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HYDRAULIC MODEL STUDIES FOR THE DESIGN OF VALVES FOR OUTLET WORKS

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HYDRAULIC MACHINERY LABORATORY

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Denver, Colorado
August, 1941

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DEPARTMENT OF THE INTERIOR
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HYDRAULIC MODEL STUDIES

FOR

THE DESIGN OF VALVES FOR OUTLET WORKS

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HYDRAULIC MODEL STUDIES
FOR THE DESIGN OF VALVES FOR OUTLET WORKS

I - SYNOPSIS

Hydraulic model studies were conducted to determine the shape of the water passage which is most effective in reducing cavitation and other objectionable characteristics of outlet valves.

Cavitation in valves occurs in the presence of negative pressure areas within the valve. Therefore, the elimination of cavitation depends upon the elimination of negative pressure areas. It has been established by these hydraulic model investigations that to insure positive pressures throughout the valve passage, three principles of design must be observed. These three principles are:

(a) The angle between the needle and the nozzle must not be diverging. Tolerable pressures are maintained when the profiles of the needle and the nozzle are parallel. However, a convergence of 1 to 3 degrees gives an increased factor of safety.

(b) The valve nozzle profile should have no point of inflection and should have a sharp edge. This keeps the minimum section at the outlet section of the valve and allows free access of air to the jet.

(c) The seating point on the needle must be on the cone portion. That is, the base diameter of the needle cone must be slightly larger than the outlet diameter of the nozzle.

II - INTRODUCTION

The first balanced valves, as used by the Bureau of Reclamation, were known as "Ensign" valves. These valves were designed for use as control valves to regulate the flow through sluice outlets in dams. They were installed on the upstream face of the dam at the entrance to the conduit. The valves were satisfactory from the standpoint of flow regulation, but they were inaccessible for maintenance. Because the control was located at the inlet of the conduit, the valve and the conduit suffered from cavitation. To obviate this condition, subsequent sluice outlet installations provided conduits through the dam with needle valves placed at the downstream ends where they could discharge freely into the air and allow the water

to dissipate its energy in some type of stilling pool. Thus the needle valve succeeded the "Ensign" valve.

The first needle valves used were relatively large for a given capacity, but with the evolution of the water passage design the size and weight of the valves were greatly reduced. This smaller valve, known as the "internal" type, is shown in figure 1. The next change in design came with the development of the "interior" type valve which is also shown in figure 1. In this valve the movable portion of the needle fits over the fixed portion rather than into it as in the case of the internal type valve. This development permitted a further reduction in the size of the valve for a given output and reduced obstructions to flow as well as abrupt changes in the curvature of the boundaries.

There are twelve 72-inch and twelve 84-inch internal type needle valves at Boulder Dam. The 72-inch valves are located in the tunnel plug, while the 84-inch valves are located in the canyon wall outlets. During the operation of these valves, especially those in the tunnel plug, severe pitting of the needles and nozzles has been encountered. The tunnel plug valves discharge into the 50-foot diameter tunnels and cause a maximum drop of about 3 inches of mercury in the air pressure inside the tunnel near the valves.

Two 84-inch diameter valves at Casper-Alcova Dam are of the interior type and have been operating under a maximum head of 162 feet. These valves also discharge into a tunnel and have shown evidence of pitting similar to the valves at Boulder Dam. As in the case of Boulder, there is an appreciable lowering of air pressure in the tunnel in the vicinity of the needle valves.

Because of these difficulties, a series of tests was conducted to determine the effects of changes in the shapes of the needle and the nozzle. The coefficient of discharge, pressure distribution in the valve, vibration characteristics, and appearance of the jet were observed and recorded for each alteration in design. Two models were made for this study: (1) a 5-inch interior type needle valve and (2) a 45-degree segment of a 10-inch internal type needle valve. It was reasoned that if the water passages could be designed to maintain positive pressures at all points on needle and nozzle, cavitation and its attendent pitting could be eliminated.

Since the completion of the experimental work contained in this report, the basis for designating valve size and coefficient of discharge has been changed from the valve outlet size to the nominal pipe size. Although this change in basis could be rather simply accomplished, the initial system is retained in this report because the experimental results were tabulated before the acceptance of the newer system.

III - FIVE-INCH MODEL INTERIOR-TYPE NEEDLE VALVE

1. General

The 5-inch model interior-type needle valve was originally intended to be used for studying the coefficients of discharge of the valve at various openings and heads. Later, however, the design of the valve was revised to permit changes in both the needle and the nozzle. This design is shown in figure 2 and in plate 1.

The original needle valve was first investigated for jet characteristics in 1936. It was found that low-pressure areas existed in the valve and that the jet was extremely rough for several partial openings. It was also found that the pressures were slightly increased and the jet was much smoother with a sharp-edged nozzle lip which had no point of inflection. There was, however, a decrease in discharge of slightly over 10 percent at full opening. At that time (1936) it was considered of more importance to maintain the greater discharge than to eliminate the low-pressure areas, so no further tests were made. The data from the 1936 tests are omitted since all of these tests were repeated in the investigation covered by this report.

Tests were run in the Denver laboratory with heads up to 70 feet and continued at Boulder Dam with hea ds up to 500 feet. In the laboratory the flow of water was measured by means of a Venturi meter and at Boulder Dam by means of a reducing pipe section on which pressures at the upstream and the downstream sections were used as a measure of discharge. The testing equipment and arrangement at Boulder Dam are shown in figure 3.

The data from both tests are included in this report.

2. Original 42-degree needle with original nozzle

This original 5-inch model was a 1:16.8 scale model of the Casper-Alcova valves. The angle on the needle cone was 42 degrees, and the corresponding angle of the nozzle was 36 degrees 22 minutes. The lip of the nozzle was rounded, as shown in figure 2.

The coefficient of discharge as used in this report is the ratio of the actual discharge of the valve to the theoretical discharge, neglecting frictional loss and contraction, that would pass under the same total head through an opening with an area equal to that of the nozzle outlet. It should be noted that the coefficient of discharge, figure 3a, increases up to about 40 feet head. This change in coefficient was observed in all cases where the nozzle had a rounded lip and is, no doubt, due to a shift in the location of the point at

which the boundary layer separates from the nozzle lip. This shift in the separation point is known to occur when the boundary layer changes from laminar to turbulent flow at a rather definite value of Reynolds' number, depending to some extent on the initial turbulence in the stream. The shift is in a downstream direction and results in additional recovery of velocity head which raises the coefficient of discharge. Negative pressures are set up by this recovery of head, and, when they reach absolute zero, the coefficient begins to decrease with further increase in head.

At partial openings of the valve the water passage formed by the rounded nozzle lip and the needle is diverging, and reduced pressures are set up at the section of minimum area. The pressures on the needle for valve openings of less than 60 percent are negative, as shown in figure 4. The valves at Boulder Dam and Casper-Alcova Dam show definite effects of cavitation in the regions indicated as low-pressure areas in the model.

The jet from this valve is never smooth and clear. The reason for this is the thickening of the boundary layer caused by the rounded lip of the nozzle. This thick layer tends to fill with air, which causes the jet to roughen.

At approximately 35 percent valve opening there is a definite change in the force required to operate the needle and at this position the jet is extremely rough. This change is clearly indicated in figure 5, which was taken from a report on field tests of the 84-inch valves at Boulder Dam.

Photographs shown on plates 2 and 3 were taken in the laboratory. It is evident that the roughness of the jet increases with the increase in head at 50 percent valve opening. "P. H." on the plate titles indicates pressure head (net head) in feet of water at the inlet flange of the valve. "Q" is the discharge in cubic feet per second. All test results on the 5-inch valve are given in actual model test results.

3. 42-degree needle with sharp-edged nozzle

The nozzle of this valve has no reverse curvature in the profile and has a sharp edge. In this report this type of nozzle is called the sharp-edged nozzle. Here again the coefficient of discharge is based on the area of a 5-inch diameter opening, although the diameter of the nozzle is actually only 4.86 inches. The reason for this substitution is that it serves to show the effect of such a change in valves already installed. For design purposes, the actual area of the nozzle should be used, and in that case the coefficient of discharge should be multiplied by 1.06.

Figure 6 shows the coefficient of discharge of this valve for various heads. It is noted that the coefficient is substantially constant throughout the entire range in heads. The jet is much smoother than the jet of the original model, as shown in plates 4 and 5.

The pressure curves of figure 7 indicate a positive pressure on the needle at all valve openings above 40 percent of full.

4. 30-degree needle with round-edged nozzle

The 30-degree cone needle with the alternate curved tip was next tested with the round-edged nozzle. This valve is shown in figure 2.

The coefficient curve, shown on figure 7a, has the same general characteristics as that of the original valve. The appearance of the jet was in general about the same as that of the original valve. The jet appeared to be roughest at a bout 50 percent valve opening. As the angle between the nozzle and the needle was converging, there was no critical point at which a noticeable change in force was required to operate the valve. The pressures on this needle were not recorded. The valve is shown in operation on plates 6 and 7.

5. 30-degree needle with sharp-edged nozzle

This valve consists of the needle used in the previous test and the sharp-edged nozzle. Like the sharp-edged nozzle with the 42 - degree needle, the coefficient-head curve for full valve opening is practically a straight line. This is especially true of the portion of the test run in the Denver laboratory. Even with the uncertainty of the discharge measurements at Boulder Dam, the average coefficient falls fairly close to the straight line, figure 7b. This valve has the lowest coefficient of discharge of any combination tested because a greater proportion of the nozzle opening is occupied by the 30-degree needle than by the needles with steeper angles.

The jet is quite smooth at all openings and under the entire range of heads. This is shown on plates 8 and 9. Plate 10 shows the valve in operation with the cone-type tip, and with the tip removed. The cone-type tip gives practically as smooth a jet as the tip having a curve. The jet is rough when the needle tip is removed for valve openings under 60 percent of full open.

Within the accuracy of the test, the coefficient of discharge is the same for all three needle tip details.

No pressures were recorded on this needle.

6. 36-degree, 22-minute needle with sharp-edged nozzle

A cone-type needle of 36-degree, 22-minute angle, equal to the angle of the nozzle, was tested with the sharp-edged nozzle. The jets, shown on plates 11 and 12, were quite smooth and were transparent near the nozzle for all valve openings and full range of head.

The coefficient curve is quite constant and is about 6 percent higher than for the 30-degree needle. The coefficients and the original data are shown on figure 7c.

Pressures were recorded on the needle at points indicated on figure 8. Positive pressures were maintained on the needle at all valve openings and under all available heads. From this test it also may be concluded that the 30-degree needle would give even higher pressures at corresponding points. It is true of these two needles that the pressure on them is directly proportional to the net head on the valve.

7. Closed-type tube with round-edged nozzle

There were two proposed methods of preventing the cavitation in the needle valves; first, the redesign of the water passages to insure positive pressures throughout the valve, and second, the elimination of the area which is subject to pitting by cutting the needle off upstream from it. The design of the closed-type tube valve was based on the second method. The end of the tube was closed so the tube could be operated hydraulically. The details of this tube valve are shown on figure 2.

This tube valve was tested with the round-edged nozzle. The results, as shown on figure 8a indicate the same general characteristics as those of the original needle valve operating at full valve opening. The coefficient of discharge for this valve is slightly lower than that of the original valve, indicating that the "water needle" offers slightly more resistance to flow than did the 42-degree needle.

The jet from this valve was quite rough at all valve openings and was extremely rough at openings below 20 percent, as shown on plates 13 and 14. No pressures were determined on the tube, but it was found that a definite positive pressure existed on the center of the jet near the tube after a solid jet had been formed. The solid jet formed at about 20 percent opening.

Tests were run on this tube with the sharp-edged nozzle at Boulder Dam. It was found that the jet was rough with this nozzle

also and that the vibration was greater than would be accepted in practical design.

8. Open-type tube with original nozzle

After the closed-type tube was observed in operation, the design of tube was altered with a view to correcting the roughness of the jet and vibration. This revised design of the tube is shown on figure 9. As it is an open tube, it must be operated mechanically. In such a design the "water needle" does not upset the jet as much as it did with the closed-type tube.

Although the jet of this valve is smoother than that of the closed-type tube valve, it is rougher than the jets from the valves using a needle, plates 15 and 16. The coefficient of discharge and also the characteristics of the coefficient curve are very similar to both the closed-type tube and the original needle valves, figure 9a.

No pressures on the tube were recorded.

9. Open-type tube with sharp-edged nozzle

The use of this tube with the sharp-edged nozzle drops the coefficient of discharge nearly 10 percent. The coefficient remains more nearly constant as shown on figure 9 b.

In general, the jet is greatly improved with the sharp-edged nozzle. At small valve openings (below 20 percent) the jet is quite rough, but at approximately that opening the jet becomes solid and is relatively smooth, as shown on plates 17 and 18.

A third tube, the torus tube shown on figure 10, was tried in an effort to maintain a smooth jet at all gate openings. This valve is impracticable because of the featheredge. Because of its shape, the tube would be likely to pit much the same as the needles did.

The tests indicated that the torus tube gave only slightly better performance than the open-type tube. From this test it appears that very little can be done to produce a smooth jet at the lower valve openings with the tube principle.

10. The proposed valve design

Based upon the observations made during the tests described in the foregoing paragraphs, a new design of nozzle and needle was made. The angle of the needle cone was 37 degrees and that of the nozzle was 40 degrees, giving a 3-degree convergence. The nozzle

opening was made 5 inches in diameter. This valve design is shown on figure 11.

This valve produced a very smooth jet at all openings under the full range of head, plates 19 and 20. A positive pressure was observed on the needle for all operating conditions, as shown on figure 12.

The coefficient of discharge remained practically steady at around 65 percent, as shown on figure 11a.

11. Vibration tests

Comparative vibration tests were run on several types of valves at Boulder Dam. The vibration meter was set on the conduit upstream from the valve. The only changes made were the interchanging of nozzles, or needles, or both. Therefore any difference in the intensity of vibration was due strictly to these changes.

The magnitude of the vibration was not determined; therefore, the results are strictly comparative. The five valves tested were: (1) the original valve, (2) the 42-degree needle with the sharp-edged nozzle, (3) the 36-degree, 22 -minute needle with the sharp-edged nozzle, (4) the open tube with the sharp-edged nozzle, and (5) the proposed new valve design.

Figures 13 and 16a, inclusive, show the relative amount of vibration inherent in each of the valves for various valve openings under approximately 400-foot head.

A comparison of these typical vibration-meter recordings shows that the intensity of vibration of the original valve is much greater than that of the other four valves when 50 percent of fully open or greater.

Regarding the valve consisting of the 42-degree needle with the sharp-edged orifice, it developed that conversely to the original valve the intensity of vibration was much less at the larger valve openings and greater at the small openings.

The intensity of vibration of the valve, using the 36-degree, 22-minute needle and the sharp-edged orifice, was much less at all valve openings than in the case of the first two valves. In this valve the water passage boundaries were parallel. In contrast with the diverging water passage boundaries of the first two valves, the shape of this valve produces much better vibration characteristics.

The tube valve vibration was not as serious as a visual inspection of the performance of the valve might suggest. The vibration was considerably greater than the valve with uniform water passage but was decidedly less than the worse operating ranges of the valves with the divergent boundaries.

The vibration of the proposed new design of valve was less than any of the other four valves tested. This holds for the full range of valve openings. The intensity of vibration was greatest at full opening, but this intensity was no greater than that of the best of the other valves tested. For the smaller regulating openings the vibration diminished suddenly to values much less than those found in the other valves.

12. Wear tests

The various combinations of needles and nozzles were tested, one at a time, at Boulder Dam at particular valve openings under full head. The valve was continued in operation until some signs of pitting were observed. It was rather difficult to evaluate the results of all of these tests; however, two or three offer very good comparisons.

The 42-degree needle with the sharp-edged nozzle was operated 13 days at 40 percent open. At the end of the test the needle showed definite effects of cavitation which could be easily detected with naked eye.

The 36-degree, 22-minute needle was put into service in combination with the sharp-edged nozzle. This valve operated at 20 percent of full opening for 8 days. At the end of this test the effects of cavitation on the needle could be detected by means of a 20 D. magnifying lens, but not with the naked eye. This needle was returned to the Denver office for examination and was not tested again.

The 42-degree needle was refinished and put under test with the original nozzle. This is the scale model of the Casper-Alcova valve. The valve was set at 40 percent of full opening and was operated six days. The effect of cavitation was very severe, as shown on plate 20a. For purposes of comparison, photographs of the Casper-Alcova prototype valves are shown on plate 20b. These photographs of the 84-inch valves were taken in 1938.

The valve of proposed new design was run for a period of 84 days at 20 percent of maximum opening. A close inspection of the needle revealed no effects of cavitation. This is shown on plate 20a. That there was no cavitation is borne out by the fact that the needle discolored while in service. There was, however, some

pitting in the nozzle. After a careful study of the nozzle it was concluded that the pitting is due to imperfections in that portion of the casting rather than to cavitation.

IV - 45-DEGREE SEGMENT OF INTERNAL-TYPE NEEDLE VALVE

13. General

The 45-degree segment model was constructed to a scale of 1:7.2, the 72-inch Boulder Dam tunnel plug valves being the prototype. The 45-degree segment with transparent pyralin sides and rib allowed visual inspection of the flow through the entire length of valve. The model was large enough for a number of piezometers, both in the needle and in the nozzle. The model was constructed in such a manner that an alternate needle and nozzle could be inserted in place of the originals. Figure 17 shows the needle valve model and the alternate 30-degree needle and sharp-edged nozzle. Figures 18 and 19 give the location of all of the piezometers.

All pressures in this series of tests were stepped up to prototype values. The prototype operating heads were 50, 100, and 150 feet. Pressures for various valve openings and heads are listed on the chart on figure 20.

14. 42-degree needle with round-edged nozzle, original design

A few of the pressures observed on the model when converted to those of the prototype are lower than 32 feet of water. As such pressures are impossible, all values in that category may be considered as perfect vacuums. Under such conditions, of course, similitude between the model and the prototype no longer holds.

The data on figure 20 is plotted on figures 21 and 22. The recorded pressures on the needle varied so much that no attempt was made to draw smooth curves. Also, at a few needle positions, pressure readings were unintentionally omitted at some piezometers. In plotting the data the pressure curve was not interpolated over such points. The low-pressure areas in the model on both the needle and the nozzle are located approximately the same as the areas being affected by cavitation in the Boulder Dam needle valves.

Figure 23 shows the averages of pressures recorded on the nozzles of two 72-inch needle valves in the tunnel plugs at Boulder Dam. There is a decided similarity between the model and the prototype test results. The prototype tests were run with a maximum head of 520 feet. The 72-inch valves discharge into a 50-foot diameter tunnel. The pressure in the tunnel is less than atmospheric

by as much as three inches of mercury when the valves are in service.

15. 42-degree needle with sharp-edged nozzle

The pressures on the needle and the nozzle of this valve are shown on figures 24 and 25. The outlet radius of this valve is 4.86 inches. There were but very slight negative pressures on the needle and no negative pressures on the nozzle. The jet was much smoother than that of the original valve with round-edged nozzle. In general, the results of the tests on the segmental model follow very closely the data found on the 5-inch model. However, the 5-inch model produced negative pressures at openings of less than 40 percent of fully open. In the tests of both valves it was found that the pressures were more consistent when the sharp-edged nozzle was used.

A series of tests was conducted on two of the Boulder 72-inch valves with sharp-edged nozzles. The outlet diameter of the nozzles was full 72 inches, unlike the reduced outlet diameter of the models tested. The data are plotted on figure 26. The segmental model and the prototype do not agree at the lower valve openings, but the prototype results agree with those predicted from the 5-inch model data.

16. The 30-degree needle with each of two nozzles

A 30-degree needle was used with each of the two nozzles. When it was used with the original nozzle the negative pressures on the needle were practically eliminated. However, negative pressures still persisted on the nozzle. This is shown on figures 27 and 28.

When the 30-degree needle was used with the sharp-edged nozzle, the pressure conditions were definitely improved. The pressures on the needle and the nozzle were found to be positive throughout for all valve openings and under all heads. This is shown on figures 29 and 30.

The 30-degree needle and the sharp-edged nozzle produced the smoothest and clearest jet in the series of tests on the segmental valve, but the coefficient of discharge of this valve was lower than that of the other valves tested.

17. Closed-type tube with original model

The needle of the original valve was removed, converting the valve into a closed-type tube valve. This valve is shown in plates 21 and 22. Air was forced into the water through piezometer holes in order that stream lines would show in the photographs. At 10

percent of full valve opening the air tended to gather in the valve body causing a change in suction at that point; so the air supply was shut off and the photograph was taken of a clear stream. As seen in the photographs, the air breaks into the jet after the water leaves the control section. The jet appeared quite rough at the smaller valve openings and there was a noticeable vibration at 20 percent of full opening, or less.

No pressures were recorded on this valve.

V - GENERAL DISCUSSION AND CONCLUSIONS

The 5-inch needle valves and tube valves were calibrated fully open. The flow was measured by means of a 12-inch Venturi meter at the Denver laboratory and by means of a reducing pipe section at Boulder Dam. Pressure measurements were made by means of mercury manometers in the laboratory and by means of pressure or vacuum gages at the dam. The margin of error is probably well within three to four percent, while the accuracy for comparative purposes would be much closer.

The original type nozzle produces an expanding water passage which tends to lower the velocity and effects a regain in velocity head. This gives a higher discharge but creates low-pressure areas in the valve. The low-pressure areas are accompanied by cavitation. The variable regain of velocity head caused by the rounded nozzle accounts for the fact that the head-coefficient curve is not a straight line for valves using the original nozzle. The difference in discharge between the rounded nozzle and the sharp-edged nozzle is due to the smaller amount of contraction in the case of the rounded nozzle. The smaller contraction, which results in a higher discharge coefficient, is accompanied by a lowering of pressure within the valve body.

Because of the change in discharge coefficient it was necessary to build a larger valve to pass a given discharge when the sharp-edged nozzle was used. The valve shown in figure 31 was designed to give the same discharge as the valve of the original design and to retain the desirable features of the proposed valve shown in figure 11. This valve has been tested also by the Hydraulic Structures laboratory and has been found to perform according to predictions.

The areas through the Boulder Dam (original internal type) valve and through the valve shown in figure 31 have been reduced to equivalent nozzle diameters and are shown on figure 32. There is a different throat section in the original type (Boulder) valve for all valve openings. This condition has been eliminated in the re-

vised design. Based upon this illustration and the results of the model tests, it is believed that the revised design, figure 31, of needle valve will produce positive pressures at all openings.

From this series of tests no definite conclusions can be drawn as to the possibility of development of the tube valve. It was noted that the tube valve had slightly less vibration than the valve of the original design, especially at openings from 30 to 70 percent. The tube valve caused much more vibration than the valve of the newer design. At the smaller openings the spray and irregularity of flow was particularly undesirable. No tests were run on the mechanics of operation or sealing of this type of valve.

The segmental model contained one rib which was large enough to accommodate a relatively large number of piezometers. Pressures observed on and around the rib indicate that the ribs would not cause cavitation if there were a positive pressure in the valve body.

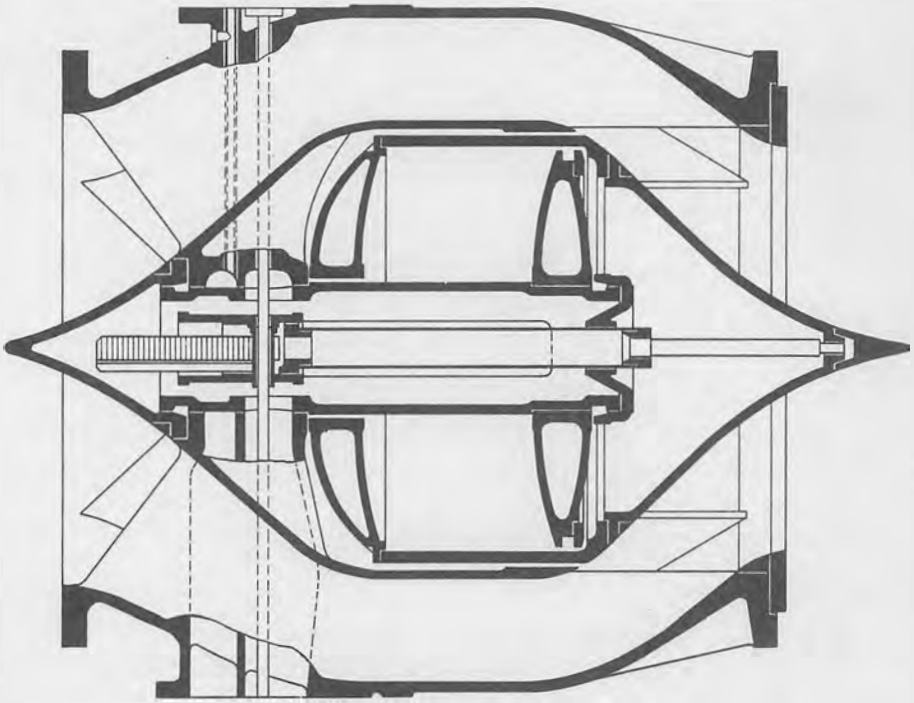
A needle valve should be designed in such a manner that positive pressures are maintained in the valve at all openings. It has been established that in order to insure positive pressures on both the needle and the nozzle, three design principles must be observed. The three principles are:

(a) The angle between the needle and the nozzle must not be divergent in the direction of flow. If the needle and the nozzle profiles are parallel, the pressures are maintained. However, a convergence of from one to three degrees will give an increased factor of safety.

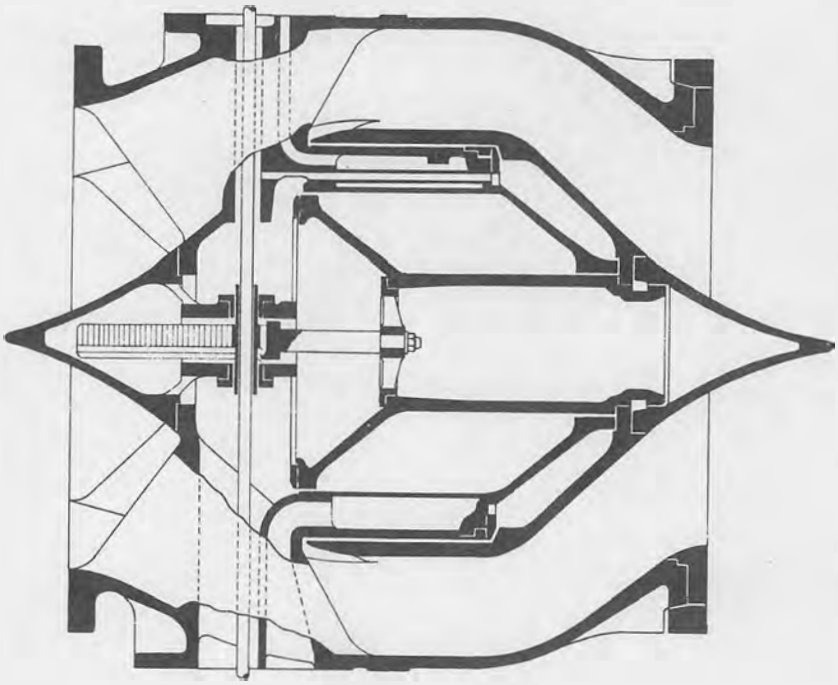
(b) The valve nozzle should have no point of inflection and should have a sharp edge. This keeps the minimum section at the outlet edge of the valve nozzle and allows free access of air to the jet.

(c) The seating point of the needle must be on the cone portion; that is, the base diameter of the needle cone must be slightly larger than the outlet diameter of the nozzle.

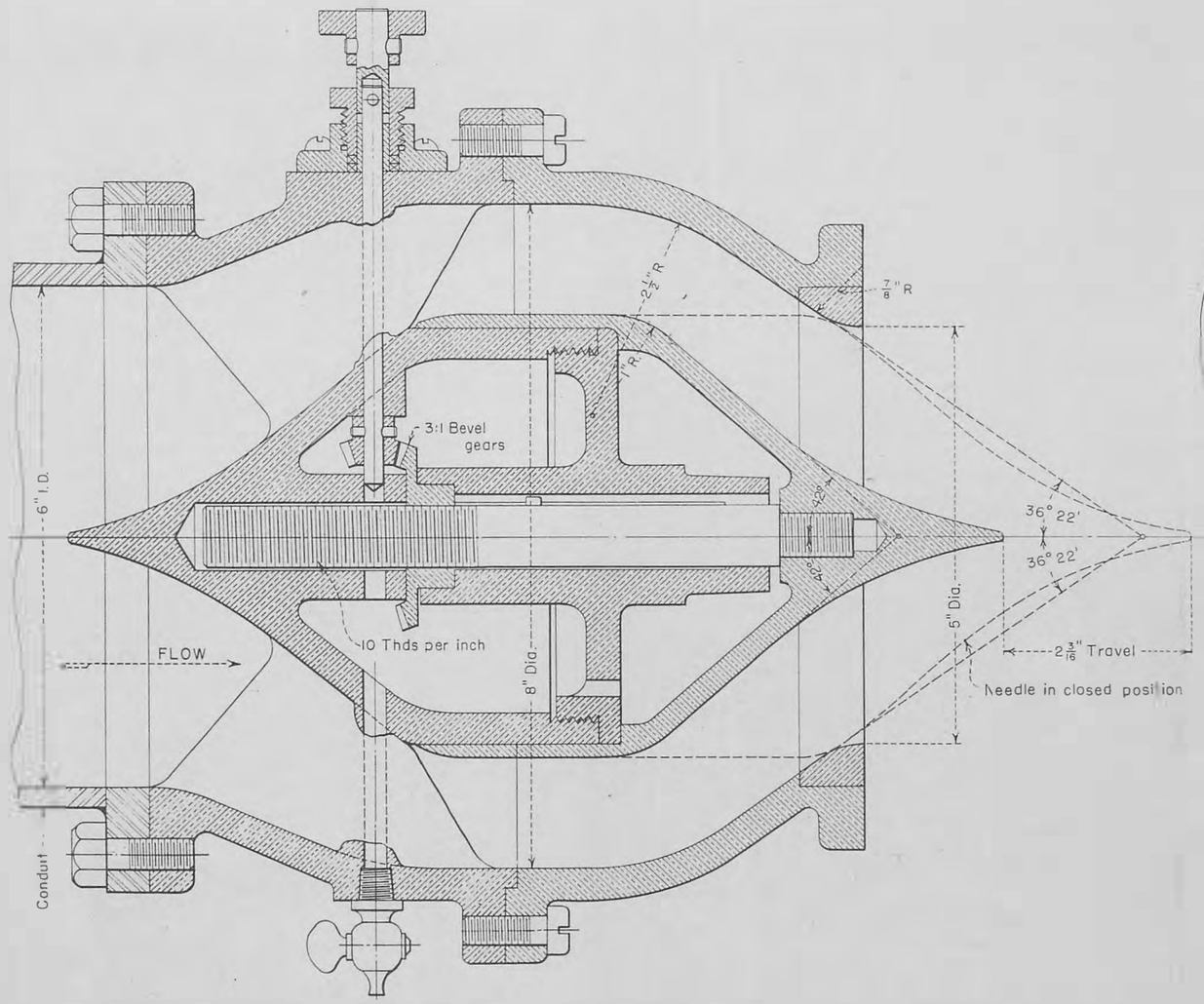
FIGURE 1



INTERNAL DIFFERENTIAL NEEDLE VALVE

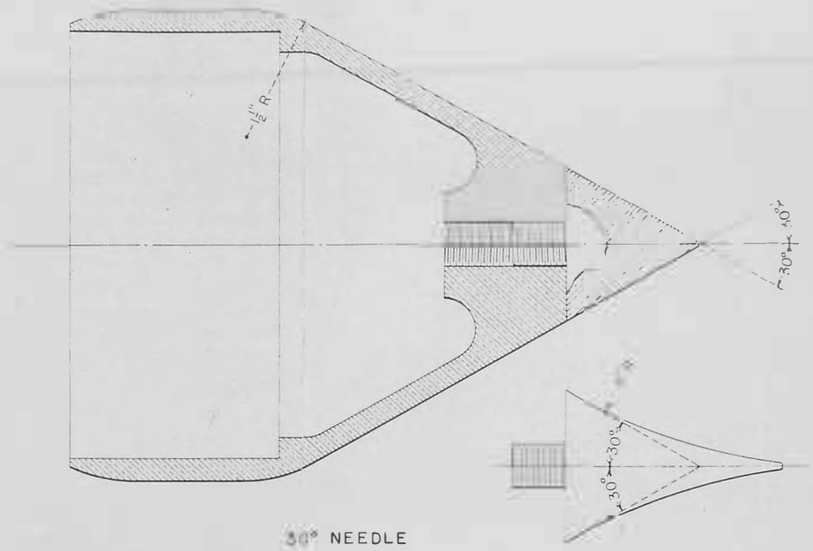


INTERIOR DIFFERENTIAL NEEDLE VALVE



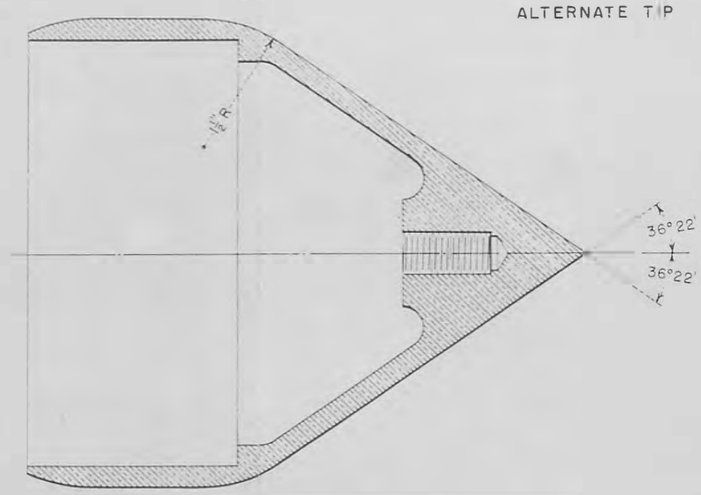
ROUND EDGED NOZZLE AND ORIGINAL 42° NEEDLE

ALTERNATE NOZZLE
SHARP EDGED

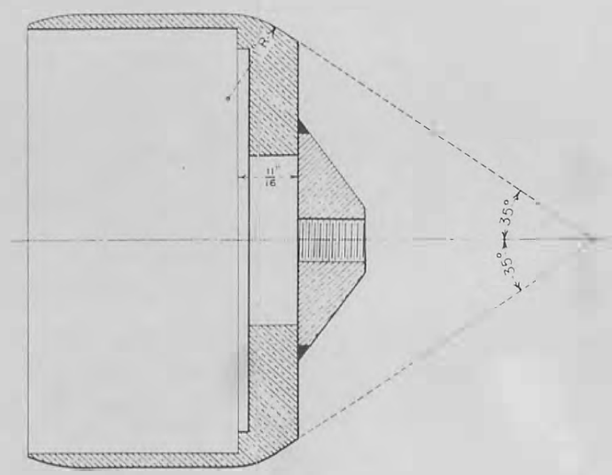


30° NEEDLE

ALTERNATE TIP



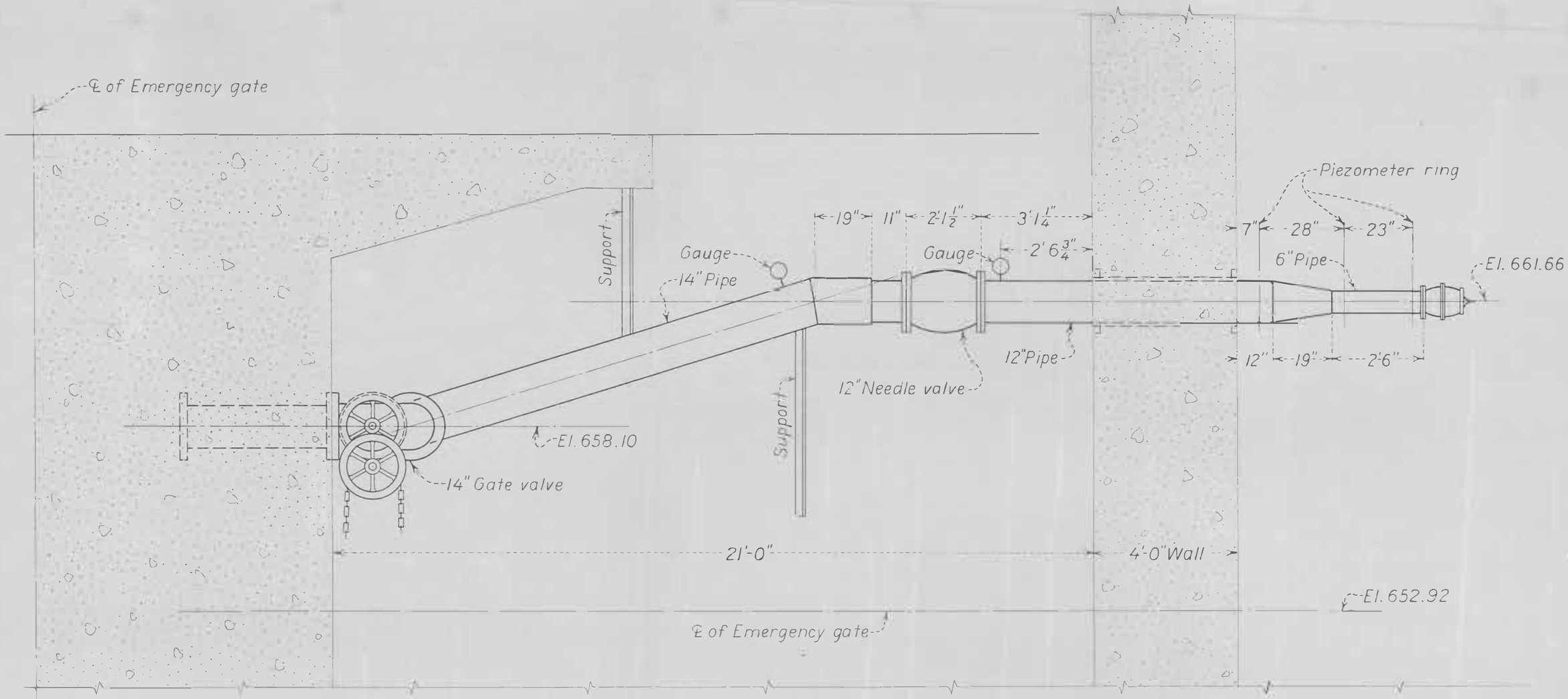
36° 22 NEEDLE



CLOSED TYPE TUBE

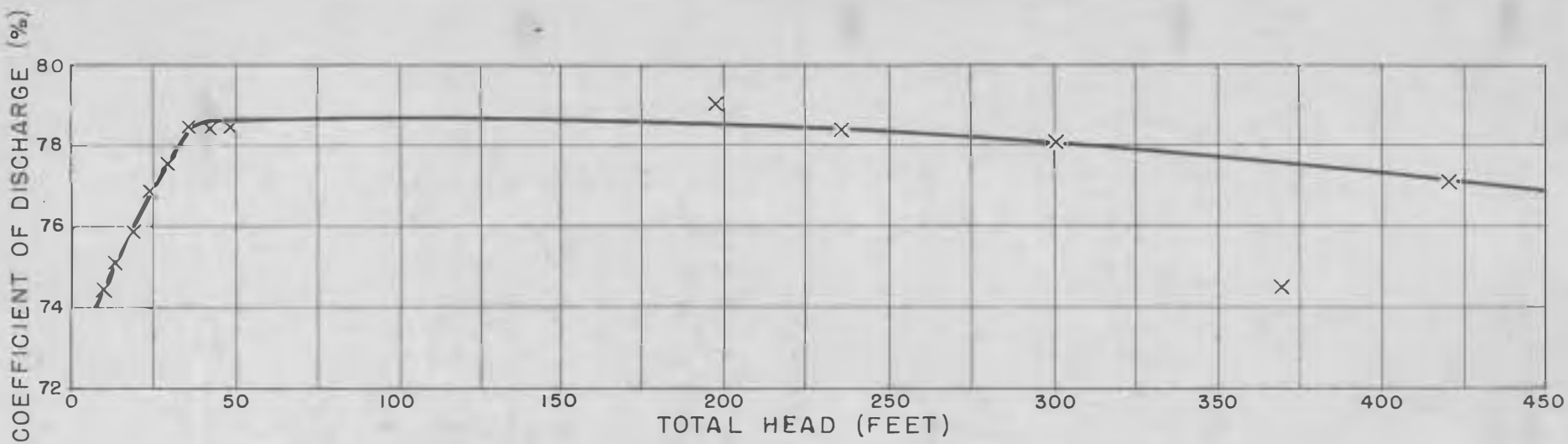
NEEDLE VALVE TESTS
5" NEEDLE VALVE, ALTERNATE NEEDLES
AND CLOSED TYPE TUBE

N.N. 18-38



5" NEEDLE VALVE

TEST SET UP AT BOULDER DAM



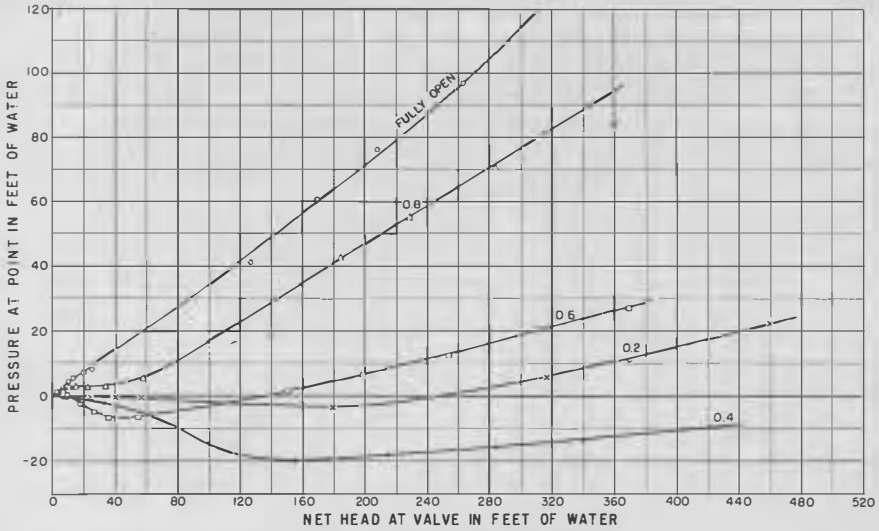
	NET HEAD IN FEET	TOTAL HEAD IN FEET	Q C.F.S.	COEFFICIENT OF DISCHARGE (%)	
TESTS IN DENVER LABORATORY	8.20	11.20	2.73	74.4	.517
	10.30	14.10	3.08	75.1	.522
	14.20	19.70	3.68	75.9	.527
	17.30	24.40	4.16	76.9	.534
	21.00	29.60	4.62	77.5	.538
	25.80	36.70	5.20	78.5	[illegible]
	30.00	42.60	5.60	78.5	.545
	33.70	48.00	5.95	78.5	.545
TESTS AT BOULDER DAM	141.00	197.80	12.14	79.0	.549
	169.80	236.80	13.19	78.4	[illegible]
	217.20	301.70	14.80	78.1	.542
	277.00	370.50	15.66	74.5	.517
	323.50	446.00	17.81	77.1	[illegible]

.531 ± 0.012

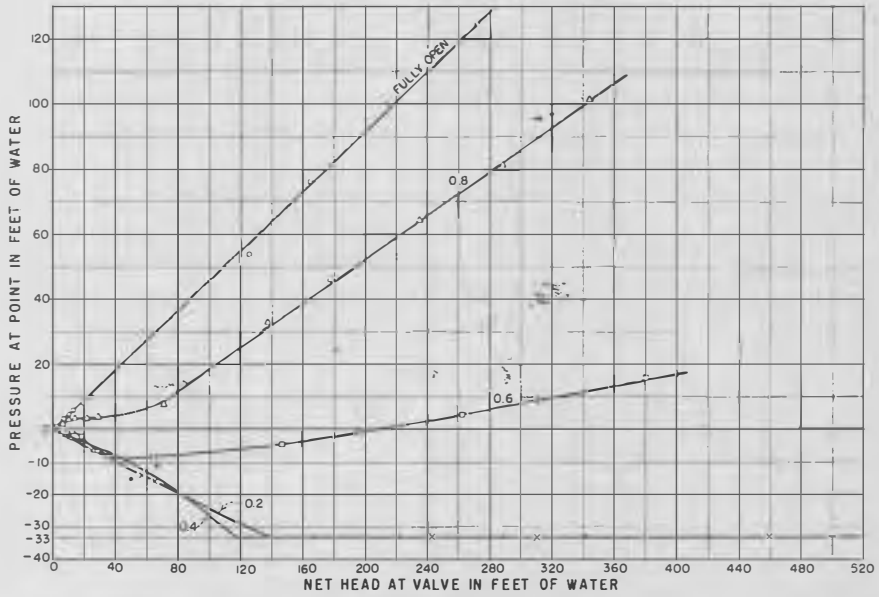
42-DEGREE NEEDLE WITH ROUND-EDGED NOZZLE

VALVE 100% OPEN

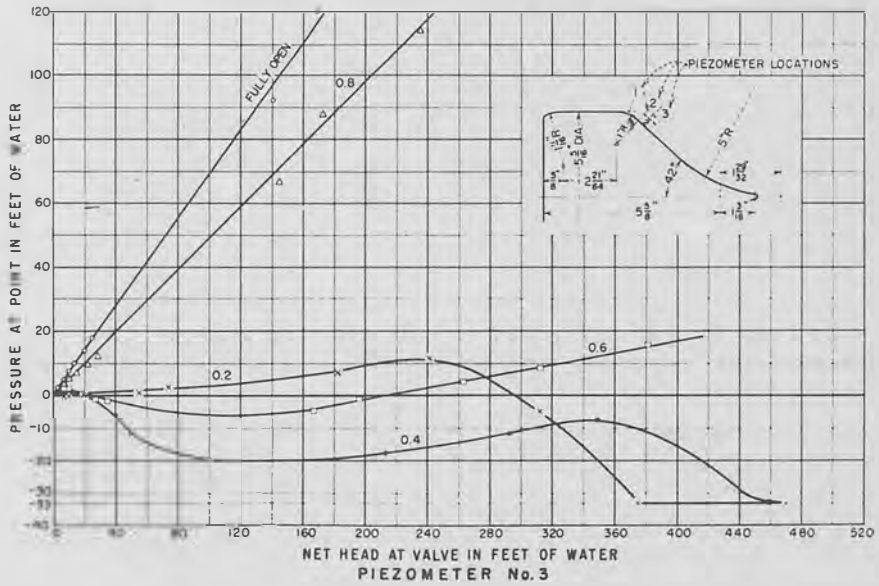
FIGURE 3a



PIEZOMETER No. 1



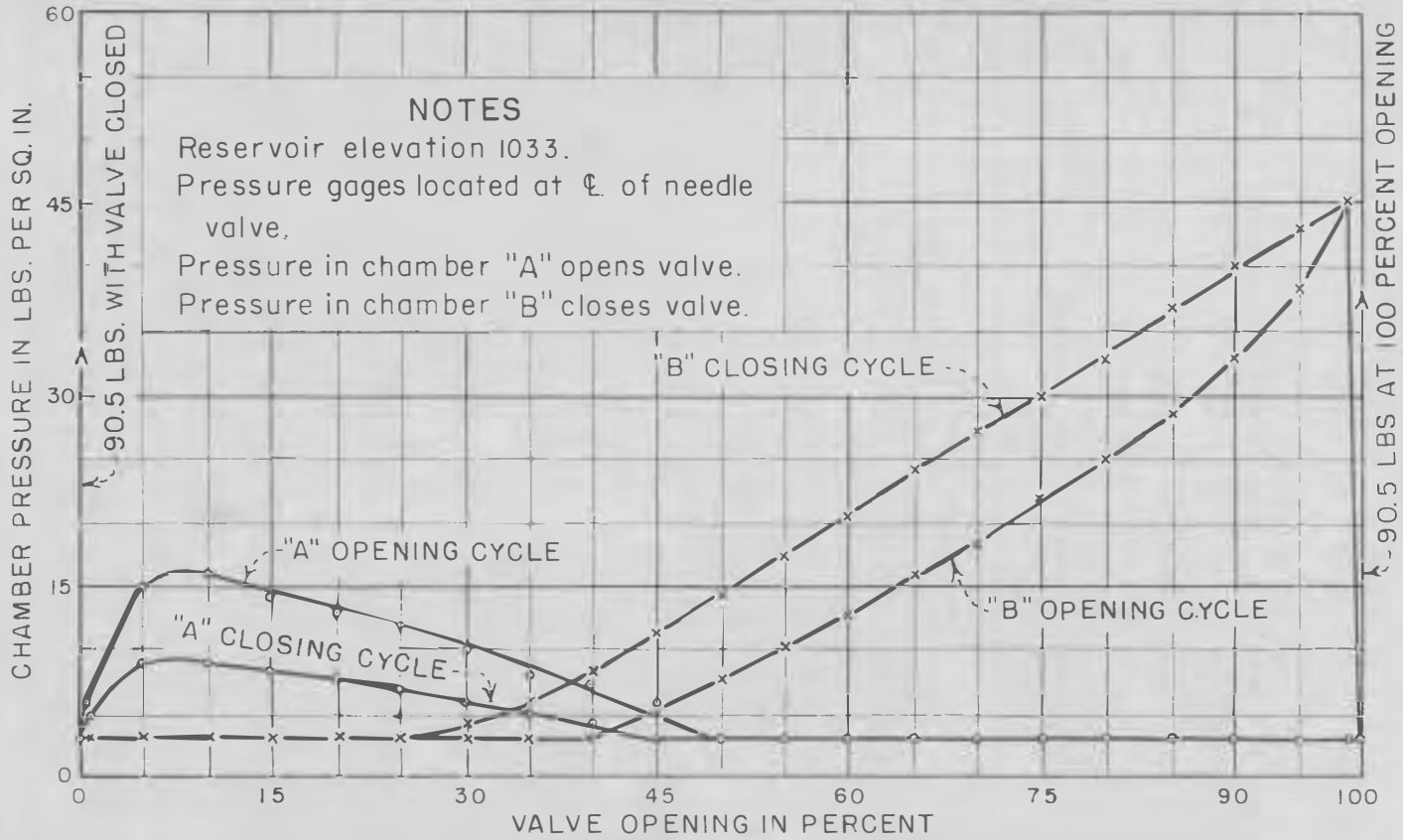
PIEZOMETER No. 2



PIEZOMETER No. 3

NEEDLE VALVE TESTS

ORIGINAL NEEDLE VALVE



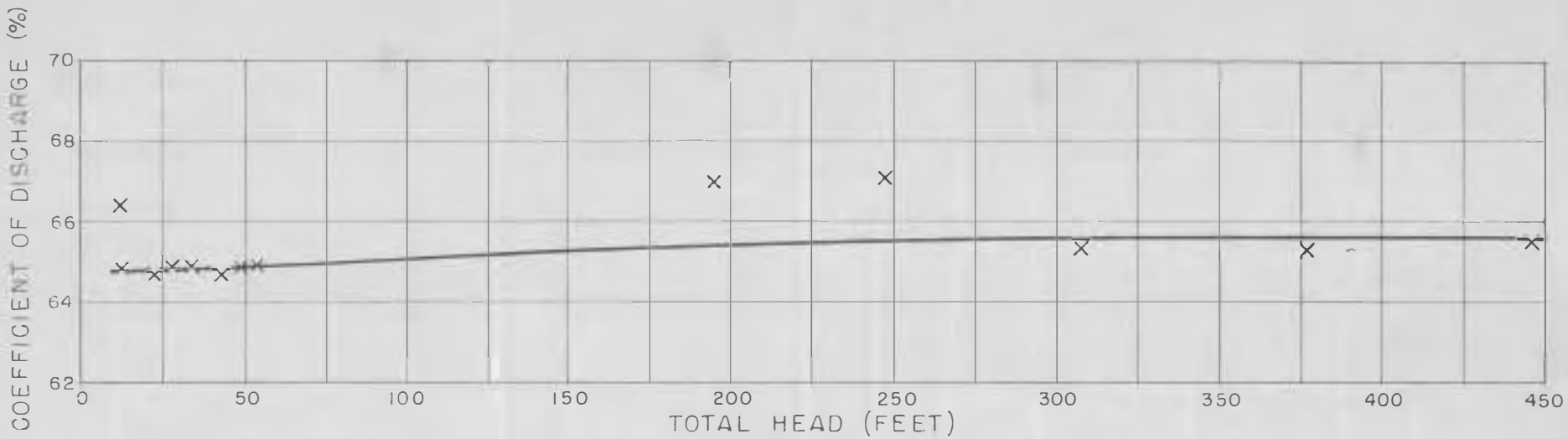
VALVE OPENING IN PERCENT	OPENING CYCLE		CLOSING CYCLE	
	A	B	A	B
0	3	90	3	90
1	6	3	5	3
5	15	3	9	3
10	16	3	9	3
15	14	3	8	3
20	13	3	7.5	3
25	12	3	7	3
30	10	3	6	4
35	8	3	5	6
40	7.5	3	4	8
45	6	5	3	11
50	3	7.5	3	14
55	3	10	3	17
60	3	12.5	3	20
65	3	15.5	3	24
70	3	18	3	27
75	3	22	3	30
80	3	25	3	33
85	3	28.5	3	37
90	3	33	3	40
95	3	38	3	43
99	3	45	3	45
100	90.5	3	90.5	3

BOULDER CANYON PROJECT
ARIZONA CANYON WALL OUTLET WORKS

84" INTERNAL DIFFERENTIAL NEEDLE VALVE

NEEDLE VALVE CHAMBER PRESSURES

FIGURE 5

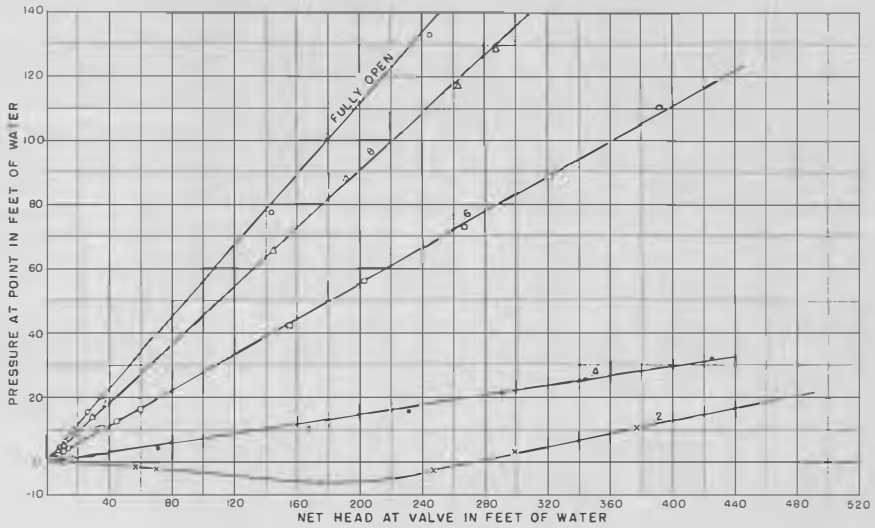


	NET HEAD IN FEET	TOTAL HEAD IN FEET	Q C.F.S.	COEFFICIENT OF DISCHARGE (%)
TESTS IN DENVER LABORATORY	9.8	12.8	2.57	66.4
	12.3	15.4	2.78	64.8
	17.7	22.2	3.33	64.7
	22.1	27.8	3.74	64.9
	27.1	34.0	4.14	64.9
	33.7	42.2	4.60	64.7
	39.0	48.9	4.96	64.9
	43.5	54.7	5.25	64.9
TESTS AT BOULDER DAM	154.7	195.1	10.22	67.0
	196.4	248.4	11.58	67.2
	247.0	307.6	12.52	65.4
	302.5	376.8	13.85	65.3
	358.0	446.5	15.12	65.5

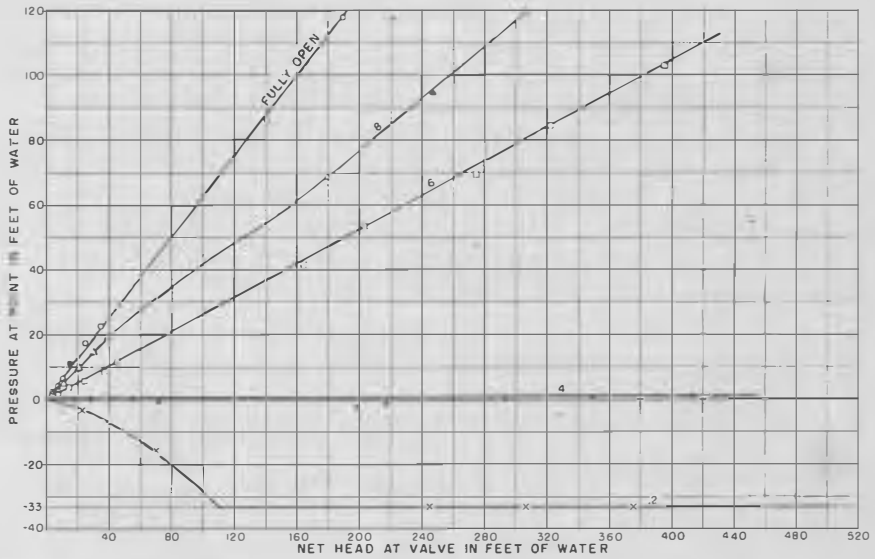
42-DEGREE NEEDLE WITH SHARP-EDGED NOZZLE

VALVE 100% OPEN

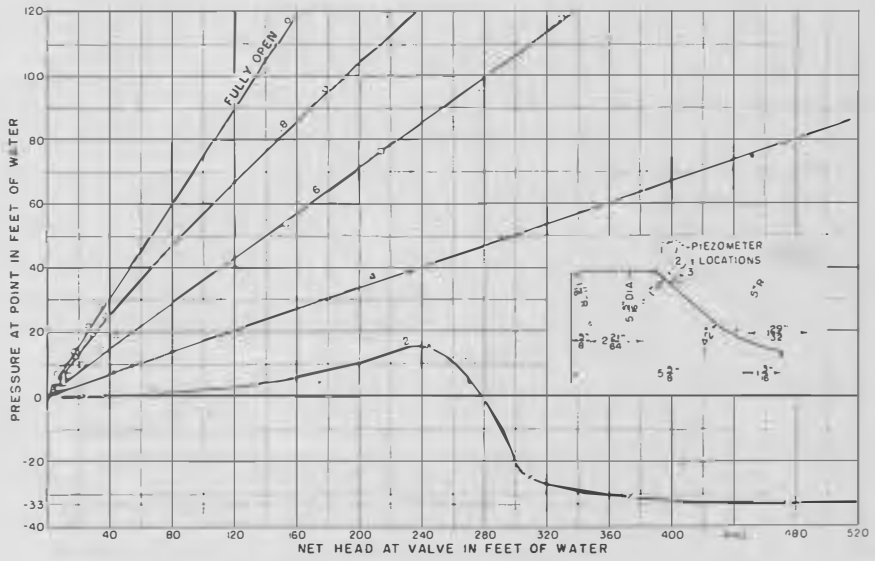
FIGURE 6



PIEZOMETER NO. 1



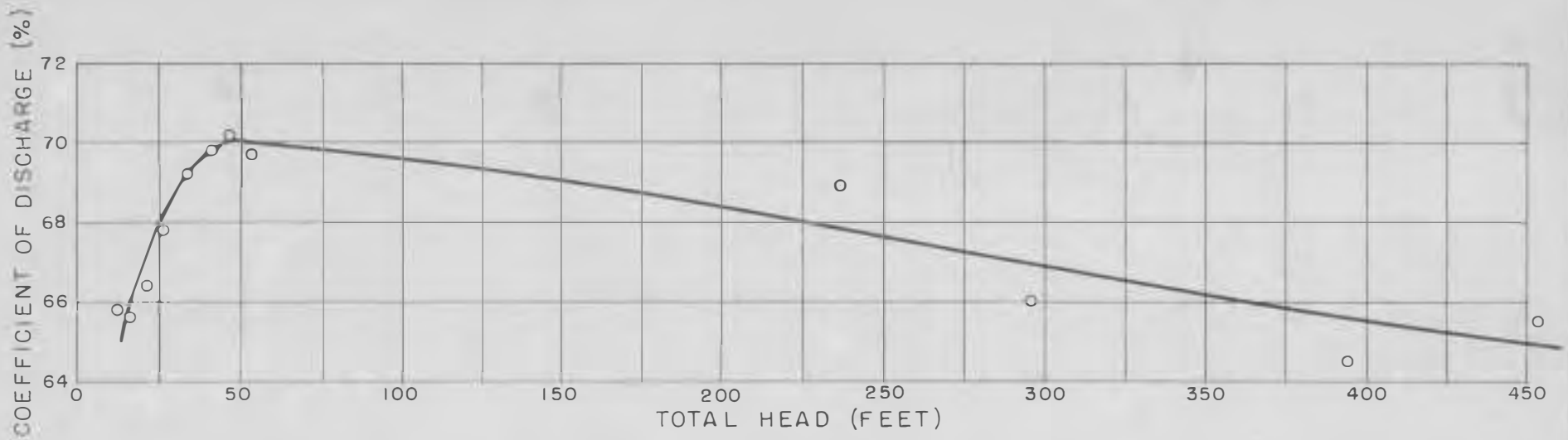
PIEZOMETER NO. 2



PIEZOMETER NO. 3

NEEDLE VALVE TESTS

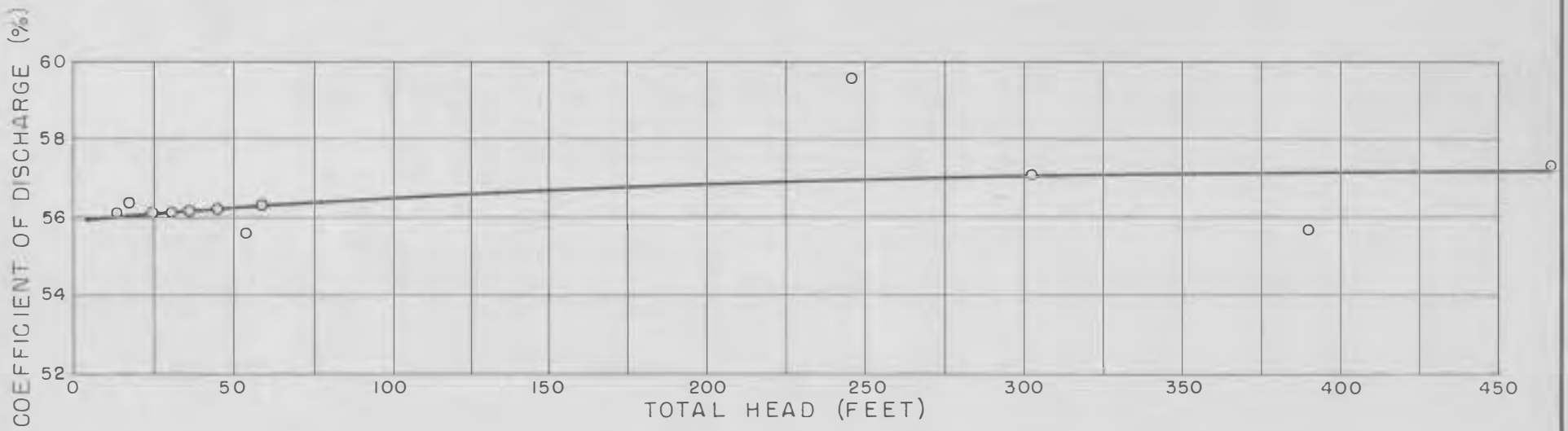
ORIGINAL NEEDLE WITH SHARP EDGED NOZZLE



	NET HEAD IN FEET	TOTAL HEAD IN FEET	Q C.F.S.	COEFFICIENT OF DISCHARGE (%)
	9.80	12.30	2.52	65.8
	12.00	15.20	2.80	65.6
	16.90	21.40	3.36	66.4
	20.70	26.60	3.82	67.8
	24.80	32.20	4.29	69.2
	30.70	40.10	4.83	69.8
	35.50	46.50	5.23	70.2
	39.80	52.00	5.50	69.7
	184.50	236.10	11.57	68.9
	236.00	295.50	12.40	66.0
	314.00	388.70	13.90	64.5
	363.00	452.60	15.24	65.5

THIRTY-DEGREE NEEDLE WITH ROUND-EDGED NOZZLE
VALVE 100% OPEN

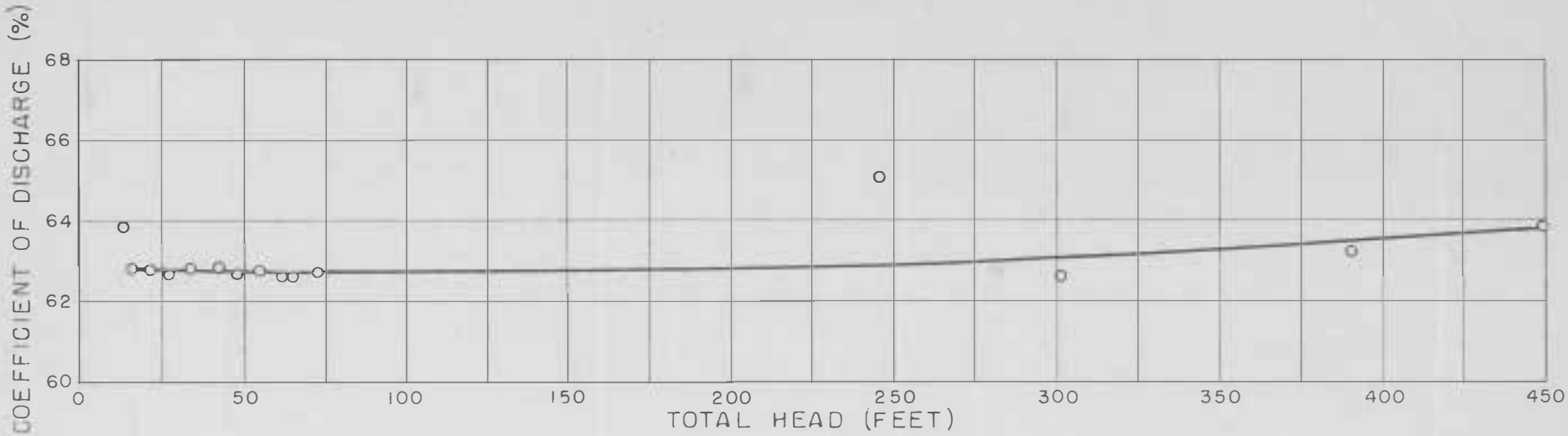
FIGURE 7.



	NET HEAD IN FEET	TOTAL HEAD IN FEET	Q C.F.S.	COEFFICIENT OF DISCHARGE (%)
TESTS IN DENVER LABORATORY	11.50	13.60	2.26	56.1
	15.00	17.70	2.60	56.4
	20.50	24.20	3.02	56.1
	25.50	30.10	3.37	56.1
	31.00	36.50	3.71	56.1
	38.40	45.30	4.14	56.2
	45.80	53.80	4.46	55.6
	49.40	58.30	4.70	56.3
TESTS AT BOULDER DAM	205.50	245.90	10.22	59.6
	257.00	302.50	10.85	57.1
	333.50	389.30	12.00	55.7
	395.50	466.70	13.54	57.3

THIRTY DEGREE NEEDLE WITH SHARP-EDGED NOZZLE
VALVE 100% OPEN

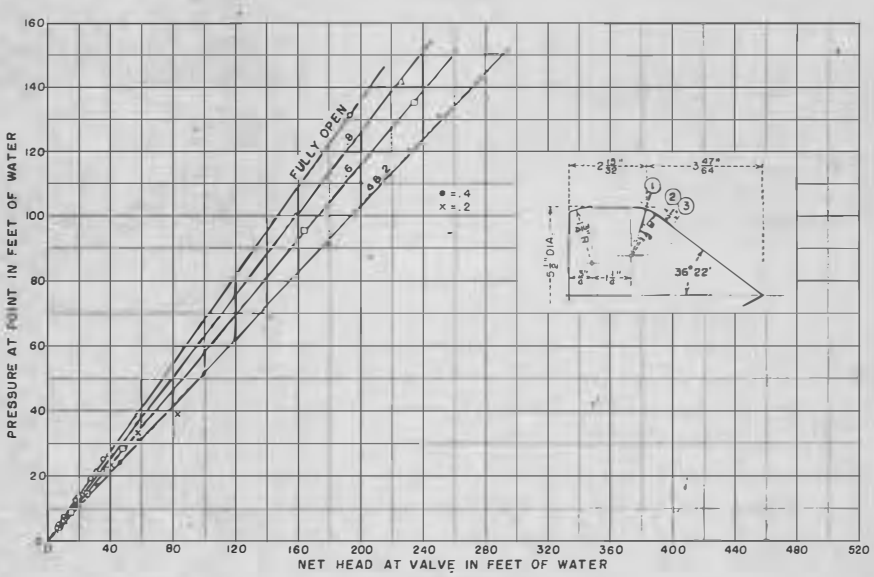
FIGURE 7b



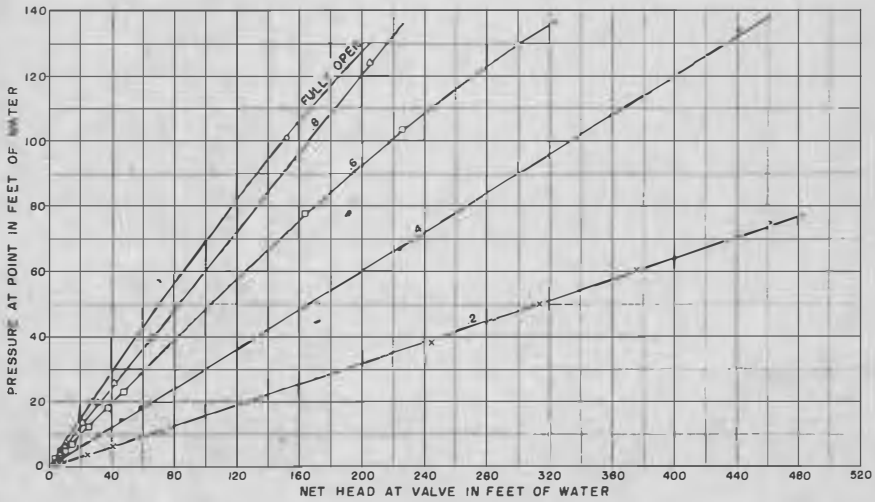
	NET HEAD IN FEET	TOTAL HEAD IN FEET	Q C.F.S.	COEFFICIENT OF DISCHARGE (%)
TESTS IN DENVER LABORATORY	10.33	12.84	2.50	63.8
	13.16	16.27	2.78	62.8
	18.00	22.23	3.24	62.8
	22.51	27.77	3.61	62.7
	27.60	34.07	4.01	62.8
	34.13	42.11	4.45	62.8
	39.80	49.09	4.80	62.6
	44.32	54.66	5.06	62.7
	50.00	61.62	5.37	62.6
	54.00	66.55	5.58	62.6
	58.50	72.17	5.82	62.7
TESTS AT BOULDER DAM	198.50	246.70	11.15	65.0
	247.00	301.50	11.86	62.6
	318.50	390.70	13.65	63.2
	365.00	449.80	14.80	63.9

36°-22' NEEDLE WITH SHARP-EDGED NOZZLE
VALVE 100% OPEN

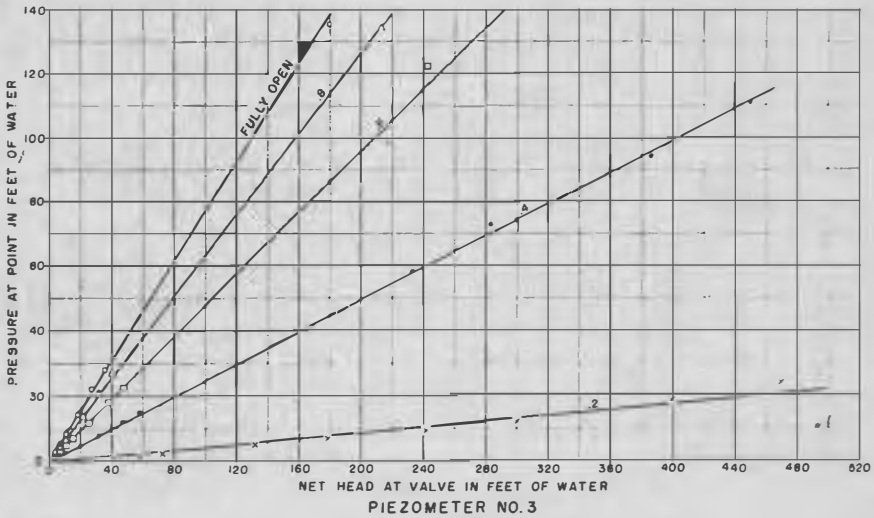
FIGURE 7c



PIEZOMETER NO. 1



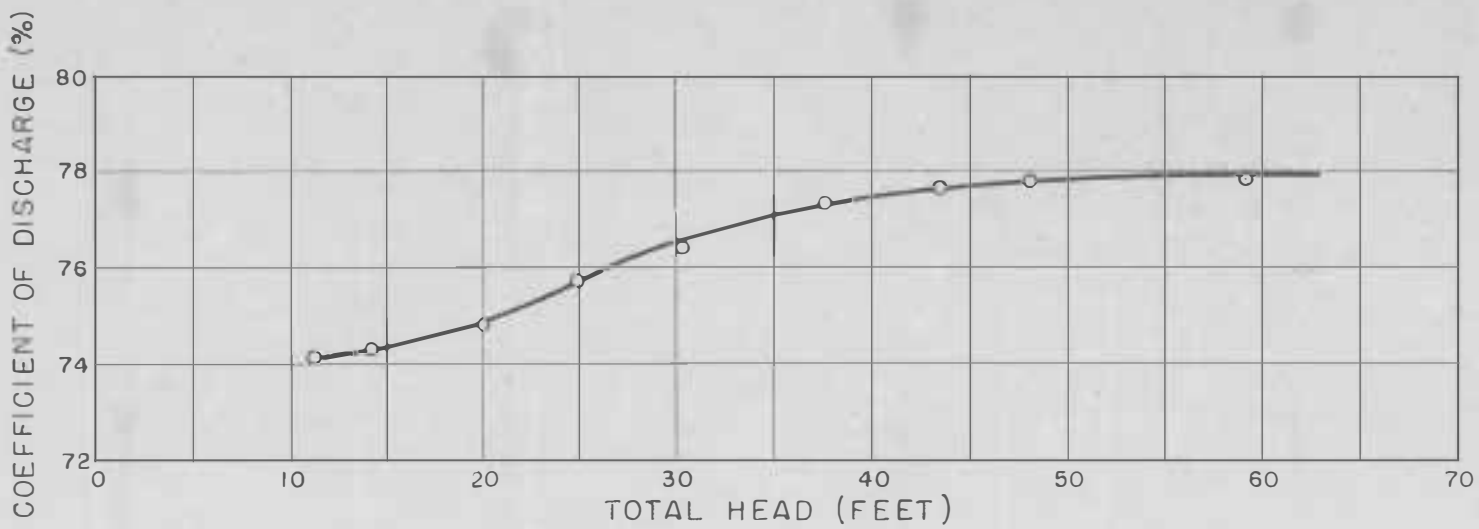
PIEZOMETER NO. 2



PIEZOMETER NO. 3

NEEDLE VALVE TESTS

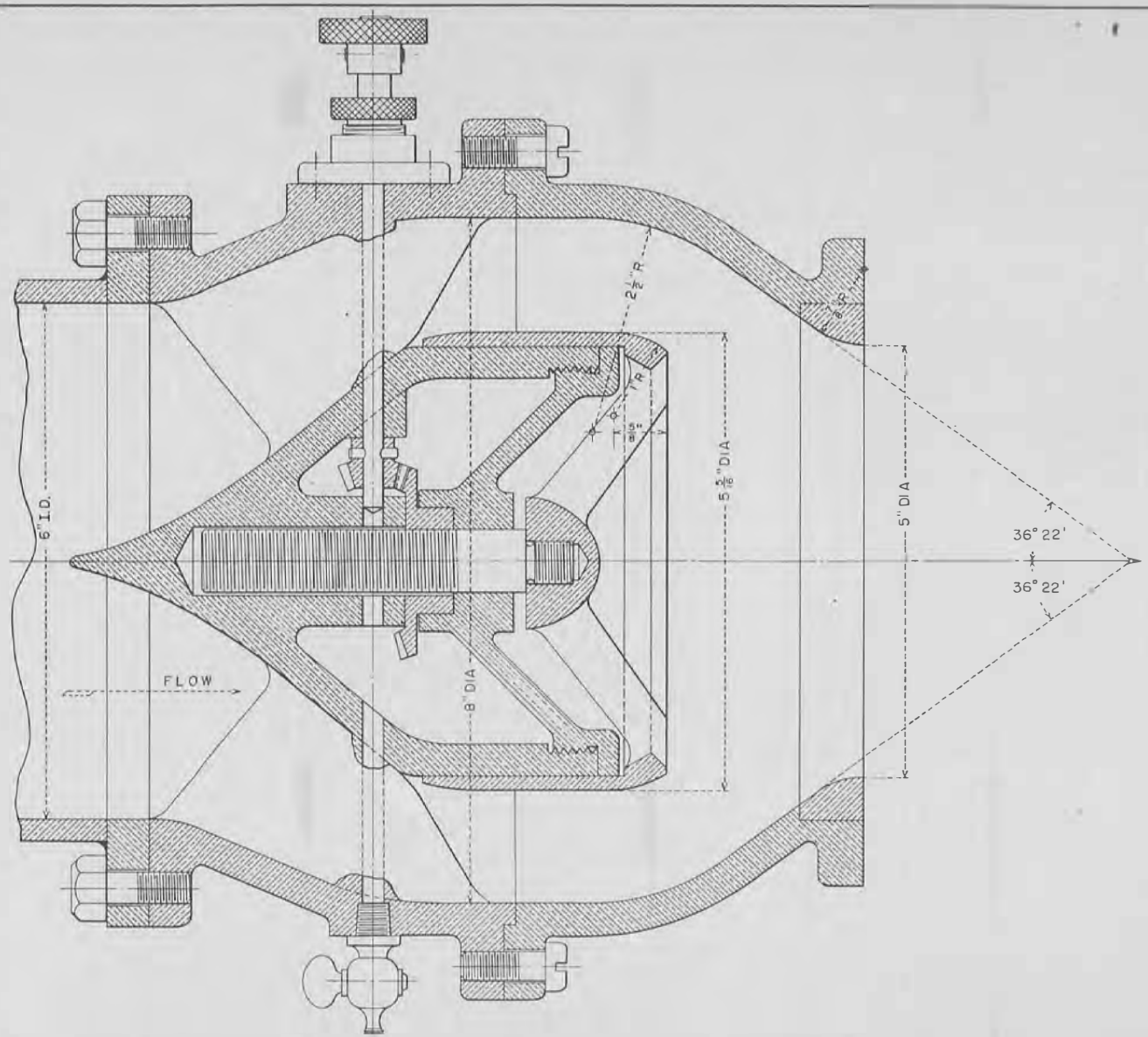
36° 22' NEEDLE WITH SHARP EDGED NOZZLE



NET HEAD IN FEET	TOTAL HEAD IN FEET	Q C.F.S.	COEFFICIENT OF DISCHARGE (%)
8.2	11.2	2.71	74.1
10.5	14.3	3.07	74.3
14.6	20.0	3.66	74.8
18.1	25.0	4.14	75.7
21.7	30.2	4.59	76.4
26.8	37.6	5.18	77.3
30.9	43.6	5.60	77.6
34.1	48.1	5.90	77.8
38.4	54.2	6.27	77.9
41.7	59.1	6.54	77.8

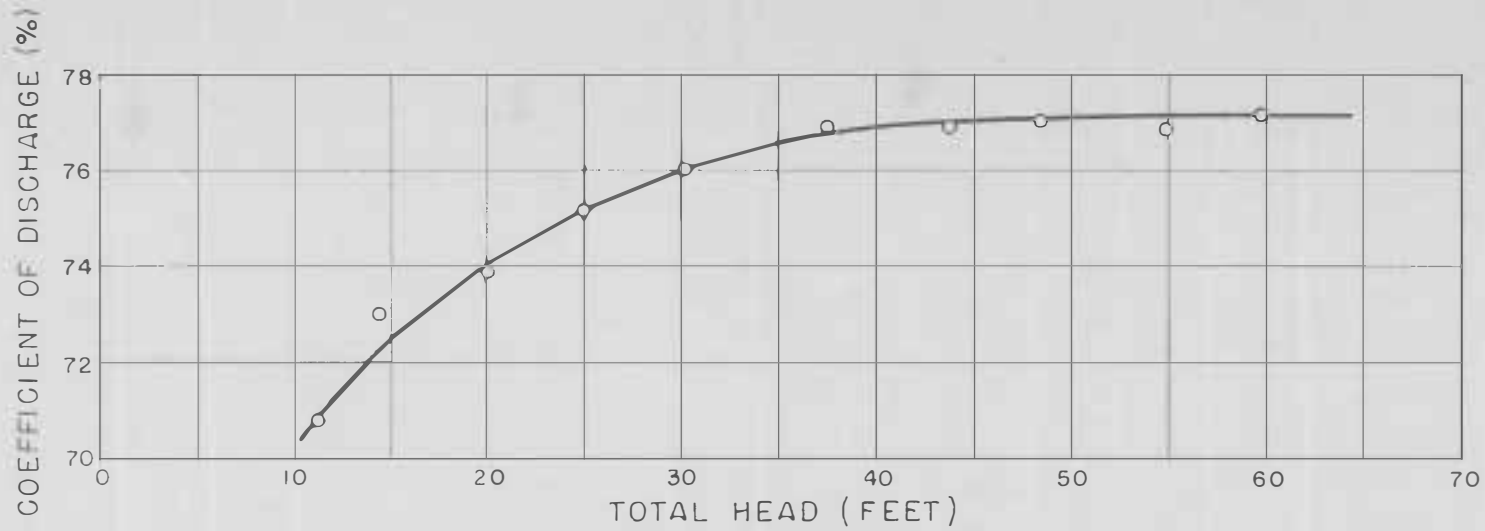
CLOSED-TYPE TUBE WITH ROUND-EDGED NOZZLE
VALVE 100% OPEN

FIGURE 8a



NEEDLE VALVE TESTS
5" OPEN TUBE VALVE
SECTIONAL SIDE ELEVATION

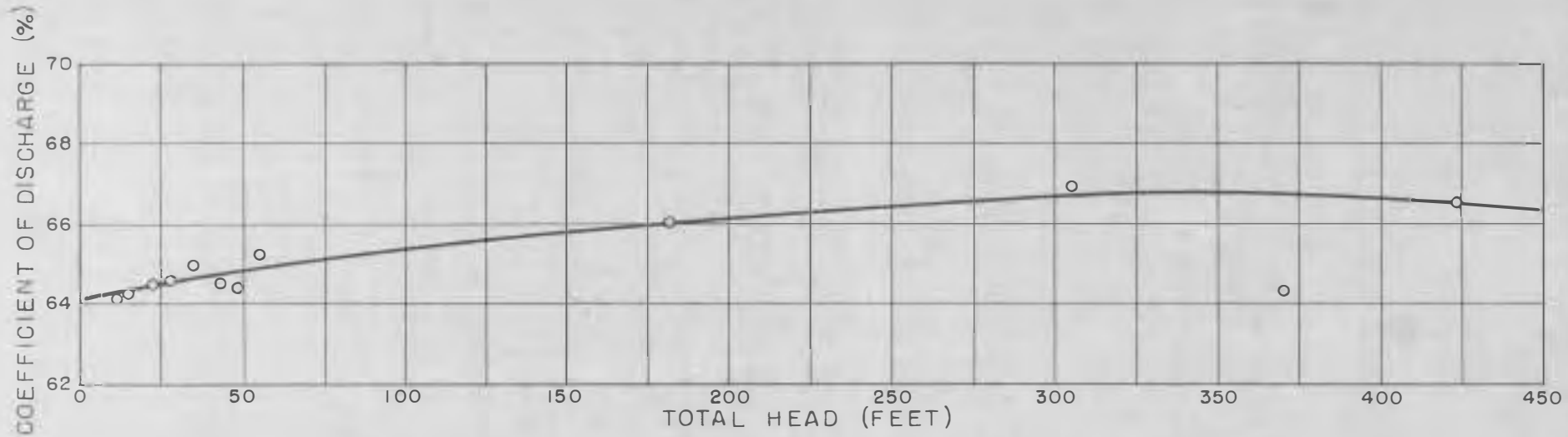
FIGURE 9



NET HEAD IN FEET	TOTAL HEAD IN FEET	Q C.F.S.	COEFFICIENT OF DISCHARGE (%)
8.4	11.1	3 64	70.8
10.6	14.3	4.13	73.0
14.7	20.0	4.89	73.9
18.1	24.9	5.45	75 1
21.8	30.2	6.01	76.0
26.9	37.6	6.70	76.9
31.3	43.8	7.24	76.9
34.5	48.4	7.61	77.2
39.1	54.8	8.10	76.9
42.6	59.8	8.46	77.2

OPEN-TYPE TUBE WITH ROUND-EDGED NOZZLE
VALVE 100% OPEN

FIGURE 9a

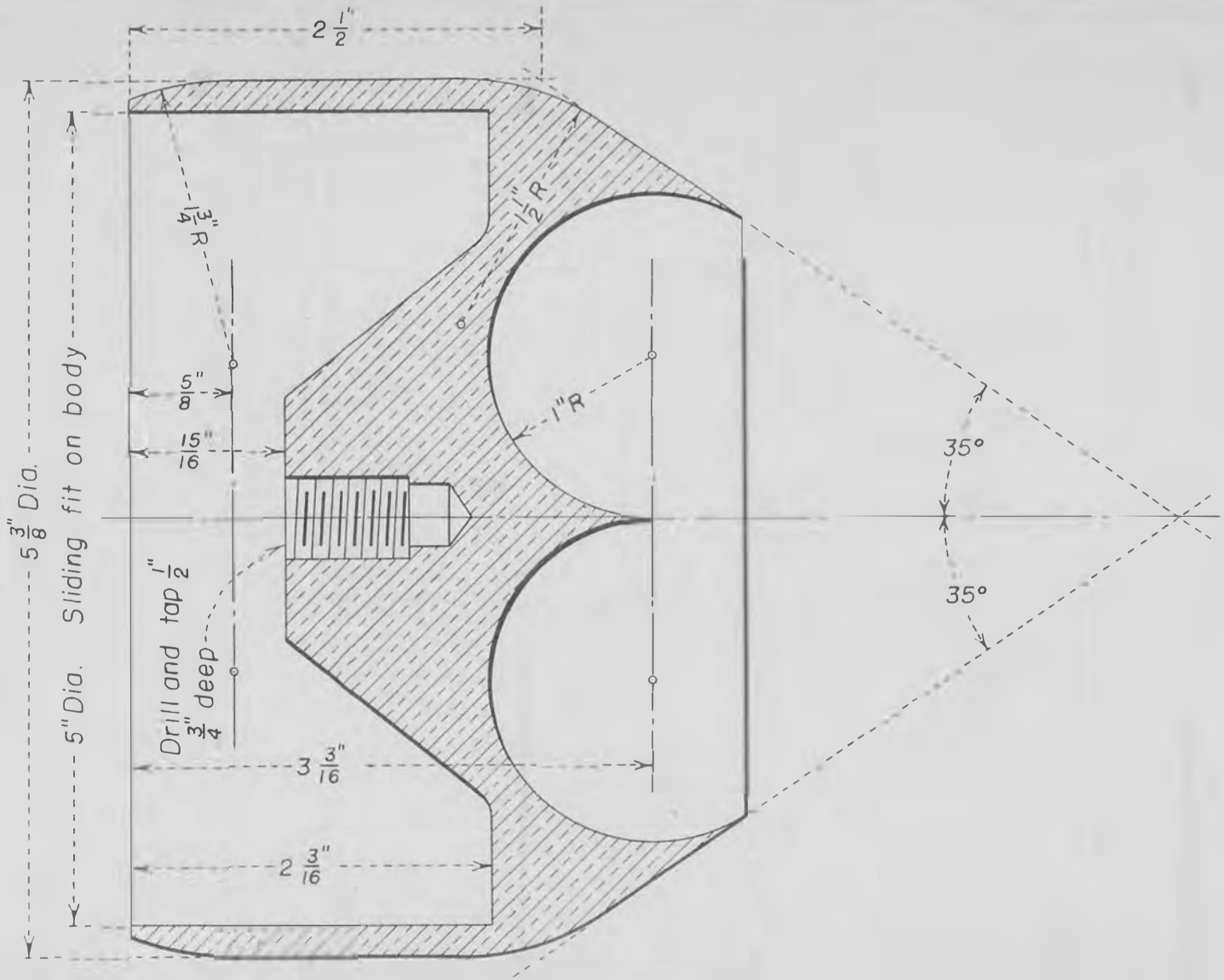


	NET HEAD IN FEET	TOTAL HEAD IN FEET	Q C.F.S.	COEFFICIENT OF DISCHARGE (%)
TESTS IN DENVER LABORATORY	9.80	12.20	2.45	64.1
	12.60	15.80	2.80	64.3
	18.00	22.50	3.35	64.5
	22.30	28.00	3.74	64.6
	27.10	34.00	4.14	64.9
	33.80	42.20	4.58	64.5
	39.30	49.20	4.95	64.4
	43.50	54.70	5.28	65.2
TESTS AT BOULDER DAM	145.50	182.20	9.74	66.0
	241.50	304.90	12.78	66.9
	300.30	371.30	13.53	64.3
	358.00	449.00	15.33	66.5

OPEN-TYPE TUBE WITH SHARP-EDGED NOZZLE

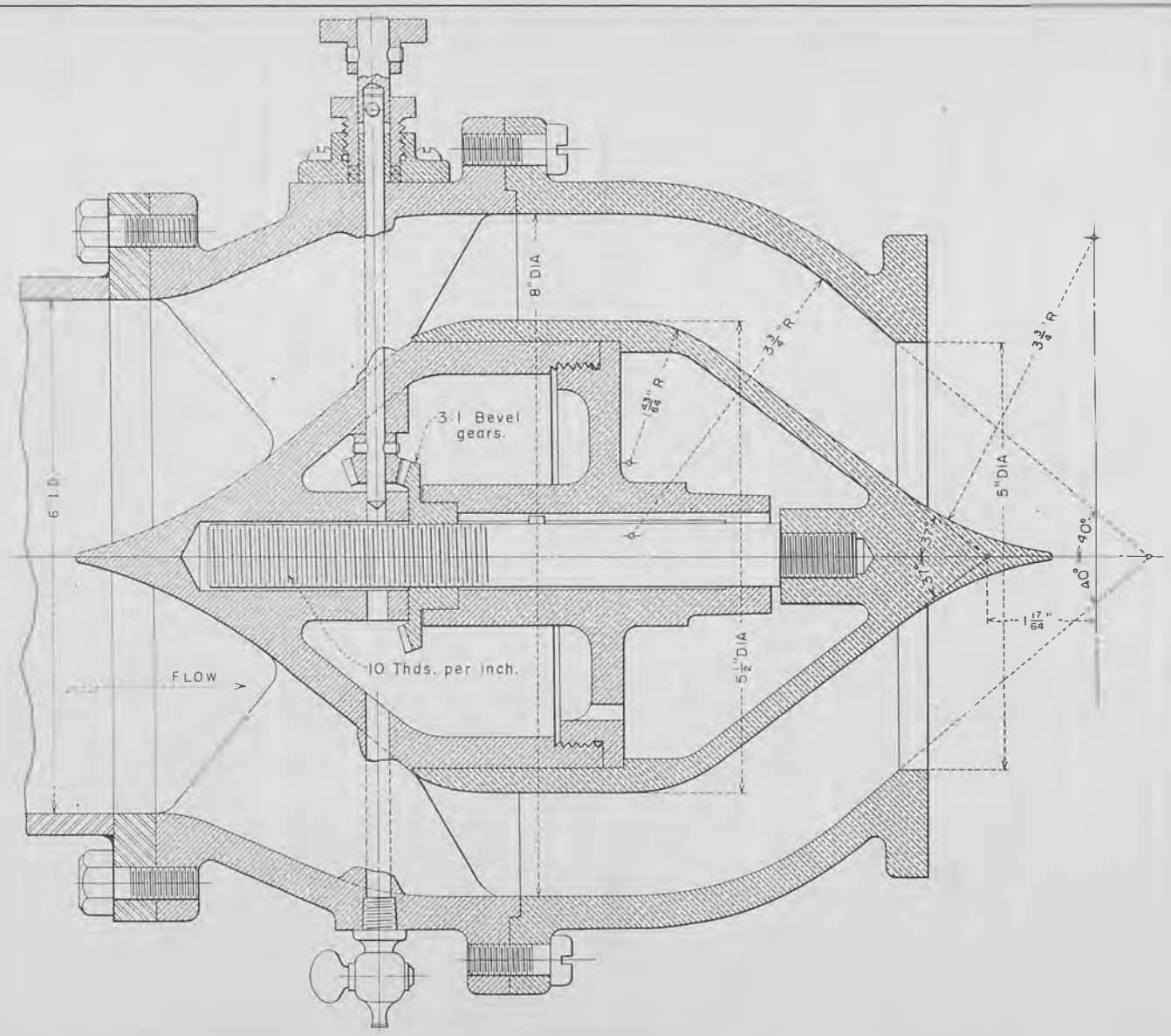
VALVE 100% OPEN

FIGURE 9b



TORUS TUBE

FIGURE 10



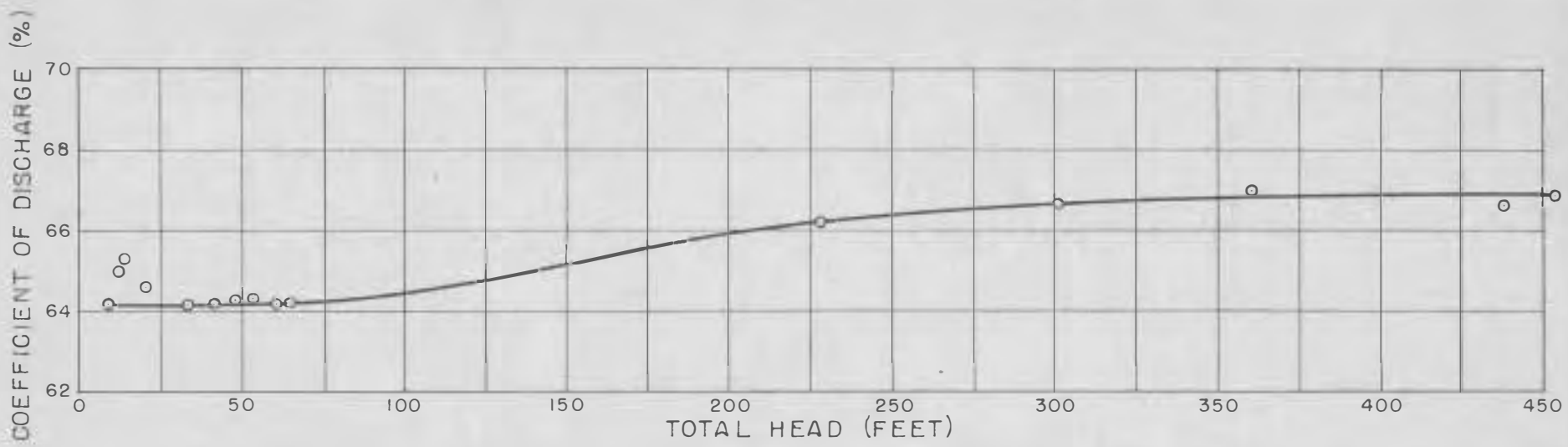
NEEDLE VALVE TESTS

5" PROPOSED VALVE DESIGN

SECTIONAL SIDE ELEVATION

J. W. A. 11-30-38

FIGURE 11



A = 0.1963

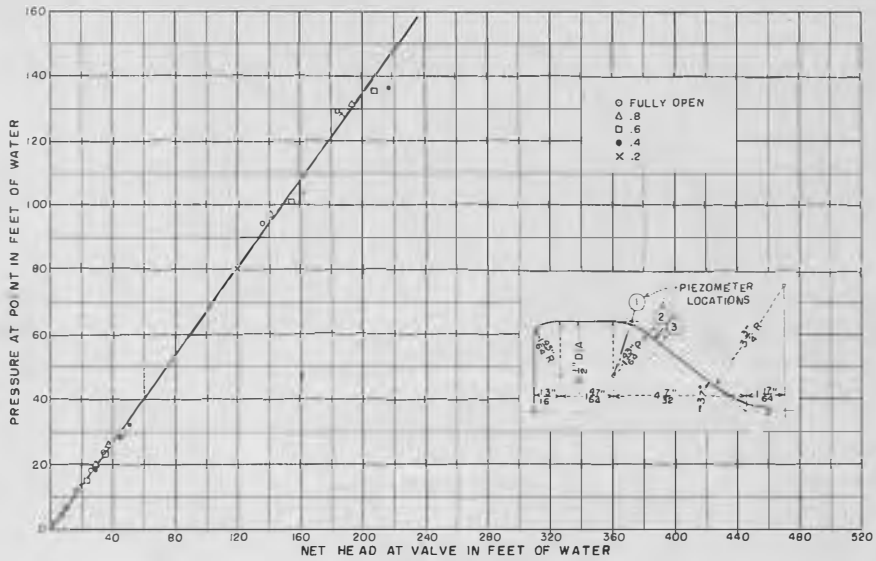
	NET HEAD IN FEET	TOTAL HEAD IN FEET	Q C.F.S.	COEFFICIENT OF DISCHARGE (%)
TESTS IN DENVER LABORATORY	7.79	9.72	2.19	64.2
	10.06	12.64	2.53	65.0
	13.74	17.29	2.97	65.3
	17.43	21.90	3.33	64.6
	26.35	32.90	4.03	64.1
	32.75	40.91	4.50	64.2
	38.30	47.80	4.86	64.3
	42.65	53.31	5.14	64.3
	47.90	59.82	5.44	64.2
	51.70	64.59	5.65	64.2
TESTS AT BOULDER DAM	177.80	228.30	11.44	66.2
	240.00	301.80	12.65	66.7
	286.50	361.20	13.90	67.0
	349.00	438.70	15.24	66.6
	360.00	454.00	15.56	66.9

$v^2/2g$ 1.93

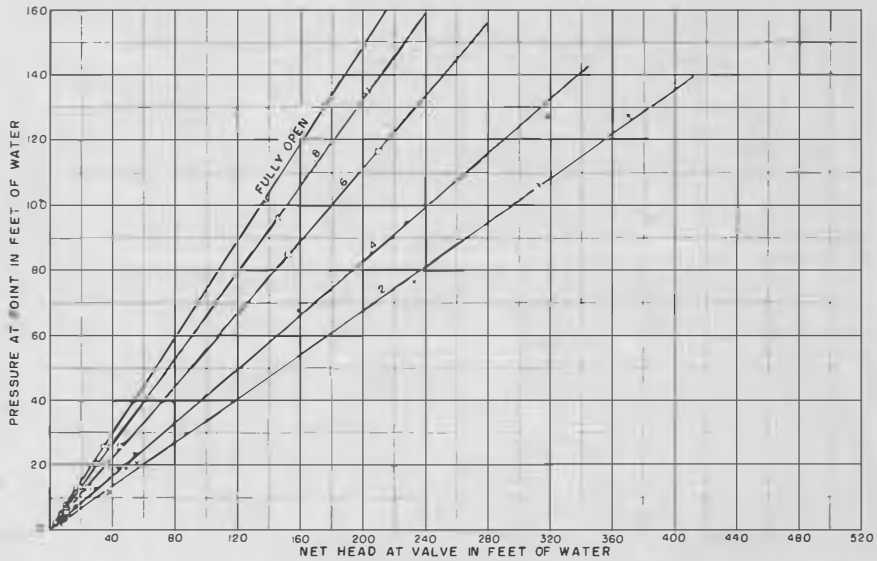
$C = \frac{Q}{\sqrt{2gH}(A)}$ 0.4

PROPOSED VALVE DESIGN
VALVE 100% OPEN

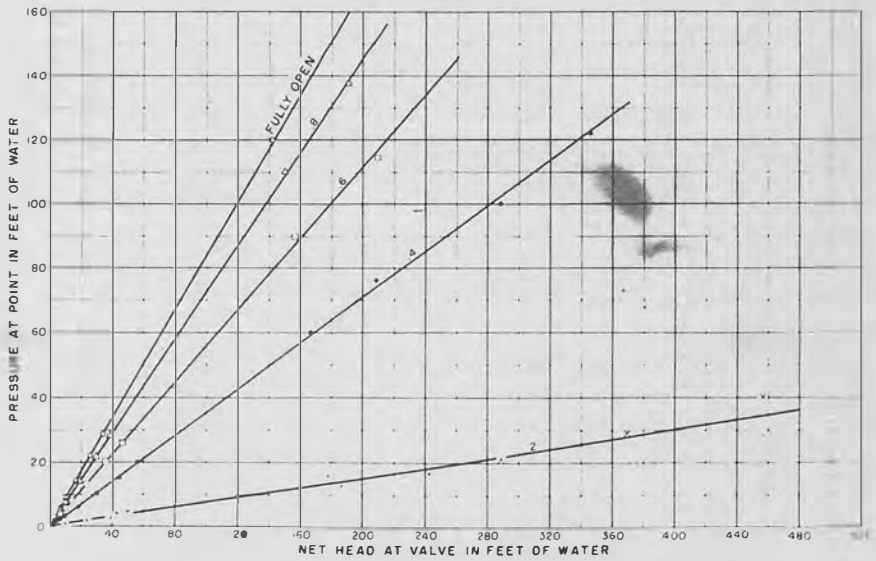
FIGURE 11a



PIEZOMETER NO. 1



PIEZOMETER NO. 2

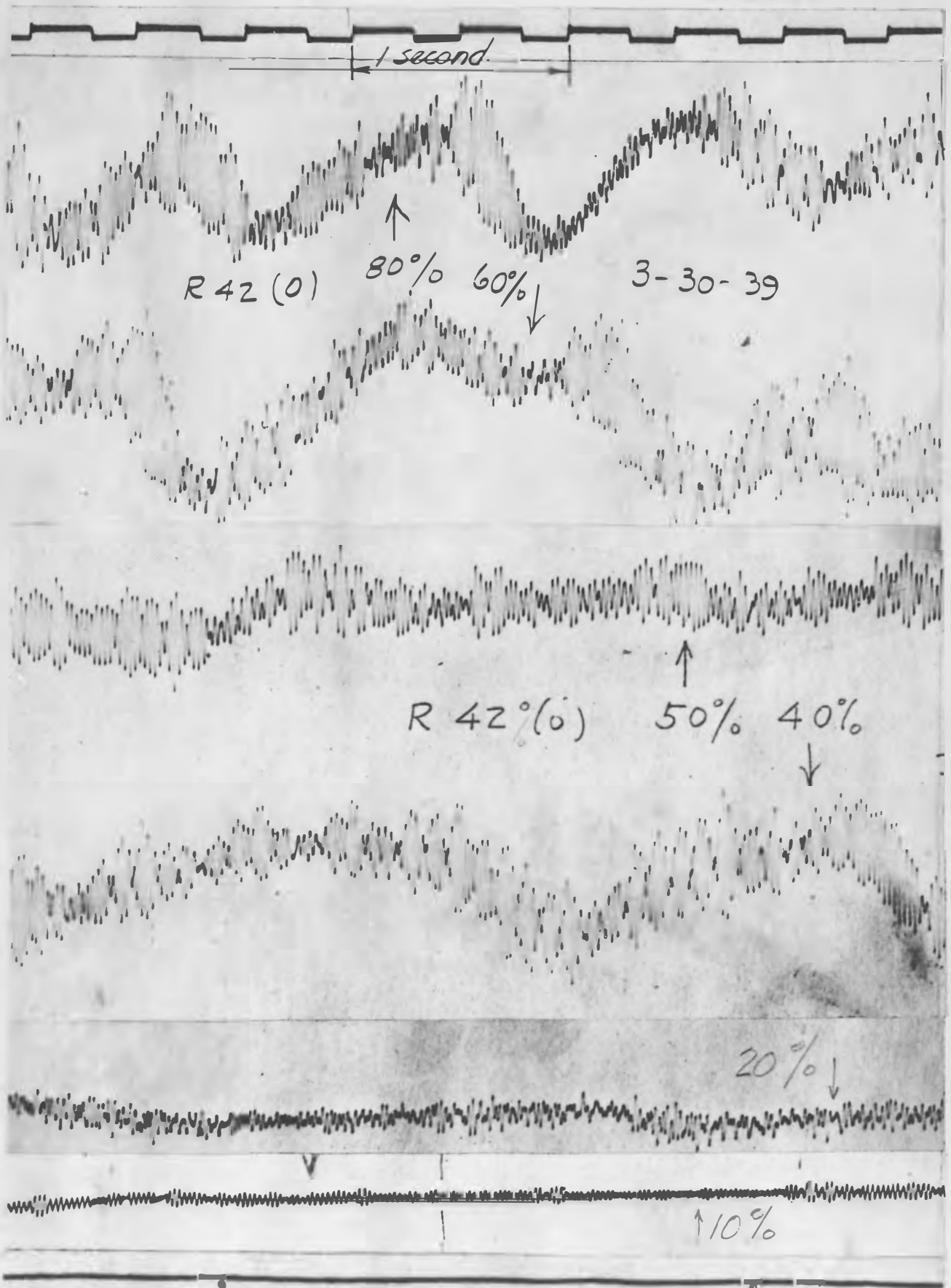


PIEZOMETER NO. 3

NEEDLE VALVE TESTS

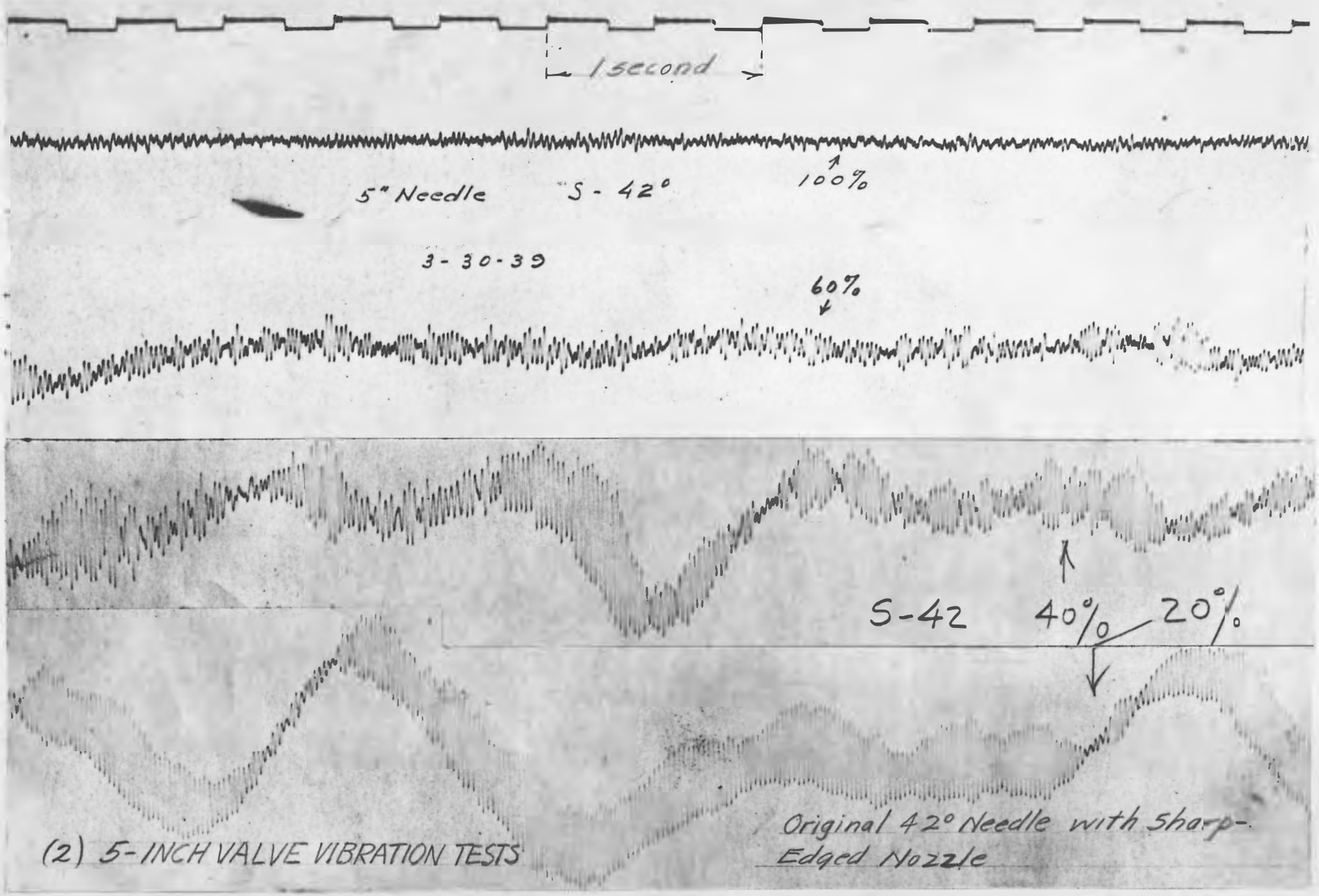
PROPOSED DESIGN

FIGURE 13



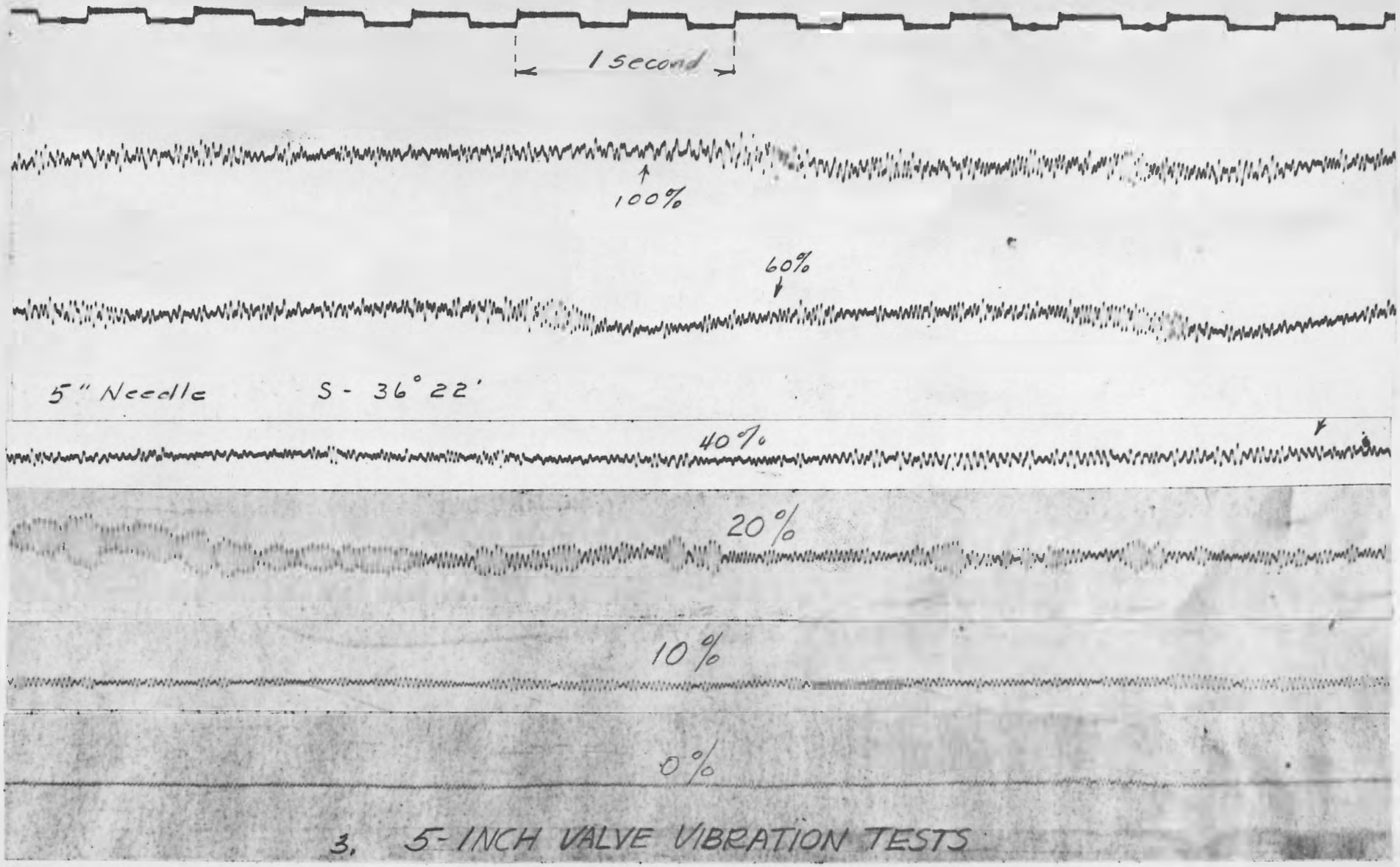
(1) 5-INCH VALVE VIBRATION TESTS.

Original Valve - 42° Needle with Round-edged Nozzle



(2) 5-INCH VALVE VIBRATION TESTS

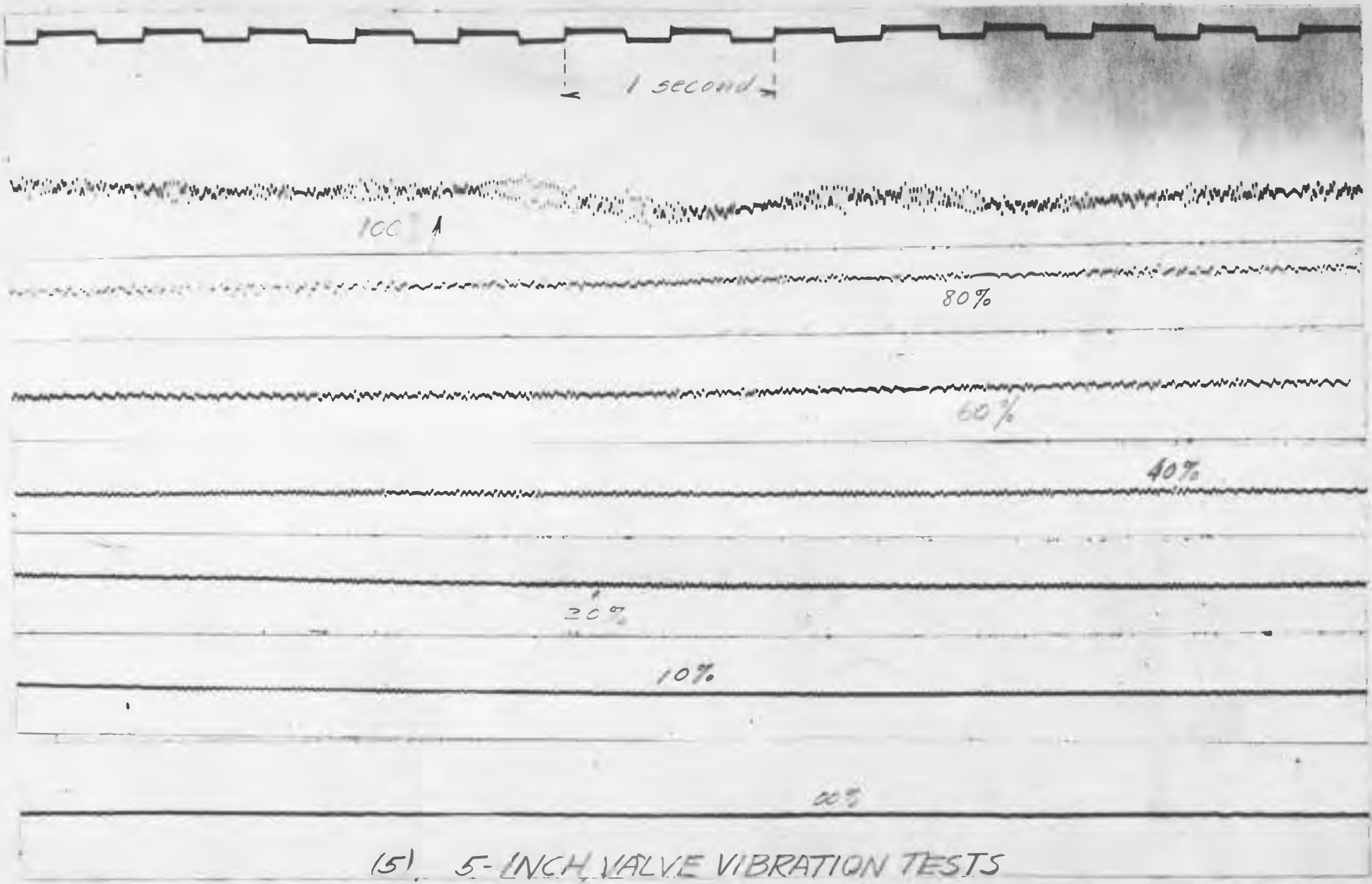
FIGURE 14



3. 5-INCH VALVE VIBRATION TESTS

36°-22' Needle with the Sharp-edged Nozzle

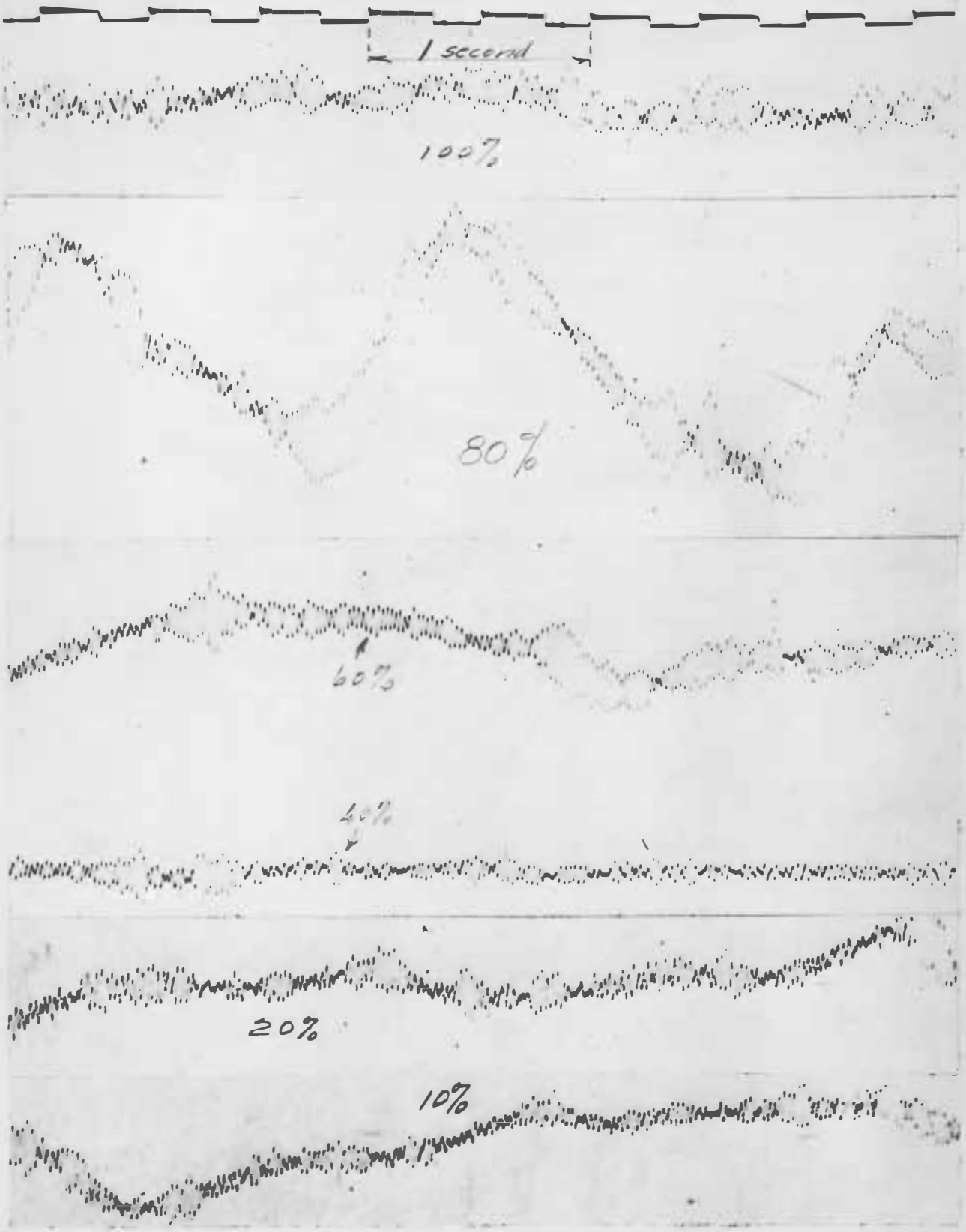
FIGURE 15



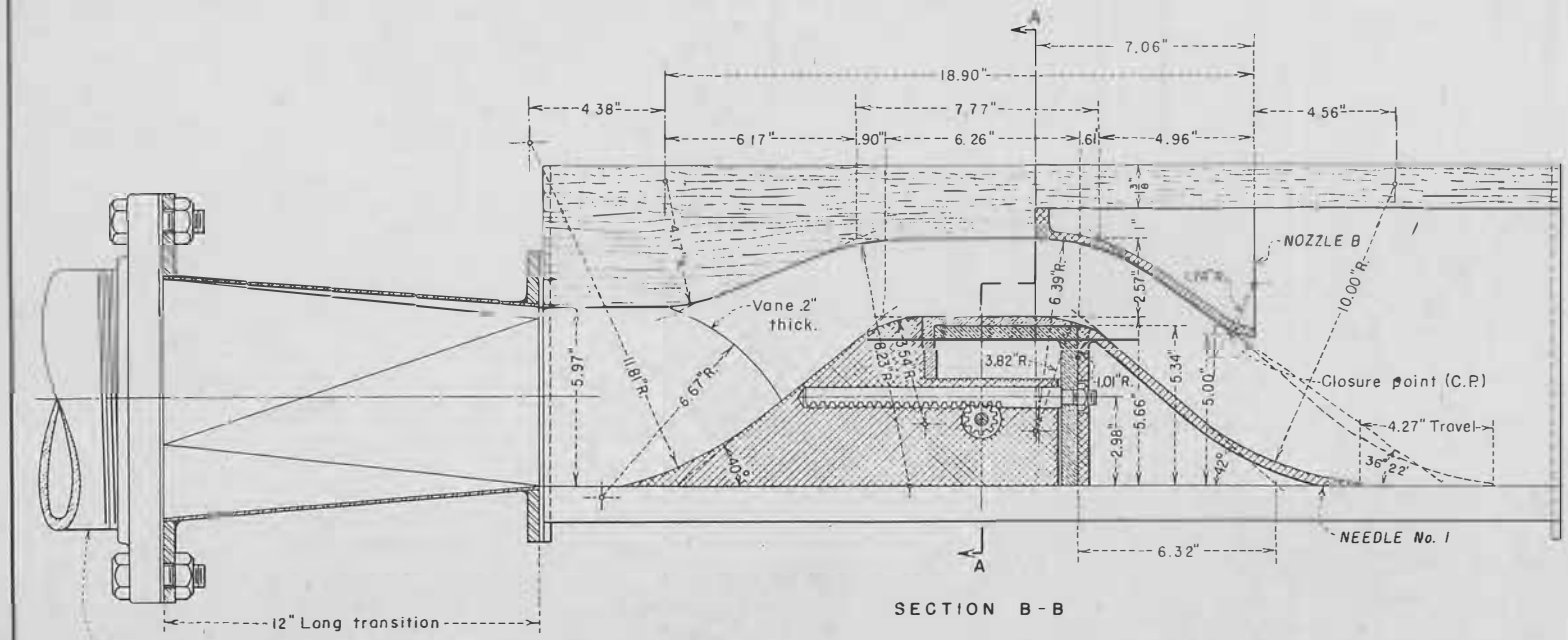
(5). 5-INCH VALVE VIBRATION TESTS
Proposed valve design

FIGURE 16a

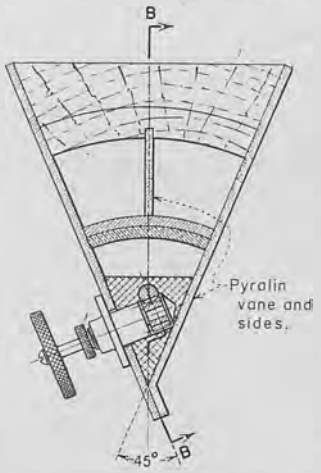
FIGURE 16



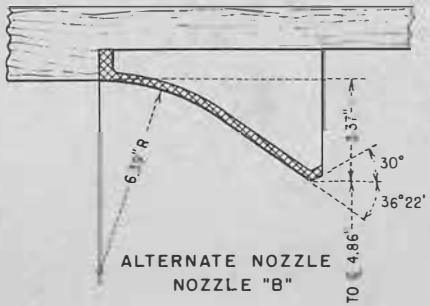
(4.) 5-INCH VALVE VIBRATION TESTS
Open tube with sharp-edged nozzle



SECTION B-B



SECTION A-A

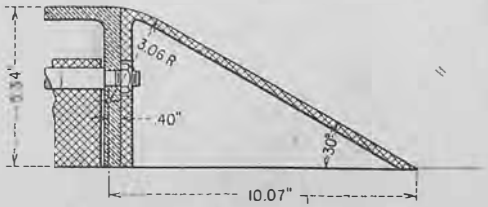


ALTERNATE NOZZLE
NOZZLE "B"

NEEDLE VALVE TESTS

ONE EIGHTH SECTIONAL MODEL
OF BOULDER DAM NEEDLE VALVE
AND ALTERATIONS

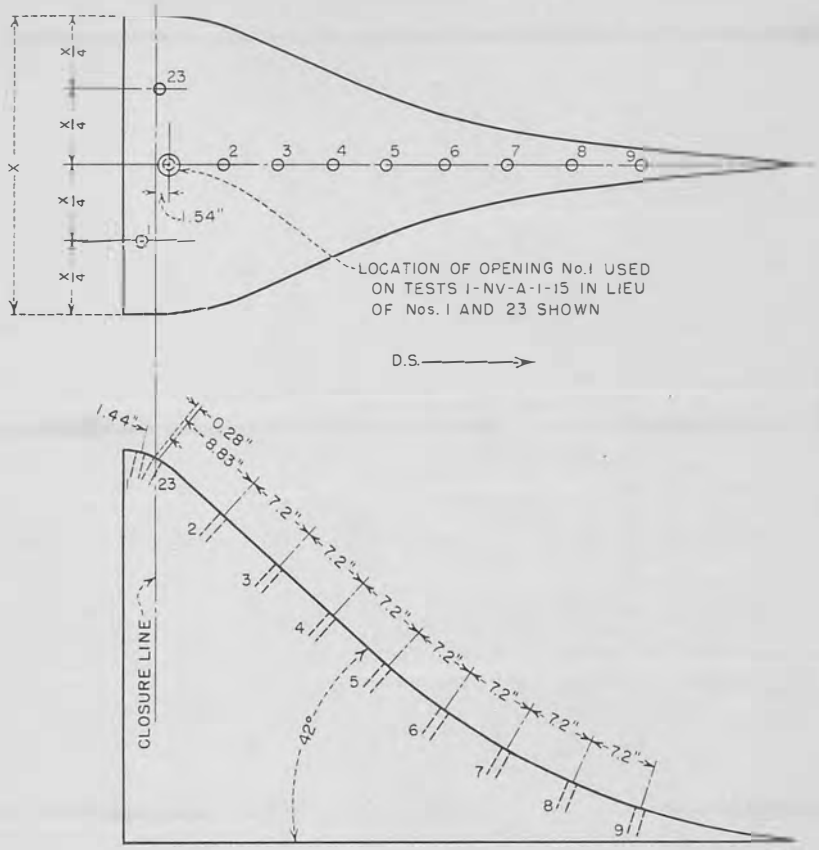
MODEL SCALE 1:7.2



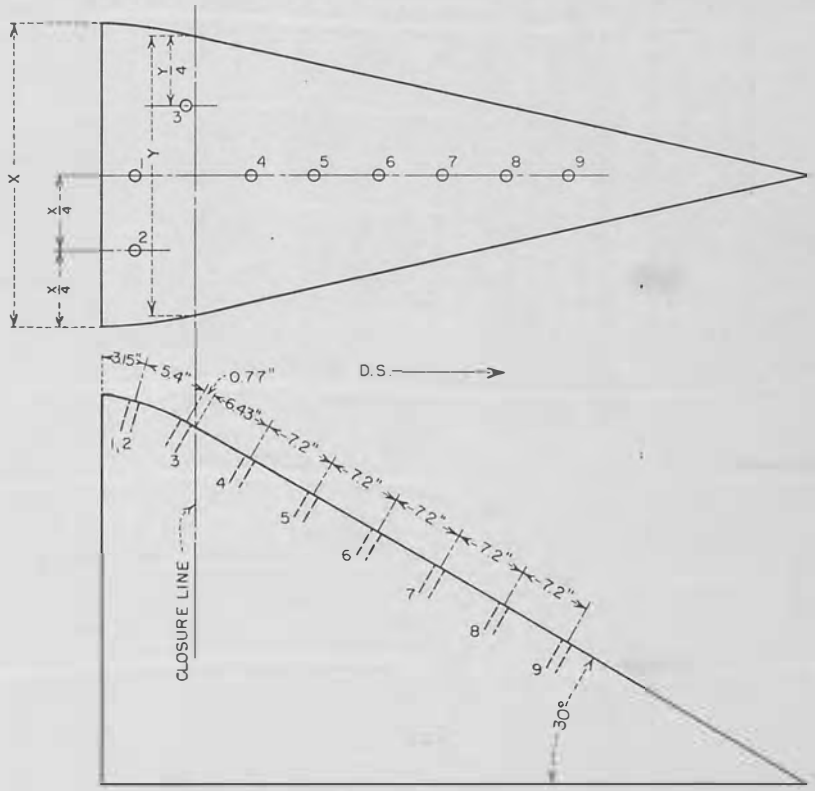
ALTERNATE NEEDLE
NEEDLE No. 2

E.S.G. 11-30-38

FIGURE 17



NEEDLE No. 1

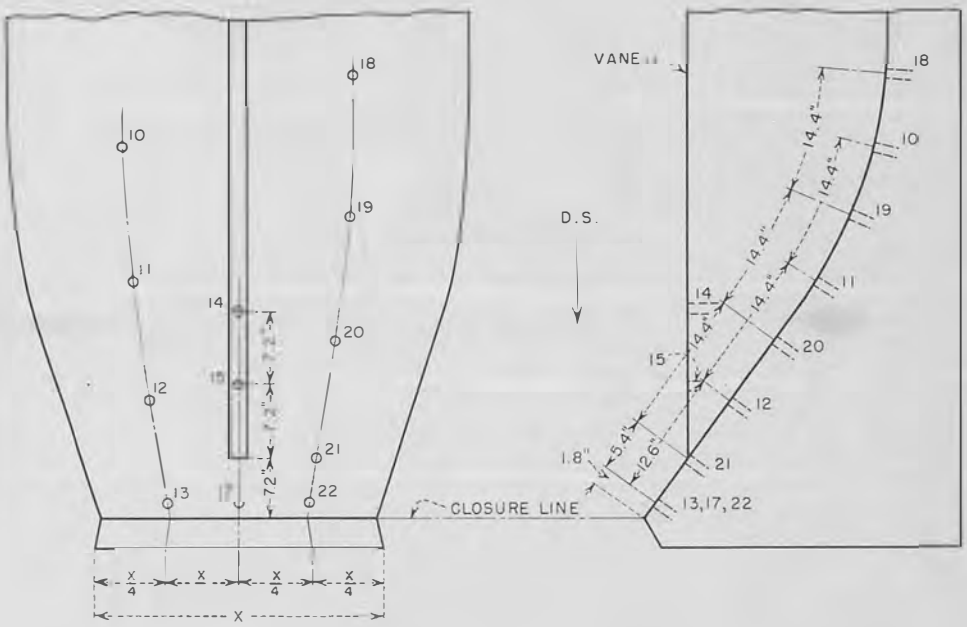


NEEDLE No. 2

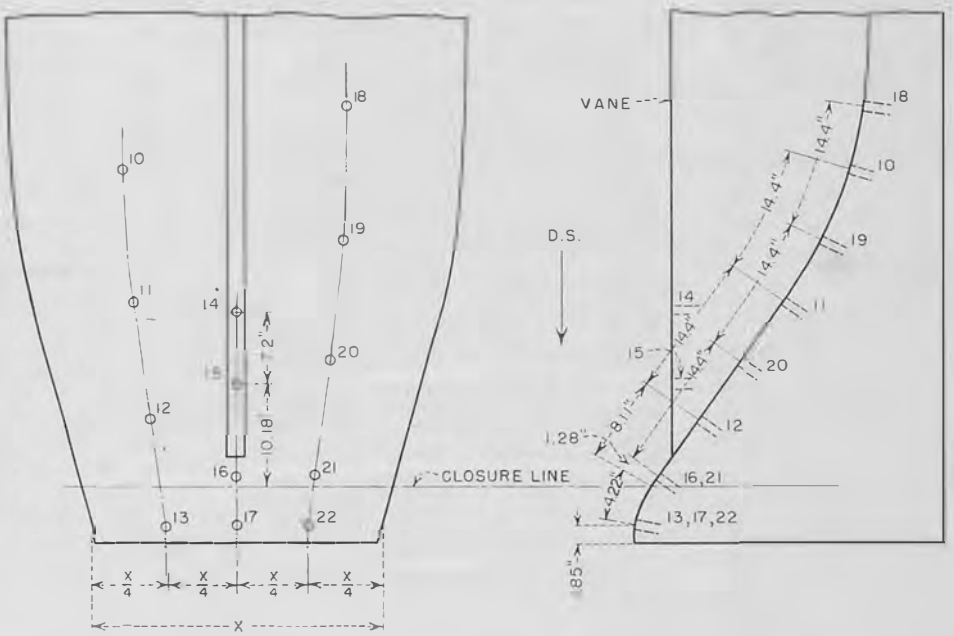
NEEDLE VALVE TESTS

LOCATION OF PIEZOMETER OPENINGS ON NEEDLES

W A H 11-8-38



NOZZLE "B"



NOZZLE "A"

NEEDLE VALVE TESTS

LOCATION OF PIEZOMETER OPENINGS ON NOZZLES

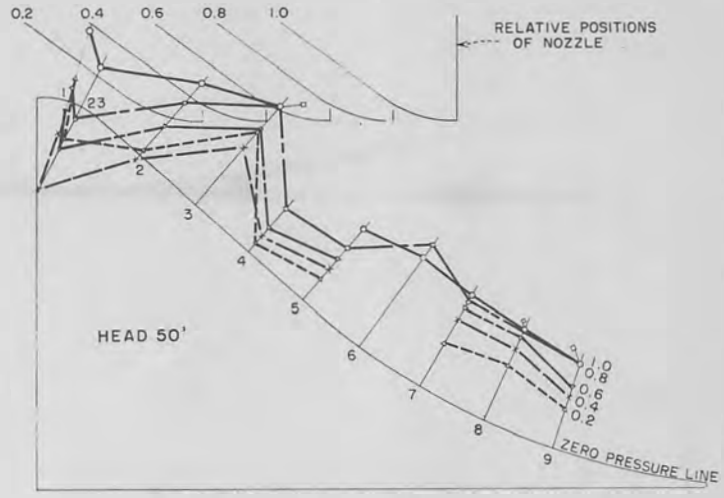
W A H. 11-8-38

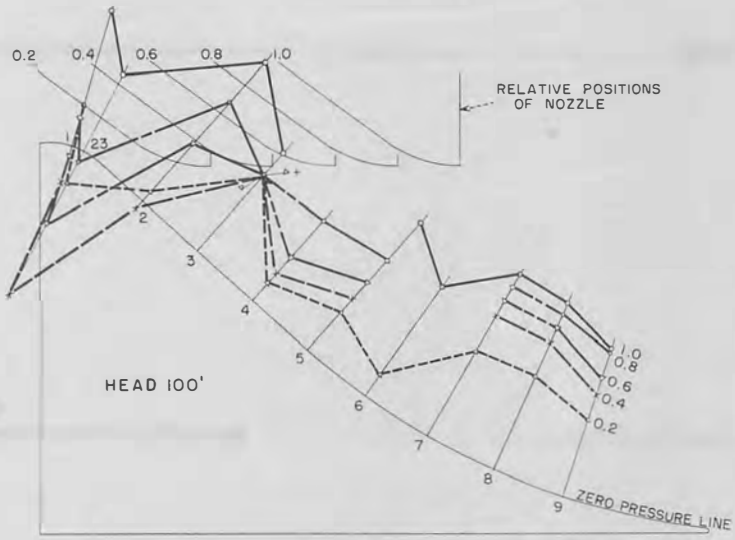
NEEDLE VALVE TESTS

DATA TAKEN FROM $\frac{1}{8}$ SECTIONAL MODEL

PROTOTYPE VALUES

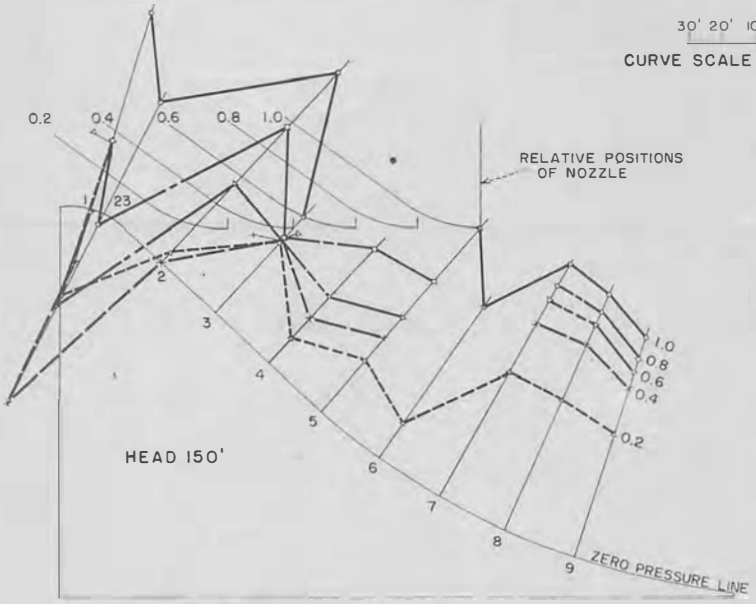
	TEST NUMBER	VALVE OPENING	HEAD	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23
ORIGINAL NEEDLE WITH ROUND NOZZLE	3-NV-A-1	1.0	50	22.38	29.20	39.79	—	28.39	33.47	31.94	30.30	26.57	43.29	37.26	20.84	0.47	25.72	19.12	-0.55	2.47	44.01	42.49	31.82	-6.21	1.56	12.98
	3-NV-A-2	1.0	100	43.13	56.55	39.79	—	51.97	41.01	57.41	55.77	47.32	83.84	73.10	41.59	0.47	50.24	37.98	1.33	1.53	83.63	81.16	59.17	-9.04	1.56	26.19
	3-NV-A-3	1.0	150	63.88	80.13	39.79	—	73.66	55.16	80.99	78.41	69.96	123.46	107.06	61.40	0.47	72.88	55.90	1.33	-47.49	117.58	114.17	84.64	-15.64	2.50	38.45
	3-NV-A-4	.8	50	4.46	21.65	39.79	17.58	20.84	38.18	30.05	29.36	26.57	46.12	37.26	[illegible]	1.41	17.23	14.40	-5.27	-18.28	46.84	43.43	29.93	-12.81	2.50	-4.00
	3-NV-A-5	.8	100	13.89	40.51	30.36	32.67	36.88	—	52.69	52.00	46.38	87.62	[illegible]	[illegible]	1.41	34.21	28.55	-9.04	-33.37	87.40	82.10	53.51	-21.30	2.50	-4.00
	3-NV-A-6	.8	150	22.38	57.49	31.30	47.76	51.97	—	73.44	72.75	63.35	128.17	[illegible]	[illegible]	1.41	44.58	42.70	-8.10	-47.52	125.13	117.00	78.03	-30.73	2.50	-4.00
	3-NV-A-7	.6	50	-3.09	11.28	30.36	9.09	16.13	—	27.22	27.48	19.02	49.89	39.15	8.58	1.41	-2.58	5.91	-8.10	1.53	49.67	46.26	28.04	-18.47	2.50	-15.3
	3-NV-A-8	.6	100	-3.09	23.54	30.36	17.58	27.45	—	47,97	47.28	37.89	92.33	72.16	18.96	1.41	-0.69	13.46	12.82	-15.45	92.12	85.87	49.74	-30.73	3.44	-25.69
	3-NV-A-9	.6	150	1.20	32.97	30.36	27.01	37.82	—	67.78	68.03	58.64	137.61	107.06	27.45	1.41	-5.41	19.12	-25.08	-42.80	136.45	127.38	75.20	-43.93	1.56	-33.24
	3-NV-A-10	.4	50	-10.63	-1.93	30.36	6.26	12.36	—	23.45	23.70	16.19	53.66	46.69	-0.85	2.35	28.55	-12.01	-16.59	1.53	52.50	50.98	31.82	-24.13	-0.33	-29.46
	3-NV-A-11	.4	100	-11.97	-2.87	30.36	10.98	20.84	—	42.31	42.57	33.17	100.82	87.25	1.98	1.41	54.01	-21.44	-20.36	-2.25	99.66	96.25	58.23	-42.05	-2.22	-49.27
	3-NV-A-12	.4	150	-17.24	-0.04	30.36	18.53	29.33	—	60.24	61.43	53.92	149.87	128.75	7.64	1.41	80.42	-16.73	-32.62	-4.13	147.77	145.30	88.36	-59.03	-7.88	-64.36
	3-NV-A-13	.2	50	7.29	1.84	29.41	3.43	8.58	1.40	15.90	18.04	12.42	58.38	57.07	22.73	1.41	54.01	48.36	-0.55	1.53	60.05	59.46	55.40	-5.26	-4.0	-11.54
	3-NV-A-14	.2	100	12.95	3.73	29.41	7.21	15.18	8.00	30.05	31.25	24.68	109.31	106.11	43.48	0.47	99.29	79.48	-1.50	2.47	106.26	106.62	95.95	1.34	-2.05	-11.54
	3-NV-A-15	.2	150	22.38	4.67	29.41	10.04	20.84	12.72	43.26	43.51	39.77	160.24	156.10	65.17	0.47	148.33	117.21	-4.33	0.58	160.03	158.50	142.17	0.40	-5.05	-28.52
ORIGINAL NEEDLE WITH SHARP EDGED NOZZLE	3-NV-B-1	1.0	50	33.70	40.51	38.84	36.45	36.88	37.24	35.71	34.08	36.00	49.67	47.31	37.66	18.50	37.80	34.03	—	18.35	48.66	48.98	42.05	30.43	18.46	29.02
	3-NV-B-2	1.0	100	62.94	74.47	73.74	69.46	68.00	67.42	65.89	60.49	57.69	93.06	88.81	70.67	33.59	70.81	63.27	—	33.44	92.99	92.37	79.78	57.79	34.50	54.48
	3-NV-B-3	1.0	150	92.17	107.48	106.75	101.53	99.13	97.60	94.19	87.84	81.27	137.39	129.37	101.79	48.68	102.88	91.56	—	48.54	134.49	134.81	114.67	83.25	49.59	78.06
	3-NV-B-4	.8	50	21.43	33.91	32.24	27.96	29.33	31.58	31.94	31.25	29.40	51.56	47.31	33.88	15.67	31.20	30.25	—	16.47	51.49	50.87	40.16	26.66	15.63	16.75
	3-NV-B-5	.8	100	40.30	61.26	57.71	50.59	51.97	54.22	54.58	53.88	51.09	94.95	86.93	62.18	27.93	57.61	54.78	—	29.67	93.93	92.37	73.17	49.30	28.84	30.90
	3-NV-B-6	.8	150	61.05	91.45	86.95	77.00	75.55	78.74	79.10	77.46	73.73	141.16	128.43	91.42	42.08	85.90	81.19	—	43.82	140.15	137.64	108.07	72.88	42.98	45.99
	3-NV-B-7	.6	50	13.89	26.37	22.81	17.58	20.84	24.98	28.17	27.48	26.57	53.45	48.25	29.17	11.89	17.05	22.71	—	12.69	52.43	51.81	38.28	21.95	11.86	8.27
	3-NV-B-8	.6	100	28.98	49.00	42.62	34.56	37.82	44.78	48.92	49.17	47.32	98.72	89.76	53.69	22.27	31.20	40.63	—	24.01	99.59	96.14	71.29	40.81	23.18	5.81
	3-NV-B-9	.6	150	45.01	72.58	53.94	51.54	53.86	63.65	67.78	69.92	68.07	145.88	133.14	81.04	33.59	49.12	57.61	—	35.33	146.75	143.30	107.13	61.56	34.50	25.24
	3-NV-B-10	.4	50	8.23	16.93	10.55	8.15	14.24	21.20	24.39	24.65	24.68	56.28	52.97	24.45	7.18	37.80	8.56	—	7.98	56.20	55.58	43.93	14.40	7.14	-2.11
	3-NV-B-11	.4	100	15.78	32.03	20.92	15.70	24.62	36.30	43.26	42.57	42.60	107.21	99.19	47.09	14.72	69.87	15.17	—	14.58	105.25	102.74	81.66	22.29	15.63	-0.22
	3-NV-B-12	.4	150	29.92	47.12	31.30	23.24	34.05	51.39	60.24	60.49	59.58	153.42	145.40	70.67	21.33	103.82	23.65	—	22.13	153.35	152.73	121.28	44.58	23.18	0.72
	3-NV-B-13	.2	50	23.32	12.22	5.83	4.38	7.64	11.77	15.90	19.93	19.97	60.05	59.57	42.37	3.41	57.61	10.45	—	5.15	59.98	60.30	58.08	15.34	8.09	0.72
	3-NV-B-14	.2	100	44.07	24.48	10.55	9.09	13.30	17.43	23.45	33.13	34.11	110.04	108.62	78.21	8.12	103.82	18.94	—	12.69	110.91	110.29	105.24	29.49	15.63	4.49
	3-NV-B-15	.2	150	63.88	36.74	17.15	16.64	17.07	22.15	31.00	35.02	49.20	160.03	158.61	115.00	15.67	151.93	26.48	—	19.30	159.96	160.28	152.40	45.53	24.12	12.98
30° NEEDLE WITH ROUND NOZZLE	4-NV A-1	1.0	50	38.09	40.95	34.53	33.91	27.53	19.25	13.95	14.28	15.54	47.06	42.92	22.73	0.47	29.49	21.95	-1.50	-19.22	47.79	47.20	34.65	-6.21	2.50	—
	4-NV-A-2	1.0	100	70.16	76.80	65.66	64.09	52.99	38.12	28.10	26.54	27.81	91.39	80.65	44.42	0.47	57.79	43.64	-1.50	-34.32	91.17	88.70	66.72	-8.09	1.56	—
	4-NV-A-3	1.0	150	104.11	113.58	96.78	94.28	77.52	55.09	41.31	37.86	36.30	134.78	118.38	66.12	0.47	85.14	63.45	0.55	-48.46	133.62	129.26	97.84	-11.87	1.56	—
	4-NV-A-4	.8	50	34.32	35.29	29.82	26.37	17.15	9.82	9.24	[illegible]	[illegible]	51.78	44.81	21.79	1.41	[illegible]	21.00	-6.21	-19.22	51.56	50.03	35.59	-7.15	2.50	—
	4-NV-A-5	.8	100	65.44	65.48	57.17	50.89	33.18	19.25	16.78	[illegible]	[illegible]	95.16	83.48	42.54	0.47	[illegible]	40.81	-6.21	-33.37	95.89	91.53	65.77	-9.98	1.56	—
	4-NV-A-6	.8	150	96.57	96.60	84.52	75.41	49.22	27.44	23.39	[illegible]	[illegible]	141.38	123.09	63.29	0.47	[illegible]	61.56	-9.99	-51.29	142.11	135.86	97.84	-18.47	1.56	—
	4-NV-A-7	.6	50	32.43	33.41	24.16	16.93	4.89	-4.33	-3.02	7.68	10.83	36.68	48.58	20.84	1.41	27.60	19.12	-5.27	-19.22	55.33	52.86	37.48	-7.15	2.50	—
	4-NV-A-8	.6	100	60.72	61.70	45.85	32.97	11.49	8.88	10.18	12.39	16.49	101.76	89.14	41.59	0.47	53.07	37.98	-6.21	-32.43	101.55	99.08	69.54	-9.04	1.56	—
	4-NV-A-9	.6	150	89.96	92.83	70.37	50.89	18.09	13.59	14.90	16.16	20.26	149.87	131.58	61.40	0.47	78.54	59.67	-8.10	-45.63	148.71	145.30	104.44	-15.64	1.56	—
	4-NV-A-10	.4	50	34.32	35.29	20.38	7.50	3.95	4.16	4.52	5.79	8.00	57.43	54.24	28.39	1.41	41.75	25.72	5.10	-4.13	58.16	57.58	46.91	-2.43	2.50	—
	4-NV-A-11	.4	100	56.95	60.76	29.82	5.62	4.89	7.93	6.41	8.62	9.89	105.54	99.51	48.20	-0.48	70.99	41.75	4.33	-0.36	106.26	104.74	82.75	-9.98	1.56	—
	4-NV-A-12	.4	150	83.36	90.00	43.02	6.56	4.89	9.82	8.29	9.56	10.83	156.47	145.73	68.00	0.47	100.23	61.56	-8.10	0.58	158.14	154.77	121.42	-9.04	2.50	—
	4-NV-A-13	.2	50	35.26	37.18	44.91	1.84	3.00	[illegible]	2.64	2.96	4.23	58.38	58.01	42.54	0.47	56.84	42.70	3.22	-1.30	59.10	59.46	55.40	-3.38	3.44	—
	4-NV-A-14	.2	100	65.44	[illegible]	14.72	5.62				5.79	6.11	111.20	110.83	80.27	0.47	107.78	82.31	6.05	-5.08	110.98	110.40	103.50	-4.32	3.44	—
	4-NV-A-15	.2	150	96.57	[illegible]	22.27	8.45	[illegible]	[illegible]	[illegible]	7.68	8.00	62.13	160.82	117.99	-0.48	156.82	120.04	-0.55	-8.85	162.86	162.27	151.60	-6.21	4.38	—
30° NEEDLE WITH SHARP EDGED NOZZLE	4-NV-B-1	1.0	50	45.63	48.50	43.96	44.29	38.84	31.51	23.39	18.99	17.43	53.45	51.08	40.49	17.55	41.57	35.91	—	17.41	52.43	52.75	45.82	31.38	17.52	—
	4-NV-B-2	1.0	100	83.36	88.11	81.69	81.07	71.86	57.92	43.19	34.08	30.64	98.72	94.47	73.50	32.64	76.47	66.10	—	32.50	97.70	97.08	84.49	57.79	33.55	—
	4-NV-B-3	1.0	150	122.03	128.67	119.42	117.86	104.87	85.28	63.00	48.23	41.95	144.94	137.86	108.40	47.74	111.37	97.22	—	48.53	142.98	142.36	124.11	85.14	49.59	—
	4-NV-B-4	.8	50	44.69	43.78	41.13	39.57	33.19	23.03	14.90	13.33	13.66	54.39	51.08	39.54	16.61	40.63	35.91	—	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—
	4-NV-B-5	.8	100	82.42	80.57	76.98	72.58	60.54	41.83	27.16	21.82	22.15	101.55	95.41	73.50	30.76	74.59	66.10	—	32.50	100.53	98.97	85.44	56.84	32.61	—
	4-NV-B-6	.8	150	120.15	118.30	112.82	107.48	88.83	61.70	40.36	31.26	27.81	146.82	139.75	107.45	44.91	109.48	96.28	—	47.59	146.75	145.19	125.05	83.25	39.56	—
	4-NV-B-7	.6	50	43.75	43.78	38.30	33.91	21.87	10.76	7.35	8.62	9.89	57.22	53.91	40.49	15.67	40.63	34.97	—	16.47	56.20	56.53	48.65	30.43	16.57	—
	4-NV-B-8	.6	100	79.59	79.63	70.37	62.21	39.79	19.25	13.01	12.39	14.60	104.38	99.19	73.50	28.87	74.59	63.27	—	29.67	104.31	103.69	88.27	55.90	30.72	—
	4-NV-B-9	.6	150	117.32	117.35	104.33	92.39	59.59	29.63	18.67	16.16	17.43	155.31	147.29	109.34	43.96	109.48	96.28	—	43.82	155.24	153.68	131.65	83.25	45.81	—
	4-NV-B-10	.4	50	44.91	45.67	37.36	27.31	8.66	4.16	3.58	5.79	8.00	58.16	56.74	44.26	16.61	48.18	39.69	—	17.41	58.09	57.47	52.42	32.32	16.57	—
	4-NV-B-11	.4	100	83.36	84.34	70.37	50.89	17.15	6.99	5.47	8.62	11.77	108.15	106.73	82.93	30.76	88.73	81.19	—	32.50	108.08	108.40	98.64	61.56	32.61	—
	4-NV-B-12	.4	150	122.03	123.96	103.39	75.41	24.70	8.88	6.41	11.45	16.49	59.08	155.78	121.60	46.79	129.29	106.65	—	47.59	159.01	158.39	144.86	89.86	48.64	—
	4-NV-B-13	.2	50	50.35	51.33	38.30	8.45	2.06	2.28	2.64	2.96	4.23	60.99	60.52	55.58	19.44	60.44	51.95	—	23.07	59.98	60.30	59.97	40.81	20.35	—
	4-NV-B-14	.2	100	89.96	91.89	68.49	15.99	3.95	3.22	3.58	4.85	6.11	109.09	108.62	98.96	35.47	106.65	92.51	—	39.10	109.02	109.35	107.13	72.88	37.33	—
	4-NV-B-15	.2	150	134.29	137.16	103.39	24.48	4.89	4.16	3.58	5.79	7.06	163.80	164.27	148.95	54.34	161.36	139.67	—	65.51	164.67	165.00	160.89	110.61	56.19	—





30' 20' 10' 0' 30' 60'

CURVE SCALE - 1" = 30' OF WATER PRESSURE



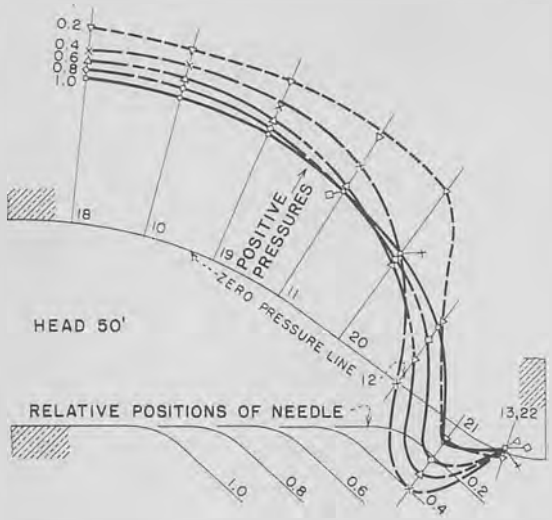
DIAGRAMMATIC ASSEMBLY OF PRESSURES MEASURED ON NEEDLE

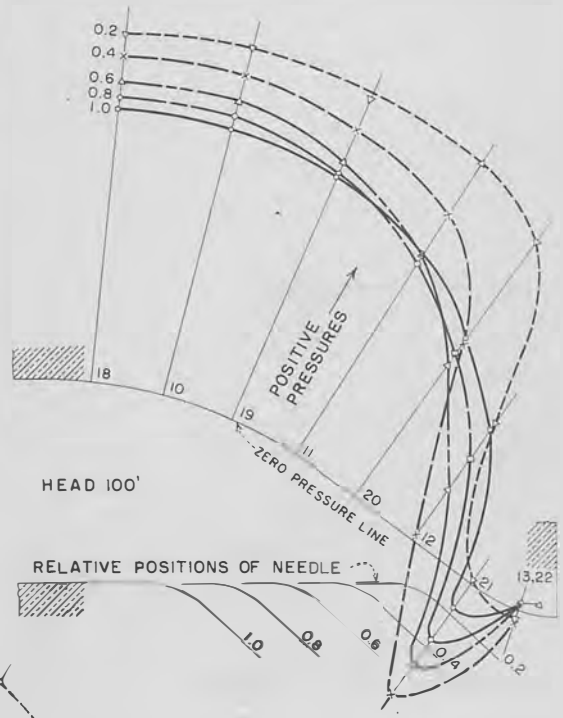
TEST 3-NV-A

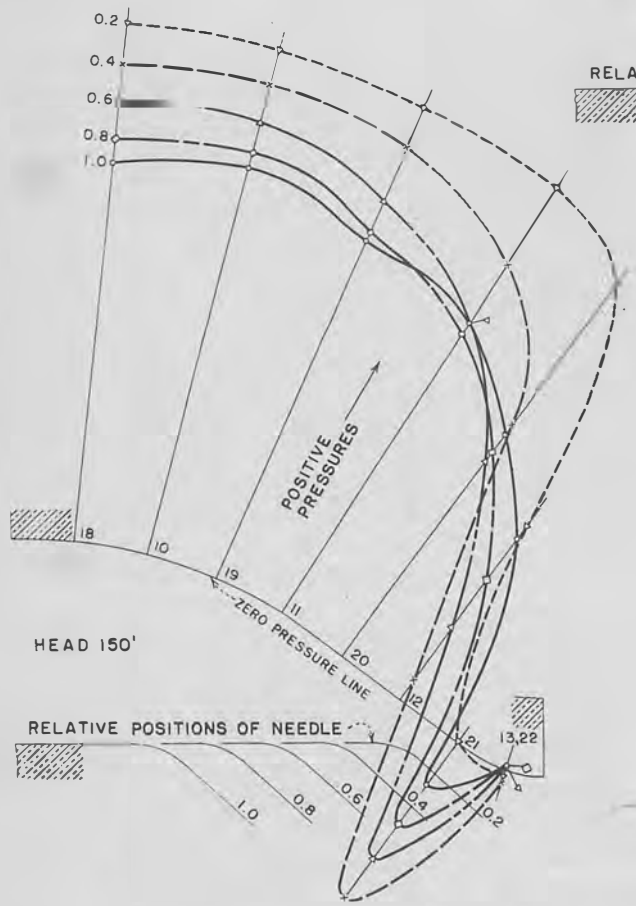
ORIGINAL NEEDLE WITH ROUND NOZZLE

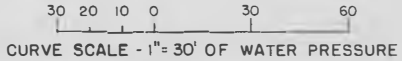
NEEDLE VALVE TESTS

W.A.H. 11-17-38









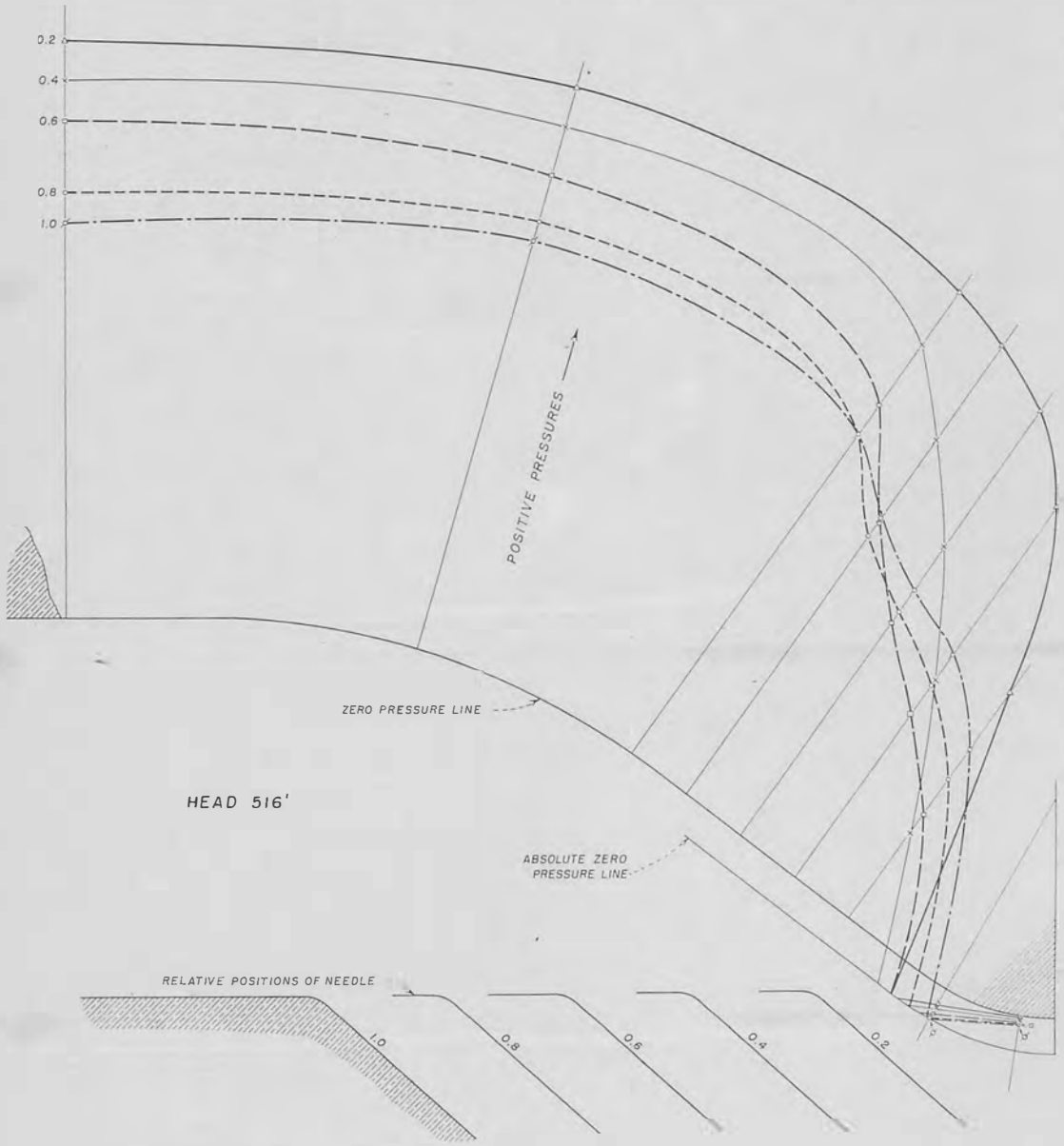
DIAGRAMMATIC ASSEMBLY OF PRESSURES MEASURED ON NOZZLE

TEST 3-NV-A

ORIGINAL NEEDLE WITH ROUND NOZZLE

NEEDLE VALVE TESTS

W.A.H 11-29-38



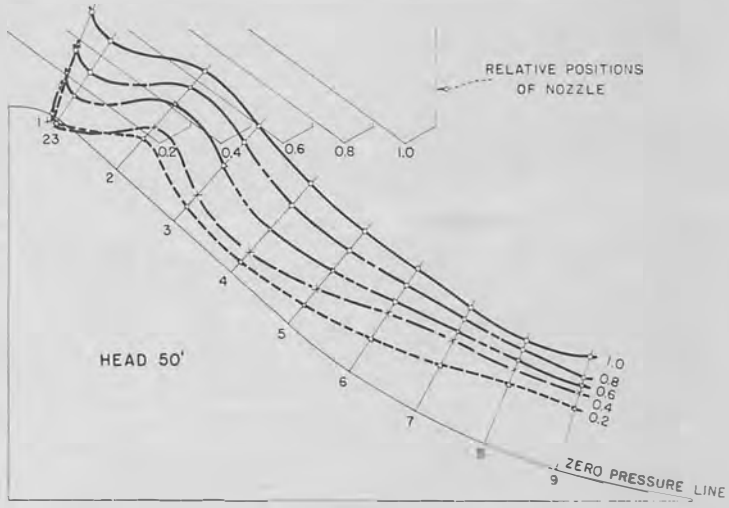
60 60 120
CURVE SCALE 1" = 60' OF WATER PRESSURE

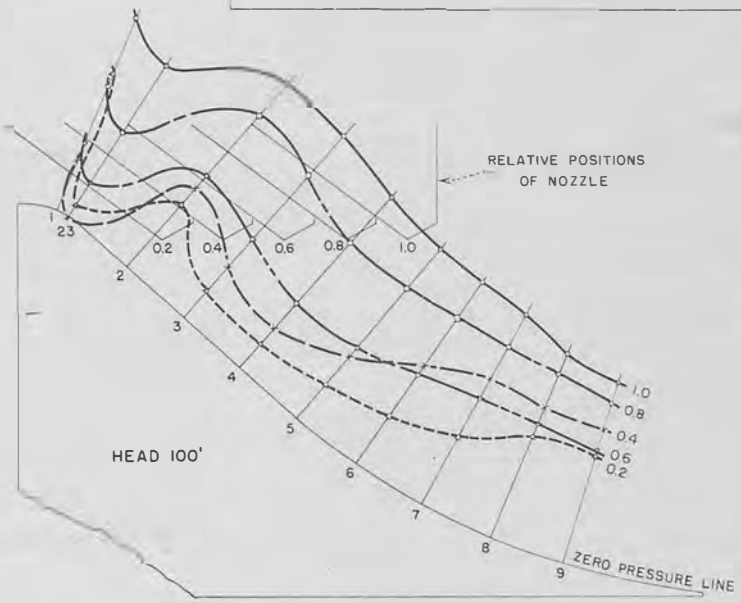
DIAGRAMMATIC ASSEMBLY OF
AVERAGE PRESSURES MEASURED ON NOZZLE
OF 72-INCH VALVES AT BOULDER DAM

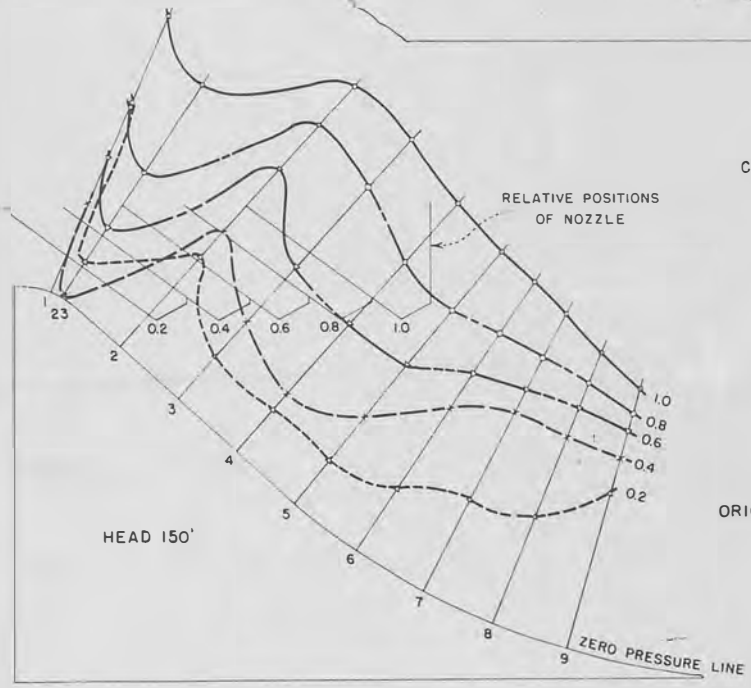
ORIGINAL NEEDLE WITH ROUND-EDGED NOZZLE

NEEDLE VALVE TESTS

H.M.M. 9-24-40







30' 20' 10' 0' 30' 60'

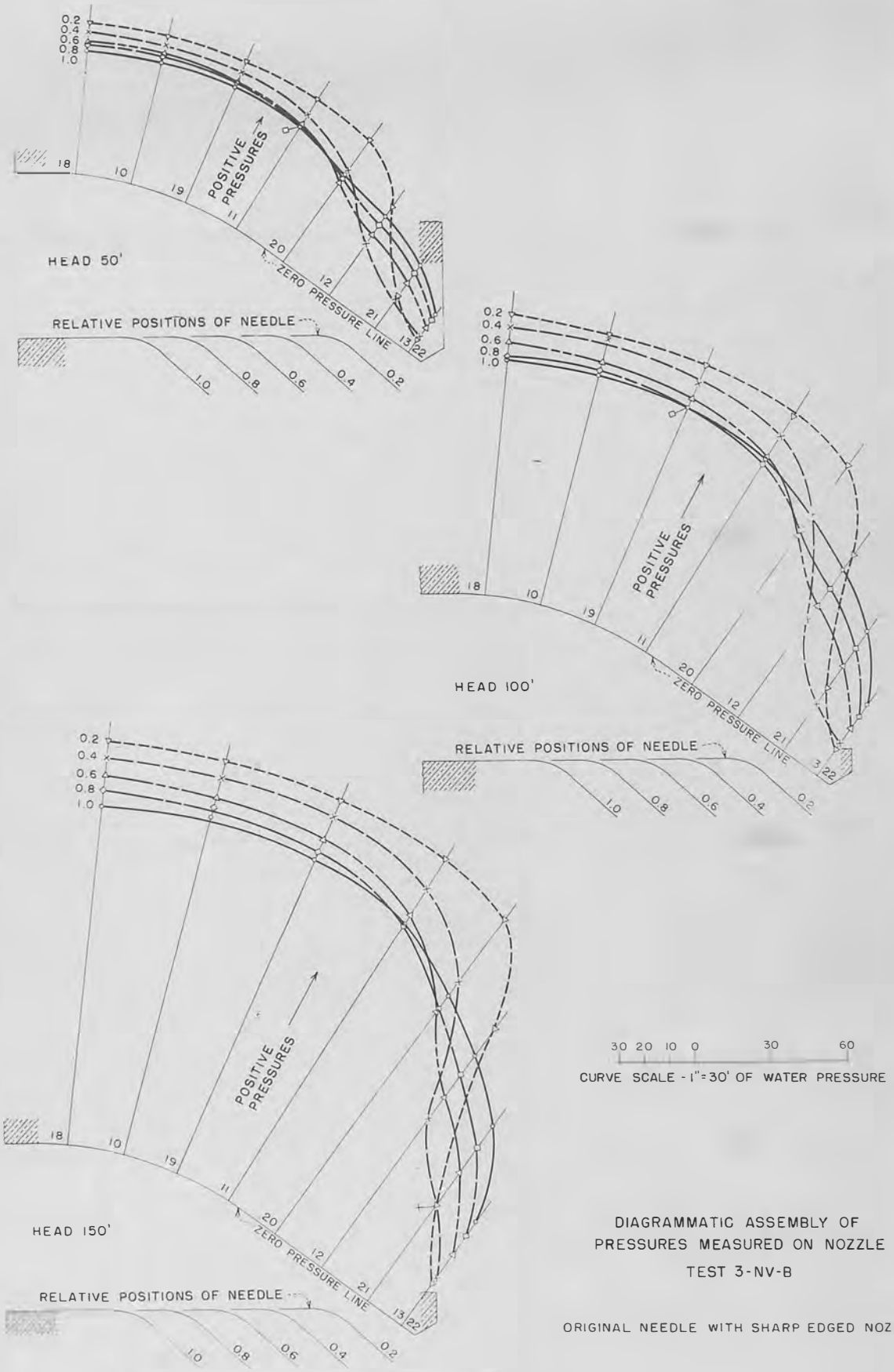
CURVE SCALE - 1" = 30' OF WATER PRESSURE

DIAGRAMMATIC ASSEMBLY OF
PRESSURES MEASURED ON NEEDLE
TEST 3-NV-B

ORIGINAL NEEDLE WITH SHARP EDGED NOZZLE

NEEDLE VALVE TESTS

W. A. H. 11-23-38



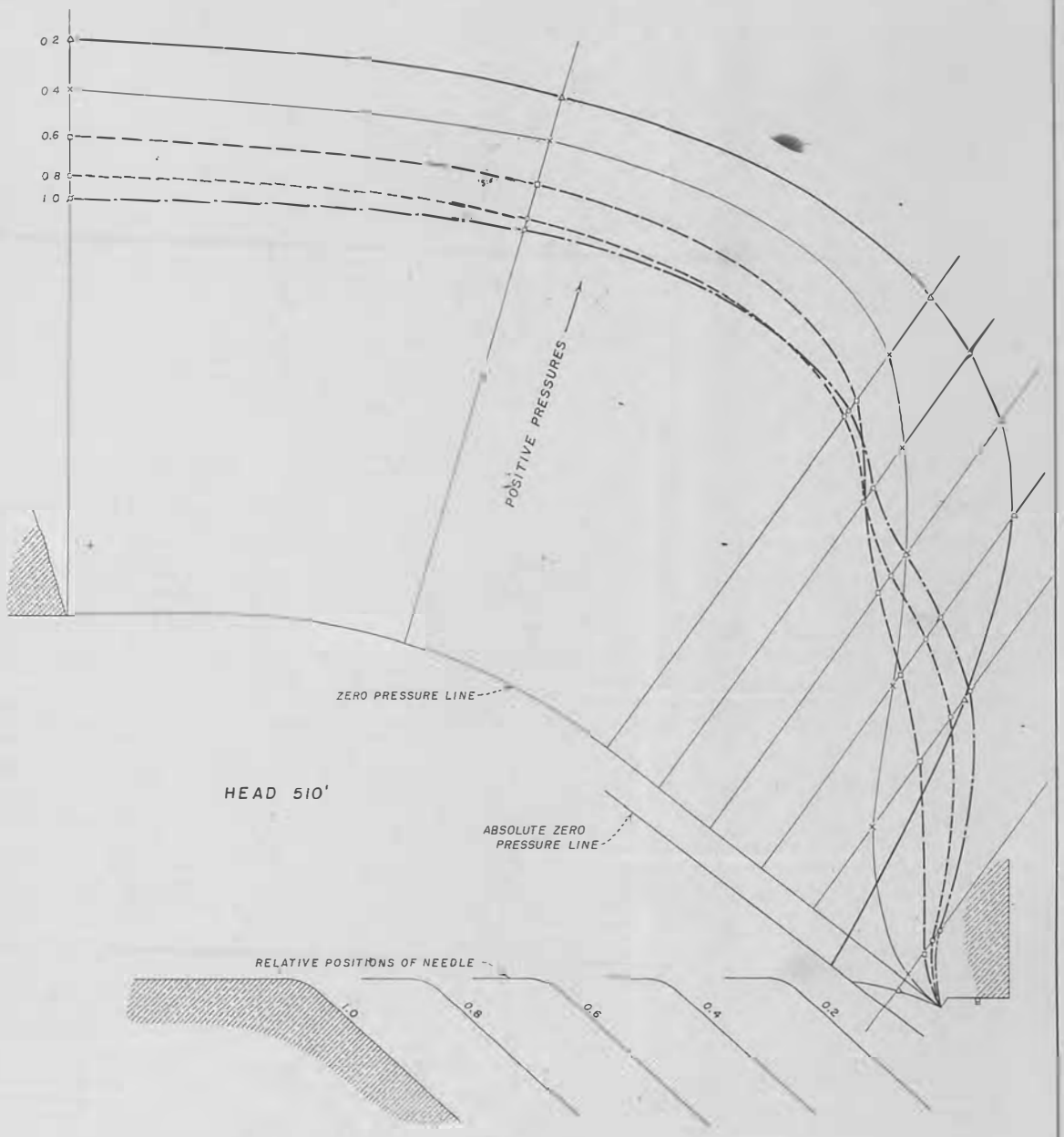
DIAGRAMMATIC ASSEMBLY OF PRESSURES MEASURED ON NOZZLE

TEST 3-NV-B

ORIGINAL NEEDLE WITH SHARP EDGED NOZZLE

NEEDLE VALVE TESTS

W A H 12-2-38



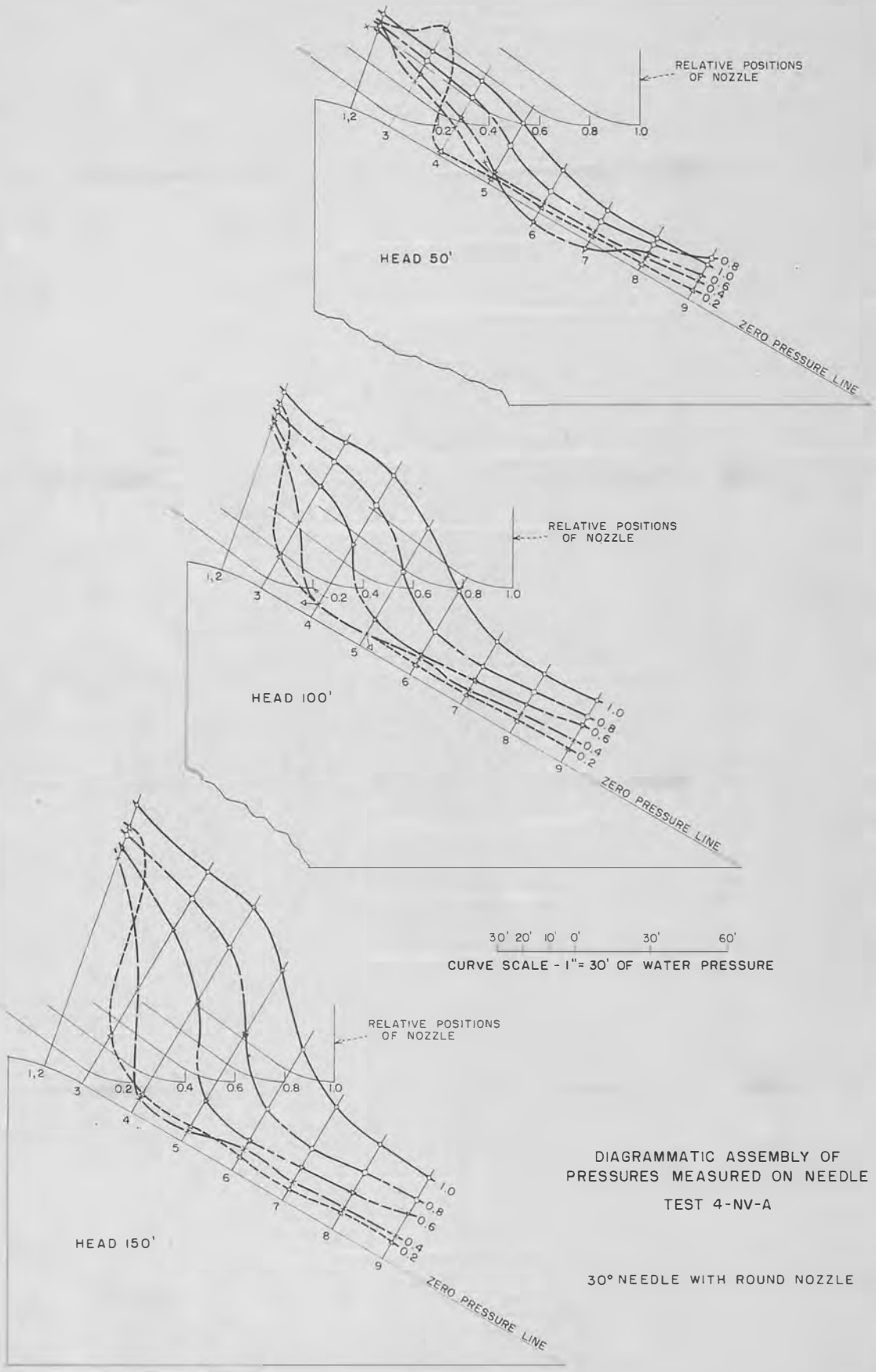
60 0 60 120
CURVE SCALE 1" = 60' OF WATER PRESSURE

DIAGRAMMATIC ASSEMBLY OF
AVERAGE PRESSURES MEASURED ON NOZZLE
OF 72-INCH VALVES AT BOULDER DAM

ORIGINAL NEEDLE WITH SHARP NOZZLE

NEEDLE VALVE TESTS

H.M.M. 9-24-40



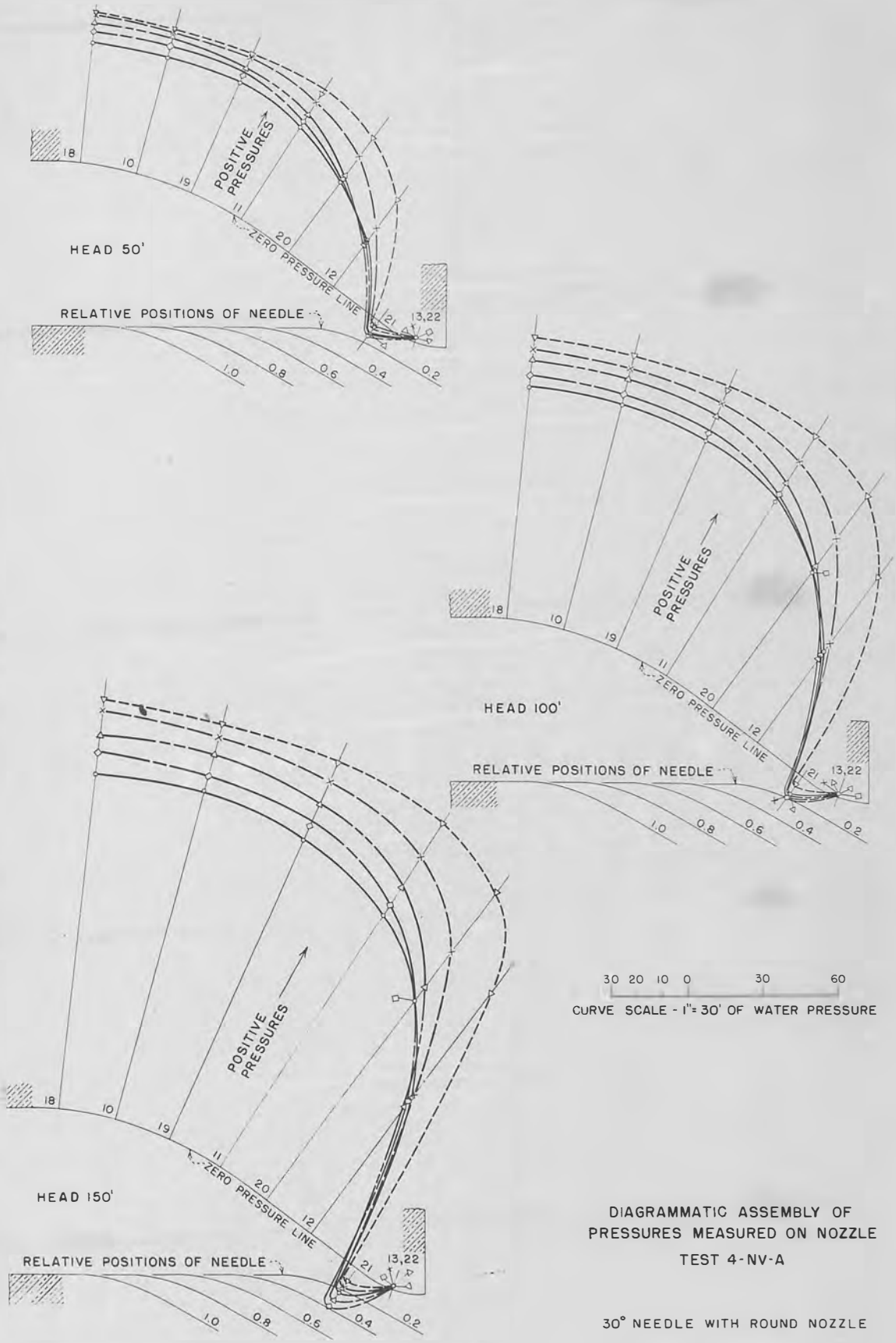
DIAGRAMMATIC ASSEMBLY OF PRESSURES MEASURED ON NEEDLE

TEST 4-NV-A

30° NEEDLE WITH ROUND NOZZLE

NEEDLE VALVE TESTS

W.A.H. 11-19-38



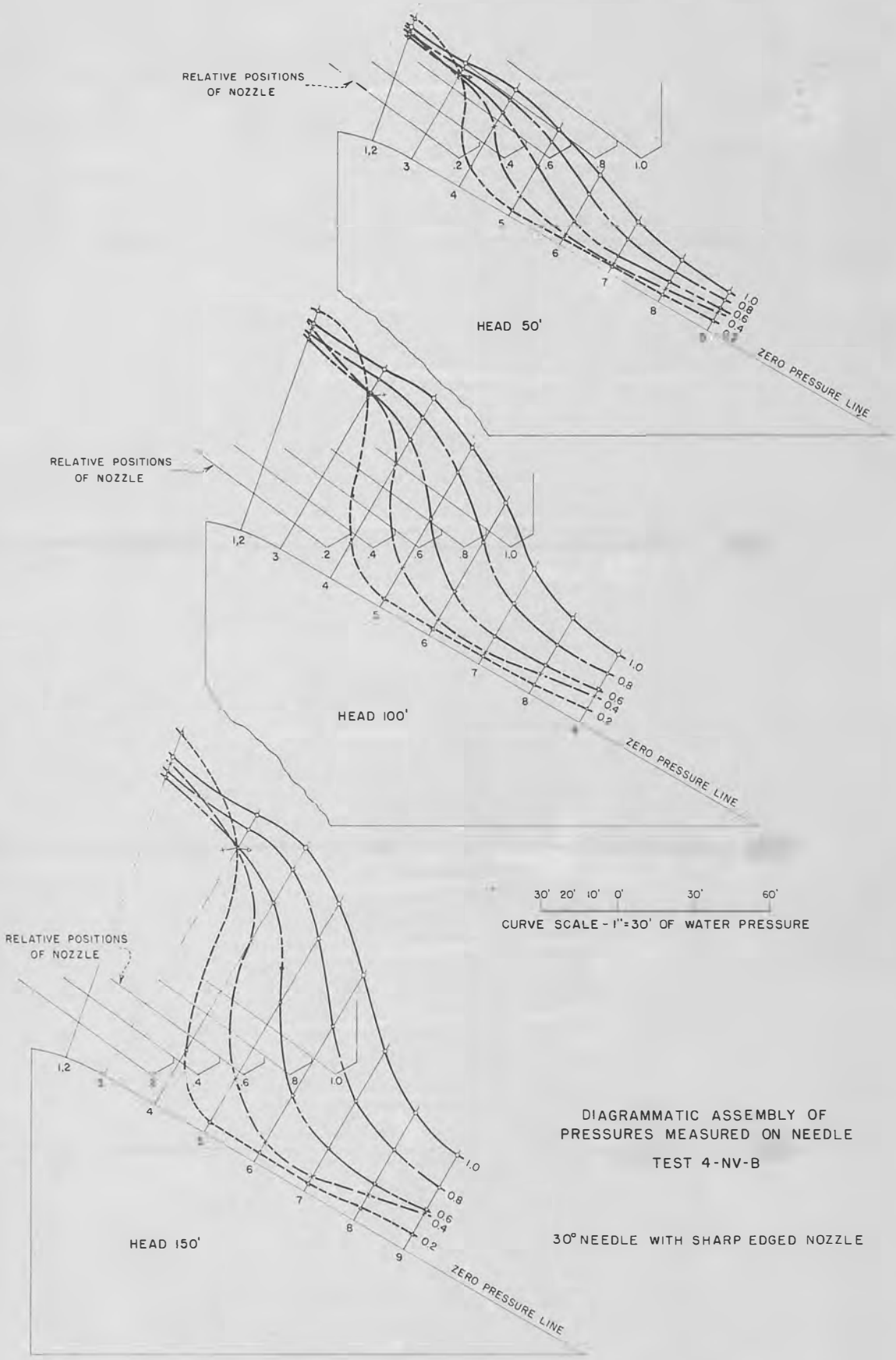
DIAGRAMMATIC ASSEMBLY OF PRESSURES MEASURED ON NOZZLE

TEST 4-NV-A

30° NEEDLE WITH ROUND NOZZLE

NEEDLE VALVE TESTS

W.A.H. 12-1-38



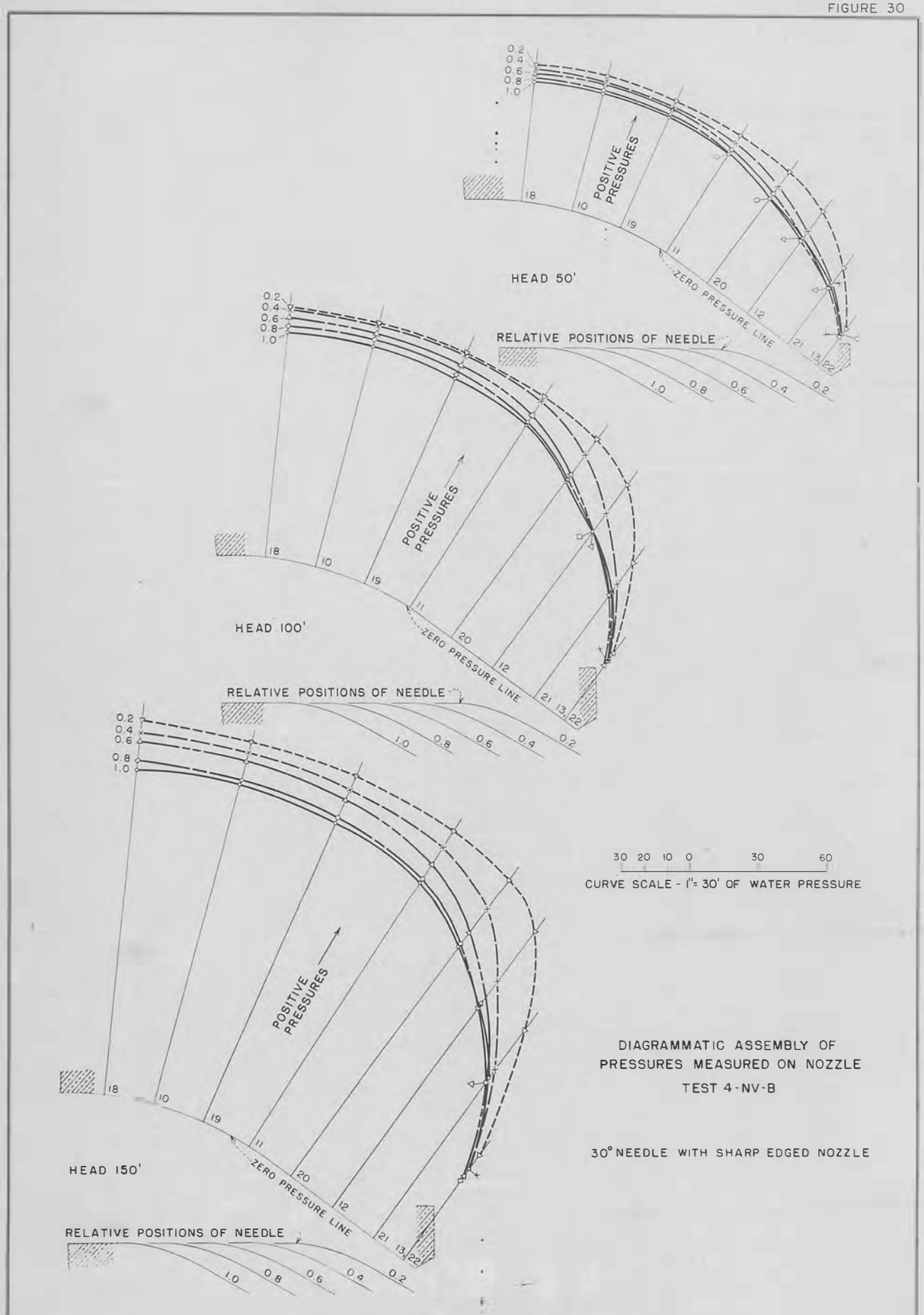
DIAGRAMMATIC ASSEMBLY OF PRESSURES MEASURED ON NEEDLE

TEST 4-NV-B

30° NEEDLE WITH SHARP EDGED NOZZLE

NEEDLE VALVE TESTS

W. A. H. 11-14-38



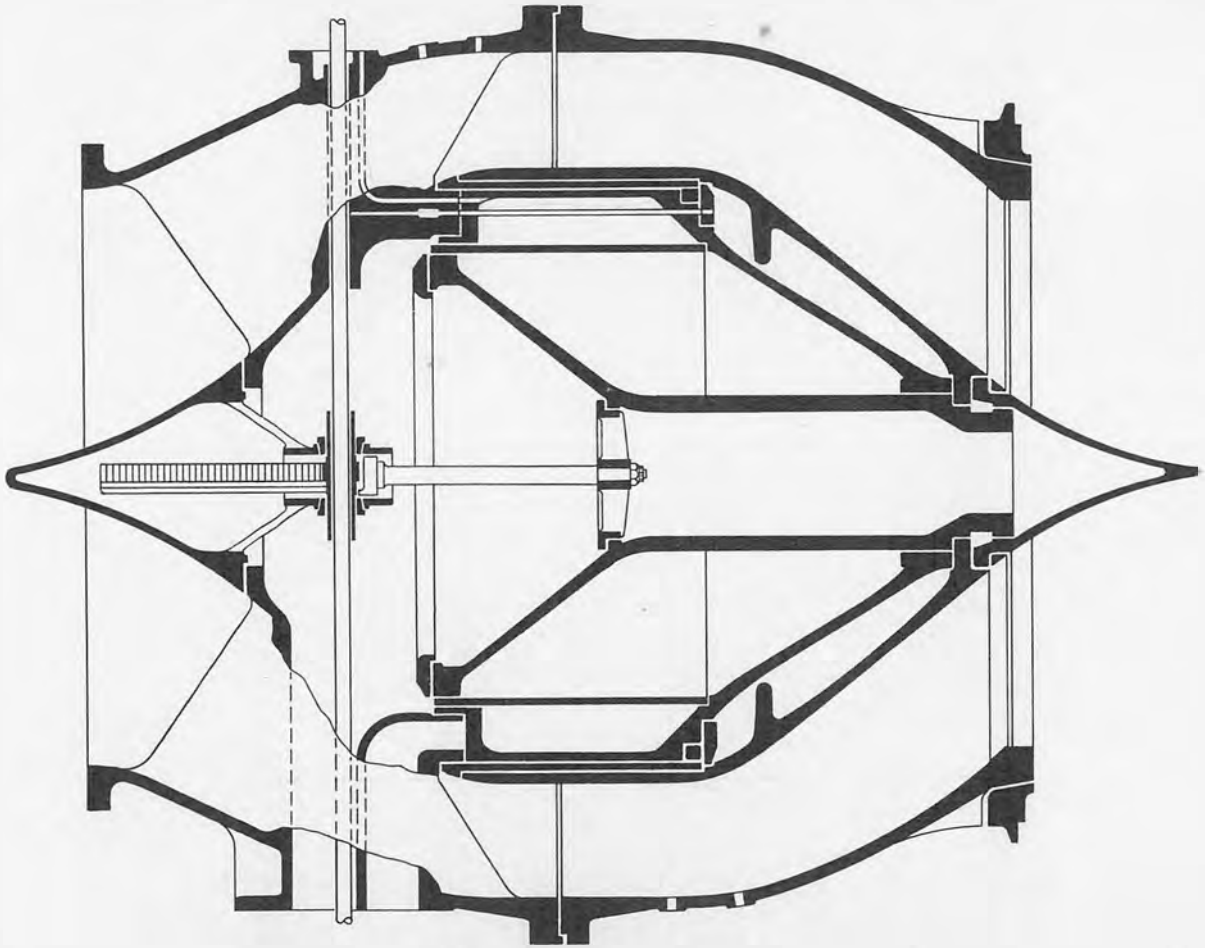
DIAGRAMMATIC ASSEMBLY OF PRESSURES MEASURED ON NOZZLE

TEST 4-NV-B

30° NEEDLE WITH SHARP EDGED NOZZLE

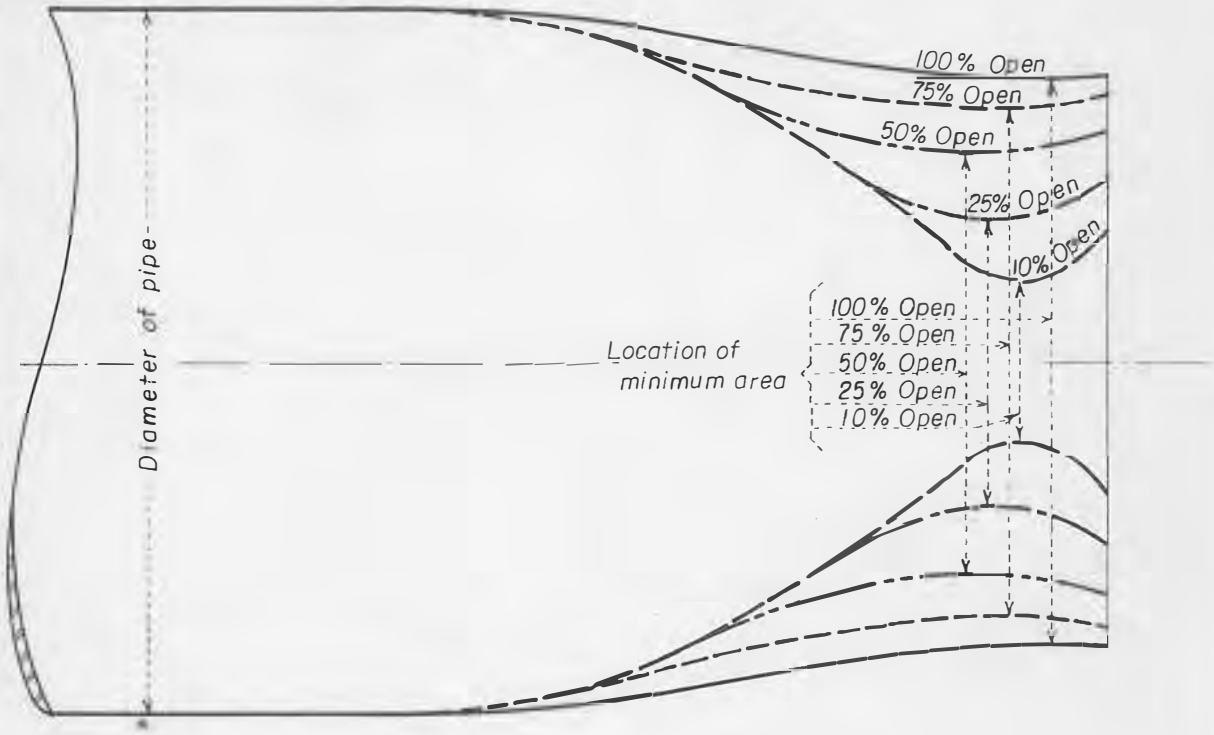
NEEDLE VALVE TESTS

W.A.H 11-26-38

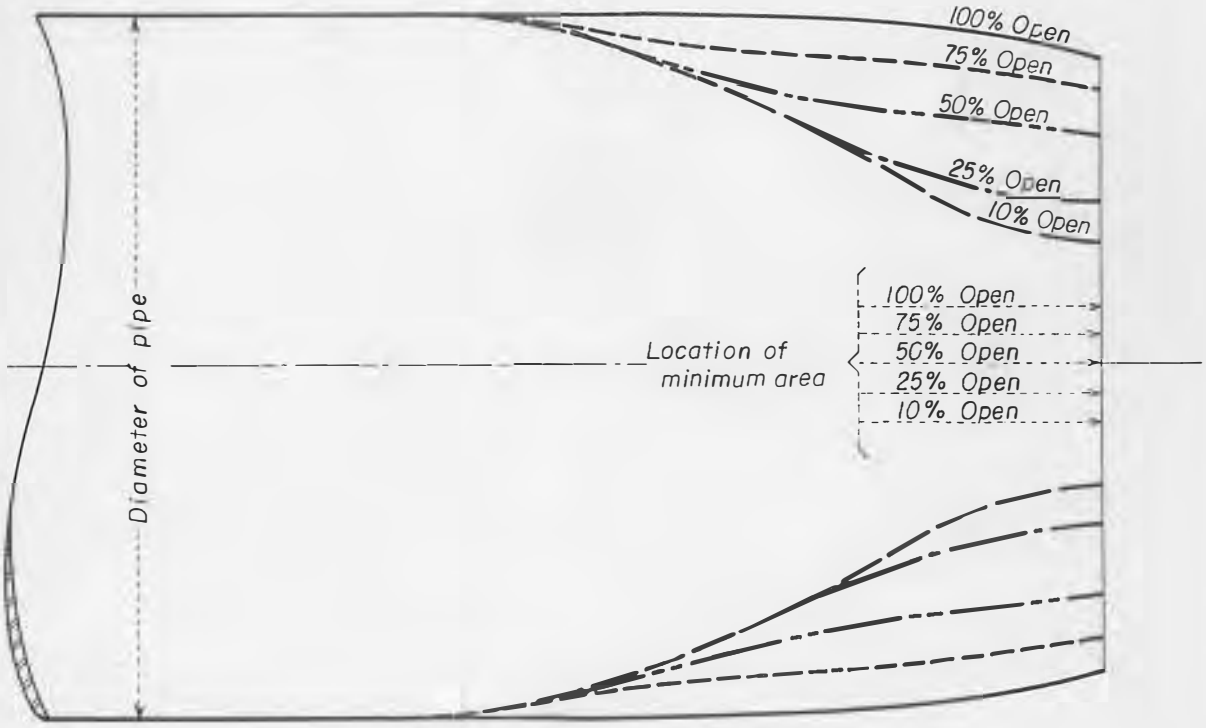


INTERIOR DIFFERENTIAL NEEDLE VALVE
REVISED WATER PASSAGES

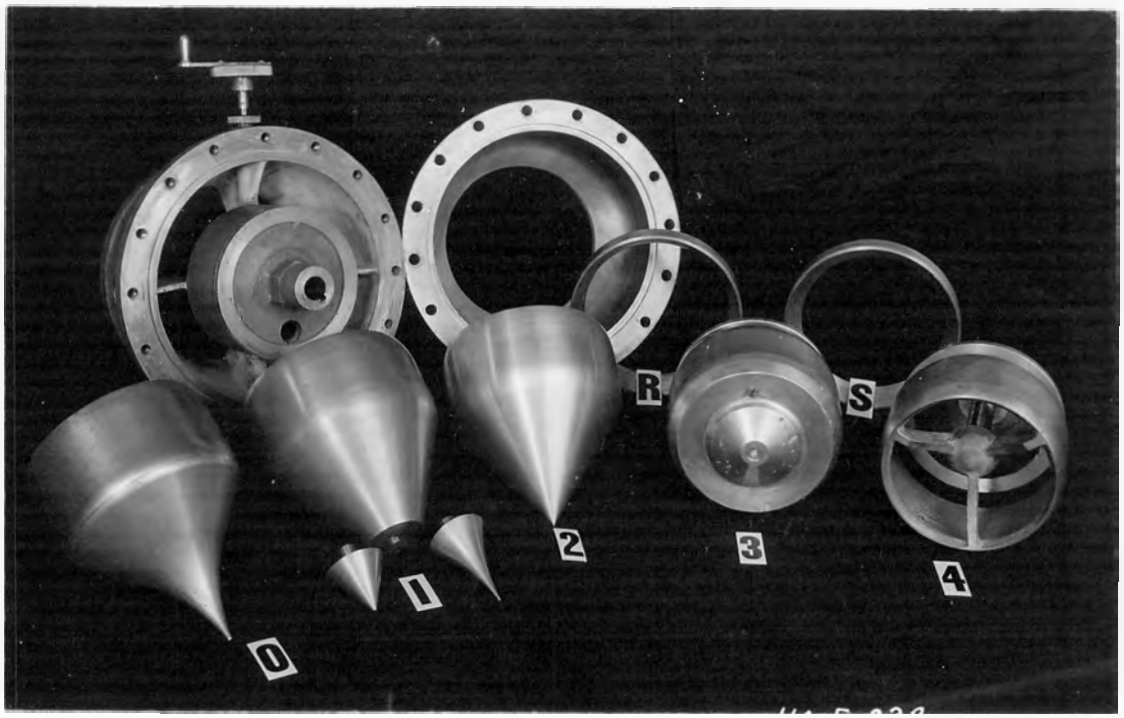
FIGURE 31



CIRCULAR NOZZLE WITH AREAS EQUIVALENT TO ORIGINAL "INTERIOR" TYPE NEEDLE VALVE

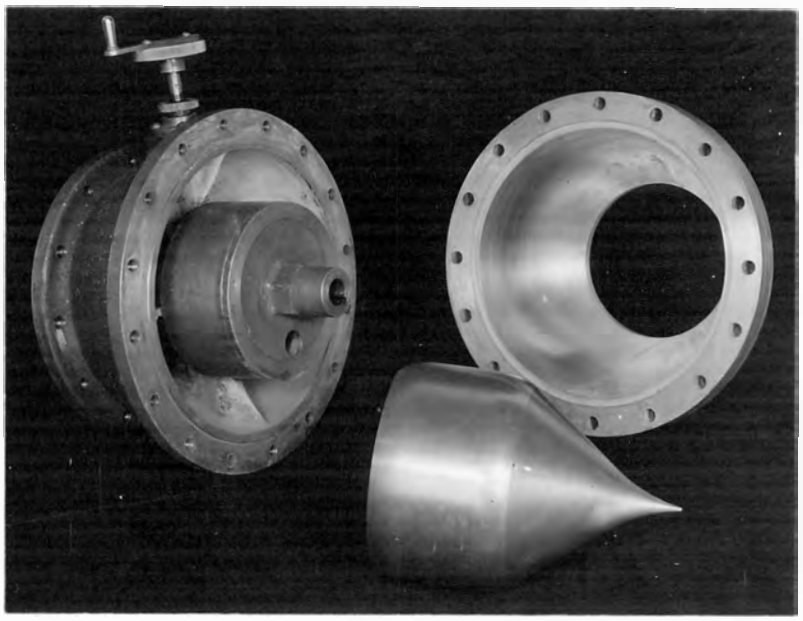


CIRCULAR NOZZLE WITH AREAS EQUIVALENT TO REVISED "INTERIOR" TYPE NEEDLE VALVE

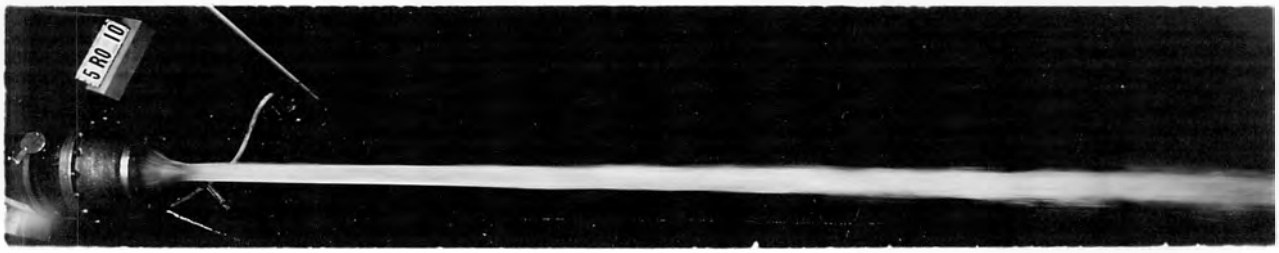


NEEDLE-VALVE TESTS
Interior-Type Needle-Valve Body

0 - Original 42° Needle.
1 - Cone 30° Needle with Alternate Tips.
2 - Cone 36°-22' Needle.
3 - Tube Valve (Closed Type).
4 - Tube Valve (Open Type).
R - Round-Edged Nozzle Insert.
S - Sharp-Edged Nozzle Insert.



NEEDLE-VALVE TEST
Proposed Shasta Needle-Valve Design



10% OPEN P.H.-54.53 Q-0.60

25% OPEN P.H.-46.60 Q-1.82

50% OPEN P.H.-27.62 Q-3.40

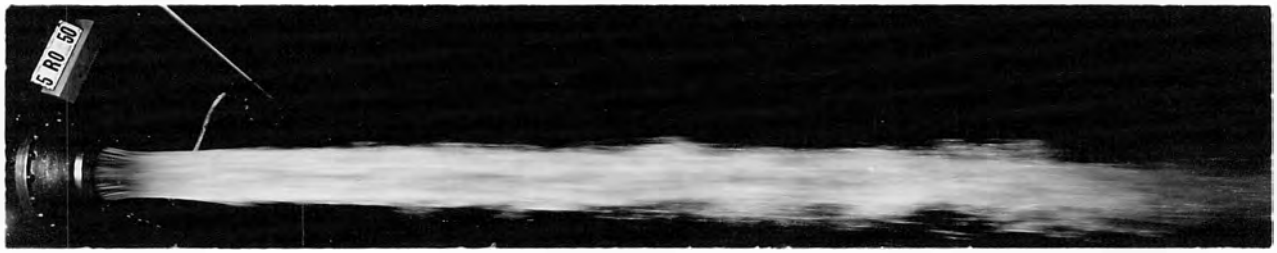
75% OPEN P.H.-19.67 Q-3.95

100% OPEN P.H.-17.98 Q-4.12

NEEDLE-VALVE TESTS
Original 42° Needle with Round-edged Nozzle

50% OPEN P.H.-11.75 Q-2.02

50% OPEN P.H.-19.40 Q-2.74

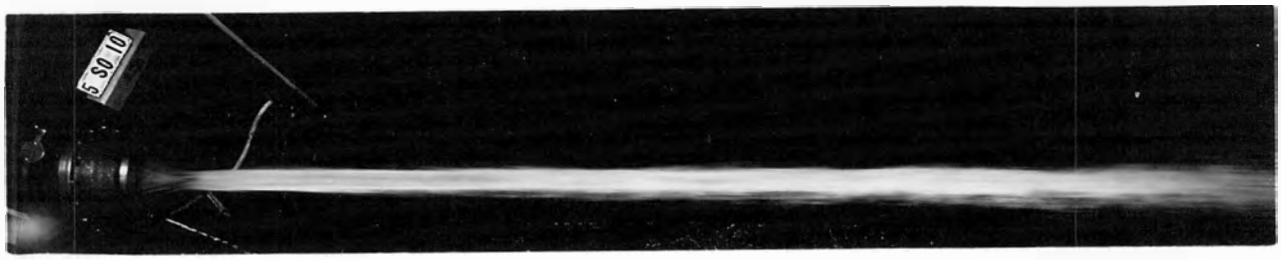


50% OPEN P.H.-27.62 Q-3.40

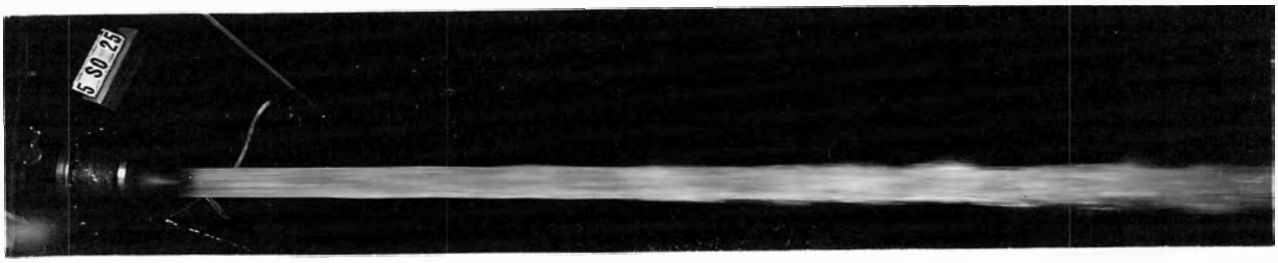
50% OPEN P.H.-39.23 Q-4.02

50% OPEN P.H.-56.20 Q-4.75

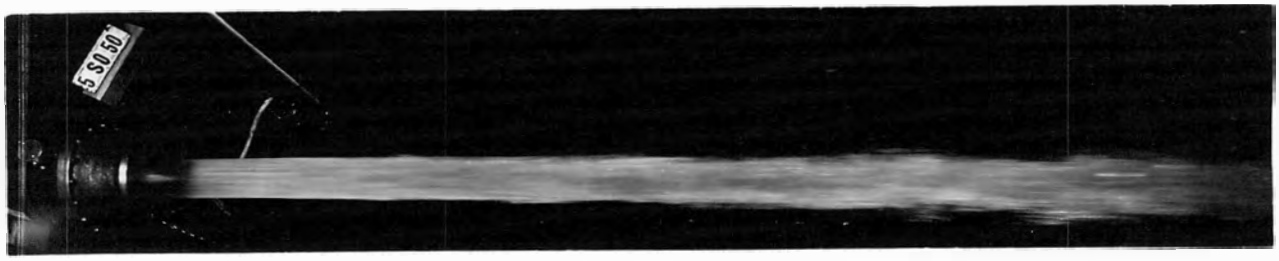
NEEDLE-VALVE TESTS
Original 42° Needle with Round-edged Nozzle



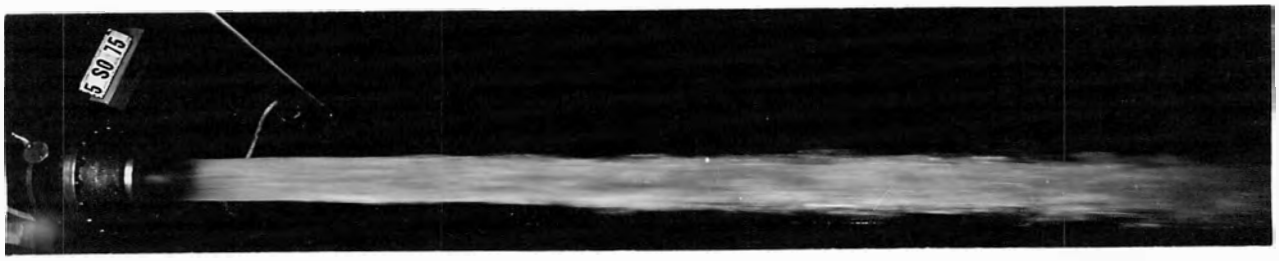
10% OPEN P.H.-54.30 Q-0.60



25% OPEN P.H.-45.47 Q-1.92



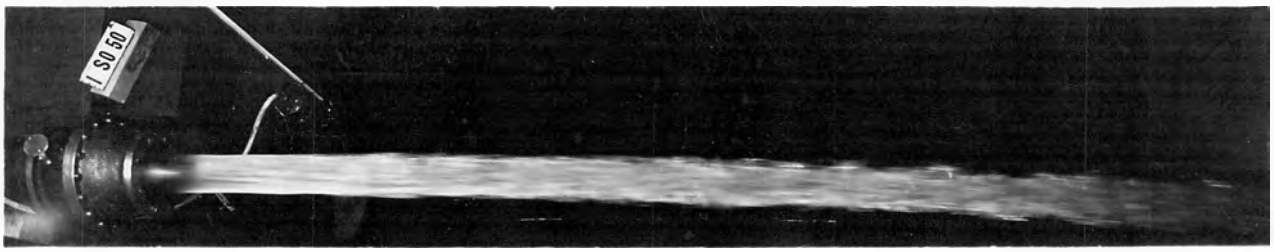
50% OPEN P.H.-33.00 Q-3.02



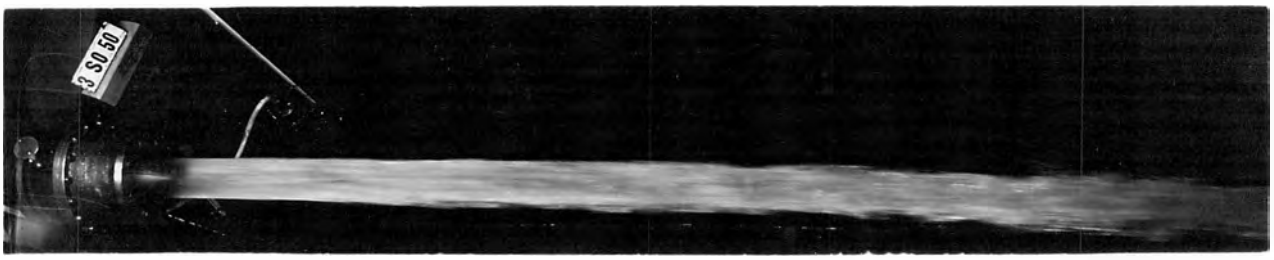
75% OPEN P.H.-26.20 Q-3.52

100% OPEN P.H.-22.80 Q-3.78

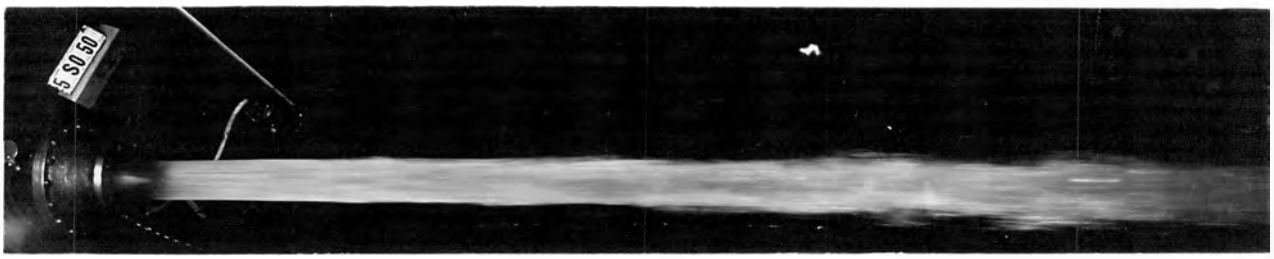
NEEDLE-VALVE TESTS
Original 42° Needle with Sharp-edged Nozzle



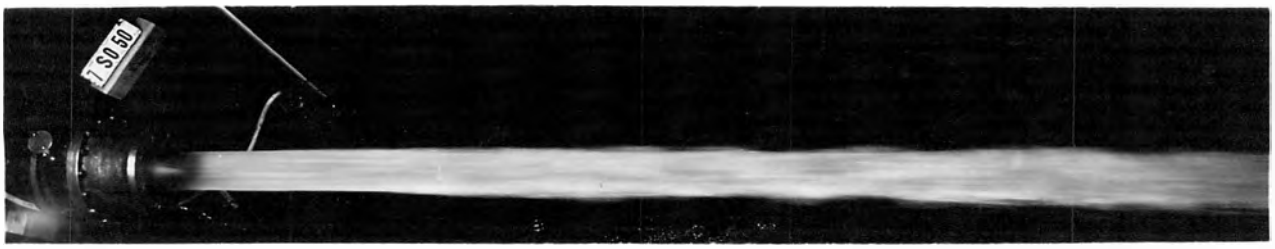
50% OPEN P.H.-13.17 Q-1.90



50% OPEN P.H.-22.52 Q-2.50



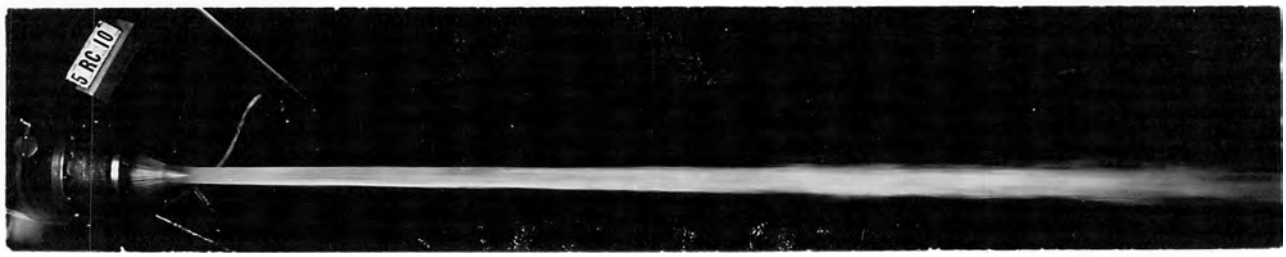
50% OPEN P.H.-33.00 Q-3.02



50% OPEN P.H.-46.32 Q-3.59

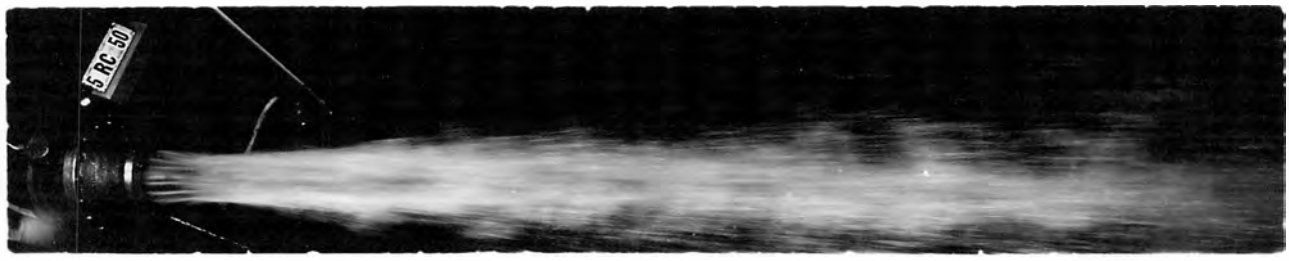
50% OPEN P.H.-56.80 Q-3.96

NEEDLE-VALVE TESTS
Original 42° Needle with Sharp-edged Nozzle

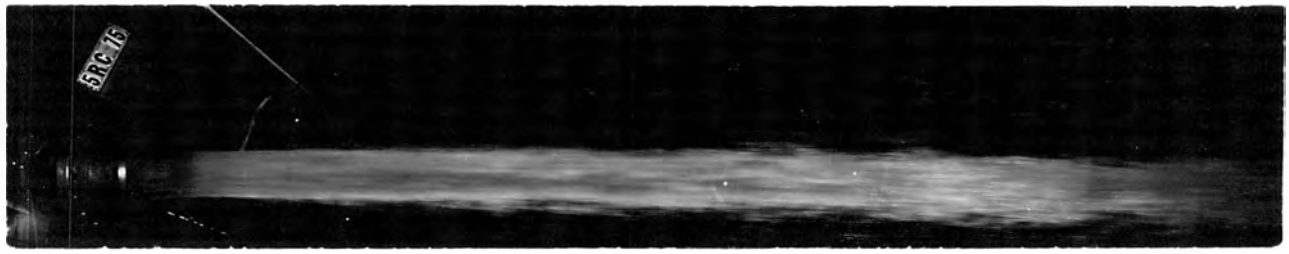


10% OPEN P.H.-53.40 Q-0.60

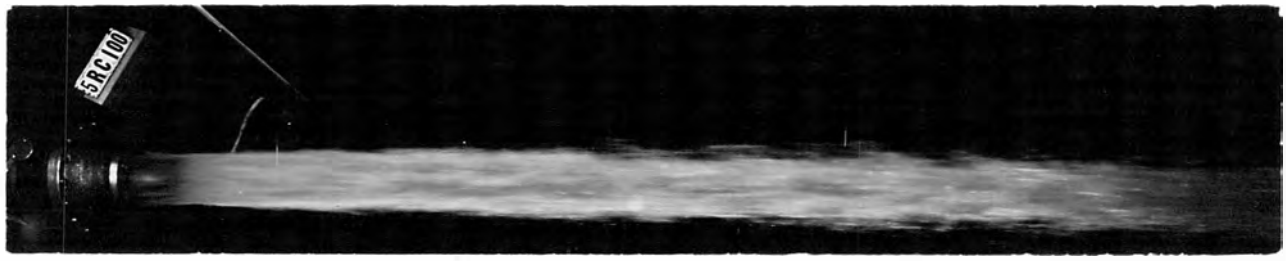
25% OPEN P.H.-47.73 Q-1.68



50% OPEN P.H.-34.13 Q-2.89



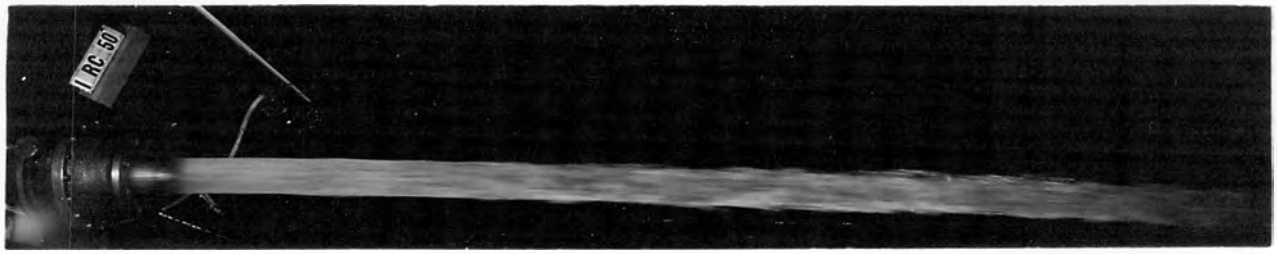
75% OPEN P.H.-24.78 Q-3.57



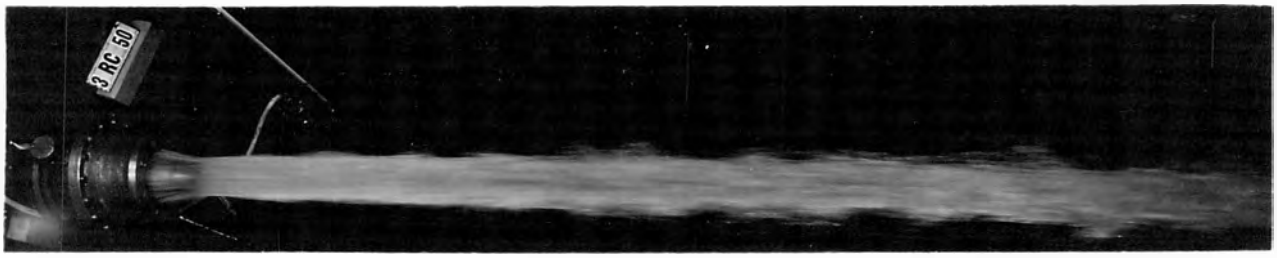
100% OPEN P.H.-20.53 Q-3.87

NEEDLE-VALVE TESTS

30° Needle (Alternate tip) with Round-Edged Nozzle



50% OPEN P.H.-14.30 Q-1.76



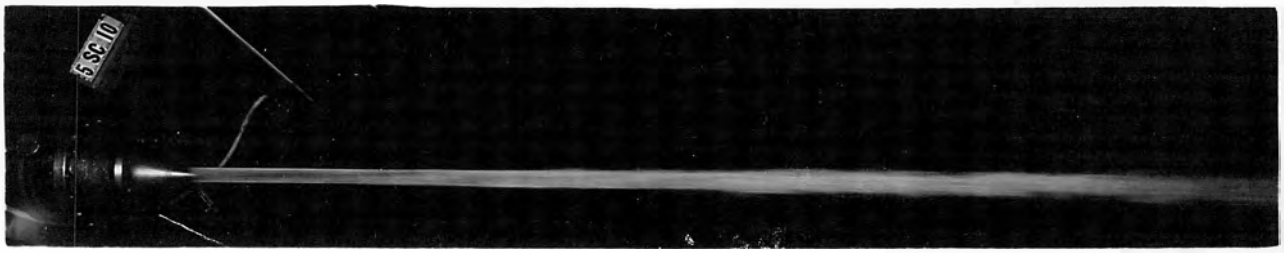
50% OPEN P.H.-24.22 Q-2.29

50% OPEN P.H.-34.13 Q-2.89

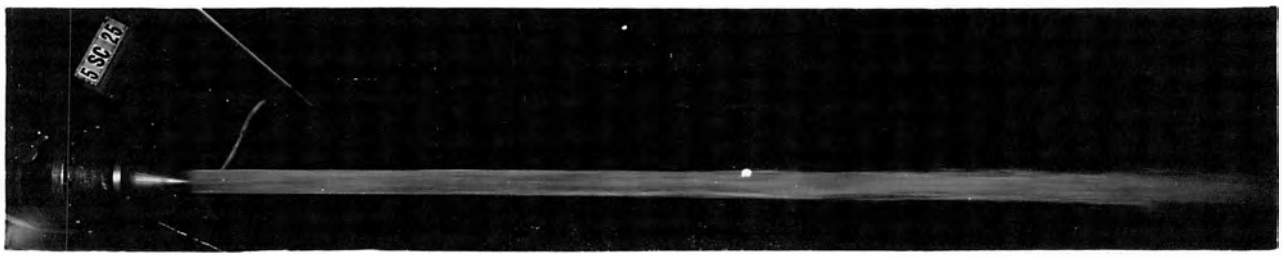
50% OPEN P.H.-47.17 Q-3.49

50% OPEN P.H.-57.93 Q-3.80

NEEDLE-VALVE TESTS
30° Needle (Alternate tip) with Round-Edged Nozzle

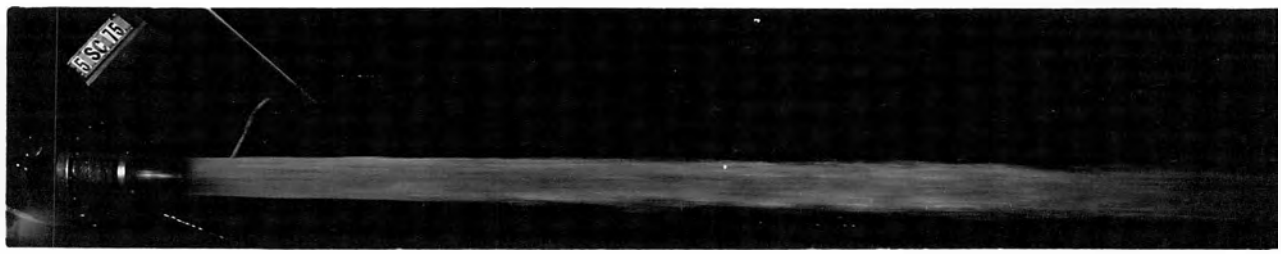


10% OPEN P.H.-53.40 Q-0.55

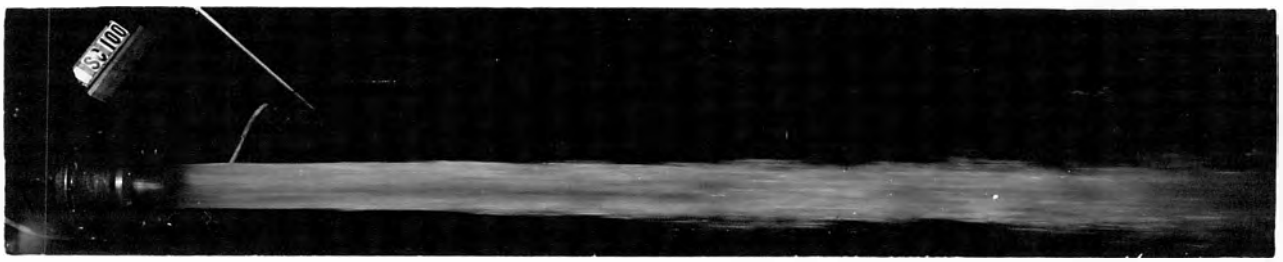


25% OPEN P.H.-49.43 Q-1.25

50% OPEN P.H.-39.23 Q-2.37



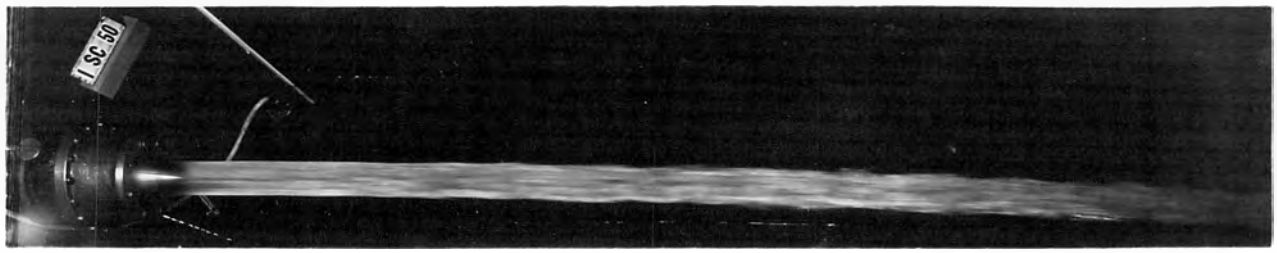
75% OPEN P.H.-31.02 Q-3.05



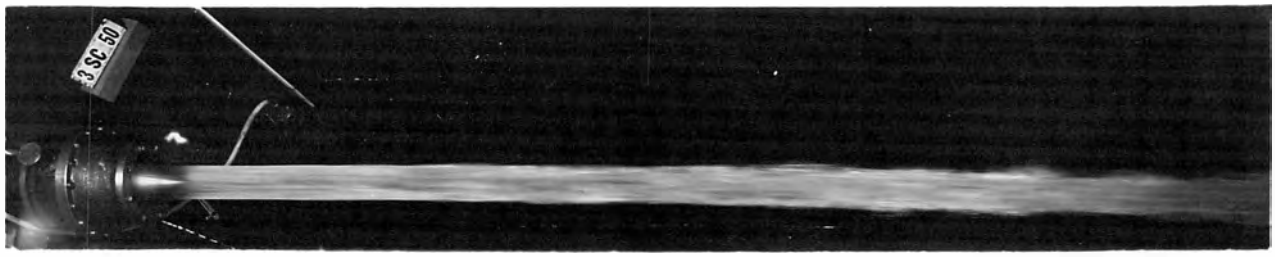
100% OPEN P.H.-26.20 Q-3.47

NEEDLE-VALVE TESTS

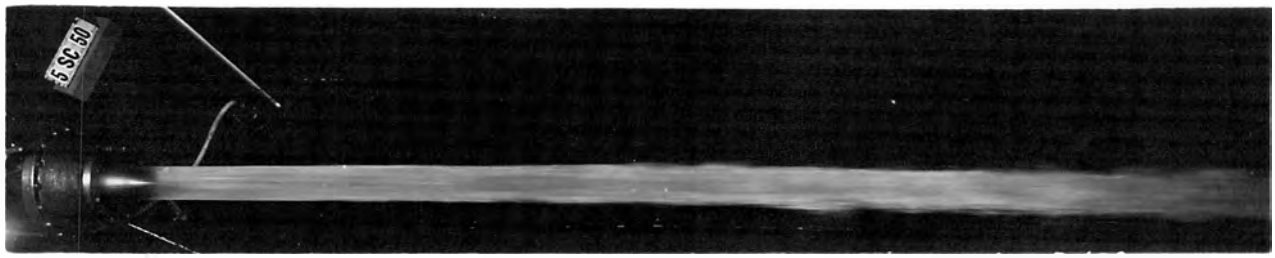
30° Needle (Alternate tip) with Sharp-Edged Nozzle



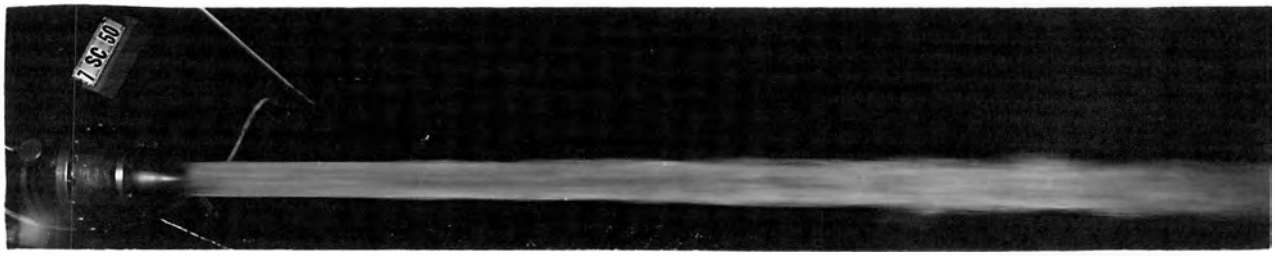
50% OPEN P.H.-15.57 Q-1.55



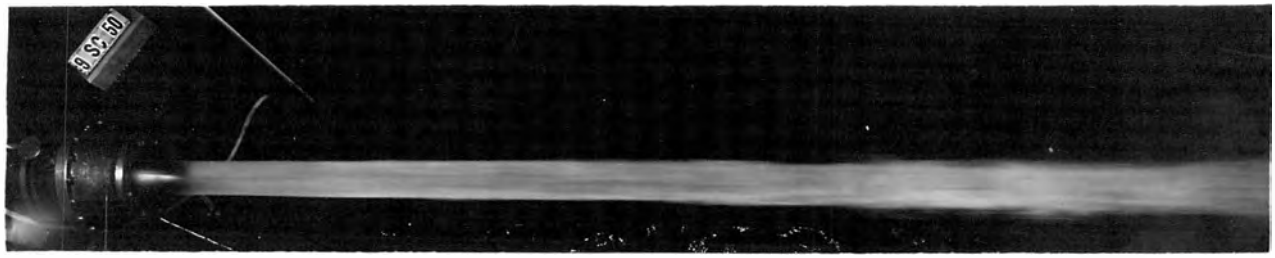
50% OPEN P.H.-26.20 Q-2.02



50% OPEN P.H.-39.23 Q-2.37



50% OPEN P.H.-53.68 Q-2.88



50% OPEN P.H.-79.75 Q-3.21

NEEDLE-VALVE TESTS
30° Needle (Alternate tip) with Sharp-Edged Nozzle

10% OPEN P.H.-55.10 Q-0.55

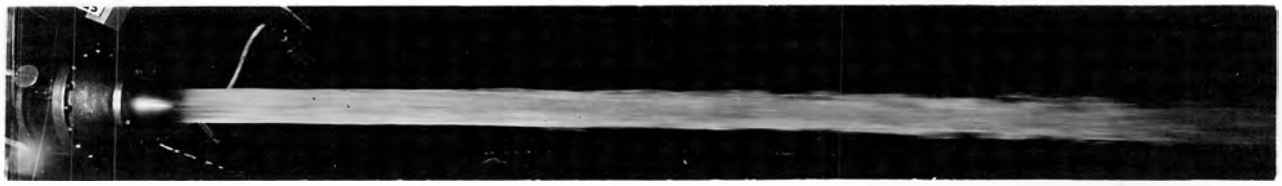
25% OPEN P.H.-49.72 Q-1.42

50% OPEN P.H.-39.80 Q-2.47

30° NEEDLE with tip removed

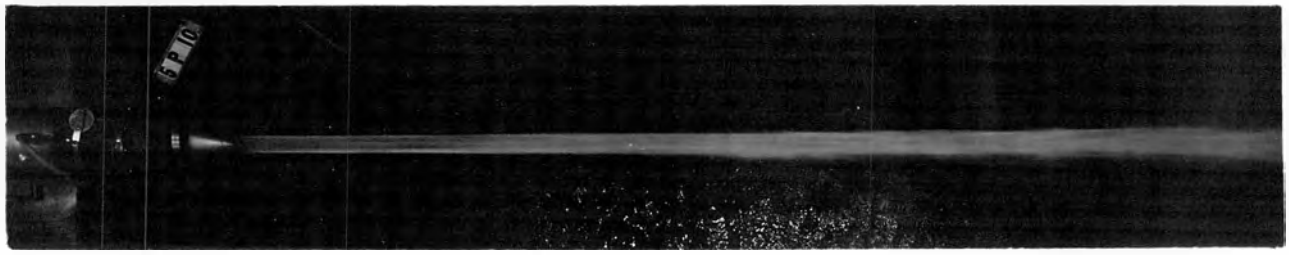
10% OPEN P.H.-55.67 Q-0.55

25% OPEN P.H.-49.43 Q-1.42

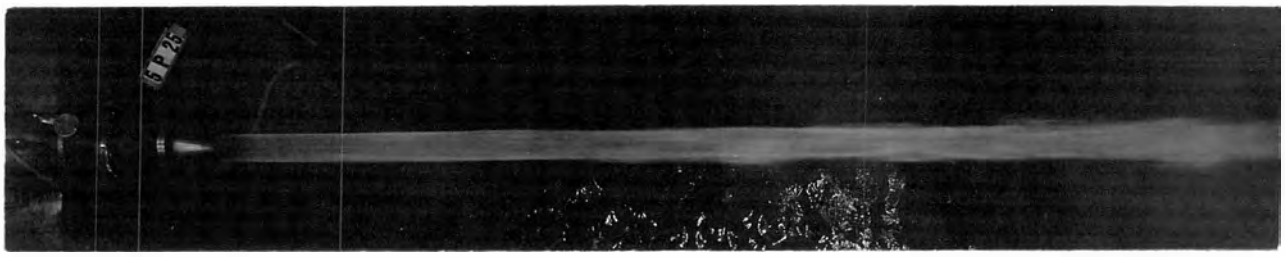


50% OPEN P.H.-39.25 Q-2.46

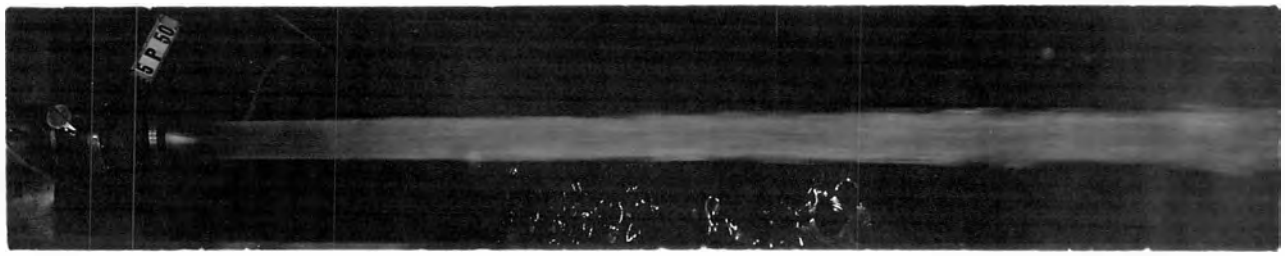
NEEDLE-VALVE TESTS
Cone 30° Needle with Sharp-edged Nozzle



10% OPEN P.H.-52.31 Q-0.70



25% OPEN P.H.-46.87 Q-1.77



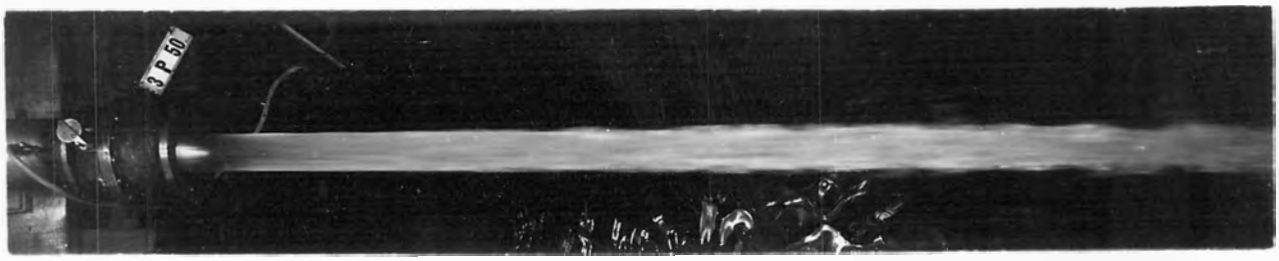
50% OPEN P.H.-38.30 Q-2.93

75% OPEN P.H.-31.50 Q-3.60

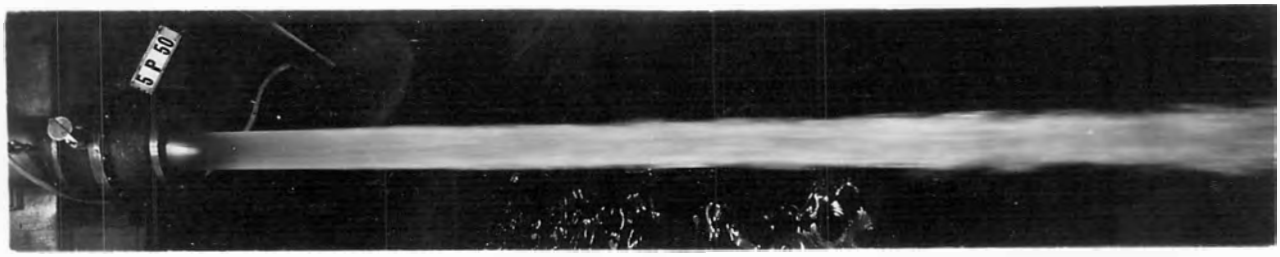
100% OPEN P.H.-27.42 Q-4.00

NEEDLE-VALVE TESTS
Cone 36°-22' Needle with Sharp-Edged Nozzle

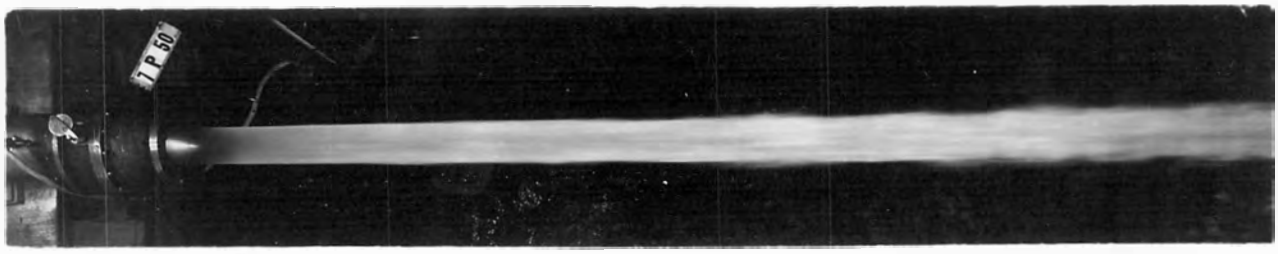
50% OPEN P.H.-14.23 Q-1.85



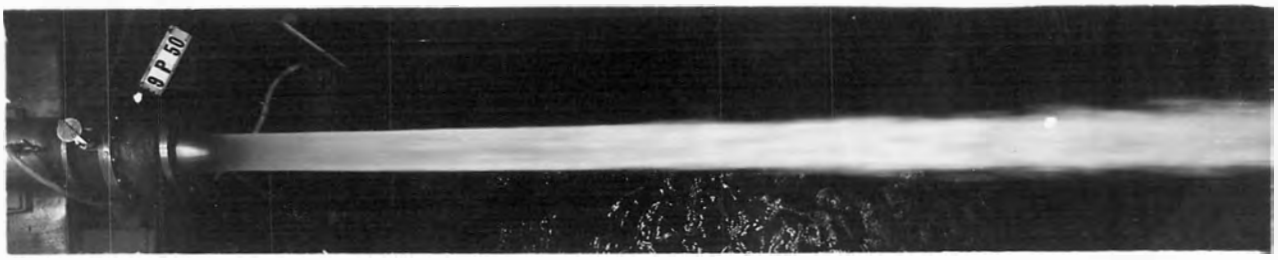
50% OPEN P.H.-25.25 Q-2.40



50% OPEN P.H.-38.30 Q-2.93

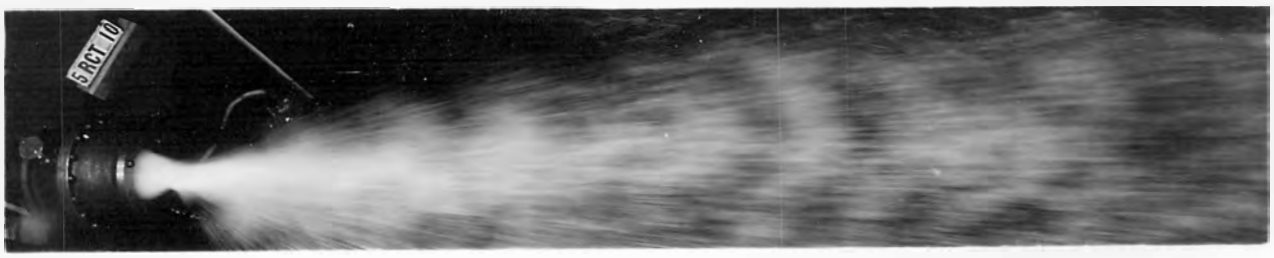


50% OPEN P.H.-53.81 Q-3.47



50% OPEN P.H.-66.05 Q-3.83

NEEDLE-VALVE TESTS
Cone 36°-22' Needle with Sharp-Edged Nozzle



10% OPEN P.H.-54.53 Q-0.70

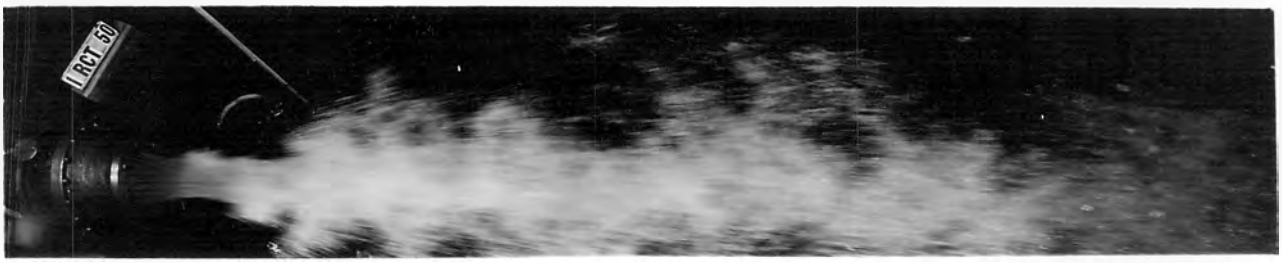
25% OPEN P.H.-47.73 Q-1.72

50% OPEN P.H.-30.73 Q-3.17

75% OPEN P.H.-21.10 Q-3.84

100% OPEN P.H.-17.13 Q-4.09

NEEDLE-VALVE TESTS
Closed Tube with Round-edged Nozzle



50% OPEN P.H.-12.60 Q-1.92

50% OPEN P.H.-21.67 Q-2.54

50% OPEN P.H.-30.73 Q-3.17

50% OPEN P.H.-42.52 Q-3.78

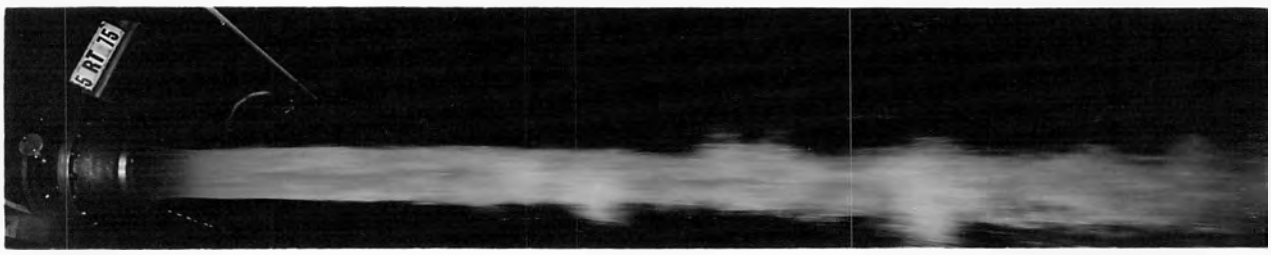
50% OPEN P.H.-61.30 Q-4.43

NEEDLE-VALVE TESTS
Closed Tube with Round-edged Nozzle

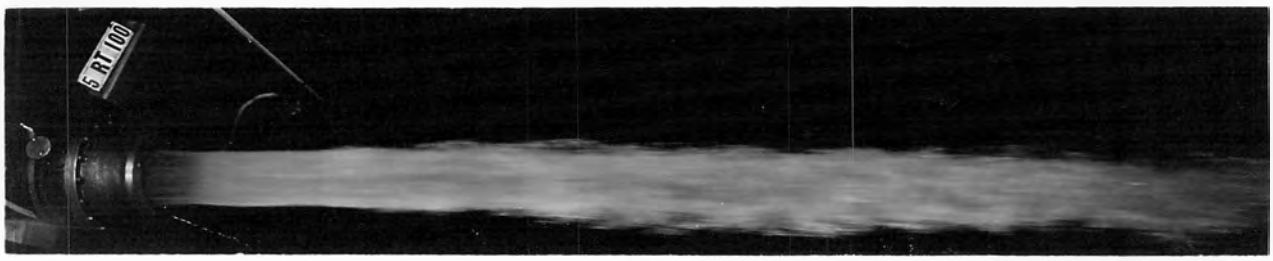
10% OPEN P.H.-54.53 Q-0.70

25% OPEN P.H.-47.17 Q-1.68

50% OPEN P.H.-31.87 Q-3.10

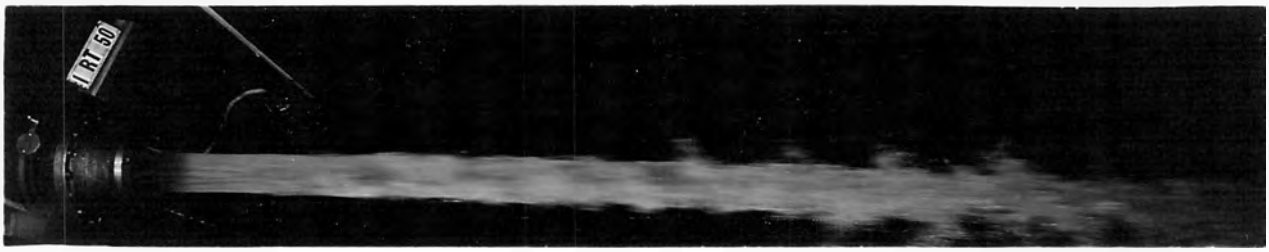


75% OPEN P.H.-21.67 Q-3.81

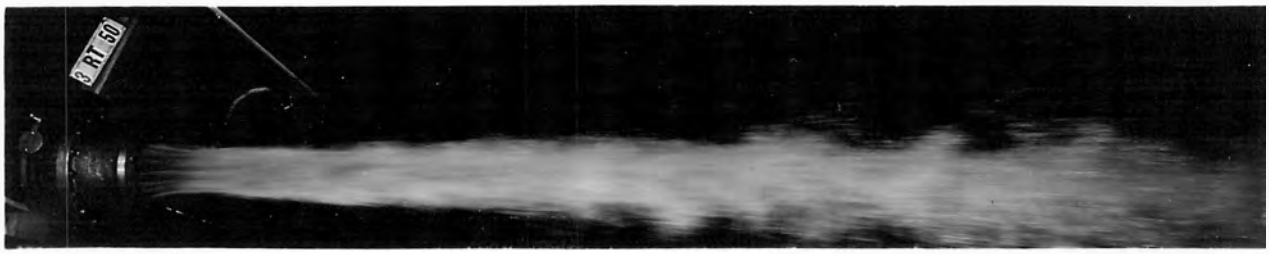


100% OPEN P.H.-17.70 Q-4.09

NEEDLE-VALVE TESTS
Open Tube with Round-edged Nozzle



50% OPEN P.H.-13.17 Q-1.76



50% OPEN P.H.-22.23 Q-2.42

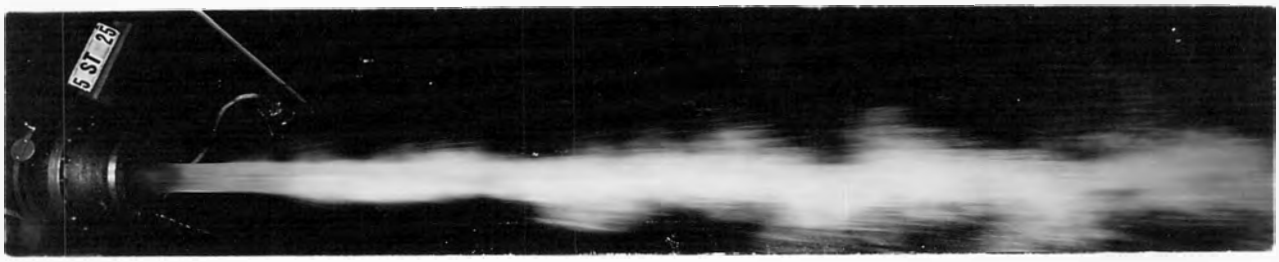
50% OPEN P.H.-31.87 Q-3.10

50% OPEN P.H.-44.33 Q-3.71

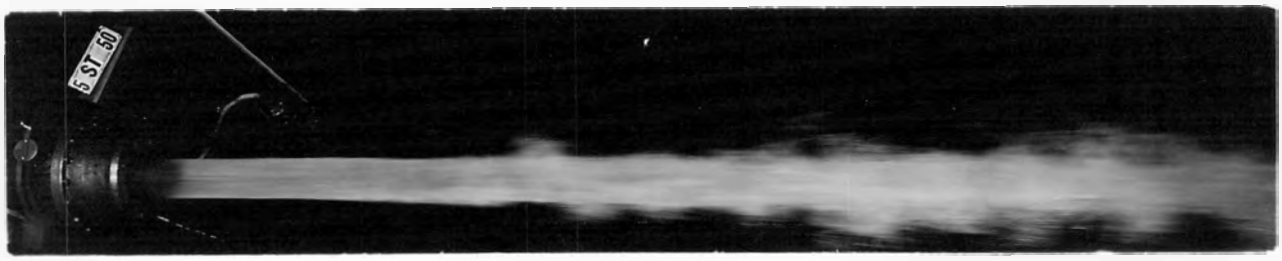
50% OPEN P.H.-50.00 Q-3.89

NEEDLE-VALVE TESTS
Open Tube with Round-edged Nozzle

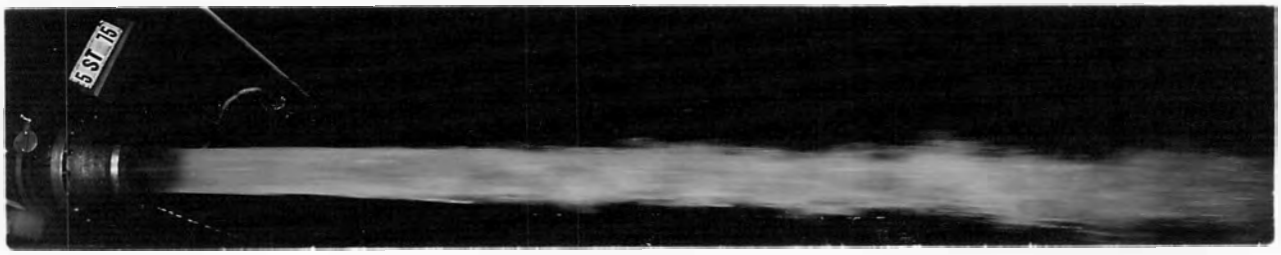
10% OPEN P.H.-53.40 Q-0.75



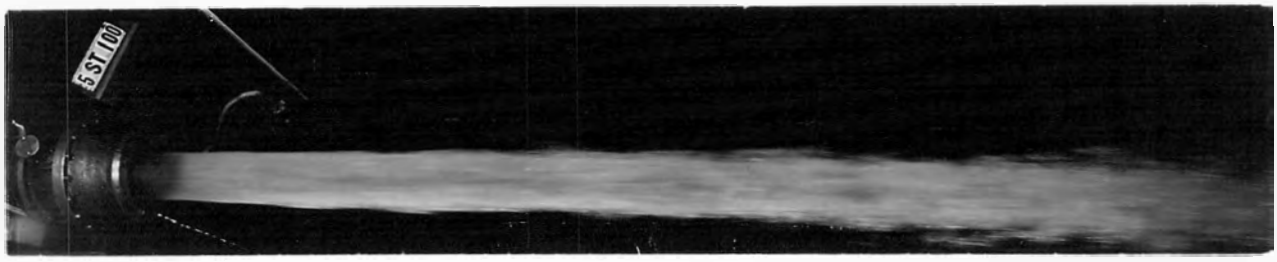
25% OPEN P.H.-46.03 Q-1.77



50% OPEN P.H.-33.57 Q-2.91

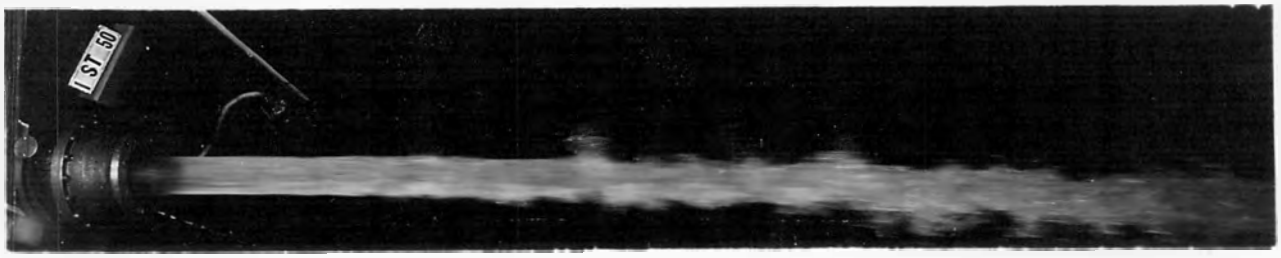


75% OPEN P.H.-25.63 Q-3.49

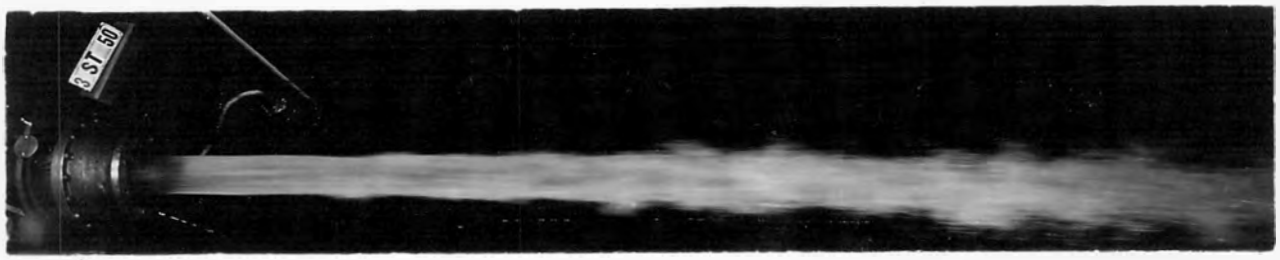


100% OPEN P.H.-22.52 Q-3.76

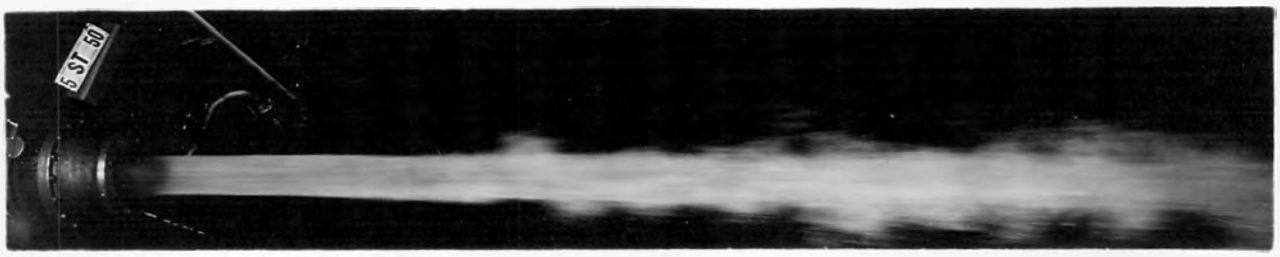
NEEDLE-VALVE TESTS
Open Tube with Sharp-edged Nozzle



50% OPEN P.H.-13.73 Q-1.84

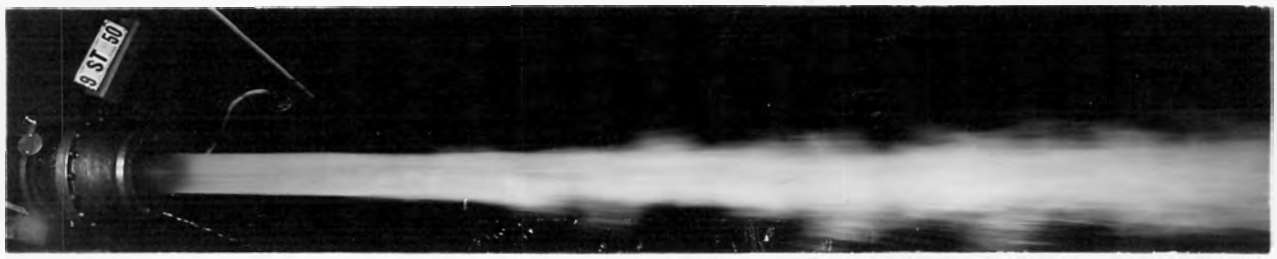


50% OPEN P.H.-22.80 Q-2.40



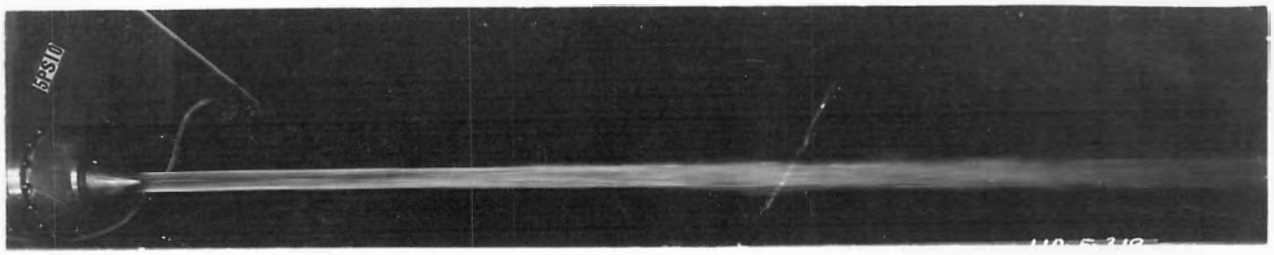
` 50% OPEN P.H.-33.57 Q-2.91

50% OPEN P.H.-47.17 Q-3.45

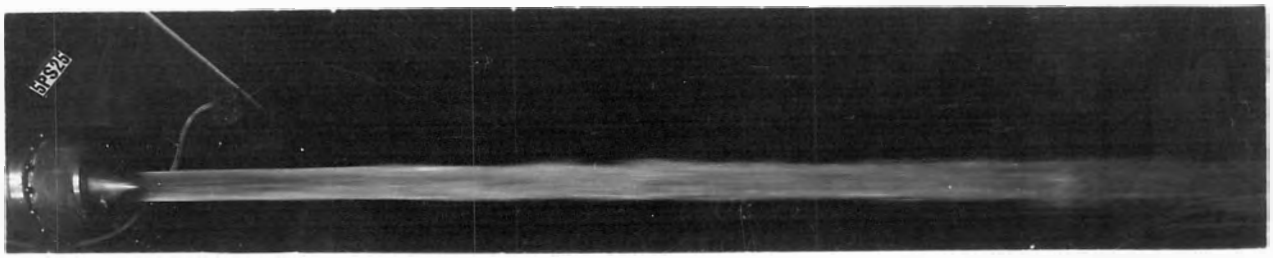


50% OPEN P.H.-57.93 Q-3.82

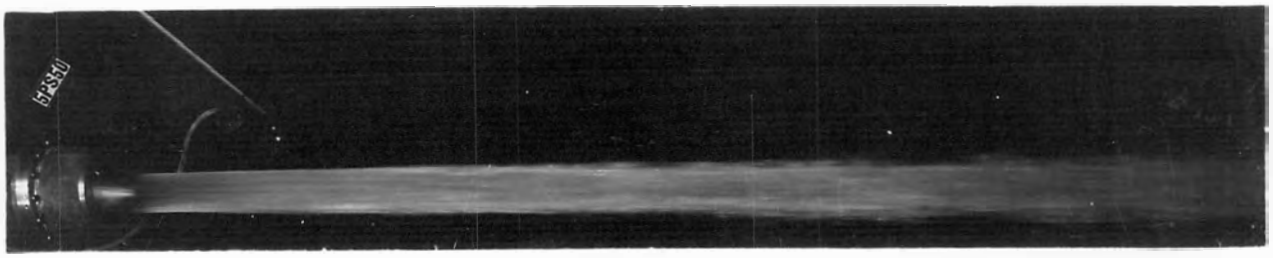
NEEDLE-VALVE TESTS
Open Tube with Sharp-edged Nozzle



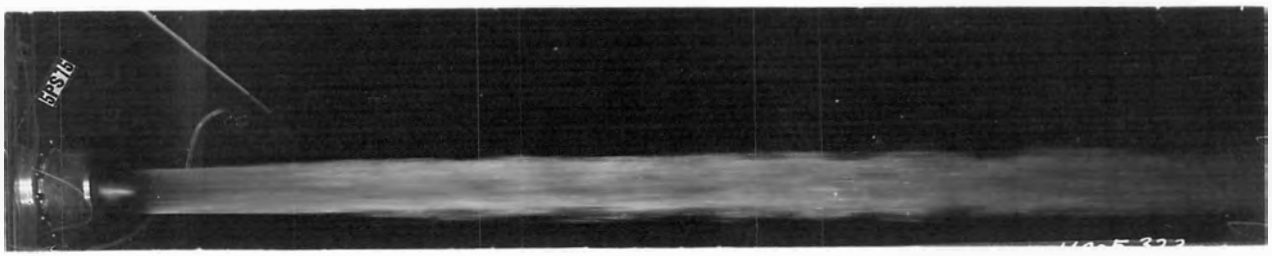
10% OPEN P.H.-50.86 Q-1.80



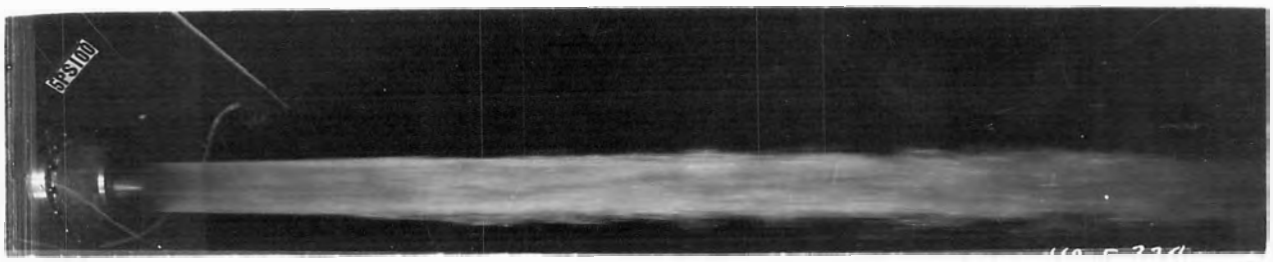
25% OPEN P.H.-44.63 Q-2.40



50% OPEN P.H.-26.21 Q-3.35

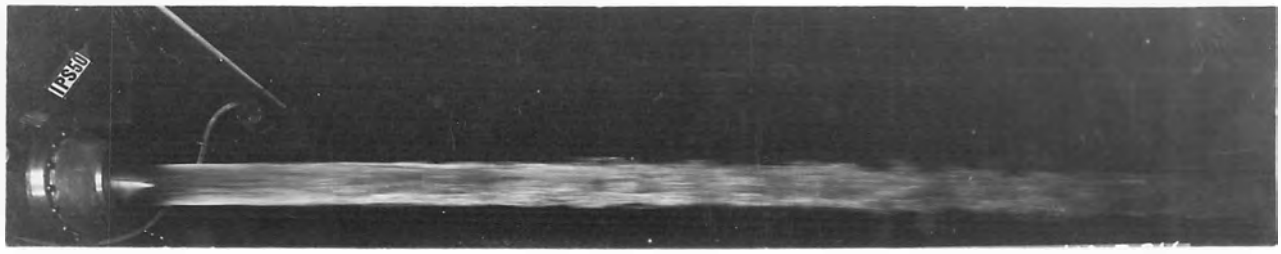


75% OPEN P.H.-29.04 Q-3.95

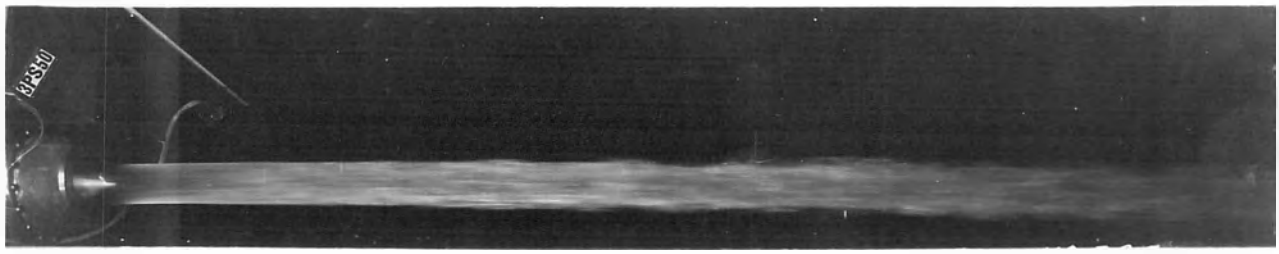


100% OPEN P.H.-25.36 Q-4.30

NEEDLE-VALVE TESTS
Proposed Valve Design

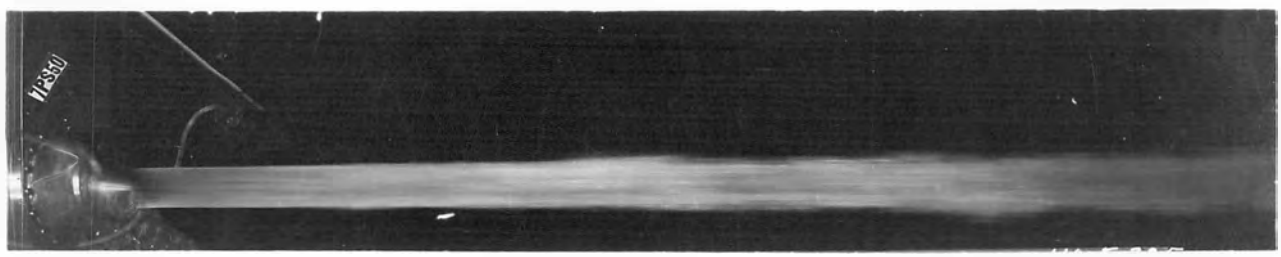


50% OPEN P.H.-13.74 Q-2.05

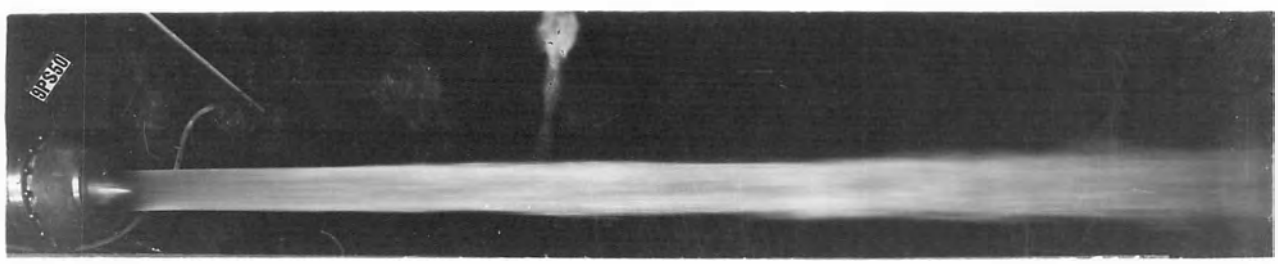


50% OPEN P.H.-23.38 Q-2.75

50% OPEN P.H.-26.[illegible] Q-3.35



50% OPEN P.H.-51.43 Q-4.05

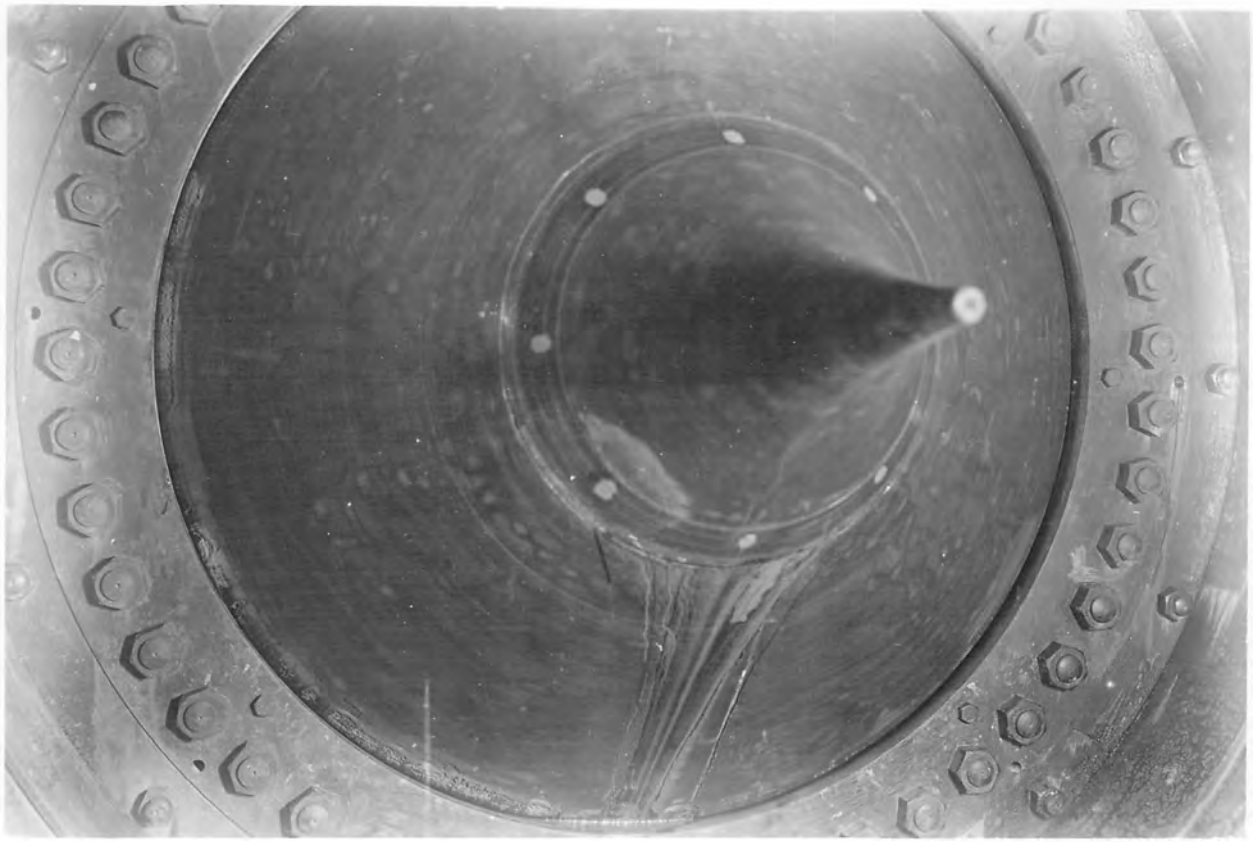


50% OPEN P.H.-63.89 Q-4.50

NEEDLE-VALVE TESTS
Proposed Valve Design

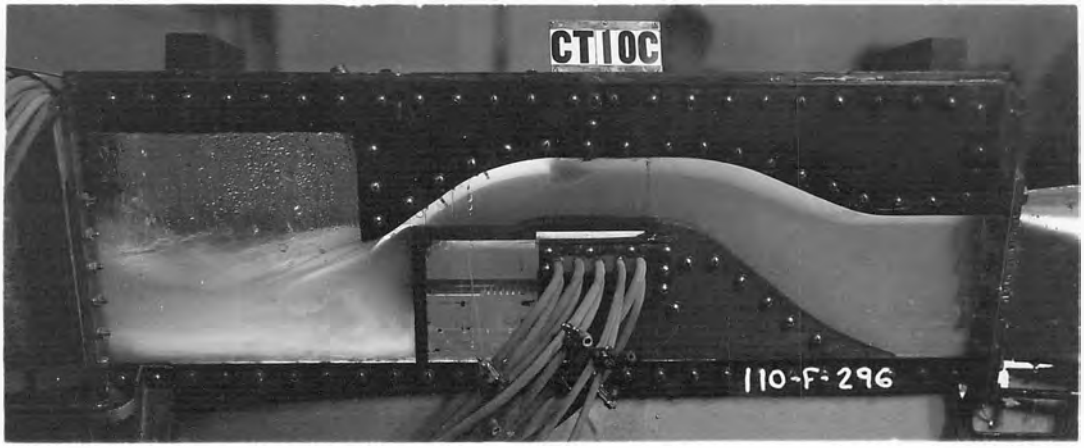
Casper Alcova Model Valve Needle after operating at 40% open for 6 days.

Needle of proposed design after operating at 20% open for 84 days.

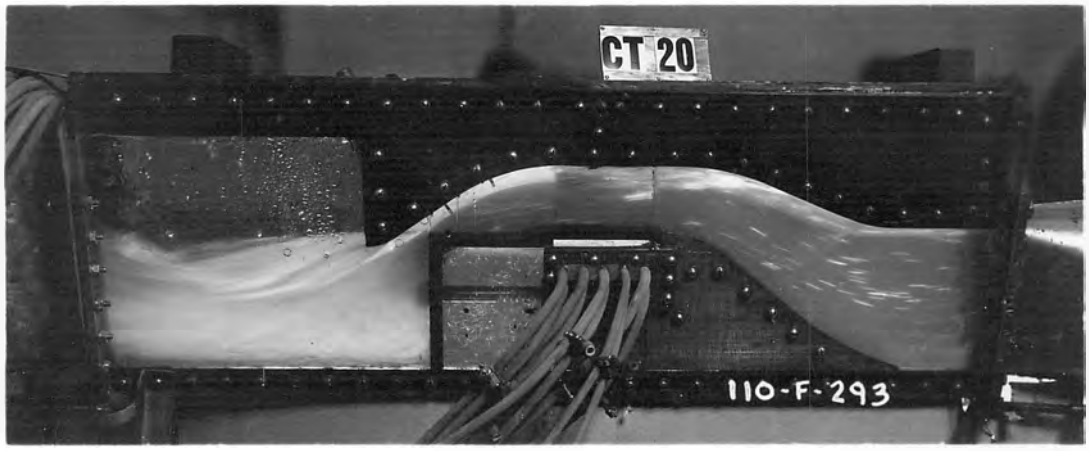


General View

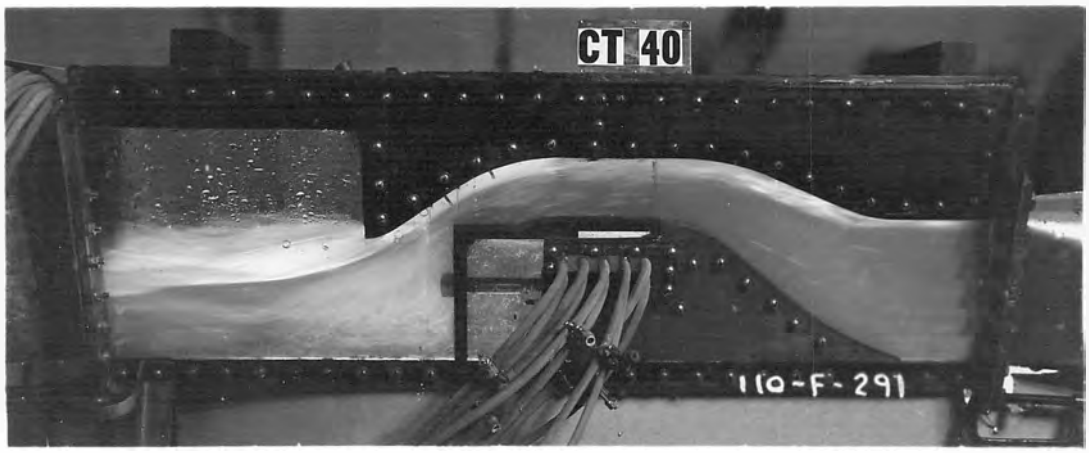
Close-up of Pitted Area
84-INCH CASPER ALCOVA VALVE



10% OPEN

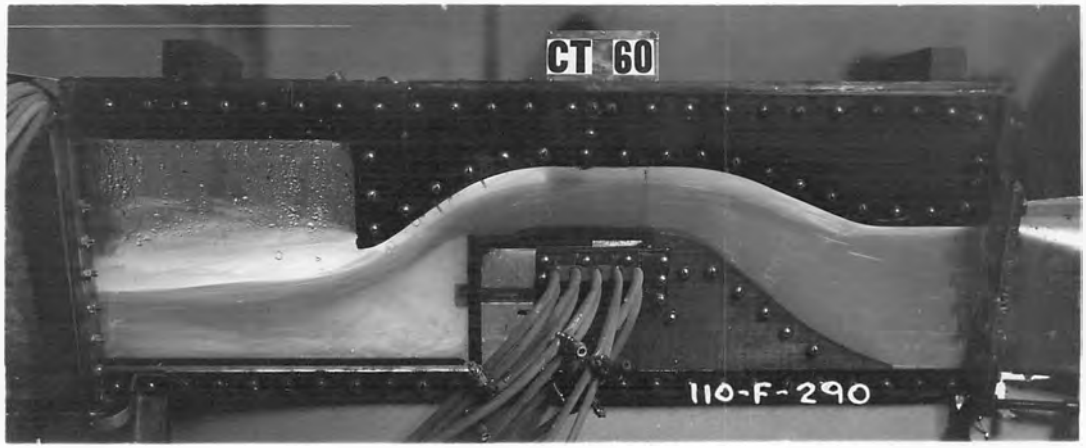


20% OPEN

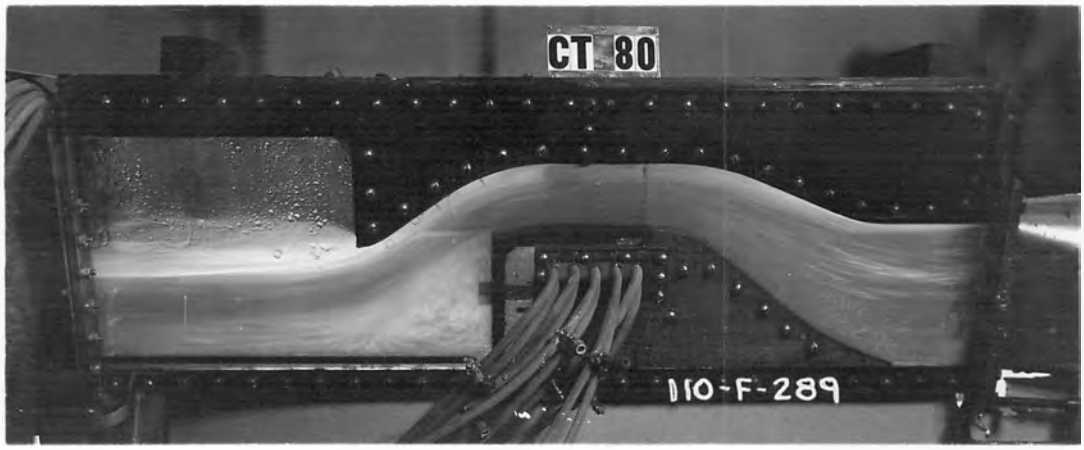


40% OPEN

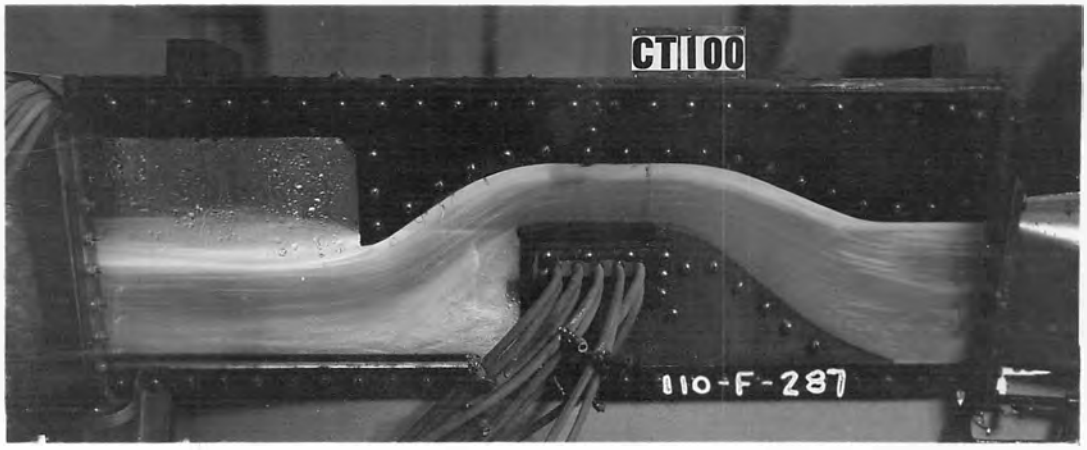
NEEDLE-VALVE TESTS
1/8 Sectional Model
Closed-type Tube with Round-edged Nozzle
Prototype Head - 100 ft.



60% OPEN



80% OPEN



100% OPEN

NEEDLE-VALVE TESTS
1/8 Sectional Model
Closed-type Tube with Round-edged Nozzle
Prototype Head - 100 ft.