chamber. With this arrangement the valve opened and closed easily without any indication of vibration or binding at any valve opening.

The coefficient of discharge obtained with this valve at full opening was 0.642, which compared favorably with that obtained from the same design in the aerodynamic model. All pressures on this valve were positive except at piezometer 8 which was slightly negative at 10 percent of full valve opening. This negative pressure was not serious, and from a pressure viewpoint, the valve was considered satisfactory. The discharge coefficient was lower than was considered obtainable with this type of valve and still have satisfactory pressure distribution in the valve.

This design and the previous valve design were such that at any time the needle or the interior of the valve needed servicing, it would have been necessary to remove the sleeve at the upstream end of the valve and remove the needle from that end. This would have involved a considerable amount of time and expense. It was apparent that the servicing of the valve could be done more rapidly and more easily if the needle were removed from the downstream end of the valve. Accordingly, the valve was redesigned as shown on figure 1C.

9. Valve 3 with special hydraulic control. This valve was considerably larger in diameter but shorter than the previous valves. It also contained a so-called spiral hydraulic control for actuating the needle. The spiral was turned by a manually operated gear arrangement.

The rotation of the hollow spiral shaft varied the opening to the ports in the hydraulic chamber, thus varying the pressure in the chamber which caused the valve either to open or close as desired. The control of the valve travel with this apparatus was satisfactory if the spiral was not turned too rapidly. The rapid rotation of the spiral did not allow time for the pressure in the hydraulic chamber to build up to its proper value and stabilize; hence, temporary control of the needle was lost. All that was necessary to regain control was to retard the speed of rotation of the spiral, and it was again possible to set the needle at any desired position without difficulty.

The coefficient of discharge for this valve was 0.674. Objectionable subatmospheric pressures on the body in the region near the entrance caused abandonment of this particular arrangement. Also, from the aerodynamic tests of the revisions to this design, shown on figure 2D, it appeared impossible to obtain a design devoid of negative pressures in a valve so limited in length.

10. Valve 4. As the interior parts of valve 2 indicated satisfactory performance, it appeared possible to obtain a suitable design by combining this part of the valve with a new and larger body, as shown on figure 1D. This combination was not satisfactory, as low subatmospheric pressures prevailed at piezometer D. The coefficient of discharge was 0.740.

11. Aerodynamic tests to determine a design for valve 5. Previous tests had indicated that the negative pressures on the valve body were partially due to the sharp radius at the entrance. By increasing this radius, as shown on figure 2E, the negative pressures on the body were eliminated if the needle travel was limited to 4 inches. Pressure conditions on needle 1, figure 2E, were satisfactory except at piezometer 22 where objectionable negative pressures were obtained. This was also true of needles 2 and 3.

After considerable study as to the cause of the low pressures at piezometer 22, needle 4 was evolved. Tests with this needle indicated positive pressures on both the needle and the valve body for all valve openings. The pressures on piezometer 22 continually decreased as the valve closed, and at some positions the pressure was nearly atmospheric.

12. Valve 5 - Anderson Ranch B. With the information obtained from the previous studies, a new 6-inch hydraulic model was constructed (figure 1E). With this design it was also possible to remove the needle from the downstream end of the valve. To provide for this without making the diameter of the downstream part of the valve large, it was necessary to reduce the clearance between the inner nappe of the jet and the needle housing.

Preliminary tests with this design showed that at valve openings

of between 97 and 100 percent the jet filled the opening at the discharge end of the valve, causing the jet to collapse and destroy itself. At the same time, the pressures inside the valve decreased considerably below atmospheric pressure. Performance of the valve at other openings was satisfactory. The jet was well defined at all valve openings, and the corresponding pressures were all positive except for piezometer 24 which was slightly negative over most of the operating range. The difficulty due to the jet filling the downstream opening was eliminated by reducing the outside diameter of downstream end of the needle housing one-eighth inch.

Further testing with this design revealed critical subatmospheric pressures on the four large vanes forming the connection between the valve body and the needle housing. One of the vanes was altered as shown on figure 3. Continued testing of the design showed that the subatmospheric pressures on the vane had been relieved. The coefficient of discharge was 0.685 as compared to 0.674 obtained with the same design in the aerodynamic model.

As the clearance between the inner nappe of the jet and the valve was considered too small for safety, the diameter of the body was enlarged to 9.5 inches and the vanes were altered to fit the new diameter (figure 3). The tests with this valve showed a maximum negative pressure on the needle at piezometer 24 of −15 feet of water for a scale head of 500 feet and a maximum negative pressure on the vane of −14.4 feet for the same scale. Other pressures in the valve remained positive. The coefficient of discharge increased to 0.695.

This design was considered satisfactory for the Anderson Ranch installation where the valve inlet diameter will be 72 inches. However, it was not possible to design a similar valve of 24-inch diameter because of the mechanical difficulty in obtaining enough space for the bolts which hold the prototype parts in place and at the same time maintain sufficient clearance between the inner nappe of the jet and the needle housing.

13. The final design. Because of the mechanical difficulties encountered in small valves of the previous design, the diameter of the valve body was increased to 9.75 inches. The interior parts of the valve remained the same except the vanes, which were extended to fit the new diameter.

As before, all pressures on the valve were positive except at piezometer 24 which decreased from −15 to −20 feet of water for a scaled head of 500 feet. This change increased the coefficient of discharge to 0.703.

The negative pressures on the needle were completely eliminated by changing the seating area of the needle from a curve to a tangent at 40

degrees with the center line of the valve. In the model, the needle seated on the downstream edge of this tangent. This was not considered practical in the prototype; so the seating portion of the needle was altered to conform to that shown in figure 4. No great difference in pressure is expected with this change in the valve seat, although it was not tested in the model. The jet emitting from the valve at various openings is shown on figure 7. A front view of the model valve is shown on figure 8.

The design as shown on figure 4 is final unless future tests on a 24-inch model to be tested at Boulder Dam under high head indicate the necessity for further changes.

14. Preparation of the data on pressure and discharge characteristics. All of the information pertinent to designing a hollow-jet valve of any size is shown on figure 4. The dimensions shown on the section through the valve have been reduced to a unit inlet diameter. To determine the dimensions of a valve with a specified inlet diameter, say 100 inches, multiply all of the dimensions shown by 100 and the result will be the dimensions of the particular valve in inches. If the dimensions are desired in feet, the correct result can be obtained by multiplying the dimensions shown by the specified inlet diameter in feet.

In figure 4B the pressure factor F is plotted against percent of full valve opening. The pressure factor has been 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. This procedure reduces F to a dimensionless number, making it possible to obtain the pressure at any point on the valve by selecting from the 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 piezometer 7 when the design head is 200 feet of water and the valve is 50 percent open, follow the 50-percent line until it intersects curve 7 and read the value of the pressure factor at the left which, in this case, is 0.127. Multiply 200 times 0.127 and the resulting pressure is 25.4 feet of water.

The coefficient-of-discharge curve based on the area of the inlet diameter is also shown on figure 4B. When the total head available at the valve is known, it is possible, with the aid of this curve, to determine the proper inlet diameter for a particular discharge. This curve was obtained by measuring the discharge and the head on the valve for various openings between the closed and the open positions and substituting in the formula

$$C = \frac{Q}{A\sqrt{2gH}}$$

where

C is the coefficient of discharge,

Q is the measured discharge,

A is the inlet area, and

H is the total head one diameter upstream.

The maximum unbalanced thrust on the valve, in pounds, was determined in a manner similar to that explained previously. It was found to be 6.995 H times the effective area of the balancing chamber in square feet. This force will act upstream through the lower range of openings and downstream for the remainder of the valve travel. The change in direction occurs between 30 and 40 percent of full valve opening.

From the nomographs of figures 5 and 6 the discharge of the 72-inch Anderson Ranch Dam valves can be determined for a wide range of heads and the complete range of valve opening. The chart of figure 5 is based on the total head one diameter upstream from the valve, whereas that in figure 6 has been based on actual gage pressure at the same point. To obtain the discharge from those charts, draw a straight line between the observed head and valve position. The discharge is given by the intersection of this line with the center scale.

An assembly drawing of the 24-inch hollow-jet valve to be tested with heads up to 375 feet, at Boulder Dam, is shown on figure 9. Upon completion of the tests the valve will be installed permanently at Jackson Gulch Dam - Mancos project, Colorado, where the maximum head will be 116 feet.

15. Conclusions. That positive pressures will exist on all parts of the valve except the large vanes is indicated by the results obtained from the hydraulic model.

The jet emitting from the valve was well defined. There was no objectionable spray.

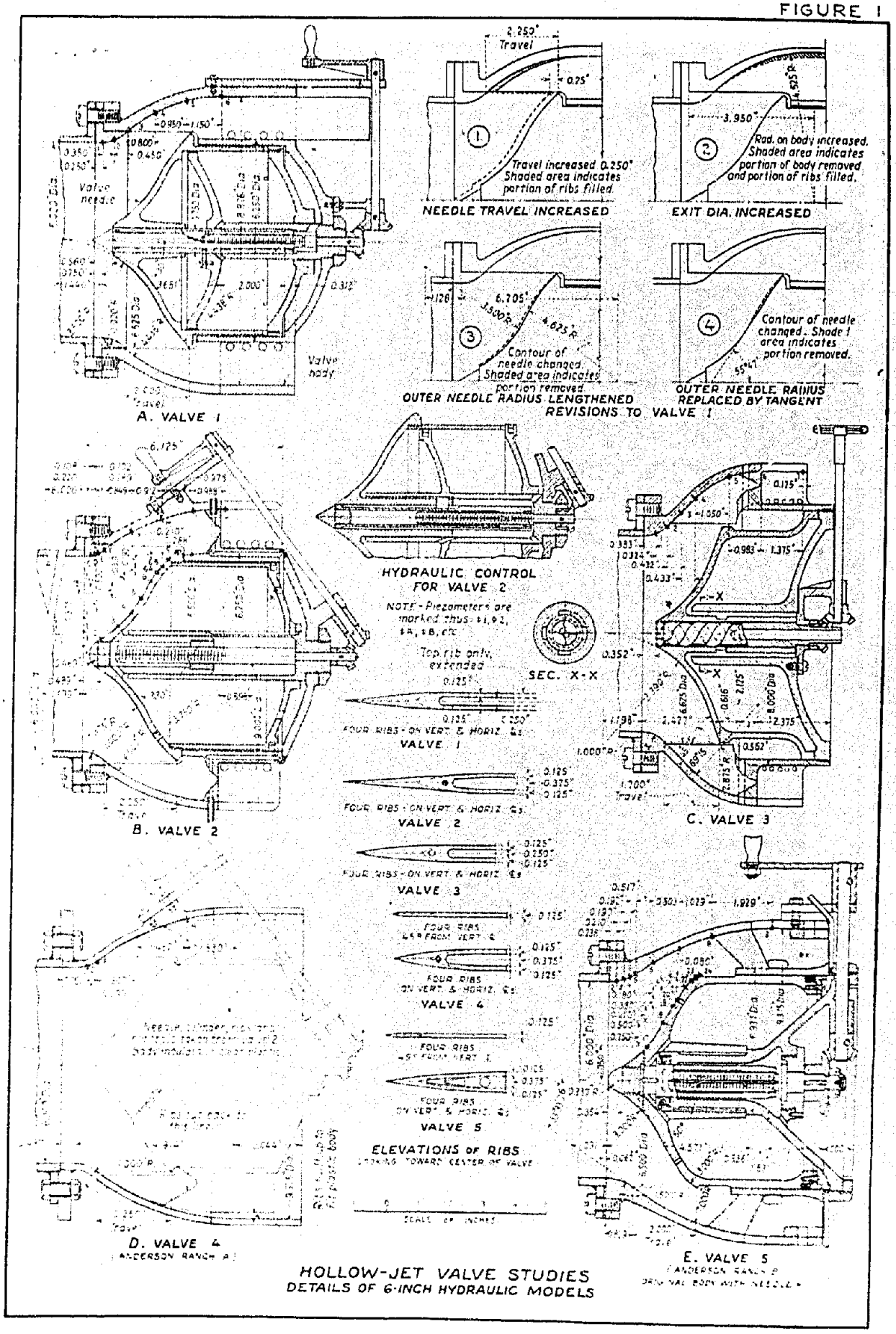
This valve should not be used for discharging under water or into a closed conduit without special provisions for aerating the inside of the jet. Tests were not made along these lines, and it is questionable whether satisfactory operation could be obtained under these conditions.

There are no limiting ranges of head or opening through which this valve cannot be operated.

The coefficient of discharge of this valve can be raised to 0.724 by increasing the needle travel 5.6 percent, without causing negative pressures on either the valve body or the needle.

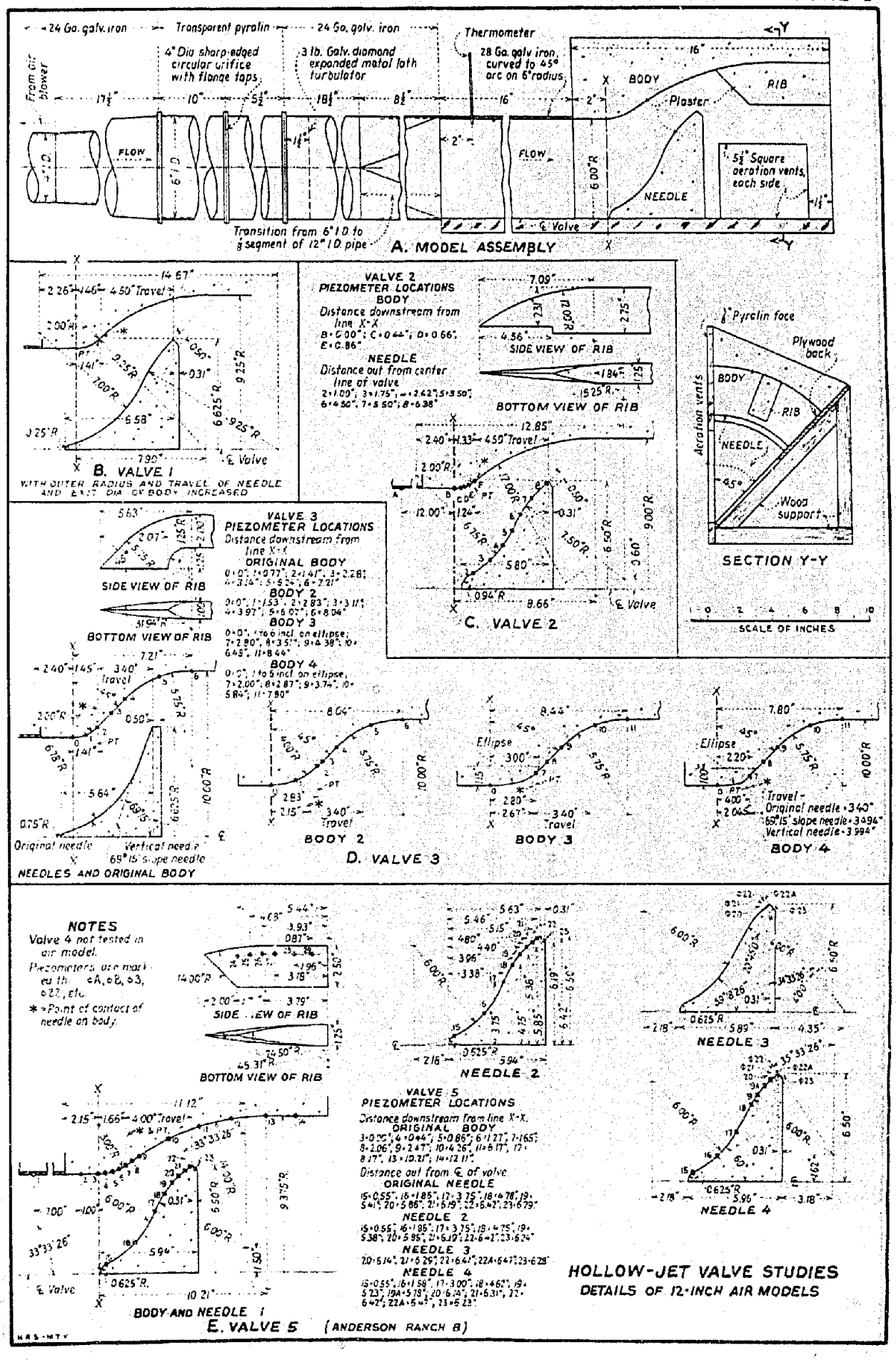
- - -

FIGURE 1



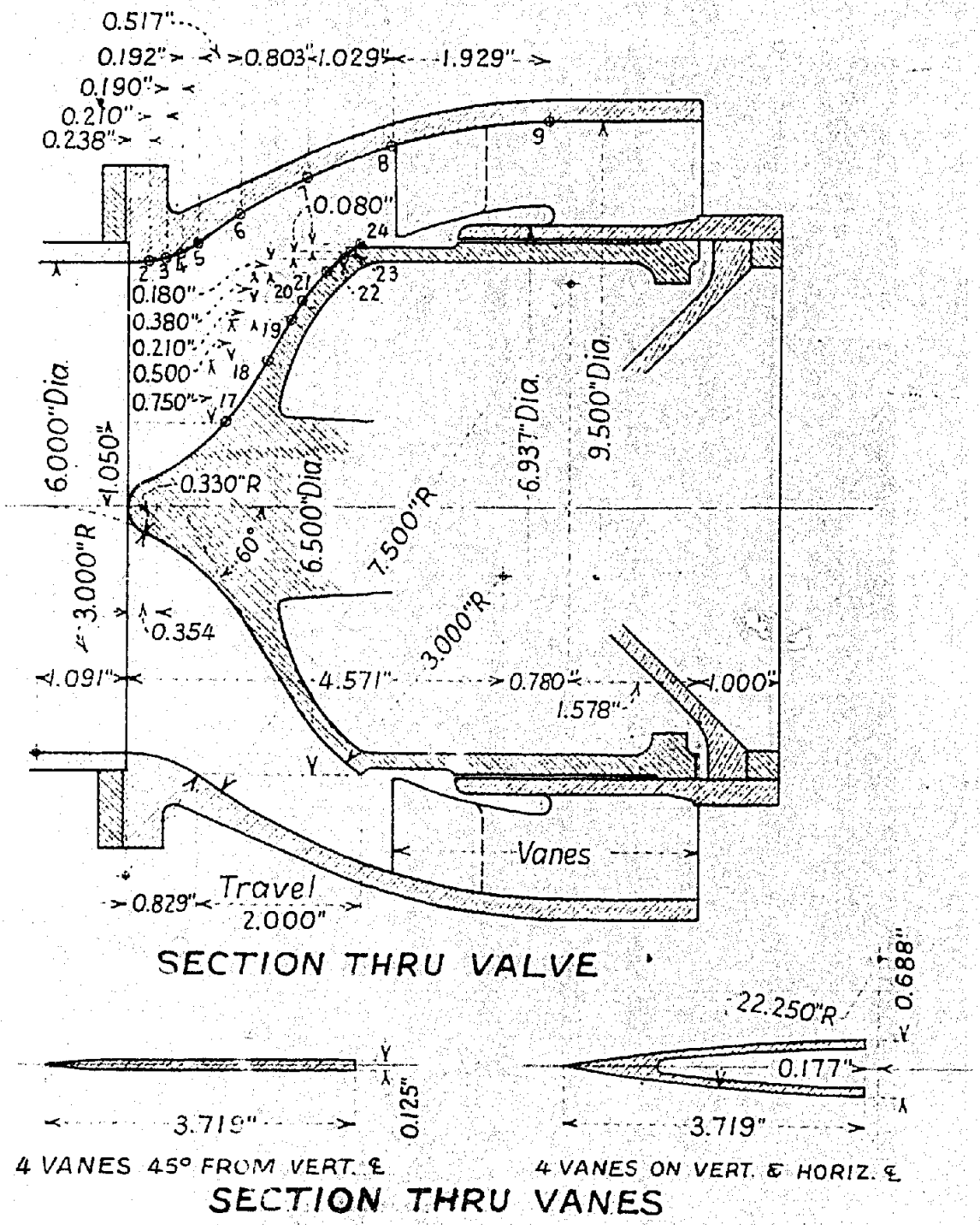
HOLLOW-JET VALVE STUDIES
DETAILS OF 6-INCH HYDRAULIC MODELS

FIGURE 2



24 Ga. galv. iron
Transparent pyralin
24 Ga. galv. iron
Thermometer
4" Dia sharp-edged circular orifice with flange taps
3 lb. Galv. diamond expanded metal lath turbulator
28 Ga. galv iron, curved to 45° arc on 6" radius
From air blower
FLOW
BODY
RIB
Plaster
NEEDLE
5½" Square aeration vents, each side
Transition from 6" I.D. to ⅛ segment of 12" I.D. pipe
℄ Valve
A. MODEL ASSEMBLY
B. VALVE 1
WITH OUTER RADIUS AND TRAVEL OF NEEDLE AND EXIT DIA OF BODY INCREASED
VALVE 2
PIEZOMETER LOCATIONS
BODY
Distance downstream from line X-X
NEEDLE
Distance out from center line of valve
SIDE VIEW OF RIB
BOTTOM VIEW OF RIB
C. VALVE 2
⅛" Pyralin face
Plywood back
Aeration vents
Wood support
SECTION Y-Y
SCALE OF INCHES
VALVE 3
PIEZOMETER LOCATIONS
Distance downstream from line X-X
ORIGINAL BODY
BODY 2
BODY 3
BODY 4
SIDE VIEW OF RIB
BOTTOM VIEW OF RIB
Original needle
Vertical needle
69°15' slope needle
NEEDLES AND ORIGINAL BODY
D. VALVE 3
Ellipse
Travel
Original needle = 3.40"
69°15' slope needle = 3.494"
Vertical needle = 3.994"
NOTES
Valve 4 not tested in air model.
Piezometers are marked th ⊕A, ⊕B, ⊕3, ⊕22, etc.
* = Point of contact of needle on body.
SIDE VIEW OF RIB
BOTTOM VIEW OF RIB
NEEDLE 2
NEEDLE 3
NEEDLE 4
VALVE 5
PIEZOMETER LOCATIONS
Distance downstream from line X-X.
ORIGINAL BODY
Distance out from ℄ of valve
ORIGINAL NEEDLE
NEEDLE 2
NEEDLE 3
NEEDLE 4
BODY AND NEEDLE 1
E. VALVE 5 (ANDERSON RANCH 8)
HOLLOW-JET VALVE STUDIES
DETAILS OF 12-INCH AIR MODELS

FIGURE 3



SECTION THRU VALVE

4 VANES 45° FROM VERT. ℄ 4 VANES ON VERT. & HORIZ. ℄

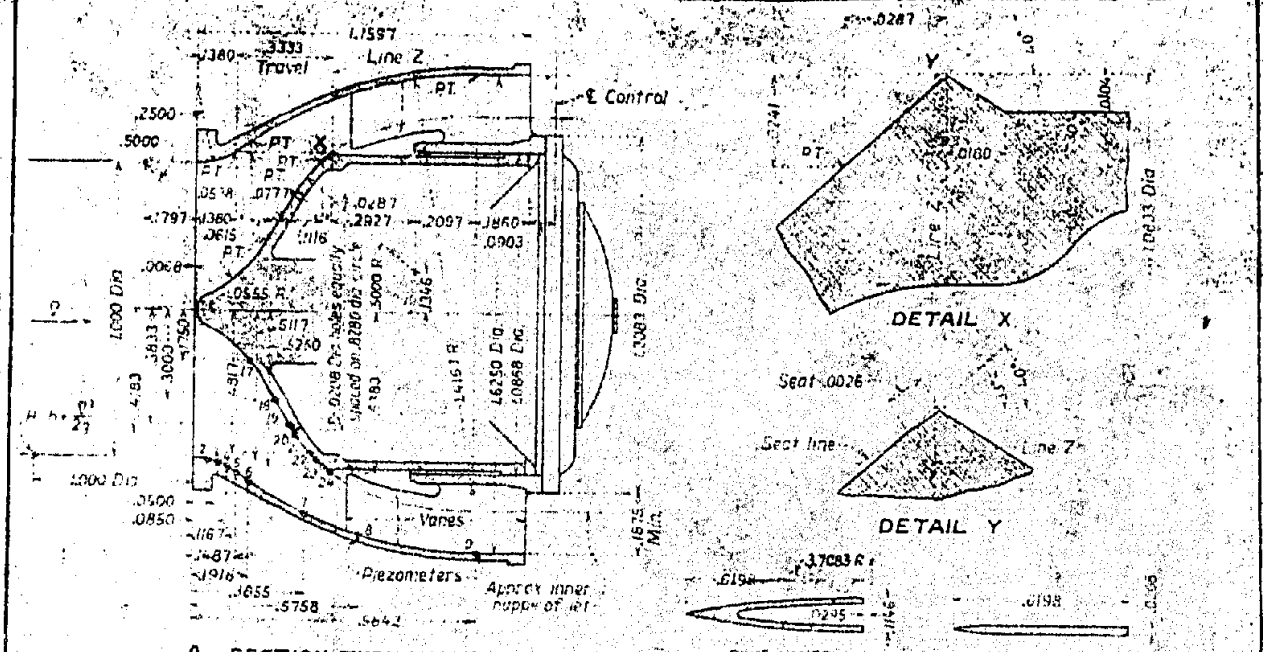
SECTION THRU VANES

HOLLOW-JET VALVE STUDIES

ANDERSON RANCH VALVE "D"

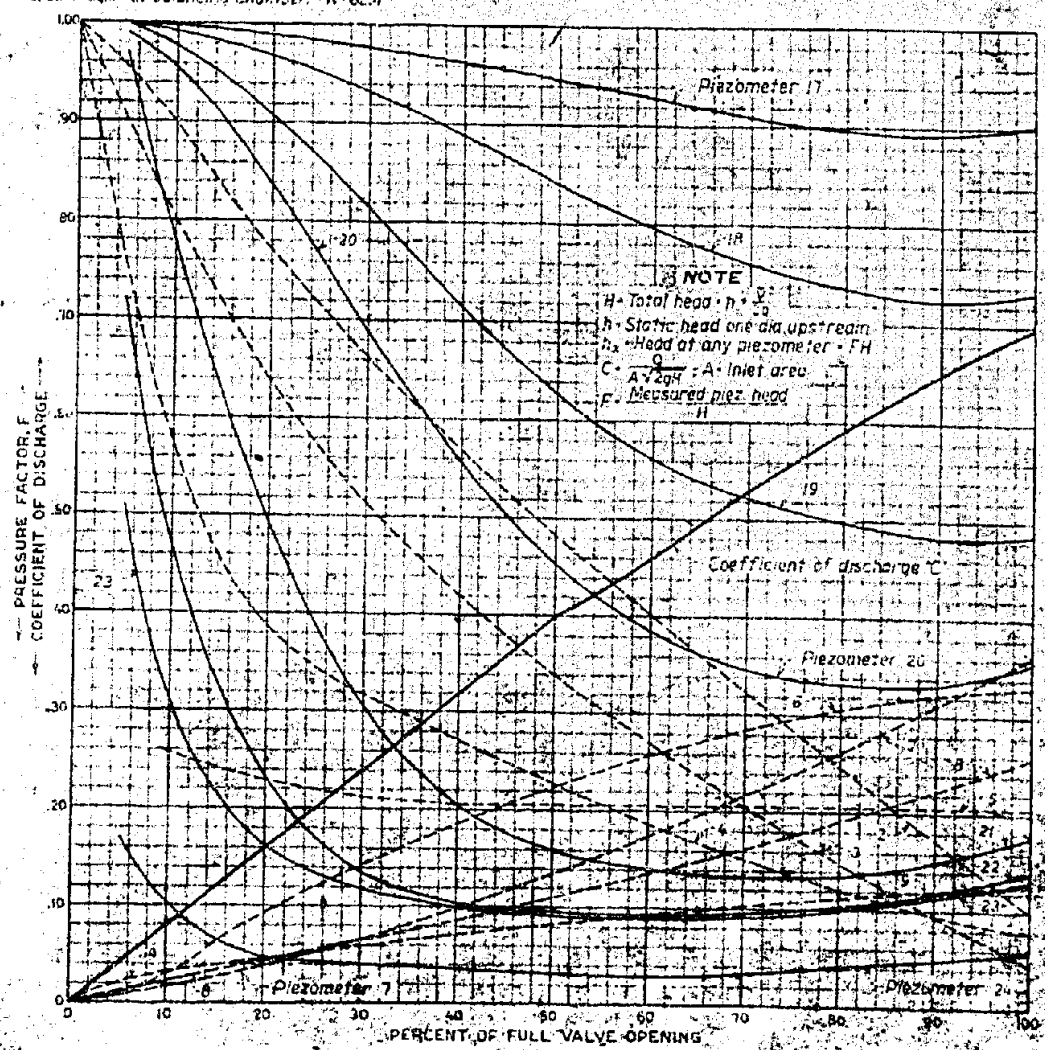
DETAILS OF 6-INCH HYDRAULIC MODEL

FIGURE 4



A. SECTION THRU VALVE

Note: All dimensions related to a unit inlet diameter.
Maximum unbalanced thrust in pounds 0.125 WH x effective area in sq. ft of balancing chamber. W=62.4

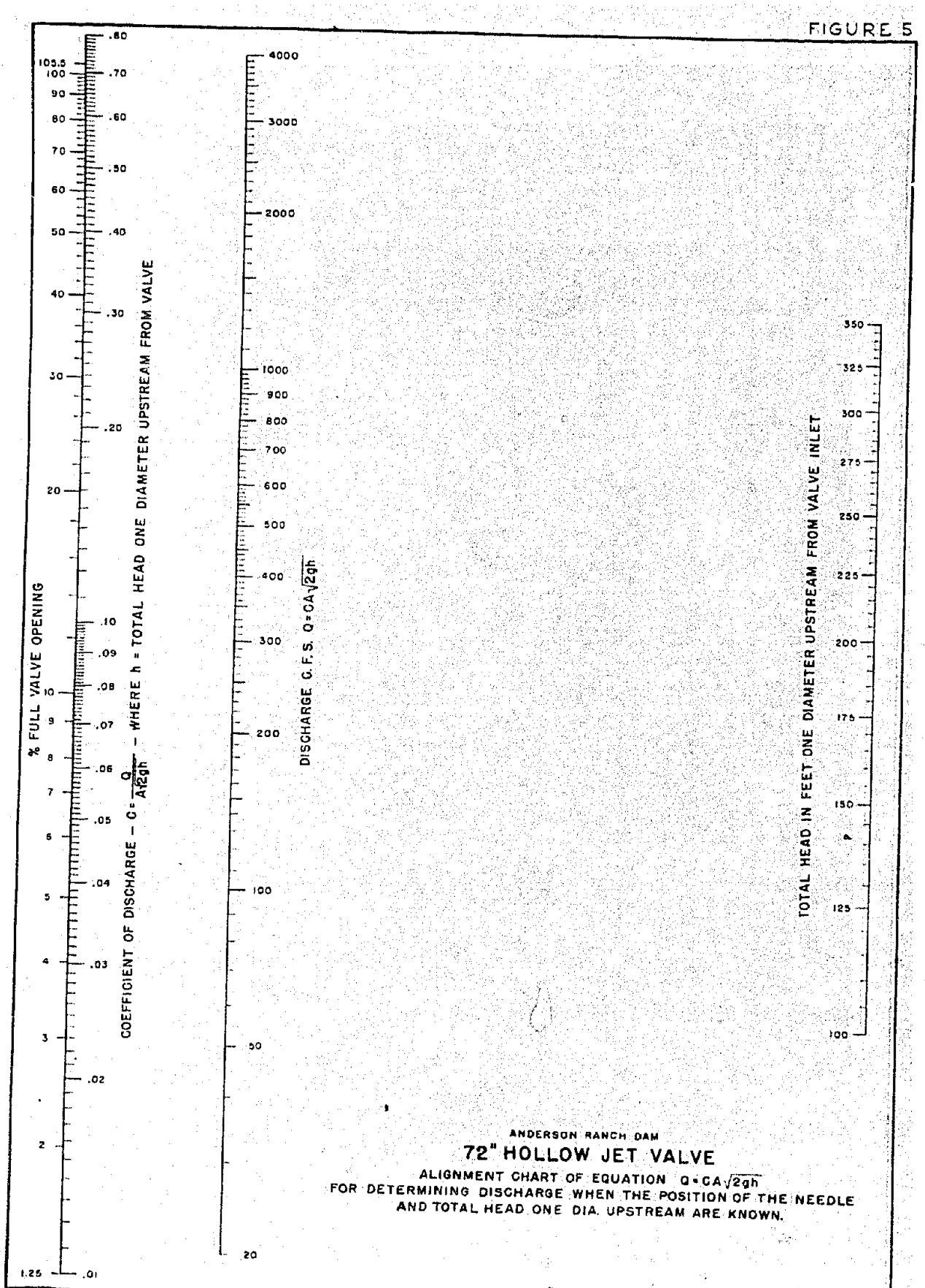


B. COEFFICIENT AND PRESSURE FACTOR CURVES
(DASHED CURVES FOR HEAD ON BODY - SOLID CURVES FOR NEEDLE)

HOLLOW-JET VALVE FOR ANDERSON RANCH DAM
PRESSURES AND CHARACTERISTICS DETERMINED FROM 6-INCH HYDRAULIC MODEL
FINAL DESIGN

REV. 7-30-45
1-19-1944

FIGURE 5



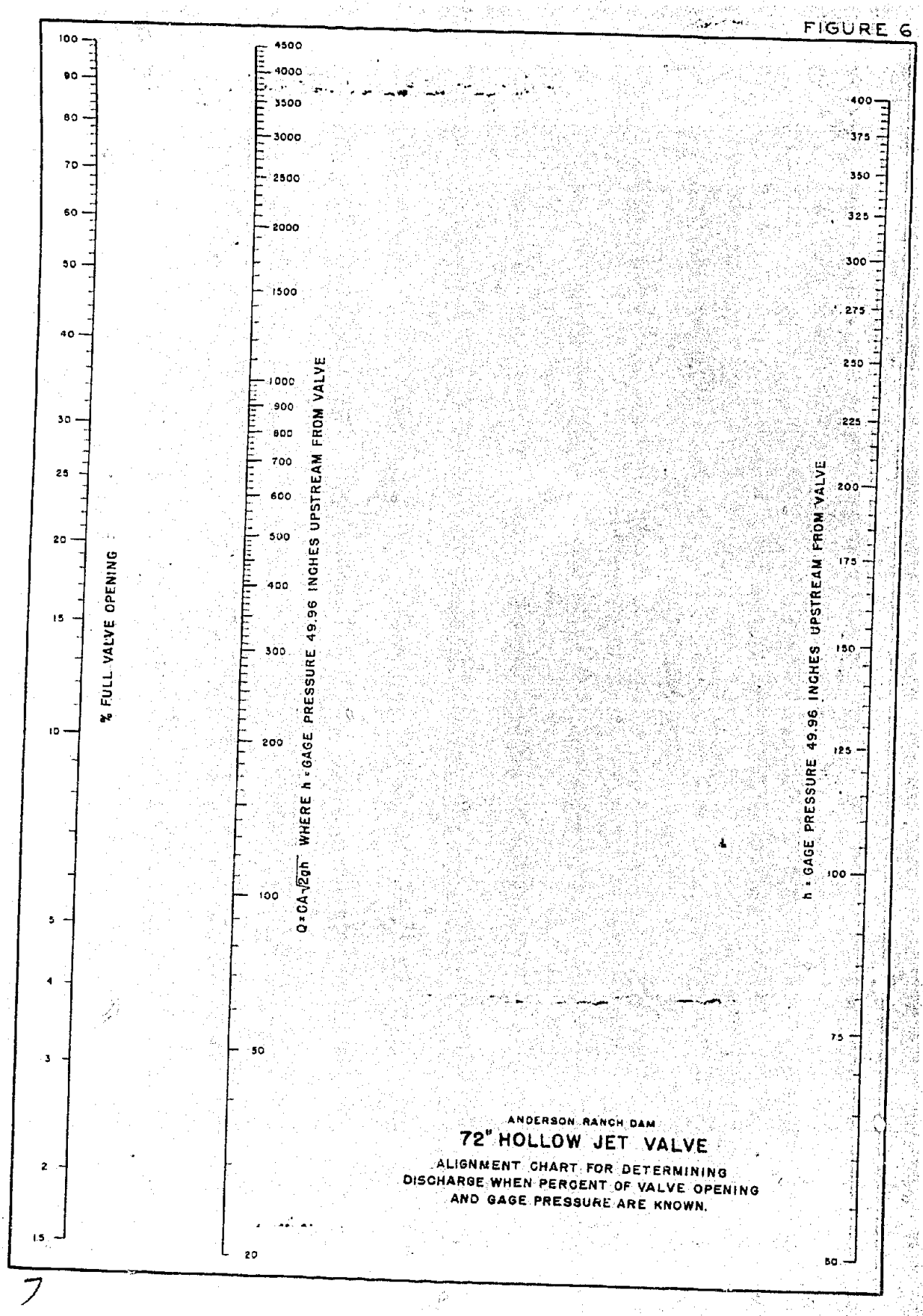
ANDERSON RANCH DAM

72" HOLLOW JET VALVE

ALIGNMENT CHART OF EQUATION $Q = CA\sqrt{2gh}$
FOR DETERMINING DISCHARGE WHEN THE POSITION OF THE NEEDLE
AND TOTAL HEAD ONE DIA. UPSTREAM ARE KNOWN.

5

FIGURE 6



ANDERSON RANCH DAM

72" HOLLOW JET VALVE

ALIGNMENT CHART FOR DETERMINING DISCHARGE WHEN PERCENT OF VALVE OPENING AND GAGE PRESSURE ARE KNOWN.

7

FIGURE 7

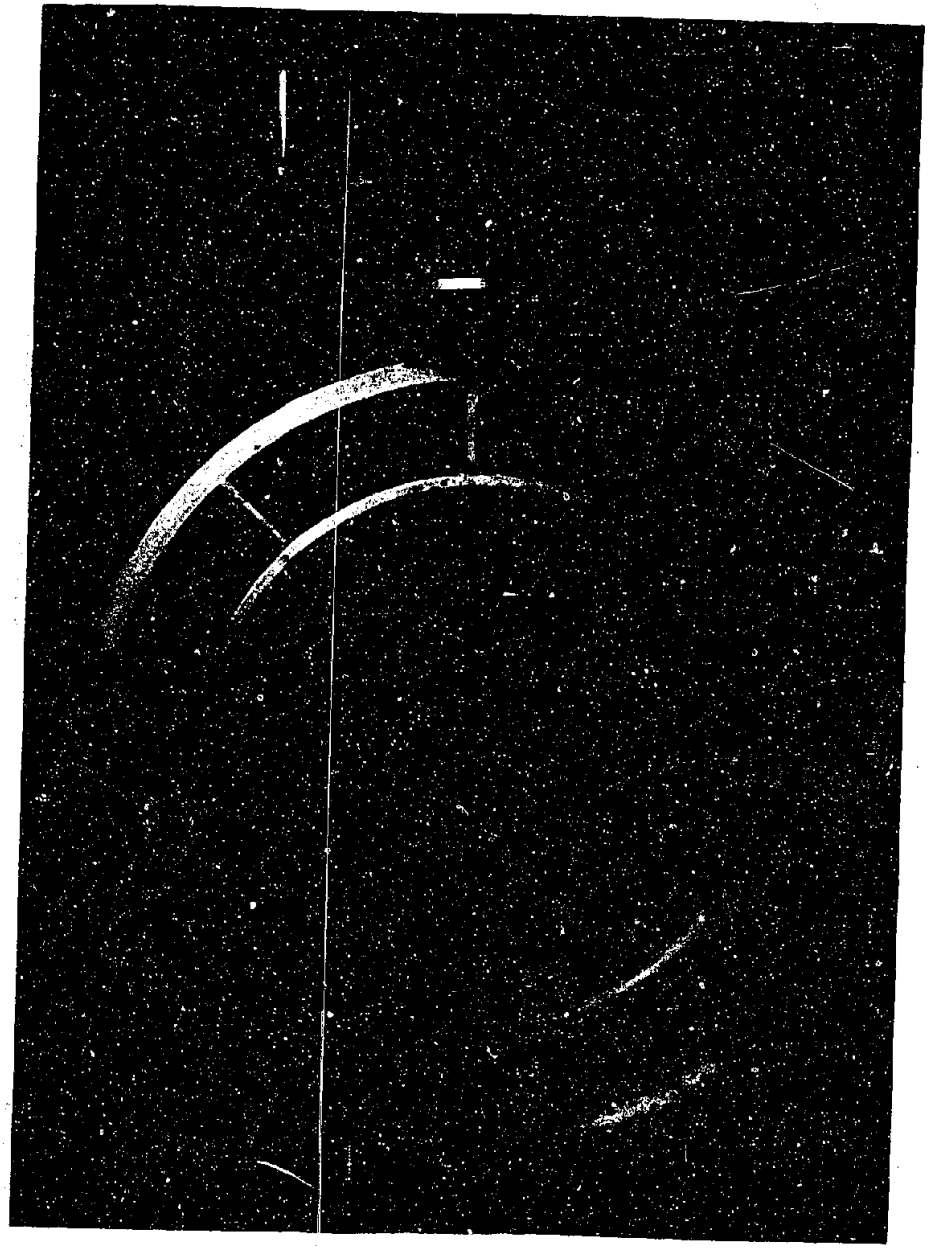
A. Valve fully open.

B. Valve 50 percent of full opening.

C. Valve 25 percent of full opening.

D. Valve 10 percent of full opening.

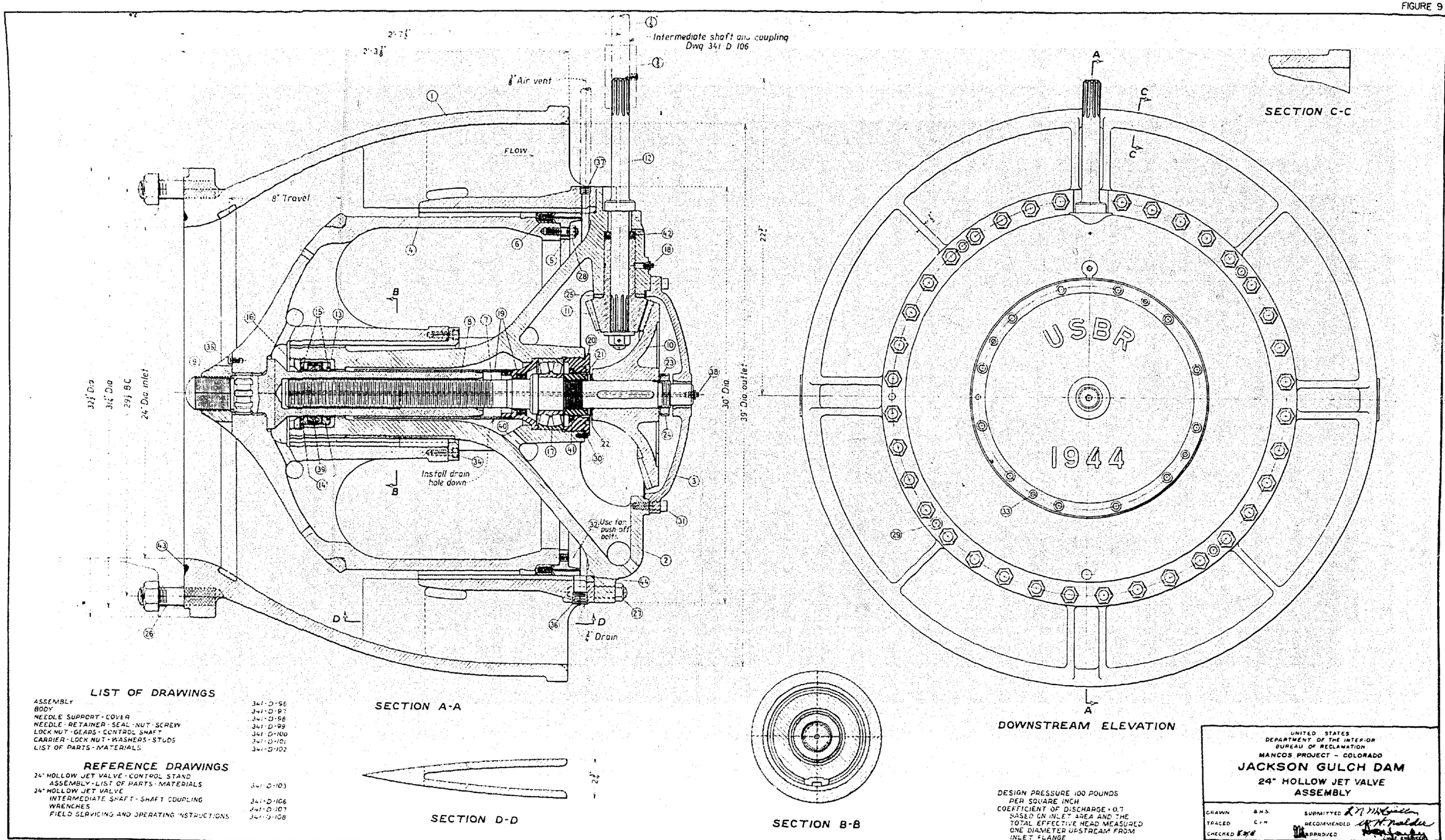
FIGURE 8



Downstream end of valve.

6-INCH HOLLOW-JET VALVE

FIGURE 9



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