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DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

THE DEVELOPMENT OF HIGH-HEAD OUTLET VALVES

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ILLUSTRATIONS

THE DEVELOPMENT OF HIGH-HEAD OUTLET VALVES

INTRODUCTION

A review of the development of valves, from the crude stone gates used over 2,000 years ago, to the sleek modern giants which are capable of controlling entire rivers, would be a fascinating topic. Many countries have contributed to this development. The United States has made its contribution in the phase dealing with large gates and high-head regulating valves. A brief historical review of the development of valves in various countries would be appropriate and would serve as a background against which the more recent developments could be viewed. The space allotted this paper and the time available for its preparation will not permit an adequate treatment. This paper will discuss only the development of high-head outlet valves in the United States with particular reference to the work of the Bureau of Reclamation, and it is hoped that other papers or discussions will contribute material covering the experience of other countries. Conditions requiring the development of high-head regulating valves are common to many countries and it would be interesting and instructive to compare the solutions which have been reached.

Definition of Outlet Valve

In speaking or writing of devices for controlling or regulating the flow of water through an outlet in a dam, the words "gate" and "valve" are used. There is some measure of confusion as to whether the distinction between gate and valve should be based on function or design form. For the purpose of discussion in this paper, the terms will be used to express function. The term "gate," unless qualified as a regulating gate, shall be understood to mean a controlling device which is designed and used principally to allow the passage of the full capacity of an outlet or to shut it off completely. In a few cases, the term "regulating gate" will be used to designate a gate which performs the function of a valve. The requirements introduced by the necessity of operating a gate under emergency conditions, which must be accommodated in a design, do not alter the primary function. A gate is predominantly in a fully closed or fully opened position. The term "valve" will be used to designate a controlling device designed primarily for the purpose of regulating the amount of flow through an outlet from zero to maximum discharge. It, therefore, is required to operate at partially opened positions and this requirement is largely the controlling factor in its design. Current practice is to calibrate models of valves so that the valves may be used as metering devices.

NEED FOR HIGH-CAPACITY HIGH-HEAD OUTLET VALVES

As the size of dams and reservoirs was increased, it became necessary for economic reasons to design projects for multiple use, such as flood control, irrigation, power development, and river regulation for navigation. Several or all of the multiple uses of stored waters might be involved in one project. The rigorous demands imposed by such multiple use of a storage dam and reservoir required that the outlets be designed to give close regulation of the rate at which stored waters be released. Since the increase in dam height was accompanied by an increase in the size of outlets, many new design problems were posed not only by the higher pressures and velocities, but also by the larger size of the control devices. Many improvements in the mechanical design of valves were made to meet the challenge of new conditions.

Regulation was obtained in some cases by providing numerous outlets controlled by gates such as those used in Grand Coulee Dam, on the Columbia River in the State of Washington, where increases or decreases in flow could be obtained in finite increments equal in value to the capacity of a single outlet. Variation in the value of an increment was obtained by installing outlets at different levels and thus different heads. This method was not completely satisfactory for reasons which will be discussed subsequently.

A more economical method of accomplishing regulation consisted of providing fewer and larger outlets with valves which could be used to regulate the quantity of flow to any required value. The requirements of valves for such a use were that they could be built and used in large sizes (high capacity when fully opened) and could be operated under high heads and at any opening without damage to the valves.

Valves which had been developed and used for relatively low heads, that is, heads up to 100 feet, proved to be entirely inadequate, expensive to maintain, and often dangerous when they were used for high heads (1)*. The development of valves to perform this function of regulating high-capacity high-head outlets will be discussed in this paper.

EARLY EXPERIENCE WITH BALANCED VALVES

One of the first improvements in the design of large outlet valves was that of reducing the external power required for operation. The forces involved were the hydraulic thrust on the shut-off element and

*Numbers in parentheses refer to bibliography at end.

the sliding friction between this element and the stationary parts. In the early designs large mechanisms, in some cases approaching the size of the valve itself, supplied the power for operation. In later designs, the power for operation was obtained by supplying pressure to special compartments within the valves and utilizing the shut-off elements as hydraulic pistons. This method of overcoming the hydraulic thrust is known as balancing, and the valves using this principle are known as balanced valves. In general, a balanced valve is one in which the hydraulic thrust on the regulating element is non-existent or is balanced automatically at all openings of the valve, making it necessary only to overcome sliding friction to attain different degrees of regulation. From this definition it is evident that the term "balanced valve" does not define a particular type, but signifies a feature of design. A valve is considered to be balanced partially when the pressures from the discharging fluid do not counteract completely the hydraulic thrust on the shut-off plunger.

The needle valve and its variations, particularly that known as the Ensign valve, named for the prominent engineer who contributed much to its development, were among the first of the balanced type used in the United States. Generally, the needle valve was used at the end of a conduit while the Ensign valve was mounted on the reservoir face of a dam or placed at some intermediate point in the outlet tunnel. The Ensign valve was used most extensively in early high-head installations by the Bureau of Reclamation. The use of large needle valves, such as the Larner-Johnson and others, placed at the ends of conduits, followed as a result of difficulties experienced with the Ensign valve.

Ensign Valve

The Ensign valve consisted essentially of: a body, or stationary bull-ring cylinder; a hollow cylindrical plunger having a bull ring at one end and a needle tip with a seat ring at the other; a support ring with ribs to support the body of the valve; and a discharge throat connected to a steel or concrete discharge conduit, Figure 1A.

Usually the valve was mounted on the reservoir face of a dam with the throat embedded in concrete and the discharge conduit extending to the downstream face, but in some special cases it was installed in a large pipe or tunnel. In either setting the water surrounding the valve flowed between the support ribs, past the seat, support, and sealing rings, onto the needle-tip surface where it was directed axially through the throat into the discharge conduit. Regulation was attained by varying the position of the cylindrical plunger. The hydraulic thrust on the needle tip was balanced by regulating the pressure in the chamber at the back of the plunger. Water reached this chamber by way of a clearance gap at the downstream end of the bull-ring cylinder, through the clearance space between the plunger and the bull-ring cylinder. The pressure at the back of the plunger for any opening was regulated either by an ordinary valve and drain pipe or a special device connected through the closed end of the bull-ring cylinder. With sufficient pressure at the clearance gap, it would be possible to move the plunger in either direction by controlling the flow through the drain line or resetting the special control device. Increasing the flow through the drain lowered the operating pressure and opened the valve while decreasing the flow raised the pressure and closed it. This system was effective for opening the valves but not always for closing them. In some cases, the pressure at the clearance gap was insufficient to overcome hydraulic thrust and friction and auxiliary pressure systems were required.

The Bureau's experience with the operation of the Ensign valves with respect to control problems and cavitation erosion will be discussed in some detail because it strongly influenced subsequent developments of outlet valves.

Control Problems

When the need developed for closer regulation of the discharge, as a result of attempts to use stored waters more economically, the simple valve control proved to be inadequate, and a definite effort was made to devise a better means for maintaining the valve plunger in any intermediate position. The simple valve in the control pipe was inadequate because the force balance on the plunger was so sensitive that any accumulation of sediment or washing out of such material from the point of throttling caused the plunger to creep open or shut. It was, therefore, necessary to provide some more positive means of bringing about a balance of forces to maintain the plunger in partially open positions.

One of the devices used in early installations was known as the resistance tube. It consisted of a stationary corrugated tube attached to the closed end of the bull-ring cylinder forming an extension of the control pipe into the cylinder, Figure 1D. The tube was grooved on its outer surface and fitted into a recess in the plunger. The resistance tube entered the recess as the valve opened, and a resistance proportional to the opening was introduced into the drain passage. This resistance increased the pressure in the clinder and tended to prevent further movement of the plunger. If for any reason the plunger should start to close, the movement would withdraw the resistance tube from the recess in back of the plunger. The resulting reduction in the flow in the drain passage would lower the pressure in the cylinder and check the closing movement. Although of simple and apparent sound design, the device proved unreliable in practice and only by careful manipulation of the control valve was it possible to attain even approximate regulation of the flow. Apparently the point of balance was not well-defined and small accumulations of sediment in the clearance gap around the bull ring, in the control tube itself, or the control valve, resulted in an unbalancing of forces which caused movement of the valve plunger. The use of the resistance tube control was abandoned in later installations because of these difficulties, and a new device known as the sleeve control was developed to replace it, Figure 1C.

The sleeve control received its name from a peculiarity of its design. A movable tube or sleeve within the control pipe was attached to the back of the cylinder. This externally controlled sleeve could be extended into or retracted from the cylinder, against or away from a special seat attached to the back of the valve plunger. The withdrawal of the sleeve from the seat increased the flow from the back of the valve plunger, reduced the pressure, and allowed the hydraulic thrust on the plunger tip to open the valve. As the valve opened, the seat again approached the end of the sleeve, decreased the flow, increased the pressure in the cylinder, and again balanced the hydraulic thrust on the plunger tip. The plunger stopped at a point where the space between the seat and the end of the sleeve was such that the pressure within the cylinder just balanced the hydraulic forces on the plunger tip. Closure of the valve was accomplished by extending the sleeve toward the seat. This control proved so successful that the principle, with slight variations and improvements, has been adapted to many of the more recent control devices. The development of this control took place during the period from 1909 to 1923, when the Ensign valve was being used for Bureau of Reclamation projects.

Cavitation Erosion

Operation of the valves during the same period disclosed another and more serious problem. Several high-pressure outlet structures, designed by the Bureau of Reclamation in the early part of the twentieth century, were provided with 58-inch Ensign balance valves for flow regulation. The outlets at the Roosevelt Dam in Arizona, the Arrowrock Dam in Idaho, the Pathfinder and Shoshone Dams in Wyoming, and the Elephant Butte Dam in New Mexico are typical installations. The outlets were similarly arranged with the valves placed on or near the upstream faces of the dams. In all cases the valves discharged into the outlet conduits. After short periods of operation, particularly where the head was in excess of 100 feet, inspection revealed considerable damage to the needle tips and to the throat liners and discharge conduits immediately downstream. The damage was so severe in many cases, as shown in Figure 2, that it was considered dangerous to continue operation of the outlet facilities.

It was recognized that the destruction was in some way connected with the presence of low absolute pressures (high vacuums). The term "cavitation" was actually used to describe erosion instead of the action which produced it, as in the current theory of cavitation-erosion. Many attempts were made to eliminate or minimize the damage but few were effective. At first, the outlets were maintained by replacing certain damaged parts or by patching the pitted areas. The concrete surfaces were chipped and the holes filled with various concrete mortars, while the pits in the metal surfaces were filled with a material consisting of powdered iron, ammonium chloride, and sulphur, known as "smooth-on." The latter proved unsatisfactory and arc-welding various metals into the cavities was tried. With few exceptions, the patches eroded more rapidly than the parent materials. When it was realized that the pitting was connected with sub-atmospheric pressures, attempts were made to eliminate them. Concrete liners of various shapes and sizes were placed in the conduits below the valves to reduce the jet expansion and thus raise the pressures. When the liners were of sufficient thickness and extended to the end of the discharge conduit, no damage occurred when the valve operated at full capacity. The liners were ineffective at partial openings. The possibilities of relieving the sub-atmospheric pressures by introducing air were also explored. Several venting arrangements were tried with little success because they were improperly located. After the apparent failure of most of these attempts, the outlets were operated as little as possible.

As the multiple use of stored waters increased, it became more and more difficult to avoid unrestricted use of the valves. A method for avoiding some of the restrictions was devised as a result of model studies of the Shoshone outlet. These studies established that most of the damage resulted from operation within a fairly well defined zone. An operational schedule avoiding the critical valve settings has helped to minimize additional damage to the Shoshone valve. Tests on a model valve with a re-designed needle and vent system, as shown in Figure 1B, have indicated that if existing Ensign valves are altered to conform, they could be operated without restriction. These alterations would be considered only for existing valves since the Ensign valve has been long abandoned for other reasons, such as cost and inaccessibility.

DEVELOPMENT OF NEEDLE AND TUBE VALVES

Since the valves installed at the dam faces or in the conduits were subject to serious damage, the design of outlets was revised to that of needle valves placed at the downstream end of the conduit. Large balanced needle valves were undergoing development about the time the trouble was experienced with the Ensign valve, and the Bureau of Reclamation began using them in structures built in the early 1920's.

Needle Valves

A needle valve (2) usually consists of an outer shell, or body; a stationary cylinder supported on ribs or vanes; and a closing or regulating element telescoping either inside or outside the stationary cylinder, Figure 4. In the case of a balanced valve, provision is made for regulating the pressure in chambers behind the plunger.

Many of the early needle valves were quite large for the amount of water handled and most of them were satisfactory for operation at moderate heads with respect to cavitation erosion. Consideration of cost and size stimulated changes in design directed toward reducing the weight per second-foot of water handled. An appreciable reduction in the size of the valve proper was accomplished by eliminating the annular external ring around the plunger. In addition the introduction of balancing materially reduced the bulk of the operating mechanism and decreased the overall length. A design incorporating these changes resulted in a valve known as the internal differential needle valve, Figure 4.

Movement of the plunger was accomplished by manipulating the pressures in the chambers inside the valve. The pressure in the interconnected Chambers A and C was regulated by varying the capacity of a drain in the needle with a manually controlled slide valve. Pressure in Chamber B, which was connected to the conduit, remained fixed. Leakage into and from the chambers through various clearances prevented operation of the control as intended. The difficulties were corrected by separating Chambers A and C and controlling the pressure in Chamber B as well as that in Chamber C. In addition Chamber A was connected to a fixed capacity drain. The multiported control device for accomplishing the required chamber pressures was known as the paradox control and it was affixed to the bottom of the valve. A separate water supply line was brought to the paradox control and this permitted hydraulic operation of the valve in the absence of water in the conduit.

Further changes in the valve, including a major rearrangement of the components resulted in a valve known as the interior differential needle valve. The principal change, as shown in Figure 5, was a revision in the method of supporting the plunger which permitted the use of a needle telescoping over the fixed cylinder instead of inside. This permitted the use of a smaller diameter and reduced the overall diameter and length of the valve. The change resulted in a saving of about 25 percent in valve weight. No basic change was made in the control system.

In both the internal and interior types of needle valves, the proportioning of the water passages was accomplished by using a technique known as area shaping. Area shaping consisted of proportioning the flow passages in such a way that the area normal to flow varied with location according to some predetermined rate. In general, the area was held constant except for the downstream portion of the valve. In this portion the area was decreased according to some smooth curve. Usually the ratio of discharge to area, or mean velocity, was plotted against distance from a reference point for the fully open position only. This plot provided a means of judging the design; a smooth curve, with no reversals, being the criterion of good design. The procedure, however, did not take into account the effect of curvilinear flow or local high velocities, or the nature of the area shaping curve at openings other than 100 percent, thus its use did not always assure a satisfactory design. The water passages of some of the first designs prepared using this procedure contained comparatively abrupt curves and slightly divergent boundaries at the downstream ends of the valves for certain positions of the regulating plunger, Figure 4. The valves operated smoothly regardless of these characteristics until they were subjected to high heads. The discharge coefficient was 0.54 based on the total head immediately upstream and the area of a conduit with a diameter 1.2 times that of the valve exit.

Severe subatmospheric pressures occurred just downstream from the curved boundaries and in the sections where the boundaries diverged, when these valves were operated under high heads. As a result, there was much damage to the boundary surface due to cavitation, Figure 3.

The first large valves of this design were used in the outlet facilities at Hoover Dam on the Colorado River and the Alcova Dam on the North Platte River in Wyoming. The damage to the valves at these projects motivated a program of model tests which revealed the source of the cavitation-erosion and provided information for revising the shape of the boundary surfaces to eliminate it (3). A 6-inch model was used for the initial studies which established that the improvement would be made at the expense of capacity, reducing it about 17 percent. The discharge coefficient of the design shown in Figure 6 was 0.59 based on the total head and area one diameter upstream from the valve, or 0.45 based on the total head and the area of a conduit 1.2 times that of the valve for comparison with the coefficient of the previous design. The model served also to demonstrate the defects of the area-shaping procedure and helped to introduce the flow net as a tool for studying the details of flow in the passages. To demonstrate that the improvement was real, two small valves, one patterned after the initial design, Figure 4, and the other shaped to include the desirable features indicated by tests on the 6-inch model, Figure 6, were tested under heads up to 550 feet. Both valves were operated at the most critical openings indicated by the initial model tests. Cavitation erosion of appreciable extent was noted within 6 days on the original design, whereas there was no sign of erosion on the revised design after 84 days of operation.

A testing program was planned with the objective of realizing the optimum balance among the factors of size, cost, capacity, jet stability, and freedom from cavitation erosion. Before such a program was initiated the need for it was virtually eliminated by the development of new and more economical types of valves which will be discussed later.

Tube Valves

A reduction in the weight of the needle valve as well as a reduction in the operating power was realized by substituting a tube for the needle plunger. There were two reasons for using the tube, from which the valve received its name, tube valve (2). First, it eliminated part of the area of the needle that was subject to cavitation-erosion, and secondly, it reduced the hydraulic thrust against which the valve had to be operated. The profile of its flow passage, designed to prevent negative pressures, was determined through model tests and a ratio diagram established, Figure 7. The discharge coefficient of this valve was 0.52 based on the total head and area one diameter upstream from the valve. The performance of the tube valve with respect to jet stability and cavitation-erosion was indistinguishable from that of the revised needle valve except for openings less than 30 percent. At openings less than 30 percent there was a fluttering of the jet which was due to the absence of the stabilizing influence of the needle tip. The design was used in a few installations where this unstable characteristic at small openings could be tolerated. This type of valve was operated mechanically by means of a large screw geared within the fixed upstream cone and extending downstream through a tube nut in the spider attached to the tube plunger.

A tube valve designed specifically for installation in the outlet conduits of Shasta Dam on the Sacramento River in California will be described later under the heading of "Valves in Conduits."

OTHER TYPES OF REGULATING VALVES

The demand for a further decrease in the cost-discharge ratio prompted the Bureau of Reclamation to initiate a program of valve development which has continued intermittently for the past 8 years with much success. One of the most notable accomplishments during this period has been the development of the hollow-jet valve, a regulating control for use exclusively at the end of an outlet conduit, which not only weighs less than the tube valve but discharges about 35 percent more water.

Hollow-jet Valve

The hollow-jet valve (4) is essentially a needle valve with the needle, or closure element, pointed upstream and the nozzle or downstream end of the body eliminated as shown by the ratio diagram in Figure 8. Water discharges from the short bell-shaped body in a tubular, or hollow-jet, the outside diameter of which remains unchanged regardless of the valve opening. The jet leaves the valve with very little dispersion at any opening, but the effect of the hollow form is to distribute the energy over a comparatively large area, facilitating its dissipation and lessening the destructive action in a stilling pool. The coefficient of discharge for full valve opening is 0.70, based on total head and area one diameter upstream from the valve. The proportions of the water passage through the valve to prevent subatmospheric pressure and cavitation were evolved from extensive laboratory tests using aerodynamic and hydraulic models. Also, the tests indicated that an increase of 3-1/2 percent in capacity could be obtained by increasing the travel of the shut-off plunger 5-1/2 percent. Although the pressures on the plunger and body near the seat were decreased by this change, they remained slightly above atmospheric. A regulating outlet valve seldom operates in the fully open position, thus a further increase in travel to allow slight negative pressures in the valve might not be objectionable. At present, this valve is designed to be operated mechanically with the assistance of partial balancing. Complete balance was not attainable without special facilities external to the valve, but partial balance, within 13 percent greater or lesser than the total hydraulic thrust, was attained by providing fixed openings in the face of the needle of the shut-off plunger. Pressure from the flowing water is transmitted to the inner compartment by way of the fixed openings to counteract the hydraulic force on the needle tip. The correct location of the openings was established through tests on 6-inch and 24-inch valves to give the minimum unbalanced force. A desirable characteristic of the hollow-jet valve is the fact that the body shell downstream from the seat is never subjected to reservoir head, and need not be as heavy as a needle or tube valve. In addition, the valve has been arranged to facilitate removal of all mechanical parts which might require maintenance. The entire needle assembly which contains the operating mechanism may be removed without disturbing the shell. Large castings and considerable machining are required and the design is undergoing further investigations involving a re-shaping of the water passages and changes which will permit fabrication of the main parts of the valve by welding rolled steel plates.

Howell-Bunger Valve

Although the hollow-jet valve has replaced most other types for installation at the ends of outlet conduits in Bureau of Reclamation structures, other types are in general use in the United States. A balanced valve of simple design and lightweight construction, patented under the name of Howell-Bunger (5), has been used in several structures. It has a discharge coefficient of 0.85 based on total head and area one diameter upstream from the valve. The valve consists of a section of pipe having a 90-degree cone and valve seat attached to the downstream end by a spider of ribs or vanes; a sliding closure cylinder telescoping on the outside of the pipe section and outer surface of the ribs, which closes against the seat on the cone; and an operating mechanism consisting of a system of shafts and gears, Figure 9. Water passes through the space between the ribs and discharges outward between the downstream edge of the closure cylinder and the seat cone. The discharging jet has the shape of a cone with the apex within the valve. Because of this characteristic, the valve is best adapted to conditions where the confinement of the jet and excessive spray are not important considerations. The valve has not been used extensively in the United States because most structures include facilities for the generation of power and such jet conditions are undesirable where exposed electrical equipment is involved. In some applications the unruly jet has been contained by concrete walls which added appreciably to the cost of the valve installation. The possibility of improving the quality of the jet by attaching the simple fabricated hood shown in Figure 9 has been investigated by model tests. Tests have shown that unless the hood is vented adequately at its upstream end cavitation pressures are induced on certain parts of the valve and hood. The hood also introduced a hydraulic thrust which unbalanced the valve and added tremendously to the power required to operate it. Separate stationary hoods have been used also, but intense vibration in this design for the higher heads has required excessive bracing and stiffening. Moreover, the addition of a hood increased the cost to an amount comparable to that of other valves. Where the quality of the jet is not an important consideration, the Howell-Bunger valve, without the hood, is an economical, high-capacity control device.

The Butterfly Valve

The butterfly valve (2), used principally for closure of power penstocks, has been adapted as a regulating control at the end of large outlet conduits in a limited number of cases in the United States. The butterfly valve, deriving its name from the shape of the shut-off element, is essentially a short tube containing a flat circular leaf which is rotated, by an external mechanism, about a diametrical axis of the tube to attain regulation.

The details of butterfly valves vary according to the manufacturers who design, construct, and sell them. All of them operate on the same basic principle and thus the discussion which follows is applicable generally. A dispersion of the discharging jet at small openings and the presence of excessive spray make the butterfly valve objectionable for most free discharge installations. This objectionable characteristic may be minimized by the use of a hood or a special confining structure containing adequate aeration facilities. The addition of such auxiliary features add to the cost of a valve installation. The capacity of this valve is low compared with the newer valves of the same size. The discharge coefficient for the designs in which the valve diameter is the same as that of the conduit is about 0.60. In nearly every butterfly valve, cavitation on the downstream surfaces of the valve leaf is a definite possibility when it is operated near the wide-open position and at high heads. This is due to the shape of the circular leaf, which is quite thick on the axis containing the pivot shaft and decreases in thickness from this axis to its outer circumference. Near the wide-open position, the leaf presents a shape similar to an airfoil which causes a local zone of intense subatmospheric pressure and cavitation.

The Regulating Radial Gate

The radial gate and its variations have been used extensively for controlling the flow in spillways and the flow from large outlets under low heads. In 1944 a radial gate was designed by the Bureau of Reclamation for use in a conduit to control the flow from the large high-head outlets in Davis Dam on the Colorado River, Figure 10. Studies on a 1 to 30 scale model (6) of a gate and outlet indicated that the radial gate was suitable for such use. The gate offered no resistance to flow at the fully opened position. Therefore, the discharge coefficient of 0.90 resulted from the design of conduit upstream. There was no measurable vibration and the flow was smooth at all openings. Although the Davis Dam is in the construction stage and it will be many months before the outlets will be placed in operation, it is the consensus that the design has excellent possibilities. However, the problem of sealing radial gates under high heads has not been satisfactorily solved. The same problem exists in the case of coaster gates and ring seal gates. The seal design now being used most extensively, the so-called music-note seal, is not entirely satisfactory. Tests are now being conducted by different organizations to obtain a solution to the problem.

Jet-flow Regulating Gate

One of the most recent developments in valves, regulating the flow from large high-head outlets, is one known at the present time as the jet-flow gate or valve (7). It was developed by the Bureau of Reclamation for use in the intermediate and upper tiers of outlets in Shasta Dam in California when the special tube valve developed previously for this purpose and used in the lower tier proved to be too costly. The valve consists of a slide gate in a special housing having an orifice at the upstream side, and a circular, rectangular, or horseshoe opening at the downstream side. It was designed to fit a conduit with a diameter 1.2 times the diameter of the orifice. As shown in Figure 11, the required size of conduit at this point may be obtained by expanding from a smaller conduit in an easy transition. The conduit downstream may be of any desired shape, so long as a satisfactory transition is made and an adequate vent system is provided to aerate the jet at partial openings. The venting system shown in the figure is an adaptation to conditions in the Shasta outlet where the expander and the vent conduit were already installed when the valve type was changed. It serves to demonstrate the marked reduction in valve size. In a new installation the vent system would be more simply designed to deliver air at a point immediately downstream from the gate.

The unique feature of the valve is the use of a carefully planned jet contraction. As water flows from the larger conduit through the orifice a contraction of the jet around its entire periphery is produced at any opening. This permits complete ventilation of the jet and eliminates flow into the gate grooves which is the usual source of damage and vibration in the case of a slide gate.

The upstream face of the gate is a smooth, planed surface which remains in contact with a special seal contained in the orifice side of the valve housing. Sealing at the upstream face virtually eliminates the hydraulic downpull force so troublesome in gate valves with the conventional downstream seal. The proportions of this valve were established through extensive tests on a 6-inch model under heads up to 350 feet to insure against cavitation-erosion. The valve is of simple construction, is capable of operating at any opening, and has a relatively high capacity. The discharge coefficient is about 0.80 for the fully open position, based on total head in and the area of a conduit with a diameter equal to that of the valve orifice. The first valves of this design have been placed in operation very recently at Shasta Dam and unofficial reports indicate that the design promises to be one of the best used by the Bureau of Reclamation for regulating the flow from large high-head outlets. The Shasta valves operated with very little back pressure so the suitability of the valve in outlets with high back pressure is still open to question. Its adaptability for the latter type of installation will no doubt be explored in the future when its use under these conditions is desired.

The possible use of the jet-flow valve for adaptation to free discharge conditions was also studied in the model. The jet was rough compared to those of the needle and hollow-jet valves and for installations requiring a well-contained jet plunging into a pool it would be definitely inferior except for special cases with unusually large, isolated pools. However, it did show promise for installations where it would discharge tangentially onto an apron because its shape was roughly rectangular.

Cylinder Gate

The usual cylinder gate installation consists of a concrete tower structure located in the reservoir and one or more cylinder gates which slide up and down over openings through the wall of the tower to regulate the outlet discharge. The gate has been used in a limited number of Bureau of Reclamation structures to regulate the release of water from reservoirs (1). The design gave very satisfactory service under low heads, but trouble was experienced with cavitation-erosion at higher heads. It has been possible however to eliminate the erosion by making minor changes in design. The main disadvantage of the cylinder gate is its inaccessibility. The large tower structure and difficulty of aeration might be considered disadvantageous also.

Plug Valve

The plug valve is essentially a cone-shaped plug which fits snugly into a housing. A hole through the plug, perpendicular to its axis, forms a passage which connects two openings in the housing or body of the valve. A 90-degree rotation of the plug closes or opens the passage. Although used extensively for small lines, or where three-way or four-way installations are required and where regulation is unnecessary, the plug valve has been adapted as a regulating device for the outlets in a few American installations. In most of these cases the valve was placed at the downstream end of the outlet conduit and discharged into the atmosphere. The discharging jet disperses widely at partial openings making it necessary to provide a confining structure when this condition cannot be tolerated. The water passage for partial opening contains abrupt changes in the boundary surfaces which are conducive to the formation of zones of subatmospheric pressure and cavitation. Special venting systems have been provided to aerate some of these zones but it is questionable if the problem has been solved satisfactorily. The plug valve merits consideration because of its high discharge capacity. The coefficient of discharge for the fully open position is nearly unity.

INSTALLATION OF OUTLET VALVES IN A CONDUIT

The early experience of the Bureau of Reclamation with valves installed at the beginning of outlets using Ensign valves was discouraging. Some of the troubles which were experienced have been described previously. Damage to the valves and conduits resulted in a departure from the practice of using valves at the entrance of conduits. Instead, the larger valves operating under high heads were placed at the ends of conduits and discharged freely into the atmosphere. The design of such outlets was more complicated and the longer conduits required to bring the outlets to a suitable position for installation of free discharge valves added to their cost. However, the higher costs appeared to be justified by the more trouble-free operation.

During the past 10 years there has been a trend towards returning to the practice of placing regulating valves near the entrance to an outlet. The most important single advantage of installing a control valve near the beginning of an outlet is the fact that only that portion of the conduit upstream from the valve is under full reservoir pressure during shutoff. The conduit downstream from the valve is subjected to only nominal pressures resulting from frictional losses and back pressure from any construction at the end of the outlet. The cost benefits that may be realized from the low-pressure condition in the outlet conduit accrue to a greater or lesser degree depending on the type of dam. Other possible advantages such as the eliminating of emergency gates and the shortening of outlets, as well as possible disadvantages such as inaccessibility and venting difficulties, are subject to diverging opinion and will not be discussed.

In some cases the free-discharge valves were replaced by ring follower gates placed near the upstream ends of the outlets. Operation of these gates was restricted to the fully opened or closed positions. An arrangement of this type was used for Grand Coulee Dam. The outlets were placed at three different levels separated by approximately 100 feet. There were 20 outlets in each tier arranged in 10 pairs. The large number of outlets, sixty, and the fact that they were subject to three different heads permitted regulation by relatively small increments. Each outlet was provided with two gates similar in design, one for service and the other for emergency operation. The severe conditions of stress and vibration exerted on the service gate during its operation fully justified the emergency gate.

A return to the use of valves in a conduit was made in the case of the Shasta Dam outlets. Each outlet was 102 inches in diameter and consisted of a rounded entrance, a horizontal segment of steel-lined conduit, and a deflector elbow at the end where it pierced the spillway face. A specially designed tube valve was installed in the outlet a few diameters downstream from the entrance. It was intended to be operated at any opening for regulation and to have a capacity that would fill the conduit downstream when fully opened. At the end of the valve was a large ventilation or aeration chamber attached to a 36-inch diameter air conduit which supplied air during valve operation at partial openings. Because the valve was designed for operation at partial opening the need for an emergency gate was virtually eliminated. A coaster gate that could be transferred to any outlet by a gantry crane served as a means of closing it under emergency conditions, or for the purpose of carrying out maintenance work on the valve.

A special tube valve, Figure 12, with a long, slim shape and operated by an internal hydraulic cylinder was developed by extensive tests using a 1 to 17 scale model and a 1 to 5.1 scale model (8). The model testing included a study of air requirements and the determination of the appropriate size of air supply conduit. Development work was curtailed before a completely satisfactory design was evolved because the need for the valves developed sooner than anticipated. Only four of the valves were installed in the four lowest outlets at Shasta Dam for the purpose of regulating releases during the filling of the reservoir. The model tests demonstrated that there was a range of openings varying from zero at low heads to the range from 65 to 90 percent opening at maximum head of 323 feet wherein operation should be restricted because of the cavitation-erosion which would result. This restriction in operating range is the reason for the statement made previously that the design was not completely satisfactory. Experience with these four valves has indicated that they were quite satisfactory and that the restricted range was easily circumvented by using different combinations among the four valves.

During construction, one of the valves was provided with piezometer openings so that pressure measurements could be made after it was installed.

Field tests of the valve, including pressure measurements and determinations of air flow, which reached a maximum of 40 percent of maximum water discharge, checked closely with the respective values predicted from the model tests. Operation of the valves at partial openings was reported to be smooth and satisfactory so far as conditions at the valve were concerned. Inspection of the outlet conduit downstream from the valve after a season's operation indicated no evidence of damage in the straight section due to the operation of the valve in a conduit.

The invert of the elbow deflector at the end of the outlet showed some evidence of cavitation-erosion. This was not unexpected as the model tests showed that negative pressures would prevail in this region for operation at partial gate opening. The damage was not great, probably because the water contained a relatively high percentage of entrained air which would discourage cavitation-erosion. The situation may be corrected by ventilating the critical area or the erosion resisted by weld-filling the damaged areas with a material such as stainless steel.

The quality of the jet for such an installation, where a mixture of air and water is discharged from an outlet, at high velocity, is such that its use would be subject to some restriction. The deflector elbow and its setting in the face of the spillway were designed to place the jet along the spillway face with comparatively little disturbance and it so operated when the valve was fully opened, Figure 13. When the jet contained a large portion of air, as it did at partial valve openings, the action of the elbow deflector was largely nullified. Shortly after emerging from the outlet the mixed fluid jet dispersed and a considerable amount of spray was generated, Figure 14.

The spray was bad enough that the valve nearest the powerhouse was not operated at partial openings except when absolutely necessary. The spray from the other three valves did not reach the powerhouse so they were operated as required. Every effort was made to accomplish the required total discharge by setting the valves at openings where the jet had the best quality. For example, two valves would be operated at 30-percent capacity, rather than one at 60-percent capacity because there was less spray.

Spray conditions made it undesirable to consider regulated flow for the higher outlets so the possibilities of using a less expensive valve or a non-regulating gate were investigated in lieu of equipping the remaining outlets with regulating tube valves. The regulating gate or jet-flow valve developed in the course of this investigation has been described previously. Although it is not intended that the jet-flow valve be used as a regulating device at Shasta Dam, its performance in this respect was studied in the model. Its performance closely paralleled that of the other valves with respect to flow conditions in the conduit and the appearance and action of the jet at the end of the conduit. A field test of one of the Shasta valves is planned.

During the studies relating to the special tube valves, regular tube valves, and needle valves were investigated in an attempt to generalize the information on the performance of valves placed in an outlet. They showed promise of operating more satisfactorily than the special tube valve because they could be operated at any opening without reservation so far as conditions in the valve were concerned. However, the lower discharge coefficients compared to the special tube valve would require larger valves to pass the required maximum discharge. Considerations of size, especially the diameter, led to a decision to use the special tube valve which had a long, slender shape. For other installations, however, either one of these two valves, the conventional tube or the needle valve, would be considered. Conditions of flow in the conduit downstream from either of these valves closely resembled those existing for the special tube valve. The air requirements were nearly identical in each case. The quality of the jet from a conduit containing a partially closed valve of any type would be quite similar. The disintegration of the jet and the spray resulting therefrom are caused by the mixture of air in the water which results from the setting and operation of the valve rather than the type.

The model studies of the regulating gate in the conduit resulted in the development of a radically different type of elbow deflector which does show promise of improving the jet delivered by an outlet, and in particular an outlet with a flat bottom. The new deflector which was tested with a flat-bottomed conduit consisted of a curved rectangular passage which turned the jet with an open water surface at the inner radius, starting at a vertical offset in the floor. The space under the jet was ventilated to prevent the formation of low pressures. The jet delivered by this deflector appeared to be more stable in the model than that delivered by the elbow deflector used at Shasta Dam. Since the model did not completely represent the conditions that would exist at the discharge end of the prototype outlet, the model results are qualitative only. Quantitative evaluation of the improvement must await the installation of an outlet with the revised deflector.

In the case of an outlet with a relatively large ratio between the conduit diameter and the valve diameter such as the tunnel outlet, the exit velocity is usually so low that very little spray exists at the exit. Much of the energy of the jet is absorbed within the tunnel. For outlets of the latter category, the use of radial or Taintor gates as regulating devices has been planned for at least one installation and several more are contemplated. The characteristics of a radial gate adapt themselves very well to such an installation and except for the sealing problem seem to be ideally suited for use as a regulating or control gate.

FUTURE DEVELOPMENTS

Future developments in the field of high-head outlet valves will probably take the form of further improvements in the types now being used. The problems of jet shape and stability, pressure conditions not conducive to cavitation erosion, and vibration-free operation have been quite satisfactorily met. There does remain, however, a fertile field for reducing costs by improvements in mechanical design.

Some study has been given to the possibilities of adapting the hollow-jet valve to welded fabrication from rolled plates. A completely balanced design has been worked out by the Bureau of Reclamation, but the present design is appreciably larger in diameter than the cast design previously discussed. The necessity of using sharp intersections for welded fabrication imposes limitations on the angles with which the fluid jet impinges on the shell and results in a larger size. Further development work to increase the discharge capacity is expected to produce a reduction in size which will make the fabricated valve less expensive than the cast type.

Model experiments with the jet-flow valve have indicated that the jet whose cross-section is roughly rectangular can be adapted to free discharge conditions. For those installations requiring a reasonably smooth jet for free discharge conditions the jet-flow valve appears to offer advantages as an inexpensive regulating device. Simplification of construction and reduction in the amount of machining may be expected to further reduce the cost.

The possibilities of improving the seals on radial gates have already been mentioned. The problem is being studied actively by several organizations and a satisfactory design is in the offing. When such a design materializes the use of radial gates as outlet regulating devices will undoubtedly be extended appreciably.

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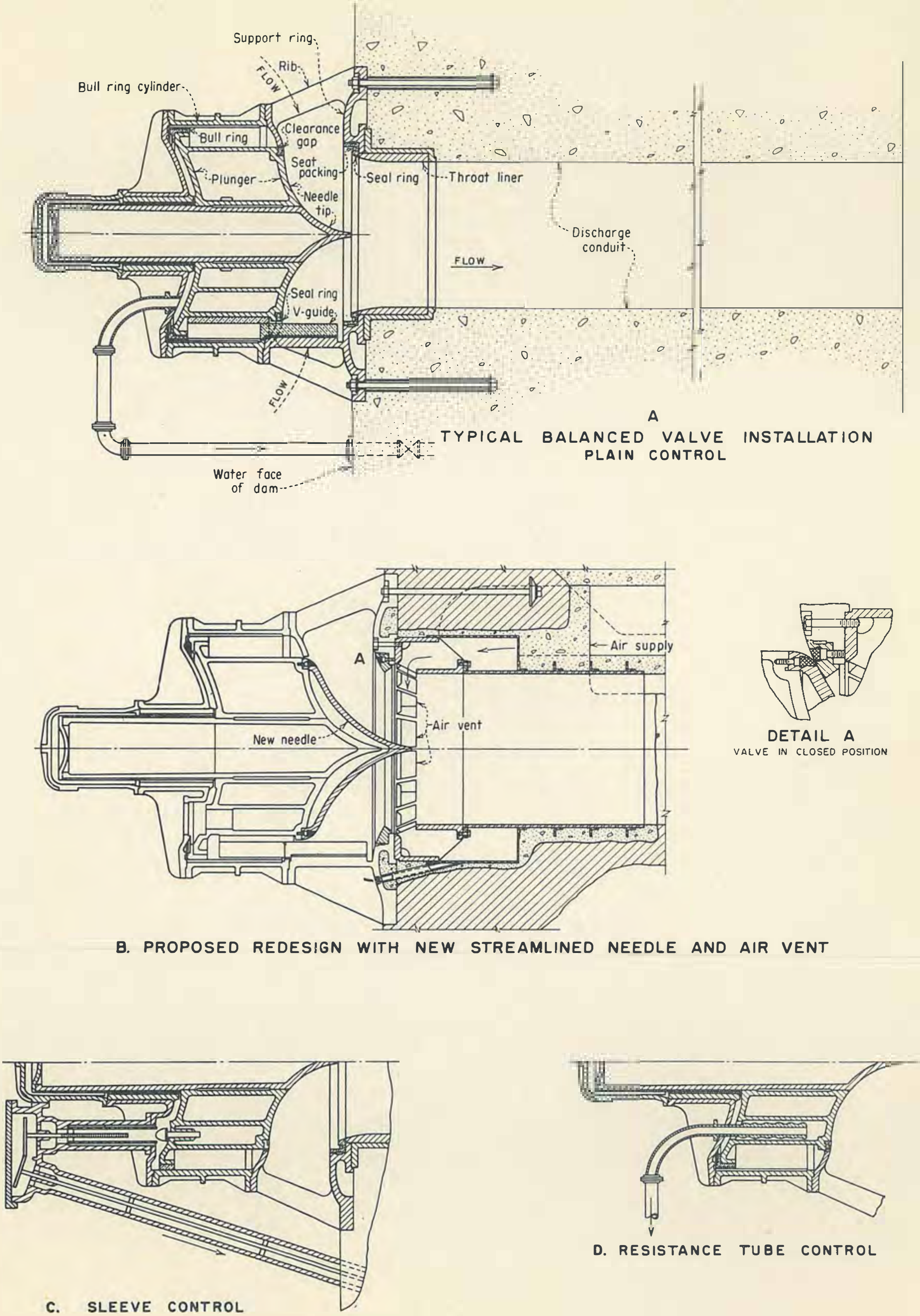


FIG. 1 ENSIGN BALANCED VALVE

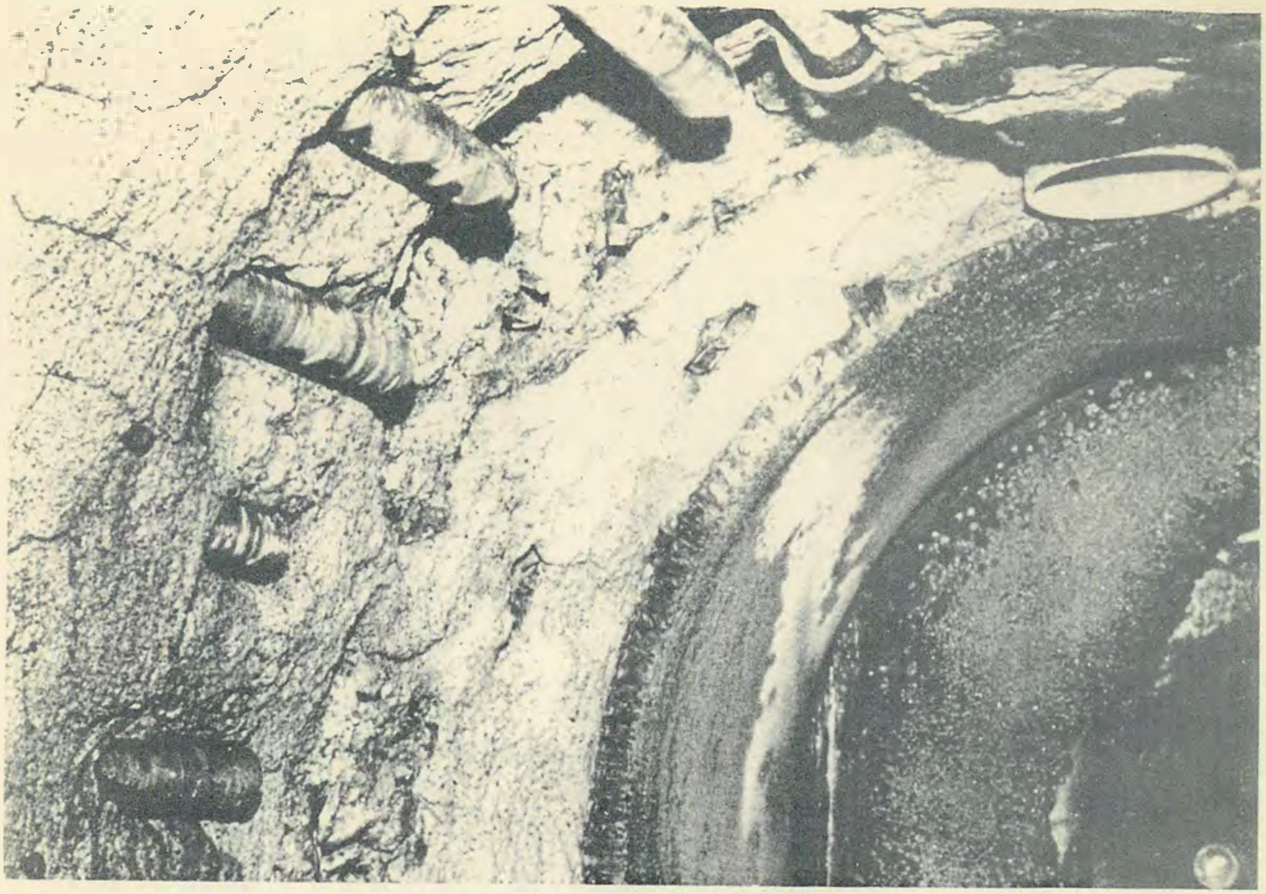


FIG. 2 CAVITATION-EROSION OF ENSIGN VALVE AND CONDUIT, SHOSHONE DAM, WYOMING.

FIG. 3 CAVITATION-EROSION OF 84-INCH NEEDLE VALVE, ALCOVA DAM, WYOMING.

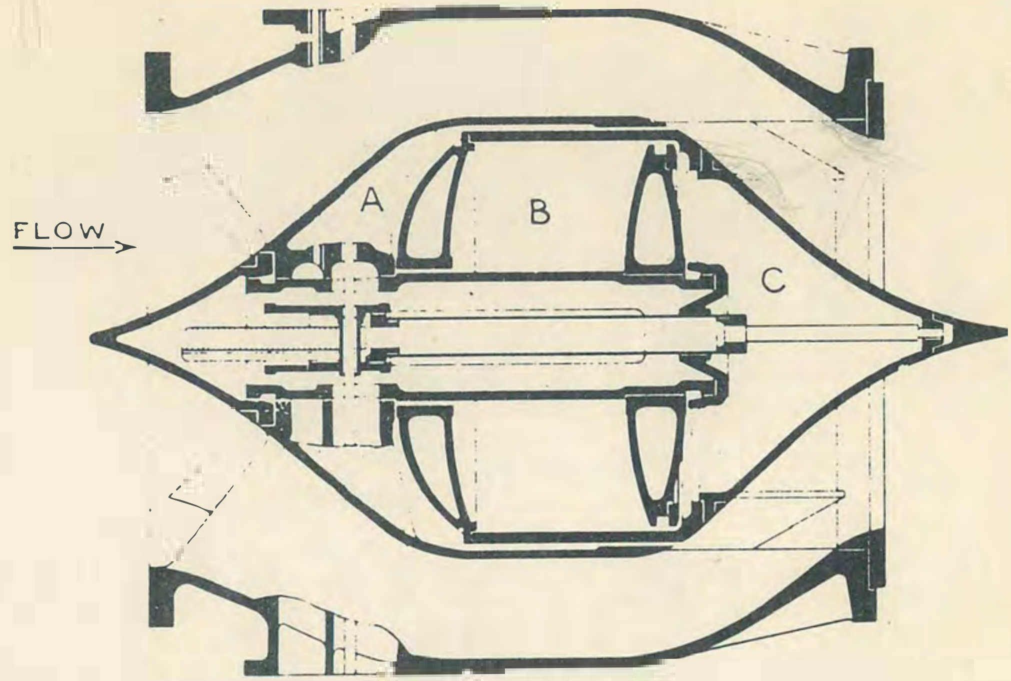


FIG. 4 INTERNAL DIFFERENTIAL NEEDLE VALVE

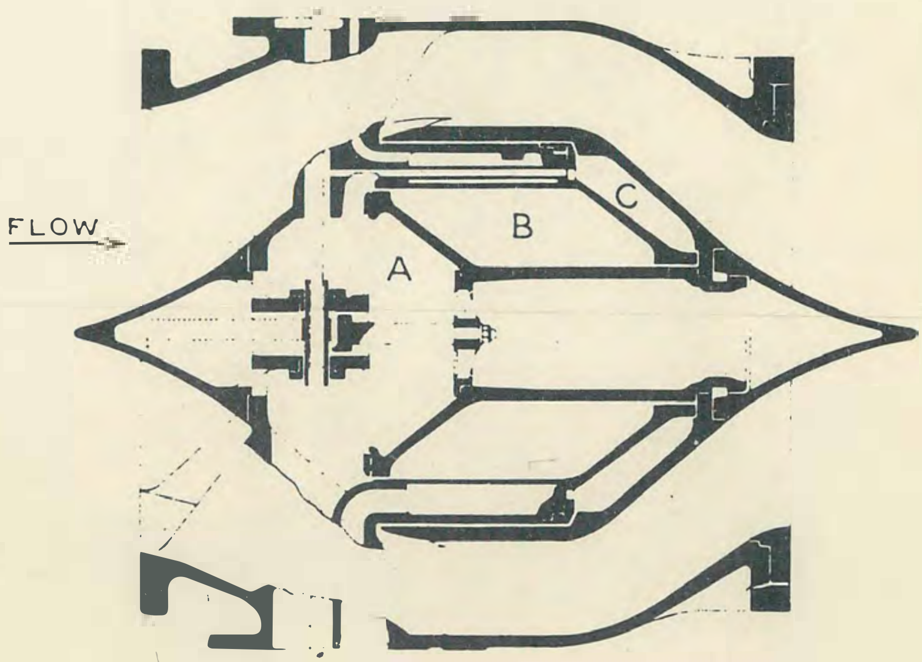
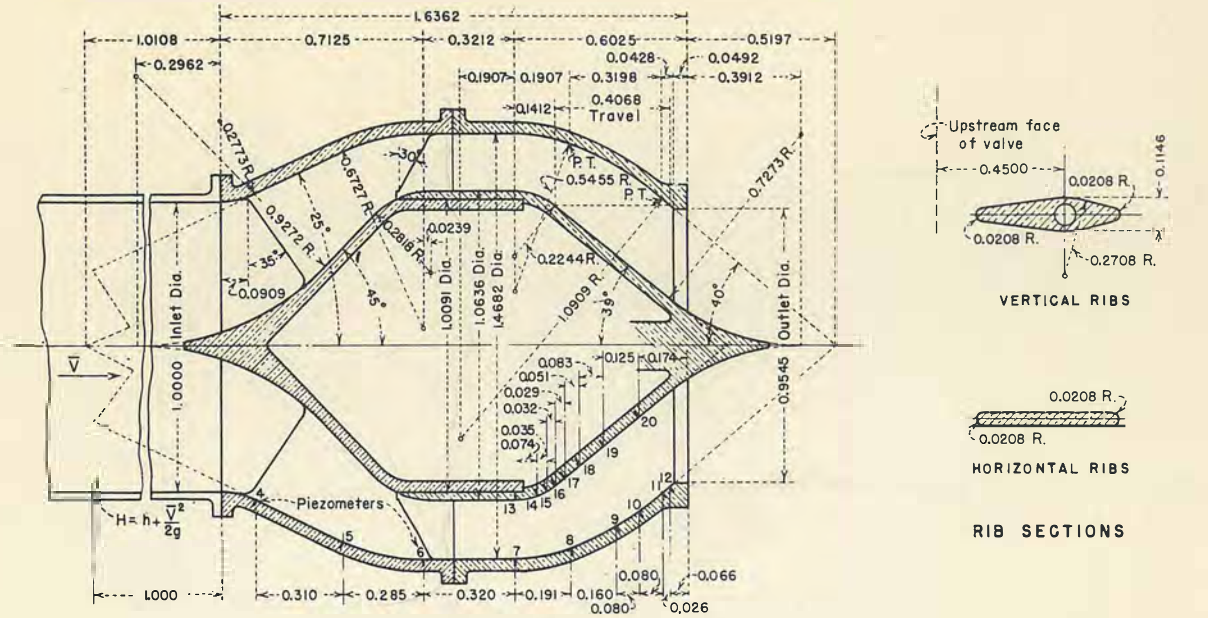
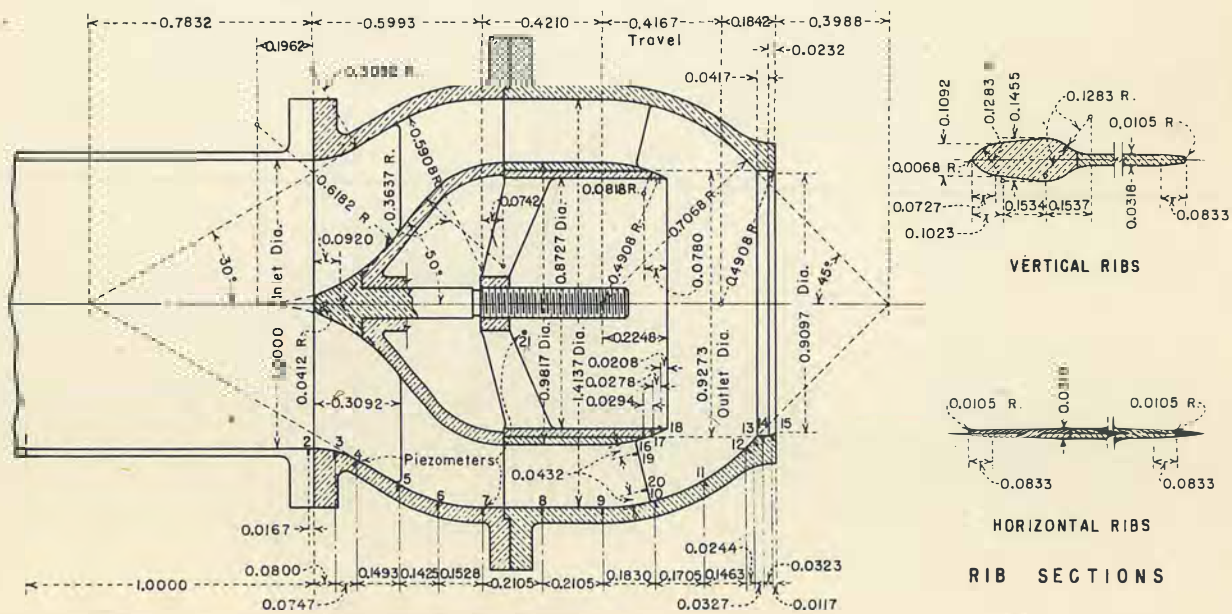


FIG. 5 INTERIOR DIFFERENTIAL NEEDLE VALVE



SECTION THRU VALVE

FIG. 6 REVISED NEEDLE VALVE



SECTION THRU VALVE

FIG. 7 REVISED TUBE VALVE

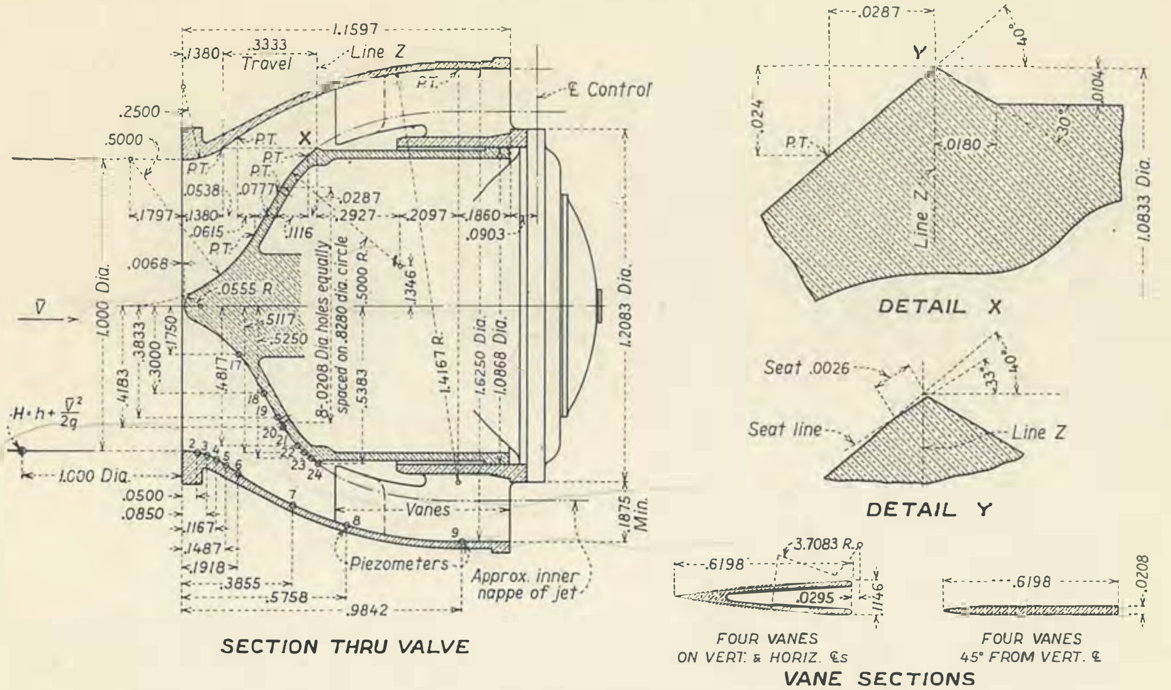


FIG. 8 HOLLOW-JET VALVE

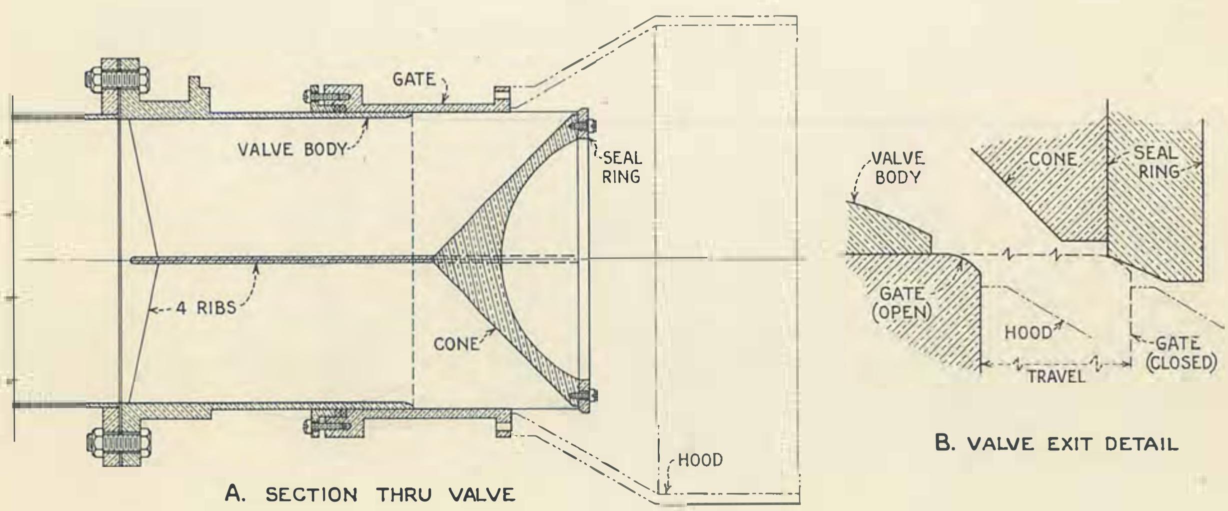


FIG. 9 HOWELL-BUNGER VALVE

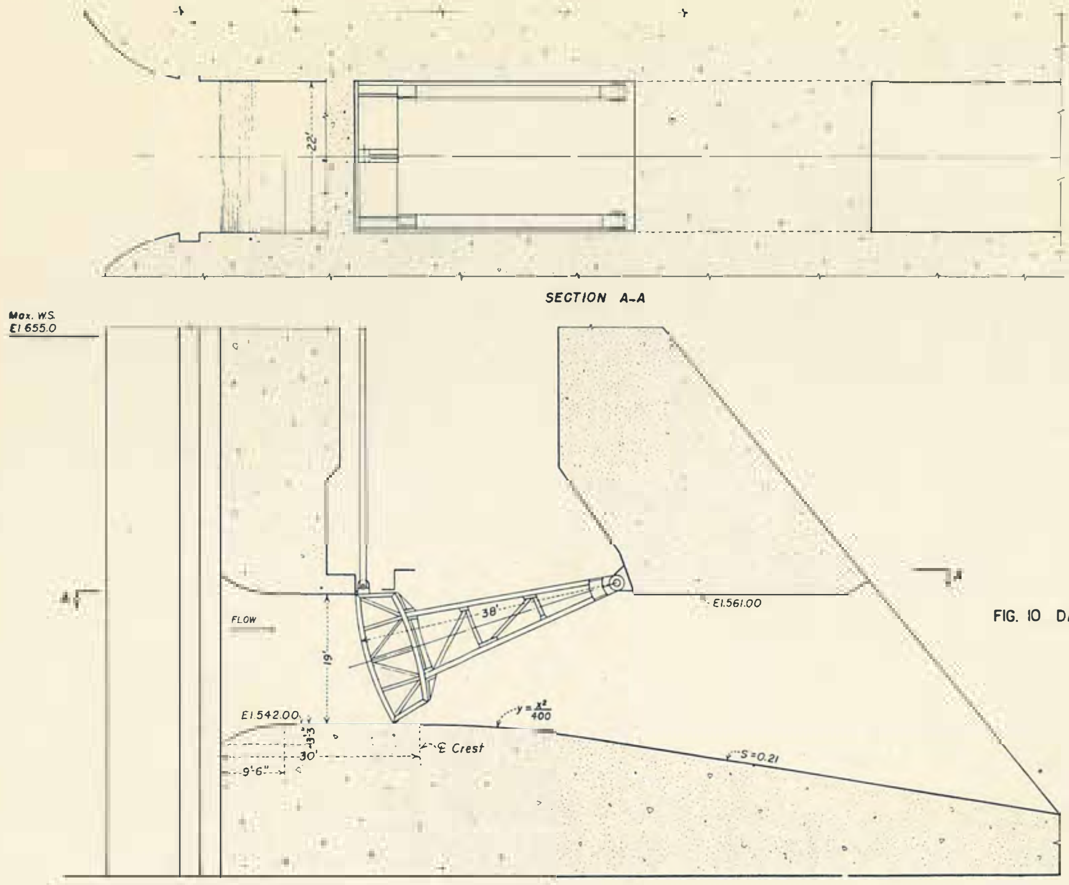
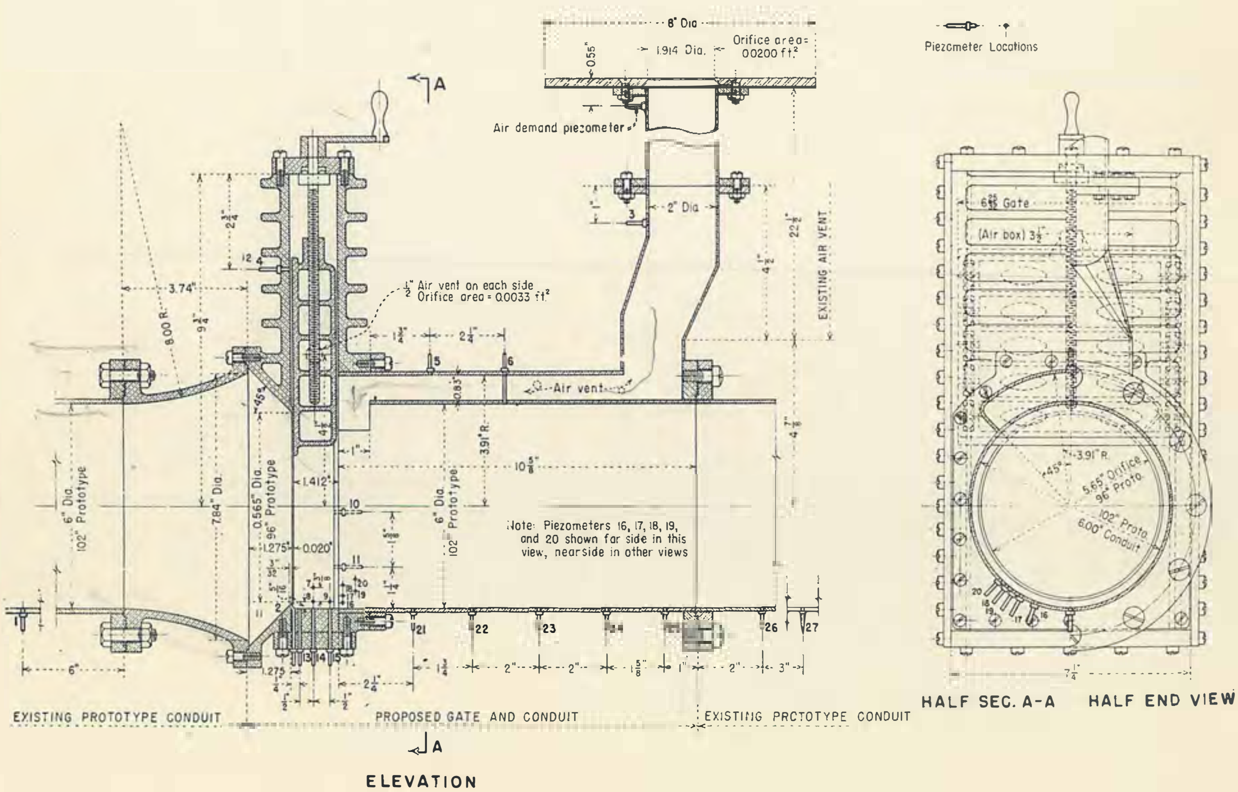


FIG. 10 DAVIS DAM OUTLET
RADIAL GATE



B. DETAILS OF GATE

FIG. 11 JET-FLOW VALVE

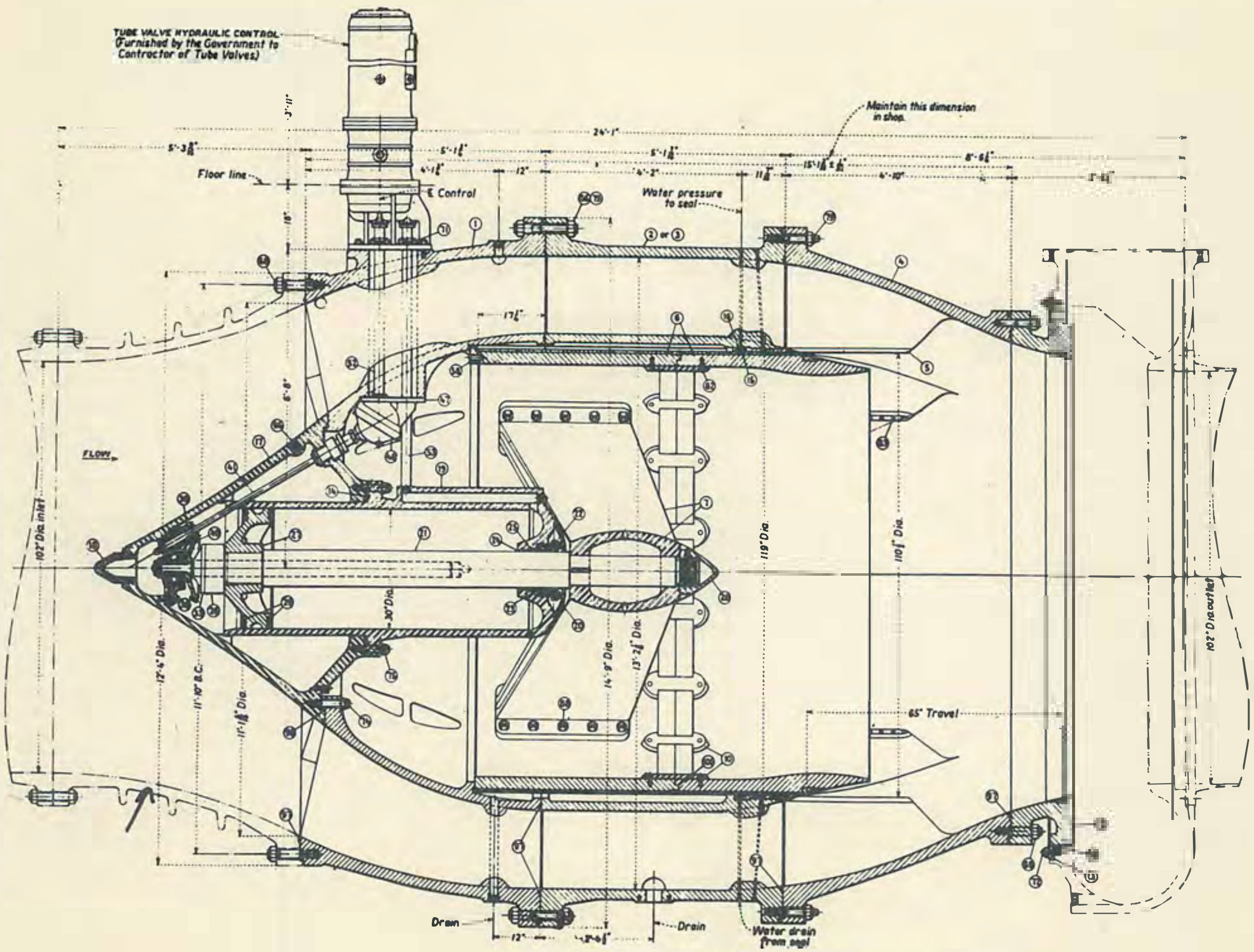


FIGURE 12 THE SHASTA TUBE VALVE

FIG. 13 DISCHARGE FROM SHASTA DAM OUTLET AT FULL CAPACITY.

FIG. 14 DISCHARGE FROM SHASTA DAM OUTLET AT HALF CAPACITY.