Paper No.
56—F-10

Cavitation Characteristics of Gate Valves and Globe Valves Used as Flow Regulators Under Heads Up to About 125 Ft

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The series of tests discussed in this paper was made for the purpose of determining whether or not gate valves or globe valves could be used satisfactorily for regulating releases from irrigation-distribution systems under heads up to about 125 ft. Both types of valves proved unsuitable for making free-flow releases because of the wide dispersion of the jets under throttled conditions. Confinement of the jets to pipelines downstream induced cavitation in and downstream of the valves and a study was made of the pressures in the pipelines upstream and downstream of 6, 8, 10, and 12-in. gate valves, and a 6-in. globe valve to evolve a means of eliminating or minimizing the cavitation. A pressure relationship or "cavitation index" was found to be a useful means of determining the limits of differential head and back pressure to either control the location of, minimize, or eliminate cavitation damage. The design of the water passage immediately downstream from the valves and the pressure within this passage were the two main factors influencing the cavitation characteristics of an installation. One of the most effective means of eliminating cavitation damage below gate valves was the placing of sudden enlargements in the pipe sections immediately downstream. No damage could be detected in the concrete lining of the sudden enlargement under heads up to 150 ft with back pressures of approximately 15 ft, although noise similar to that which accompanies cavitation was present at heads in excess of about 90 ft.

A limited number of tests were made to study the resistance of rubber-like products to cavitation-erosion and their use in protecting the downstream pipe wall against this erosion. The conclusion was reached that such protection should not be used except in cases where cavitation will be mild.

Some consideration was given to venting the area in the top of the pipe just downstream of the valve, but this was considered objectionable because of the influence of entrained air on flow conditions and measuring devices, particularly propeller meters, placed downstream. Moreover, it was doubtful that air admitted to this region would reach all critical zones of local cavitation.

The information obtained from the valve investigation is very useful as design criteria for irrigation-distribution systems where valves are used for regulating the releases.

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Contributed by the Hydraulic Division for presentation at the Fall Meeting, Denver, Colo., September 10–12, 1956, of The American Society of Mechanical Engineers.

The Problem

As land and water resources of the Western United States become more fully utilized, closed-conduit distribution systems are used more extensively to conserve the water which would be lost by seepage and evaporation from open-earthen-ditch systems. Usually these closed systems have been designed to operate at pressures not to exceed about 50 ft of water, but in recent years they have been planned for more than double this pressure. The use of higher pressures posed several problems, that in particular being concerned with cavitation.

Two general types of valves were considered, the irrigation and waterworks gate valves and the globe valve. The wide dispersion of the jets below these valves indicated that confinement of the jets would be necessary, Figs. 1 and 2. The necessity of confining the jets below the valves introduced problems involving cavitation and vibration. When valves are operated at partial openings, low-pressure zones form in the fluid in and downstream of the valves and at the edges of gate-valve recesses. Under certain differential heads these pressures reach the vapor pressure of water and cavitation with vibration is induced. The pressure conditions are influenced by the back pressure on the valve and the conditions of flow surrounding the jet, the latter being influenced by the shape of the flow passages immediately downstream of the valves. A cavitation number or index containing the upstream and downstream pressures and the differential head was used to analyze the cavitation characteristics and evolve criteria for the design of regulating valves installed in distribution systems.

High heads and long pipelines made it important that the flow through the regulating valves not be shut off suddenly; also, that the cavitation tendencies be reduced to a minimum. A special valve was designed to meet these conditions.

Test Procedure

The valves were placed in settings with several diameters length of pipe upstream attached to the laboratory supply system and several diameters length of pipe downstream. The downstream pipe contained another valve for regulating the back pressure on the test valve and a 45-deg downpipe to return the flow to the laboratory supply system, Fig. 3. This downstream section was removed for free-discharge tests.

Piezometers were placed at points upstream and downstream of the test valves for investigating pressure distribution, determining the head, and indicating the head losses. Water measured by venturi meters was supplied to the test valves by two 12-in. centrifugal pumps in series. Test data for all valves were recorded for various valve openings and discharges. Test valves were obtained on loan from several manufacturers. Only two valves were installed in concrete pipe to represent actual field installations.

Pressures in the conduit upstream, downstream, and in some of the valves were obtained for various discharges and openings.

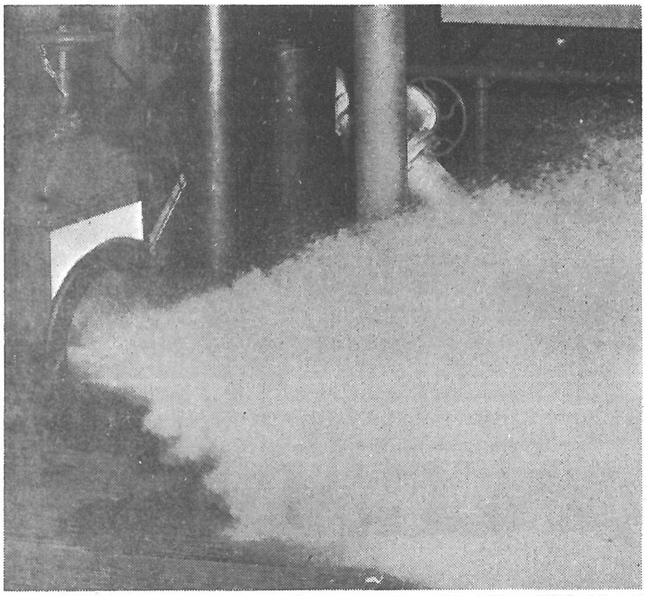


FIG. 1 JET FROM HUB-END GATE VALVE $17^1/_2$ PER CENT OPEN WITH 6.1 CFS FREE DISCHARGE UNDER 125-FT HEAD

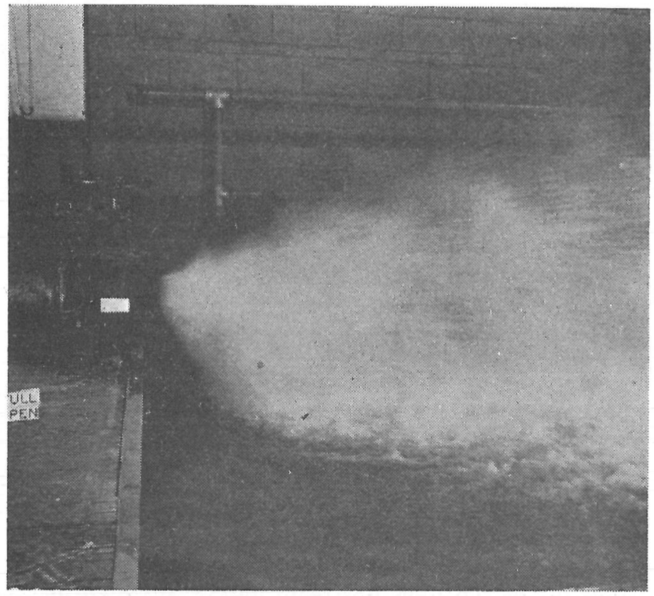


FIG. 2 JET FROM GLOBE VALVE, FULLY OPEN WITH 4.30 CFS FREE DISCHARGE UNDER 63-FT HEAD

Cavitation-index values were computed from these data. Sections of concrete-lined pipe were placed at various distances downstream of a standard 6-in. gate valve to determine the location of cavitation-erosion for various back-pressure conditions. A section of 12-in. concrete pipe was placed below a 12-in. hub-end gate valve for one cavitation test. An 8-in. valve with a 14-in. tee section placed immediately downstream was tested to evaluate the influence of a sudden enlargement on cavitation. Protective lining materials for pipe sections immediately downstream of the valves were tested in special venturi and magnetostriction-oscillator cavitation equipment.

CAVITATION CHARACTERISTICS OF GATE VALVES

When a gate valve in a conduit is partially open and a high-velocity jet of water passes through the opening, a low-pressure zone is formed in the fluid downstream from the leaf. Low-pressure zones also form downstream from irregularities in the flow boundary such as the downstream edge of the leaf recess noted by the area marked X in Fig. 3. The pressures in these zones are influenced by the differential head across the valve and the downstream pressure; thus it was considered possible to determine the permissible head differential for a given back pressure, or the back pressure required to prevent cavitation in these low-pressure zones (keep the pressure in the zones above the vapor pressure of the water). This could best be accomplished by using some form of cavitation number or index. Several plots of pressure data were made before an appropriate index was discovered.

The relationship used was

Preferred form

$$K = \frac{H_2 - H_v}{H_t - H_2}$$

$$\sigma = \frac{P_o/\gamma - P_v/\gamma}{V_o^2/2g}$$

where

K = dimensionless number–cavitation index
H_2 = pressure head in pipe 12 pipe diameters below valve
H_v = vapor pressure relative to atmospheric pressure (negative)
H_t = total head (pressure plus velocity) 2 pipe diameters upstream of the valve

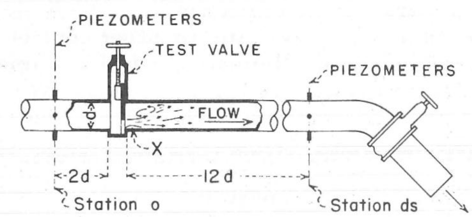


FIG. 3 VALVE TEST ARRANGEMENT

The cavitation index in this case is similar to that normally used to define flow conditions where cavitation is concerned. The numerator is identical with that normally used, assuming the terms apply to conditions in the cavitation zone, and the denominator is the pressure drop, or head, creating velocity in the cavitation zone, assuming no loss has occurred ahead of the cavitation zone.

Plots of K against discharge coefficients C for different gate openings revealed that the coefficient was constant when there was no cavitation in the system and that it decreased as cavitation developed by an increase in differential head. These plots offered a means of indicating the conditions for incipient cavitation or for determining the critical cavitation index (K_i). The coefficient used in this case was that given in the expression

$$Q = CA\sqrt{(2gH)}$$

where

Q = flow quantity, cfs
A = nominal area of pipe, sq ft
g = acceleration of gravity
H = differential head on valve in feet measured between stations 2 pipe diameters upstream and 12 pipe diameters downstream of valve
C = coefficient of discharge

The first attempts to establish critical values of K based on audible cavitation were made from plots of the data for given openings by taking those values of K at the intersection of two

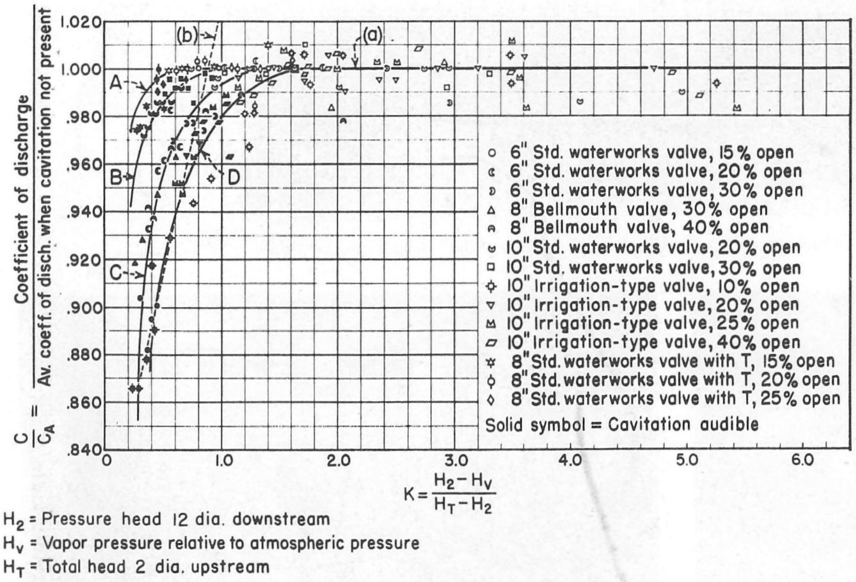


FIG. 4 CAVITATION INDEX FOR GATE VALVES

was considered as one means of permitting the use of gate valves as flow regulators with low back pressures. The alteration of the flow passage to form a sudden enlargement immediately downstream of the valve seemed to offer another possible solution. Some idea as to the nature, location, and extent of damage caused by cavitation was needed to evaluate these possibilities. Tests were performed for this purpose by using rubber-lined and concrete-lined pipe sections below the valves and special specimens of rubber material vulcanized to metal shapes in special cavitation-testing facilities.

A section of 12-in. pipe with a neoprene lining vulcanized in it was placed downstream from a 12-in. irrigation-type gate valve. The intensity of the cavitation obtained in this arrangement was not sufficient to provide any visual evidence of damage after many hours of operation, so some means of accelerating the tests was sought. Metal blocks with specimens of $^1/_{16}$, $^1/_8$, and $^3/_{16}$-in. lining vulcanized to them were tested in a special venturi-type cavitation test apparatus. The time involved to give visual evidence of cavitation, as shown in Fig. 6, was so great that other specimens were prepared for testing in a magnetostriction oscillator. Lining thicknesses of $^1/_{16}$ and $^3/_{16}$ in. were represented by these specimens. Damage similar to that for metal but at a very slow rate was obtained for the $^1/_{16}$-in-thick specimen. A tear or rupture at the center of the $^3/_{16}$-in. specimen occurred after a very short period of testing, Fig. 7. The tests indicated that the value of rubber lining would be questionable for any but mild cavitation.

Whether or not a rubber-lined section should be used even for the mild cases would depend on where cavitation occurred under the various operating conditions. Since concrete has relatively little resistance to cavitation-erosion, short sections of concrete pipe were placed at different locations below the valves to investigate where cavitation would occur. A section of concrete pipe was first placed below a 12-in. valve, but only slight damage occurred adjacent to the valve because of inadequate laboratory facilities for testing this size valve at high heads. An arrange-

lines on the plots, as shown in Fig. 4. One line (a) represented the average discharge coefficient for the valve opening without cavitation, and the other, a sloping line (b), represented the average for the points where cavitation was definitely audible. The initial analysis gave a maximum value of K_i of about unity which appeared to be about the same for all valve openings. However, further analysis, using additional data, showed a decrease in efficiency at values of K higher than those for which audible cavitation was noted. In some cases this critical value of K seemed to be near 2.0. The coefficient for any condition divided by the coefficient where there is no cavitation was used to generalize the data for all valves and openings, Fig. 4.

The cavitation-index equation was investigated assuming general cavitation to occur in the pipe immediately downstream of the valve leaf, and a loss from the gate to the recovery pressure downstream equal to the Borda loss expressed by $H_L = (V_G - V_p)^2/2g$, where V_G = velocity under gate and V_p = velocity in pipe downstream. This was done to determine whether or not the cavitation influencing the efficiency of the system was of a general nature and downstream of the leaf. An evaluation of the critical cavitation-index values for various gate openings showed an increase with increase in opening until the valve was about 65 per cent open then a decrease with larger opening, Fig. 5. From this curve it appears that the critical value of the cavitation index should reach a maximum at about 65 per cent valve opening. While the K_i-value is about 1.0 for this case, a value somewhat different might be expected, depending upon where the downstream pressure is measured and whether or not the data are referred to a common base. Local regions of cavitation also might be an influencing factor. This seems to be the case for gate valves because the value of K_i at all conditions tested is much greater than indicated by the curve for general cavitation, Fig. 5.

A comparison of the curve for general cavitation conditions, with points based on the data of Fig. 4, indicates the presence of local regions of cavitation.

The graphs for the tests made thus far had disclosed that cavitation was present to some degree at all values of K below approximately 2.0, that cavitation was present in mild form for values of K greater than about 1.0, and that the intensity and severity of cavitation increased with decreasing values of K below 1.0. These results seemed to offer a source of design criteria so studies were made to further define the limitations.

Protection of the flow-passage surfaces attacked by cavitation

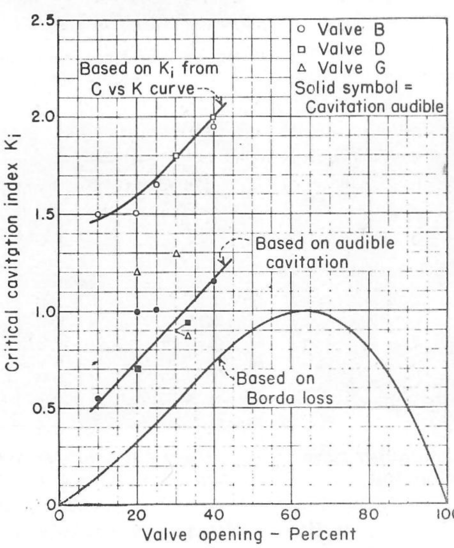
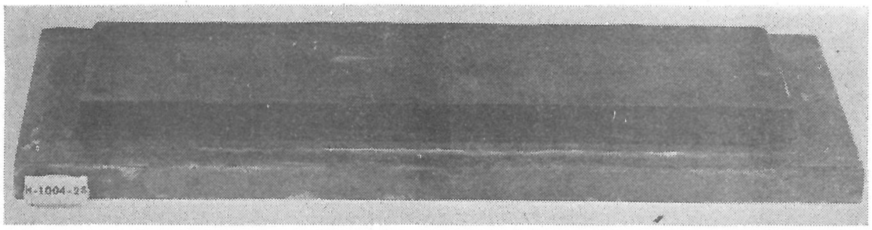
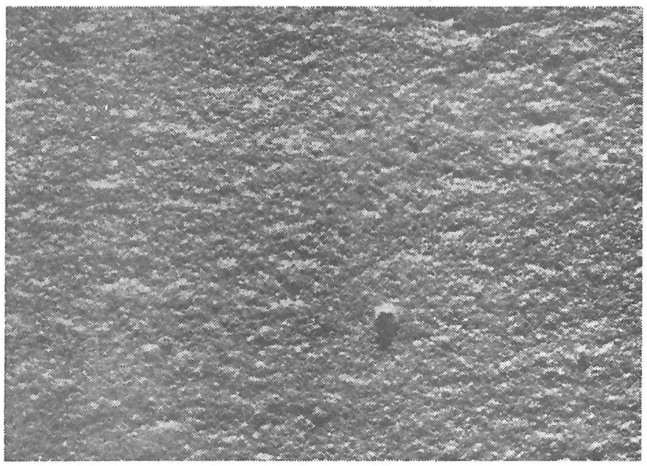


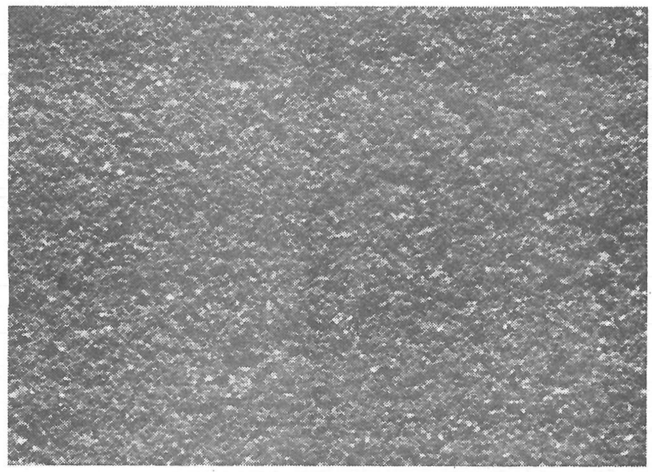
FIG. 5 CRITICAL CAVITATION INDEX FOR GATE VALVES



(*a*) Test specimen for venturi cavitation equipment, $^{1}/_{16}$-in. rubber vulcanized to steel

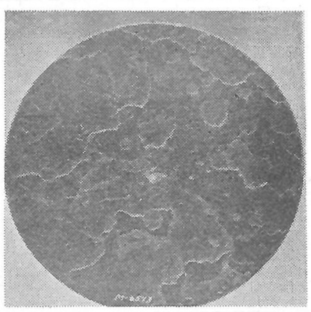


(*b*) Surface not subjected to cavitation

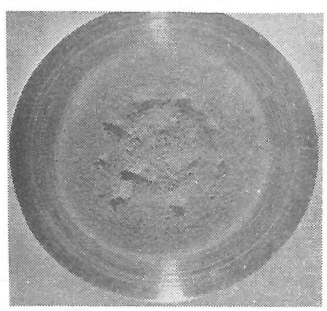


(*c*) Surface subjected to cavitation for 100 hr

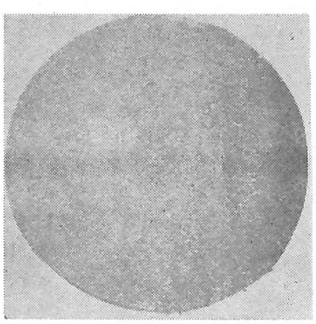
Fig. 6 Cavitation-Erosion of Rubber Surfaces in Venturi-Type Cavitation Equipment



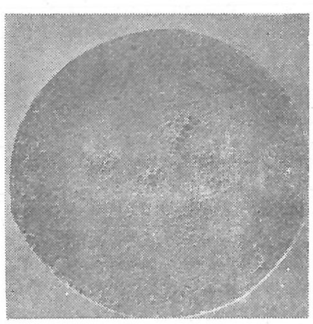
(*a*) $^{5}/_{8}$-in-diam steel specimen before test



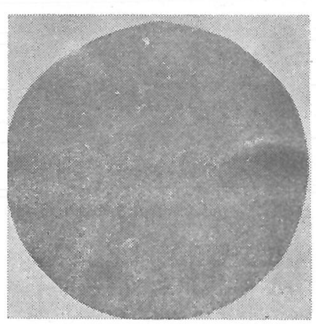
(*b*) $^{5}/_{8}$-in-diam steel specimen after 10 hr testing



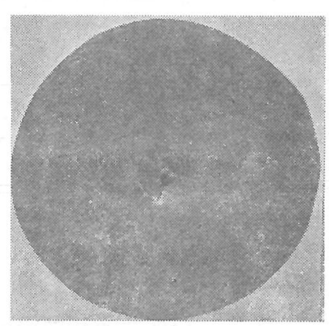
(*c*) $^{1}/_{16}$-in-thick rubber specimen before test



(*d*) $^{1}/_{16}$-in-thick rubber specimen after 34 hr testing

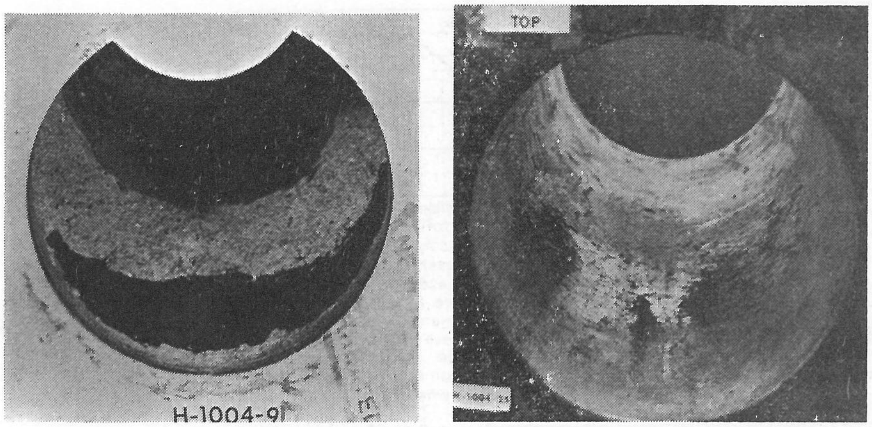


(*e*) $^{3}/_{16}$-in-thick rubber specimen before test



(*f*) $^{3}/_{16}$-in-thick rubber specimen after 5 hr testing

Fig. 7 Cavitation Erosion of Surfaces in Magnetostriction Oscillator



(*a*) Damage to 2-ft-long concretepi pe section attached to 6-in. waterworks standard gate valve operated for $7^1/_2$ hr with upstream head of 127.2 ft, downstream head of 13.6 ft and cavitation index of 0.36

(*b*) Damage to 2-ft-long concrete pipe section placed $8^1/_2$ ft downstream from 6-in. waterworks standard gate valve, operated for 7 hr with upstream head of 168.5 ft, downstream head of—23.8 ft and cavitation index of 0.20

FIG. 8 CAVITATION DAMAGE IN CONCRETE PIPE BELOW GATE VALVES OPERATED AT PARTIAL OPENING

ment using a 6-in. standard waterworks valve and a 2-ft-long section of 8-in. pipe, lined with 1 in. of concrete, was then used.

The tests showed that cavitation with the valve partially open first began at the downstream edge of the leaf recess and that the cavitation envelope extended farther and farther downstream as the back pressure on the valve decreased or the head increased.

With the 2-ft-long, concrete-lined section of pipe placed different distances downstream, it was possible to determine where damage would occur under various conditions. The location of the damage varied with the back pressure and thus the cavitation index. It was possible to get cavitation damage as much as 20 pipe diameters distance downstream of the valve by decreasing the back pressure, Fig. 8. A plot of distance of damage below the valve against cavitation index showed that the damage would be confined to the downstream end of the valve when the index exceeded 0.4, and that the damage occurred farther and farther downstream as the downstream pressure was reduced and the cavitation index was decreased below this value, Fig. 9. Most of the tests on this valve were at about 20 per cent opening and 130 ft of upstream head. For the openings tested there seemed to be a circulation of water on top of the jet and immediately downstream of the gate leaf. This appeared to prevent the occurrence of general cavitation conditions in this region. Cavitation pressures no doubt occur in this region as the gate leaf nears the wide-open position. Inadequate pump capacity for the large openings prevented determining if, and under what conditions, the cavitation pressures would occur in this region. In most cases in irrigation-distribution systems the valves would not be operated at the larger openings except under reduced head

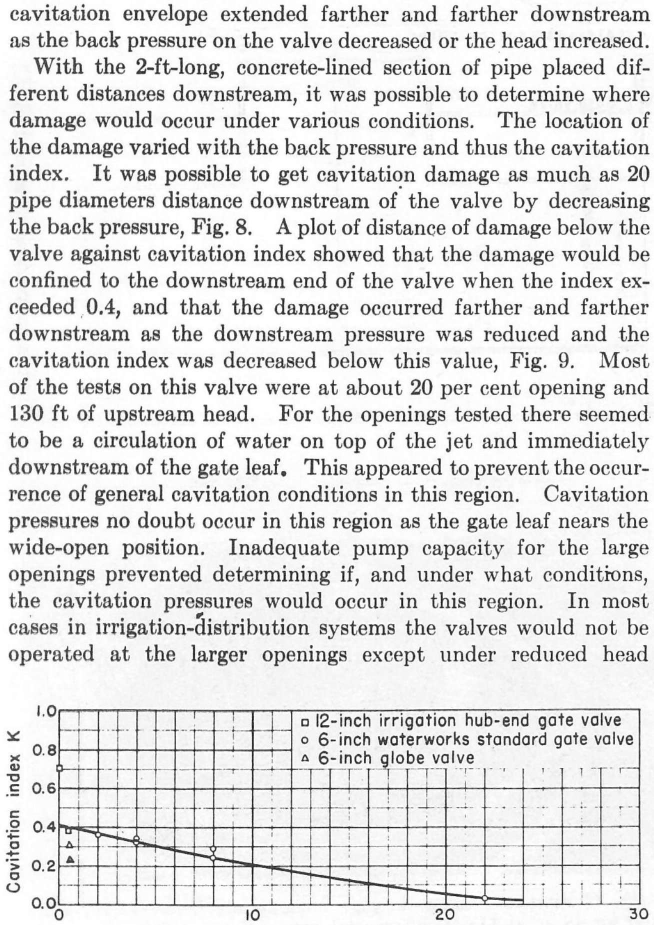


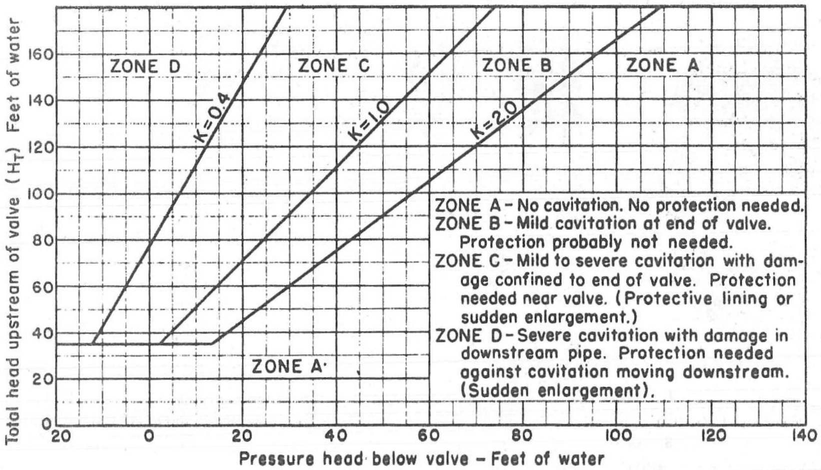
FIG. 9 DISTANCE OF CAVITATION DAMAGE DOWNSTREAM OF VALVE

where cavitation is not likely to occur; thus, this factor was not important in this particular study.

A change in shape of the flow passage immediately downstream of a valve will alter the flow conditions and thus the cavitation characteristics. The placing of a cone downstream may increase the cavitation tendencies while a sudden enlargement will decrease the tendency. A sand-cement-mortar-lined, 14-in. tee section placed immediately below an 8-in. standard gate valve showed no damage after 9 hr operation under heads of 150 and 118 ft with the valve $6^1/_4$ and $12^1/_2$ per cent open. A cavitation index curve (A) for this arrangement is shown in Fig. 4.

An examination of the data taken from the various gate valves indicated that the test results could be used as design criteria for turnouts controlled by valves. For values of K above 2.0 there was no evidence that cavitation was present. For values of K above 1.0 and below 2.0 the cavitation was of very mild nature. For values of K below 1.0 the intensity of cavitation increased as the value of K decreased. For values of K above about 0.4 the damage caused by cavitation was confined at the downstream end of the valve. For values of K below 0.4 the damage occurred farther downstream as the value of K decreased. From a computed value of K for a particular installation and the foregoing information, it was possible to ascertain whether or not cavitation would be of particular concern and to decide what steps should be taken to alleviate the conditions. A design chart which indicates the seriousness of the cavitation conditions and the treatment to be applied was prepared by the designers. The chart based on a vapor pressure of 31 ft of water below atmospheric provides a rapid convenient means for examining an installation for cavitation tendencies and corrective treatment. It is believed that the proposed corrective treatments are the most practical at the present time. A plot of the chart data was prepared for this paper (Fig. 10).

Actually, the placing of a suddenly enlarged section immediately below the valves in all cases would assure a minimum of cavitation damage. It appears that this treatment would be satisfactory for heads up to 150 ft when the valve openings are kept below about 50 per cent. A gate valve developed by the Bureau includes features for minimizing cavitation tendencies and for preventing excessive water hammer by rapid closure. The shaping of the valve body immediately downstream of the



Note: Plot based on -

$K = \frac{H_2 - H_V}{H_T - H_2}$ = Cavitation index.

H_2 = Pressure head 12 dia. downstream.

H_T = Total head 2 dia. upstream.

H_V = Vapor pressure relative to atmospheric pressure (assumed to be -31 feet).

Fig. 10 Cavitation Characteristics of Gate Valves in Pipeline

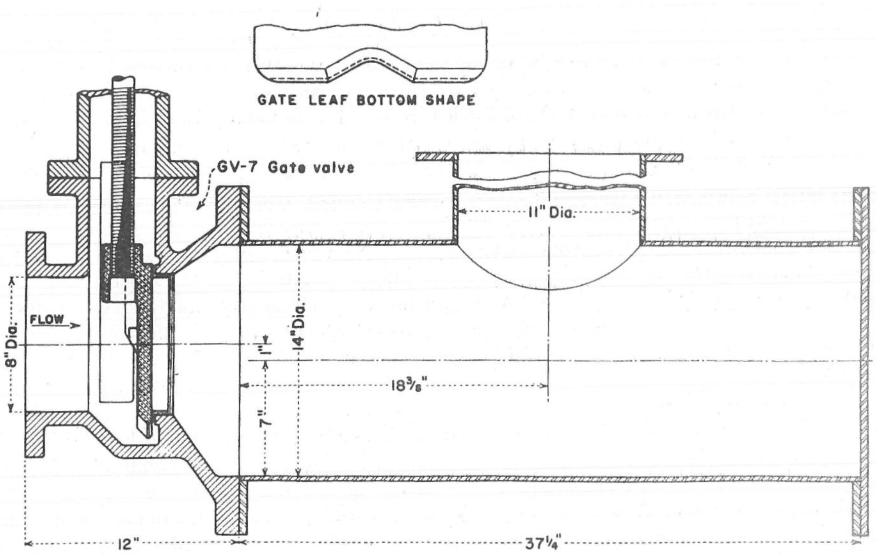
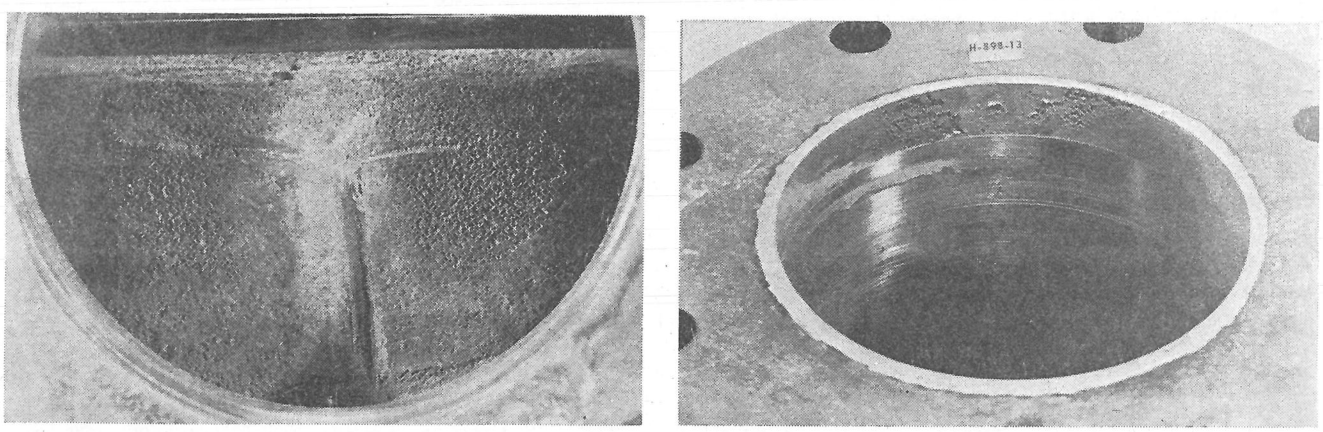


Fig. 11 GV-7 Valve With Sudden Enlargement



(*a*) Cavitation damage on downstream surface of diaphragm after 365 hr operation at 105-ft differential head—Valve disk seating against flow

(*b*) Cavitation damage in pipe immediately below valve, operated for 48 hr at 118-ft differential head—Valve disk seating with flow

Fig. 12 Cavitation Damage in and Below Globe Valve seat to make a sudden enlargement, as shown in Fig. 11, reduces the cavitation tendency. The inverted V-notch at the bottom of the gate leaf insures against rapid shutoff as the gate nears the closed position, thus preventing excessive water hammer. The valve has not been tested for cavitation tendencies, but it should prove even better than a standard gate valve when used with a sudden enlargement to release flows under high heads. However, considerable testing is still required to establish ultimate limits of this type of design, both in head and relative size of valve and expanded section.

Cavitation Characteristics of Globe Valves

The initial tests on globe valves were made on a valve having screw joints. The tests were made at about two thirds opening with the flow tending to close the disk and then tending to open it. The sharp edges of the pipe within the valve were conducive to cavitation and some damage was noted in the pipe a short distance downstream of the edge of the downstream joint after 64 hr of operation under a differential head of 126 ft, with the flow tending to close the disk. Considerable pitting of the downstream surface of the separating diaphragm was noted after the valve was operated for 129 hr under the same head conditions, with the flow tending to open the disk (Fig. 12).

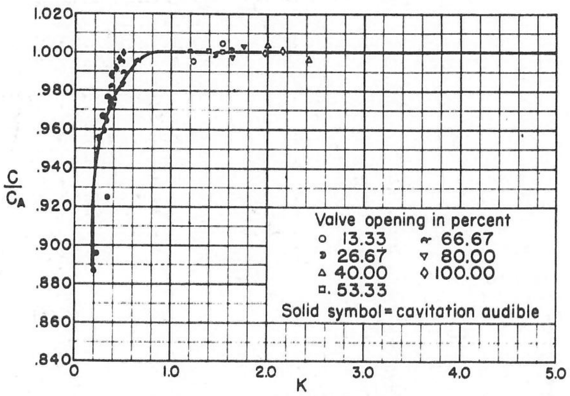


Fig. 13 Cavitation Index for 6-In. Globe Valve—Disk Seating Against Flow

valve was decreased by cavitation when the opening was small and increased by cavitation when the opening was large, Fig. 14.

Since cavitation is mainly confined within a globe valve, it is important that any installation using one, provide sufficient back pressure in the pipe 12 diameters downstream to keep the cavitation index K above 1.0. Damage was confined to the valve (did not move downstream) for index values as low as 0.23, Fig. 9. Globe valves cannot be operated at high differential heads and low back pressures without cavitation being present.

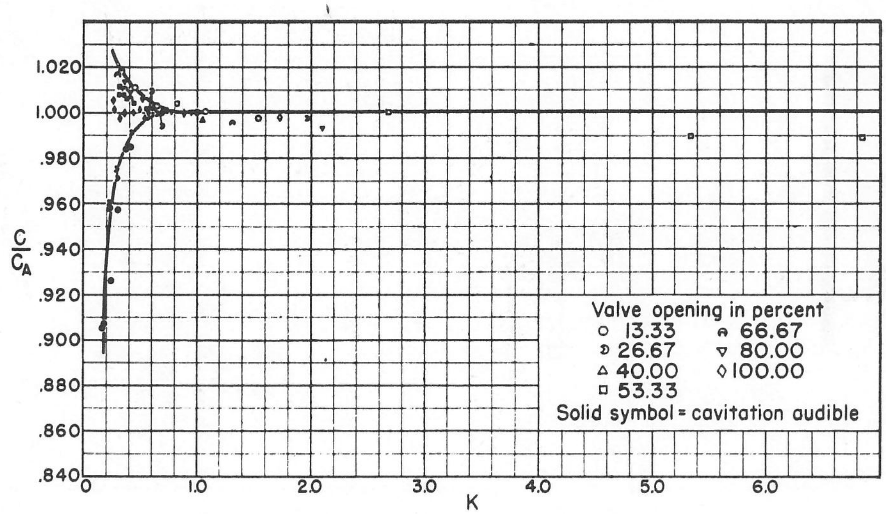


Fig. 14 Cavitation Index for 6-In. Globe Valve—Disk Seating With Flow

It was believed that the objectionable features of the screw joints would be eliminated by using valves with flanged joints. Tests on a 6-in. globe valve with flanged joints gave clear evidence of cavitation in similar locations after the valve had been operated for 48 hr at a differential head of about 118 ft, with the flow tending to close the disk.

The critical cavitation index for globe valves seems somewhat smaller than for gate valves. In fact cavitation was not audible at any value of K greater than 0.9 and the index curves for flow tending to open or close the valve disk show the critical value to be about 1.0 (Figs. 13 and 14). This was the case when the flow was tending to close the disk even though the efficiency of the

Acknowledgments

This series of studies extended intermittently over a period of 8 years and several persons of the Laboratory staff took part in the testing and analytical work. Special credit goes to J. C. Schuster and D. J. Hebert for their part in the analytical work and to L. V. Wilson and P. E. Bailey for their part in the laboratory testing.

GPO 843050