

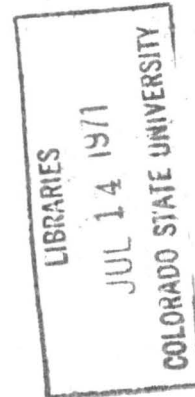
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PROPOSED MODIFICATIONS TO THE GROSS  
DAM OUTLET WORKS

by

Maurice L. Albertson  
J. Paul Tullis  
Sellards and Grigg, Inc.



November 1968

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Prepared for  
Denver Board of Water Commissioners

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## SUMMARY

Serious problems due to cavitation damage have been encountered at the outlet works from Gross Reservoir. All valves installed as original equipment have been extensively damaged by cavitation and have either been repaired, replaced, or are in need of repair. The situation is urgent, due to the fact that only one throttling valve is presently available to the site. If this valve becomes inoperable the system cannot operate safely or with reliability.

The following is a report describing the problems and listing alternatives and recommendations for correcting the difficulties. Two general approaches for solving the problems are considered: (1) Modifications to the existing outlet works and (2) constructing a new free discharge outlet works at the end of the conduit system.

The results of the investigation document that modifications to the existing structure is the most reasonable solution. The present outlet works are, in general, well designed and adequate for the required task. With minor modifications, this system can be made to operate reliably and with a minimum of maintenance.

Seven recommendations are listed for resolving the situation at the outlet works. These include enlargement of the air supply system, repairs to the downstream chamber, selection of throttling valves, the utilization of a small by-pass valve, and proper operation of the valves.

## II

### RECOMMENDATIONS

Numerous alternatives for solving the problems that exist at the Gross Dam Outlet Works are presented in Chapter V. Here are presented those alternatives which are most highly recommended.

#### Recommendation #1

It is considered imperative that the air supply system be enlarged. The method suggested in the alternatives, Chapter VII, should satisfy this need.

#### Recommendation #2

Since, under unusually large discharge, partial submergence may occur in the downstream chamber it is necessary to: (1) Make a complete structural examination of the bulkhead wall to insure it can withstand the anticipated pressures, and (2) complete the necessary repairs in the chamber to insure it will be water-tight when submerged.

#### Recommendation #3

No modifications in the downstream conduit are recommended to eliminate the possibility of choking. It is believed that if a choking problem actually exists, its occurrence will be so infrequent as to make a major expenditure for its elimination impractical.

#### Recommendation #4

The valve system recommended as the most appropriate for the task (all factors considered) is the one listed in Chapter VII as alternative #4. (That is, 1 - 36-inch hollow cone valve, 1 - 48-inch needle valve, and 2 - 42-inch ball valves). This is, of course, based on some relaxation in the demand requirements. The details of the needle valve installation are very critical.

If absolutely no variation from the present requirements is possible then alternative #1 (2 - 48-inch needle valves and 2 - 42-inch ball valves) is recommended.

Recommendation #5

If the decision is made to incorporate hollow cone valves in the system and operate them submerged, a model study to verify their performance should be conducted.

Recommendation #6

It is recommended that when further major repairs on the ball valves becomes necessary, they be replaced rather than expending additional money on repairs.

Recommendation #7

A throttling valve should be installed in the 12-inch by-pass line for release of discharge below about 30 cfs.

### III

## INTRODUCTION

Gross Dam was constructed in the early 1950's as a multiple-purpose facility, to serve as part of the Denver water supply system, for flood control, and as a recreation facility. The outlet works were first operated in Mid 1952. By 1960 it was apparent that cavitation damage was occurring in the 48-inch Hardie-Tynes needle valve which was the main release valve. In 1961 this valve was removed, modified and repaired, hopefully to eliminate future cavitation damage. Within 5 years cavitation had again caused enough damage to the valve that it was removed from service. In February, 1966 a 36-inch hollow cone valve was installed as a replacement and is still in operation. During the times when the needle valve was out of service, the ball valves had to be used for release. Consequently, all three Davis Ball Valves were extensively damaged by cavitation. One has already been replaced and is currently being repaired, and the other two are in need of major repairs.

The serious problems encountered with the outlet works at Gross Dam prompted the Denver Board of Water Commissioners to seek consulting help to analyse the situation and to make recommendations for remedying the difficulties. The assigned task consisted of evaluating the present outlet works to determine if they are, in general, suitable for the task, and can be made to operate satisfactorily with minor changes, or if major modifications are necessary. Assuming that the present system can be modified successfully, alternate solutions were requested for:

1. Selecting the most suitable type and size of valves
2. Expansion of the air supply system, if needed
3. Eliminating the conditions which might cause choking in the downstream transition, if such was deemed necessary
4. Determining what modification might be necessary in the downstream chamber so it can operate under submerged discharge conditions

After the problems were isolated by discussions with the Water Board, visits to the site, and careful study of the plans, a set of field tests were planned and carried out to obtain data necessary for the final analysis.

In arriving at the several alternatives and recommendations, the analysis was supported and documented by the results of past and current research on valves conducted at Colorado State University by the authors, and research by various other investigation.

## IV

### STATEMENT OF THE PROBLEM

#### Description of the System

The outlet conduit from Gross Reservoir consists of a single concrete conduit with changes in cross section along its length. Figure 1 shows the general plan and profile of the conduit and its control structures. There is a single low level intake structure at elevation 6998. Discharge from the reservoir is into South Boulder Creek, at approximately elevation 6958. Under normal conditions there is a head differential of approximately 200 to 295 feet, with a maximum head differential of 299 feet through the vault.

Control of the discharge is accomplished in the valve vault located at approximately Station 8+00. Figure 2 shows the general layout of the valves in the vault. On each of the lines is a 42-inch Davis ball valve whose function is solely to act as a guard valve upstream from the four operating valves. The operating (control) valves, on each of the four lines consist of three additional 42-inch Davis ball valves and one 36-inch Howell-Bunger valve. All of the ball valves, with the exception of number two (2), were installed as original equipment. Number 2 was recently installed to replace an identical valve which is presently undergoing repair for cavitation damage. The number one (1) and number four (4) ball valves have also been heavily damaged by cavitation.

The control valves discharge into a transition chamber which reduces to an 8-foot concrete tunnel. The tunnel discharges into a ten-foot-square box flume which in turn leads to South Boulder Creek. All discharge through the outlet works is measured by a critical-depth flume 4000 feet downstream.

#### Operating Requirements

##### Normal Operation

In over ten years of service, a normal pattern has evolved for the operation of the Gross Outlet Works. It has been operated in a rather narrow range of heads and discharges. The maximum discharge to pass the system was 893 cfs, which occurred on June 29, 1957. The normal minimum flow to pass the outlet works

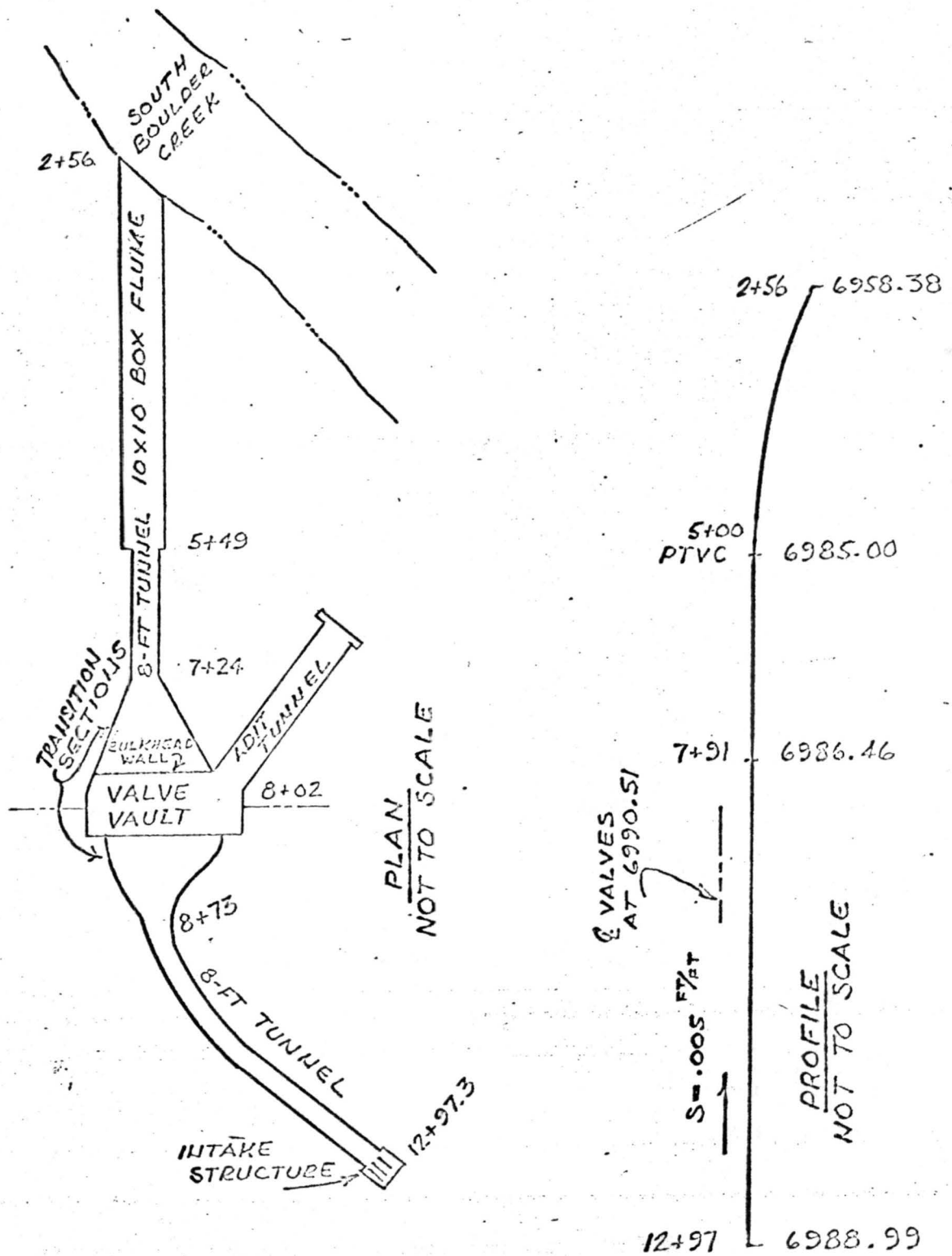


FIG. 1 : PLAN AND PROFILE  
GROSS RESERVOIR OUTLET WORKS

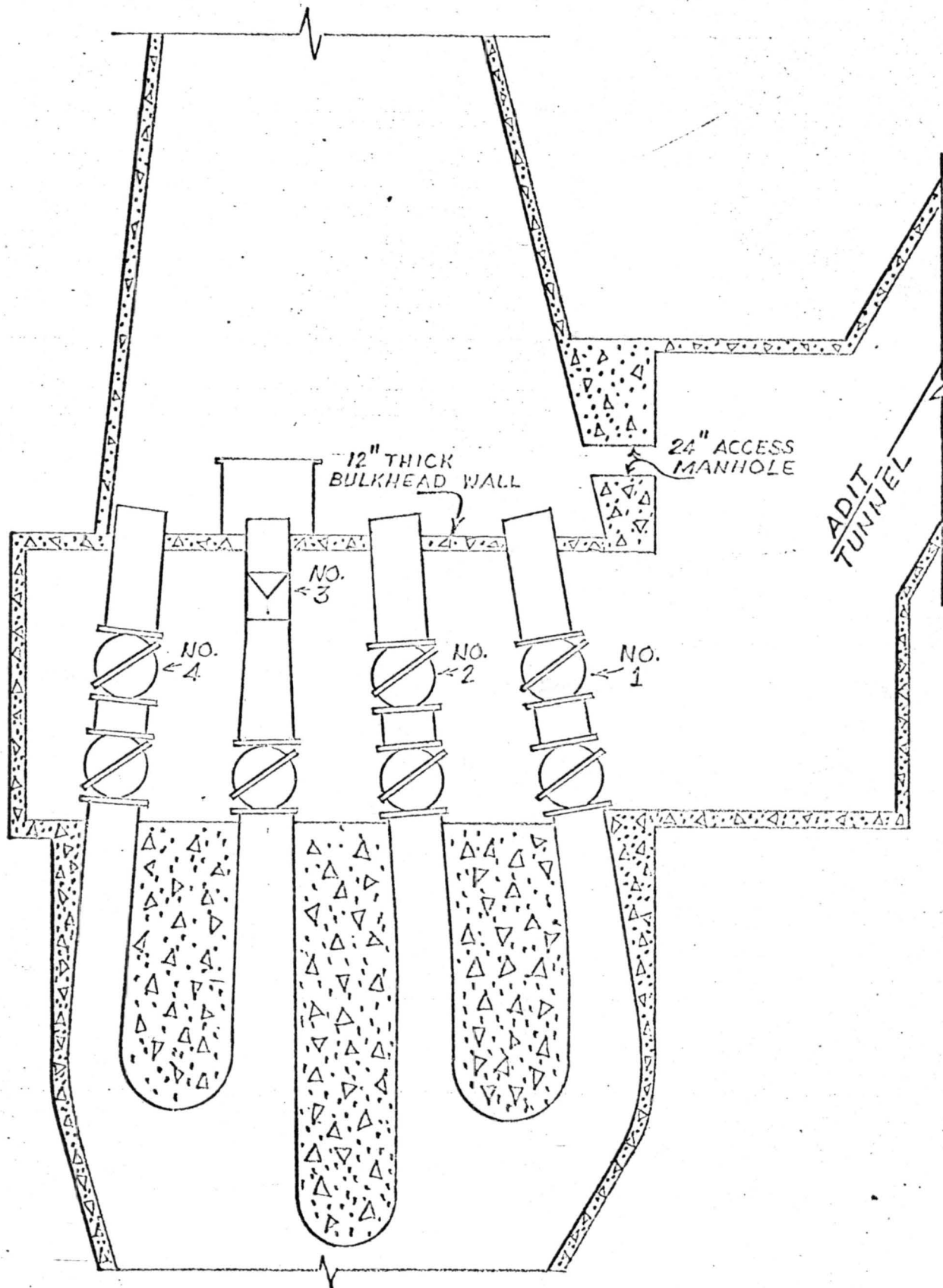


FIG. 2. LAYOUT OF VALVE VAULT

is approximately 5 cfs. The range of heads experienced has been from 295 feet, with the water at the top of the flashboards, to 154 feet, which occurred on May 17, 1965.\* For an idea of recent operational levels, Figure 3 shows the extreme monthly values of head and discharge observed over the last three calendar years.

### Unusual Operation

Due to water law requirements the reservoir outlet works must be capable of passing a discharge of 1200 cfs when the reservoir head is 37 feet. This is a requirement of the State Engineer and dates back to the construction of the reservoir. It is unknown what significance the 37 feet head has, but the 1200 cfs undoubtedly represents downstream appropriations. Based on the past records of the reservoir, it is highly unlikely that the outlet works will be operated at either figure in the future.

### Other Considerations

The capacity of the South Boulder Creek channel downstream of Gross Reservoir is a control factor to be considered. It is reported that discharges in excess of 500 cfs cause flooding at the downstream community of Eldorado Springs. Located between Gross Reservoir and Eldorado Springs is the intake to the Ralston Reservoir Feeder Canal which has a capacity of approximately 400 cfs. A combination of these two controls shows the maximum allowable sustained discharge from Gross Reservoir to be approximately 900 cfs.

### Hydraulic Problems

#### Ball Valve Cavitation Damage

During the time interval that the Hardie-Tynes needle valve was being replaced by the Howell-Bunger valve, the 42-inch Davis ball valves were used as regulating valves. They were operated as semi-free discharge valves and all suffered severe cavitation damage. The damage was especially severe on the

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\* These heads are referred to the valves. The Water Board records of head are based on USGS datum. Reservoir head 275 feet, for example, is elevation 7275. The valves are at elevation 6990, USGS datum. Thus 7275 elevation is equivalent to 285 feet head on the valves.

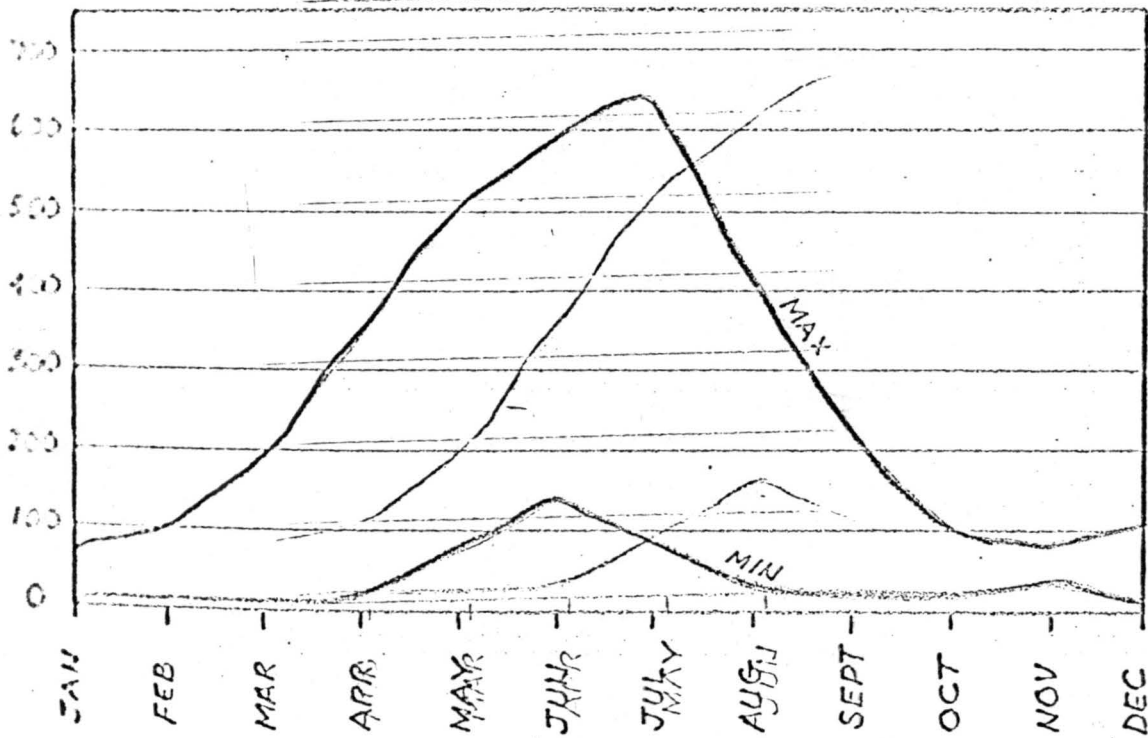
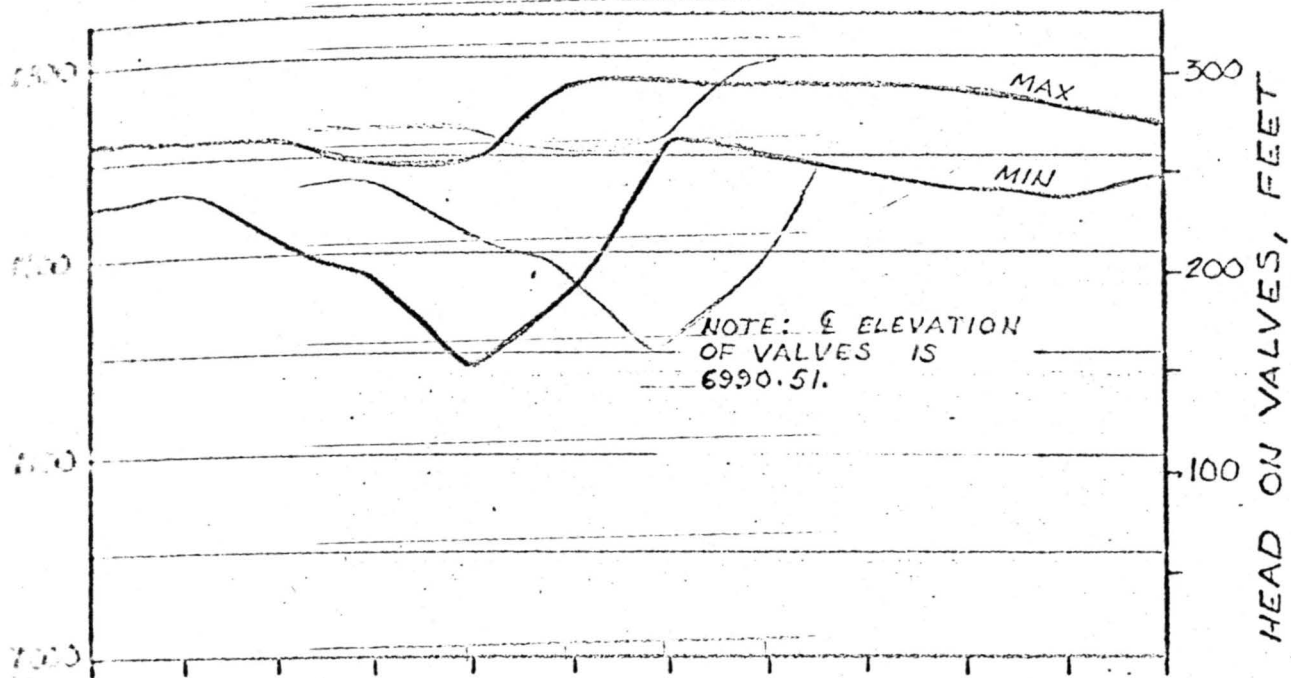


FIG. 3. EXTREME HEAD AND DISCHARGE CONDITIONS AT GROSS DAM DURING CALENDAR YEARS 1965 THRU 1967

lower edge of the ball and at 2 o'clock and 10 o'clock points on the valve and pipe walls immediately downstream from the ball.

#### Howell-Bunger Valve

The existing Howell-Bunger valve normally operates as a free discharge valve with discharges less than approximately 600 cfs. There is a 72-inch stationary cylindrical steel hood to control the diameter of the hollow jet downstream. To date, there have been no major problems with the valve under the limited operating range experienced. It does, however, appear that the air supply to the valve is inadequate. This subject is considered later in the report.

There is slight but identifiable cavitation damage occurring on the inside of the stainless steel hood, downstream from the sliding control cylinder of the valve.

The major problem with the Howell-Bunger valve is that it is commonly understood that it cannot operate submerged without dangerous vibrations. Data on this question, however are very limited. At this time the exact conditions under which the valves will become submerged are not known. Submergence would depend on the head, as well as the discharge, and cannot be determined without either a model or prototype test.

#### The Weakened Bulkhead Wall

The bulkhead wall forming the downstream end of the valve vault is constructed of 12-inch thick reinforced concrete. The wall, as originally constructed, could withstand substantial pressure. Due to a weakened condition, however, the strength is doubtful for submerged flow conditions. To date, the downstream chamber has not been pressurized so the bulkhead wall has never been tested.

Choking in outlet tunnel: - Due to the large air requirement of the valve, the resultant bulking of the air-water mixture, and the contraction of the downstream transition, choking may occur in the 8-foot diameter tunnel downstream of the valve vault. The result of the choking would be to increase the energy (head) required to force the air-water mixture through the tunnel. The choking could lead to sufficient backwater in the transition section to submerge the valves at large discharges.

Inadequate air supply: - The downstream transition section does not have an adequate air supply. This fact is evident by the high velocity of the air going through the access ports into the chamber for only moderate water discharges. The result of the inadequate air supply is an abnormally low pressure in the downstream chamber. The pressure was low enough to break the glass in the observation window above the Howell-Bunger valve.

#### Excessive Unseating Torque of Existing Ball Valves

An additional problem which has been experienced is breakdown of the operators on the ball valves. This is being caused by the excessive torques required to unseat the ball under high heads. This problem was amplified when the ball valves were required for continuous service due to failure of the needle valve.

## FIELD TESTS

Field tests were conducted on the outlet works of Gross Reservoir on September 21, 1968. The purpose of these tests was to determine the overall hydraulic characteristics of the outlet works in general, and specifically to:

1. Determine the vibration levels of each valve for various flow rates and for several combinations of valves in use
2. Obtain data necessary to evaluate the discharge capabilities of the various valves
3. Evaluate the adequacy of the present air supply system
4. Observe any evidence of choking in the transition section or backing up of water into the chamber

The testing was performed by the three consultants with support by the Denver Water Board personnel. Sincere thanks is expressed to all who assisted in this testing or in any way made it possible. Listed in Table I of the appendix are the personnel who assisted with the testing.

Testing Procedure

A visit to the site was made several weeks before the testing was to be conducted. This visit enabled detailed planning of the instrumentation and equipment needed, and development of the test procedures.

Prior to the tests, pressure gages were placed upstream and downstream of the #2 ball valve to record pressure levels before and during each test run.

In order to determine at what discharge the 8-foot tunnel began to flow full, plastic tubing was placed in the tunnel with the open end pointing upstream. Tubing was attached to the wall at the 5-foot and 8-foot levels at approximately station 7+10. The tubing led through the 24-inch manhole into the adit tunnel. When the water reached either the 5-foot or 8-foot levels in the conduit, water was expelled from the tubing.

A simple air-water manometer was fabricated from tubing at the site to measure the pressure difference between the downstream transition section and the ambient pressure outside.

An accelerometer was used to measure vibration levels. Twenty-seven different runs were made, each with different valve openings on an individual, or a combination of several valves. Tables I and II in the appendix list the test results. Fig. 4 shows the location of points where vibration was measured on the valves. Each valve opening was maintained long enough for a steady reading of discharge to be established in the measuring flume downstream.

## Results

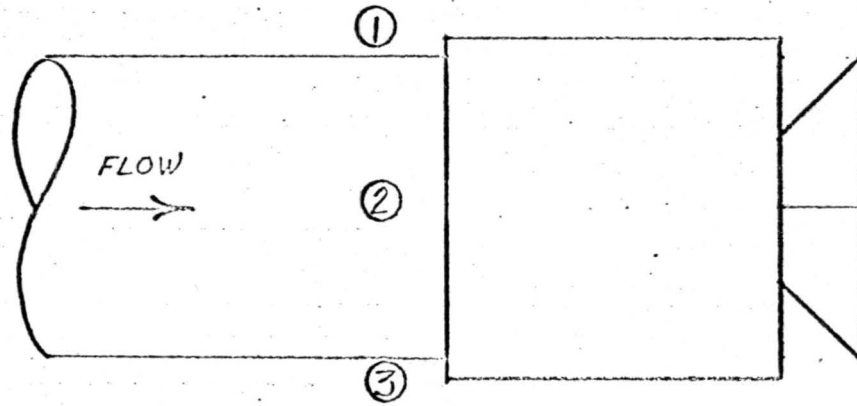
### Head-Discharge

The head-discharge relationship for the hollow cone valve (#3) and one ball valve (#2) are presented in Fig. 5 and in Table II in the appendix. These curves show the variation of discharge with valve opening for a reservoir elevation of 277 feet. These data can be used to evaluate discharge coefficients for the valves for estimating future discharges without the need to wait for readings from the critical depth flume. Such data are presented in Fig. 6.

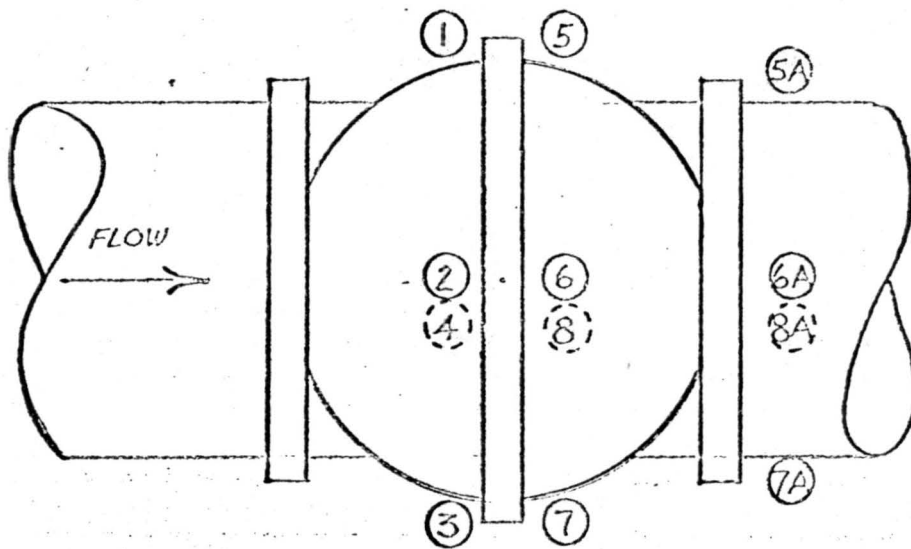
### Accelerometer Readings

Considerable information on the vibration levels that exist in the outlet valves under a variety of conditions was obtained. These data are tabulated in Table III in the appendix. Several important facts are available as a result of these data. However, only that part which is pertinent to the immediate problem of developing a plan to correct the past and current difficulties will be discussed in this report. If after selection of the final system, additional information is desired on the cavitation and vibration characteristics of the ball valve, such information can be furnished.

The first comment, is that the magnitude of the vibrations (measured as acceleration) verify that very heavy cavitation is occurring at various locations in and downstream of the ball valves. The location of the maximum vibration intensity, which indicates the location of maximum damage changes with valve opening. At small openings cavitation appears to be most intense in the upstream portion of the valve. As the opening increases the intensity shifts further downstream until the maximum vibrations occur inside the downstream conduit. The location of major cavitation damage appears in the downstream pipe and on the downstream side of the



HOWELL-BUNGER VALVE



BALL VALVE

FIG 4. LOCATION OF VIBRATION MEASUREMENTS ON THE BALL AND HOLLOW CONE VALVES

NOTE: RESERVOIR ELEVATION DURING TESTS WAS 7277.

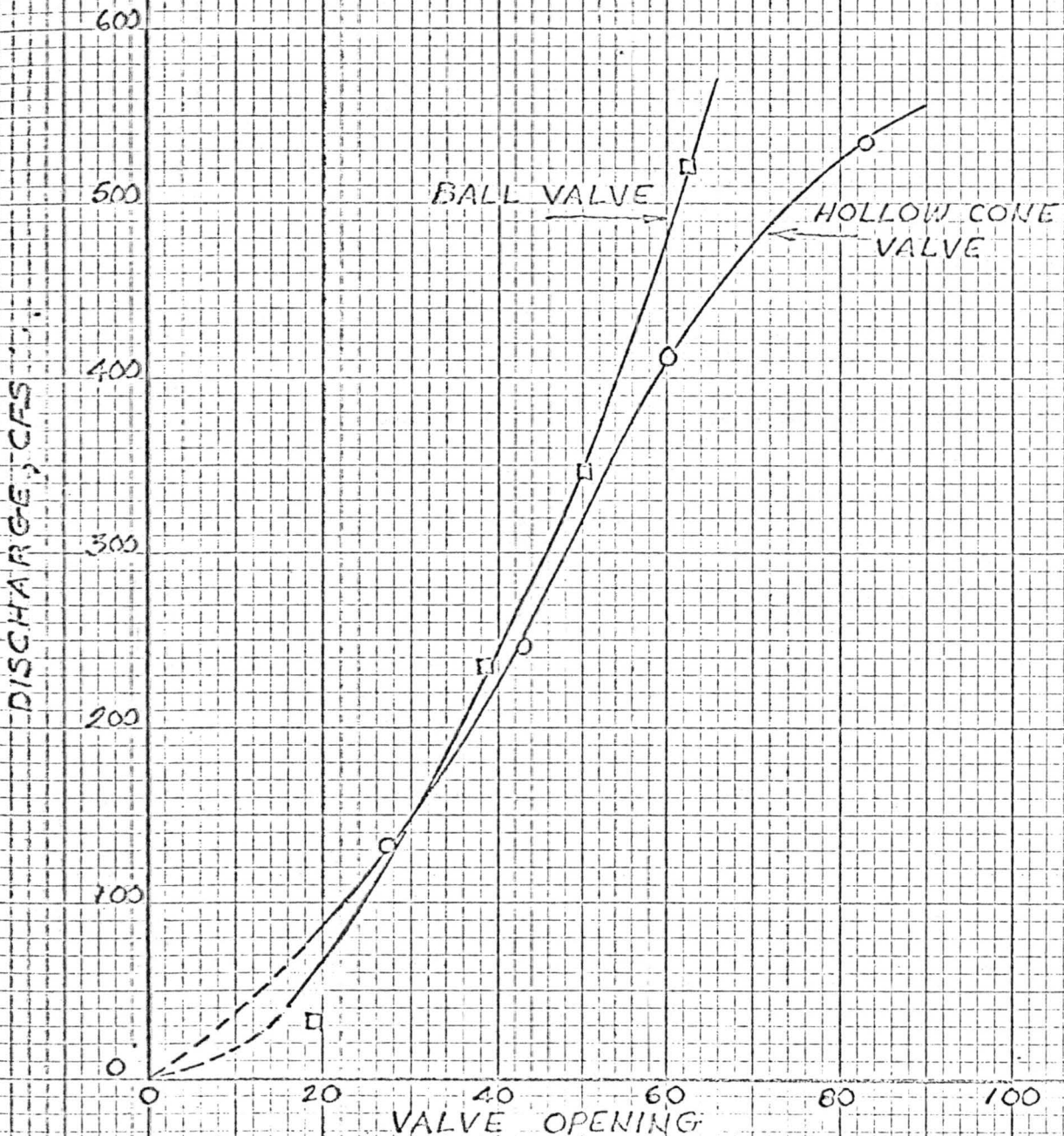


FIG 5. FIELD TEST DATA FOR DISCHARGES FROM #2 & #3 VALVES AT VARIOUS OPENINGS

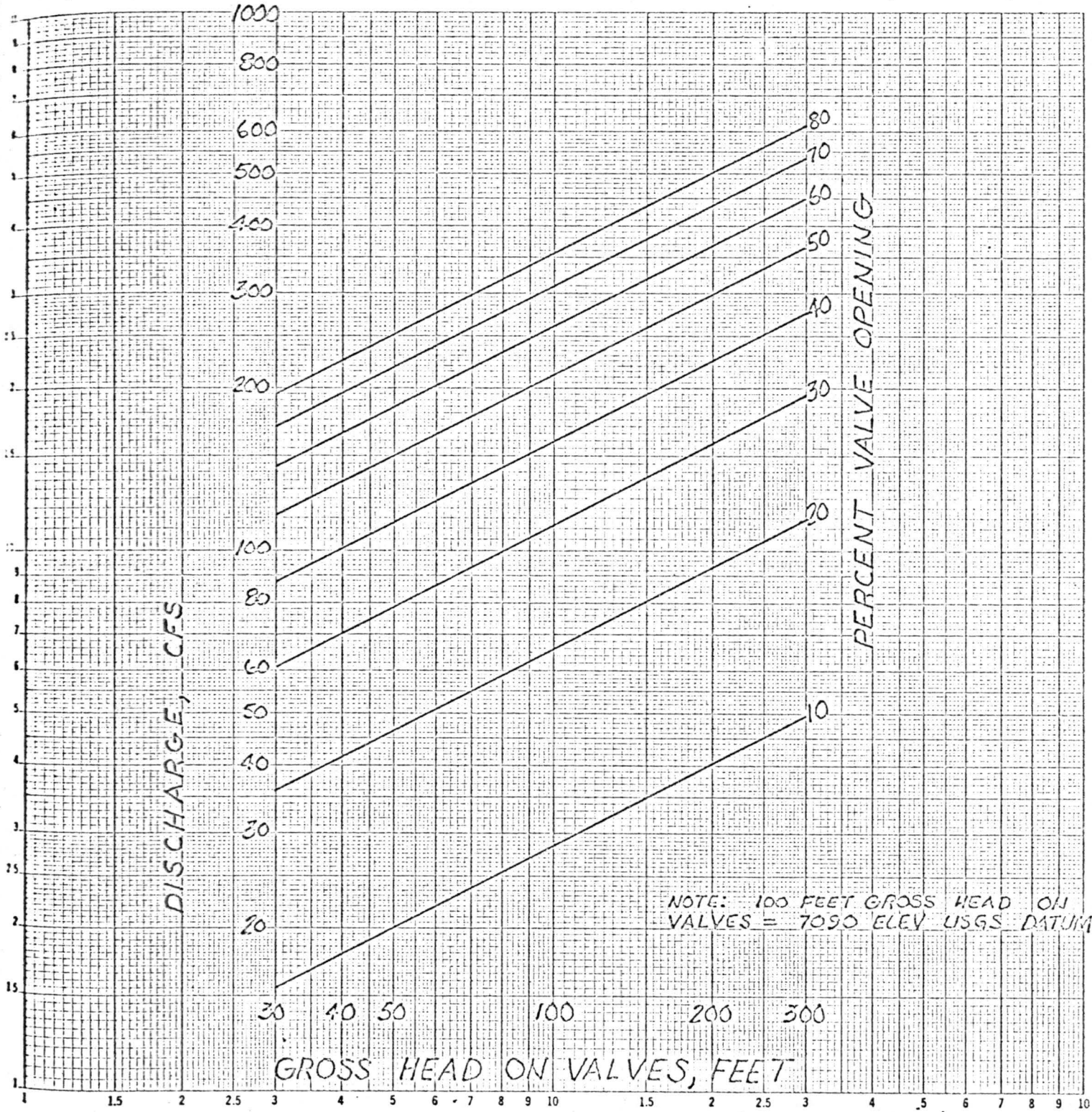


FIG 6 RATING CURVE FOR EXISTING 36-INCH HOWELL-BUNGER VALVE AT GROSS DAM

plug of the ball valves. Even though considerable cavitation is occurring within the valve, little if any cavitation damage is noticeable. This is due to the nature of the cavitation. Inside the valve, the cavitation is a "fine grained" cavitation, that is formed by small local separation zones. In addition, the flow inside the valve is subjected to some back-pressure which decreases the cavitation intensity. Downstream of the plug a large separation zone exists which causes large scale cavitation. It is the large scale, or "pounding" cavitation which does the major cavitation damage.

The second observation pertinent to this study is that the vibration readings taken on the hollow cone valve verified that no cavitation is occurring in the valve over the range of discharge and openings tested (0-83%).

The last comment, and a very important one, is that little if any vibrations were induced into the hollow cone valve when one or two ball valves were used simultaneously with the hollow cone. This can be seen from the data by making two comparisons:

First, compare runs 16 and 19. Run 16 is for the hollow cone valve 60% open with 421 cfs discharge. Run 19 is for #2 ball valve open 25% (100 cfs) and the hollow cone open 59% (420 cfs). The vibration level for run 19 ( $8,000 \text{ in/sec}^2$ ) is larger than the readings for run 16 ( $3,700 \text{ in/sec}^2$ ). This indicates there may be some increase due to multiple valves but the difference is not conclusive.

Second, compare runs 14 and 21. For these two cases the vibrations in the hollow cone valve were less when more than one valve was used. Also referring to the data from run 20 indicates no significant variation in the accelerometer level. If anything, it shows a decrease due to multiple valving.

In summary, it is believed that the use of multiple valving, when necessary will not influence the performance of the hollow cone valve, provided the valves are not submerged.

#### Pressures in Transition Section

Fig. 7 shows the negative pressure in the transition section versus percent valve opening on the #2 ball valve. The pressure was recorded in the 24-inch access manhole, but should be nearly the same as the pressure in the transition section itself. This negative pressure is a measure of the air deficit being provided to the transition section.

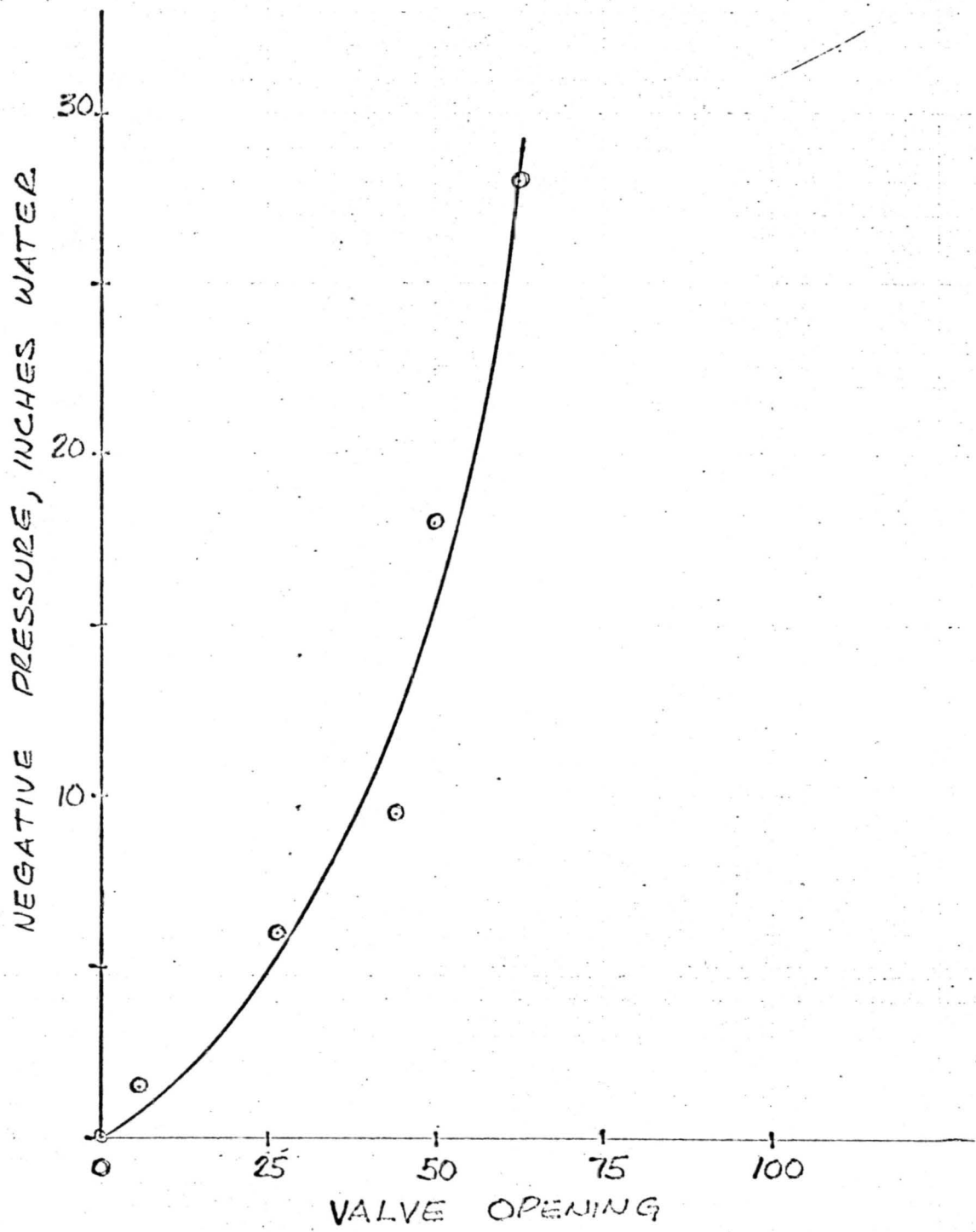


FIG 7. NEGATIVE PRESSURES INSIDE DOWNSTREAM CHAMBER FOR #2 BALL VALVE IN OPERATION

## Flow Conditions in Downstream Conduit

The tests to determine when the entrance to the 8-foot diameter tunnel began to flow full indicated that at about 200 cfs the tunnel was full. The discharge from the plastic tubing contained large amounts of air, indicating that the flow in the tunnel was heavily aerated.

Under no discharge conditions, at the head available, did any back-up of water into the downstream chamber occur. The maximum discharge was about 778 cfs. At this discharge the 8-foot tunnel was flowing full. Its open channel flow capacity is approximately 600 cfs based on fully established uniform flow.

The head loss for 1200 cfs going through the 175 feet of 8-foot tunnel is slightly less than 4 feet. Therefore, one may expect that 4 feet of static head over the crown of the tunnel would be the highest water level to occur in the transition section for a discharge of 1200 cfs, neglecting the energy of the jets. The four feet of static head would bring the water level to 6998.1 in the transition section. The center line of the valves is at elevation 6990.5 so the valves could experience a maximum submergence of 7.6 feet over the centerline.

## ANALYSIS OF OUTLET WORKS

This chapter analyses the various components and requirements of the system which were mentioned in chapter IV as being problem, or potential problem areas. The information in this chapter serves as a basis for the alternative solutions listed in the following chapter.

Demand Requirements

It is not the intent of this report to criticize the State Engineer's requirement but to point out several reasons why such a requirement is no longer appropriate.

It has been mentioned that an existing maximum system requirement of 1200 cfs at 37 feet reservoir elevation (above the centerline of the valves) exists. The design of the original system had this capability, provided submergence of the valves did not occur. Calculations indicate that if no backpressure on the valves exists, the four valves (3 - 42-inch ball valves and 1 - 48-inch needle valve) have the capability of passing 1200 cfs at a reservoir head of 37 feet. If, however, the valves are submerged, the head drop and discharge through the valves decrease. It is thus impossible to predict the actual maximum discharge through the system at low heads without a model study.

First, the original construction of the reservoir was such that at a water surface elevation 37 feet above the valve centerline, the total reservoir storage was 338 acre feet. Since the reservoir has existed for over 10 years considerable sediment has, no doubt, been deposited - - significantly reducing the capacity of the reservoir at lower elevations. However, even if no sediment were deposited, at a discharge of 1200 cfs, the lake would be emptied in something like 10-12 hours.

Second, assuming that some deposit of sediment has occurred, it is very probable that large quantities of sediment would be discharged if the lake level ever dropped to such a low elevation.

Third, the combined capabilities of the canal system handling the outflow from Gross Reservoir is 900 cfs. Above

this value excessive flooding of Eldorado Springs occurs.

It is not suggested that the 1200 cfs requirement necessarily be relaxed but that the head required for this discharge be increased to a more reasonable figure.

### Suitability Of System

The most satisfactory system for closed conduit flow from high reservoirs is the use of free discharge valves. Under this condition the possibility of cavitation damage, vibrations and pressure surges in the system are minimized, provided proper valves are selected. The outlet works at Gross Dam were designed to have the capability of either free discharge or submerged discharge. Since its initial commission the heads and discharges through the outlet works have been such that submergence has probably never occurred, consequently, the system is essentially free discharge.

The difficulties which have occurred are not due to the overall design of the works, which are well designed and constructed, but due to the installation and operation of the throttling valve.

Two general methods of approach to solving the existing difficulties exists:

1. Modify the existing system
2. Move the outlet works downstream where it will be completely free discharge under all conditions

The second alternative was investigated but is considered unnecessary due to the large costs involved and the general suitability of the present system. The only advantage to alternative #2 would be to eliminate the possible choking in the transition, and submergence which may exist at large discharges. However, since these conditions have not yet been encountered in over 10 years of service it would seem uneconomical to expend a large sum of money to eliminate a minor problem which may never be encountered. Consequently, this report stresses modifications to the existing system as the most appropriate solution to correct the present difficulties and insure satisfactory operation in the future.

### Conduit System

The complete conduit system is well designed and constructed. Consequently, no major modifications in this system are recom-

mended. The two areas of possible concern: (1) Choking and submergence of the flow in the downstream transition and (2) the structural strength of the bulkhead wall are discussed below.

### Choking and Submergence

The outlet transition section and downstream 8-foot tunnel are difficult to analyse hydraulically. Because of the bulking of the air-water mixture leaving the valves, and the high velocity flow entering the transition section, one cannot accurately estimate the total energy at the entrance to the 8-foot tunnel. The nature of the flow in the 8-foot tunnel, the water level and the pressure in the transition section depend on the energy of the flow entering the tunnel. One must therefore consider numerous factors when considering the problem of choking or submergence in the downstream section. The most satisfactory method of solving this difficulty would be with a model study. However, as a result of the field tests, the pattern of discharge required, and lake elevation for the past 10 years, the problems of choking and submergence do not appear to be acute.

The field test indicated that there was no noticeable choking or backing up of water into the chamber for flows up to 778 cfs. The past system deliveries show that the maximum flow ever delivered was 893 cfs, with the normal flow much smaller. These conditions occurred under large reservoir heads, which is the normal condition for the reservoir.

It is possible that if large discharges at low head were required, submergence of the valves might occur. However, this possibility is so slight that extensive modifications to eliminate its possibility are not suggested.

### Bulkhead Wall

At the present time the bulkhead wall separating the valve vault and downstream chamber has been weakened due to replacement of the needle valve with the hollow cone valve. Consequently, its present structural strength is questionable. Also, some patching around the 36-inch valve and the various openings into the chamber would be necessary in order to waterproof the chamber.

To improve the air supply system additional openings through the bulkhead wall are proposed, which will further decrease its structural strength.

The analysis of the wall should consider at least two general

problems: (1) The possibility of the wall failing by shear at the junction with the conduit, and (2) the possibility of a bending failure.

### Air Supply

At present there are two permanent air inlet ports to the downstream chamber: One into the hood of the hollow cone valve and the other through the west side of the chamber. Both are connected by conduits to the air plenum at the top of the adit tunnel. In addition, two small observation windows and a 24-inch diameter access hole can be used to supply air to the chamber from the adit tunnel. Even when the adit tunnel and the temporary inlets to the chamber are utilized, the supply of air to the chamber is far from adequate. This fact was verified during the field tests. Even at moderate discharges (around 300 cfs), considerable pressure differences exist in the downstream conduit as evidenced by Fig. 7. Also, the velocity of air passing through the ports and the resultant noise, verifies the lack of adequate openings into the chamber.

This problem is both annoying to the operators, due to the high noise levels, and dangerous to the valves due to the increased cavitation potential caused by the sub-atmospheric pressures in the chamber.

To correct the present deficiencies it will be necessary to first, greatly increase the square footage of the openings into the downstream chamber, and second, utilize the complete adit tunnel for an air plenum at discharges above about 200 cfs.

### Valve Vault

A critical situation presently exists at Gross Dam. There is currently only one valve at the site which can be used safely for discharge--the 36-inch hollow cone valve. The other three valves are ball type valves which, as evidenced by their past performance, will be subjected to heavy cavitation damage and operator breakdown when used for throttling at high heads. Consequently, if the 36-inch valve becomes inoperable, the system cannot be operated without great danger of costly repairs being incurred.

### Original Needle Valve

The original throttling valve installed at the site was a 48-inch Hardie-Tynes needle valve. This valve was severely damaged by cavitation, repaired, and finally replaced by the

hollow cone valve after several years service. In selecting replacement valves it is of great importance to understand the cause of the failure of the needle valve so that similar problems can be avoided in the future. The following discussion attempts to explain the cause of the cavitation damage in the needle valve.

When a water jet discharges into an infinitely large body of air under atmospheric pressure, the pressure in the jet will normally be atmospheric. The specification for an infinitely large body of air is required so that no localized pressure reductions occur due to insufficient air supply.

The construction drawings of the needle valve installation at Gross Dam are partially reproduced in Fig. 8. The primary cause of the cavitation damage to the needle is the downstream discharge pipe. The use of this pipe essentially eliminated the free discharge effect of the needle valve and created sub-atmospheric pressures sufficient to cause damaging cavitation.

The above statement is explained as follows: Referring to Fig. 8, the critical area is at position A where the jet emerges from the needle valve. The curvature of the body near the downstream flange, making a smooth transition with the downstream pipe, causes the jet to expand, placing the water under tension. The pressure reduction near A, and the expansion of the jet are increased by the inability of atmospheric air to reach this critical area due to the expanding jet. Thus, the expanding of the jet and its aspirator effect tend to evacuate the air from the pipe and cause it to flow full, as a water-water vapor-air mixture.

The above factors, combined with the overall sub-atmospheric pressure which exists in the downstream chamber due to insufficient air supply, created favorable conditions for cavitation in the discharge pipe from the needle valve. This also explains why modifications in the shape of the needle did not reduce or eliminate the cavitation damage.

To eliminate this situation in the future, three precautions must be exercised:

1. Install the needle valve so that its downstream flange is flush with the inside wall of the chamber.
2. Modify the outlet port of the valve so it has a sharp edged orifice to eliminate the possibility of local cavitation near the flange.
3. Increase the air supply to the chamber.



## Hollow Cone Valve

The 36-inch hollow cone valve is operating satisfactorily. It is operating free of any excessive vibrations, and has the ability of adequately controlling and supplying the discharges required. There does, however, appear to be some evidence of possible cavitation damage on the hood.

The only major problem of concern is the performance of this valve under submerged conditions. Some information is presently available indicating that under high heads, such valves cannot be used submerged. No information is presently available on their performance at low heads.

If a hollow cone valve is to be incorporated into the selected modification scheme, it is suggested that a model study be performed to determine the submerged performance of the valve.

## Ball Valves

All three original ball valves were extensively damaged by cavitation when they were used for release when the needle valve became inoperable. In addition, considerable difficulty with the operators has been encountered due to the large seating torques. Presently one valve has been replaced, by a similar valve, and is being repaired. The other two valves are heavily damaged and one operator inoperable.

Due to the flow pattern of the ball valves and the lack of any backpressure, these valves should never be used for throttling at reservoir heads above about 70 feet. At higher heads cavitation will occur. If the ball valves are ever required it is suggested that they be operated 100% open with all throttling being done with the needle or hollow cone valves.

## Bypass Valve

It is not uncommon that discharges less than 30 cfs are required during the winter months. Using a 36- or 48-inch valve to supply such a small discharge is not practical; both from the standpoint of its ability to control such small discharges and the lack of economy due to wear on such a large valve for such a meager flow. It is recommended that the present 12-inch bypass line be modified for use at small discharges. This could be accomplished by installing a needle or hollow cone valve as a free discharge valve, if space permits, or using a stainless steel ball valve and downstream pipe. Such an addition would extend the life of the large throttling valves.

## Life Expectancy of Valves

A general statement about the estimated length of time that a particular valve can be used for service is impossible. The answer is too dependent upon the details of the installation. For example, if the Hardie-Tynes needle valve was properly installed with an adequate air supply it would, no doubt, last several times longer than it did.

To give some guidelines relative to the expected life of the valves suggested in this report, the following is offered: If a needle valve is selected for throttling and it is designed and installed based upon the recommendations of this report, including expansion of the air supply system, it is believed that the valve should require little maintenance for about 20 years. With proper design and installation little, if any, cavitation damage is anticipated.

The life expectancy of a hollow cone valve, relative to a needle valve, would be less. This is due to the nature of flow in the hollow cone. It is expected, however, that most of the cavitation damage would occur on the hood and not in the valve itself, making repairs relatively easy and inexpensive.

## Operation of Ball Valves

It will no doubt take some time to complete modifications at the outlet works. If during this time period the hollow cone valve becomes inoperative, the ball valves will have to be used for throttling. One of the purposes of this study was to recommend a procedure for operating the ball valves in such a situation.

Results of the field tests showed that at all openings, normally used for throttling, heavy cavitation was occurring. The highest intensity occurred at about 50% open. This is also the opening at which most of the damage occurred in the valve and downstream conduit. Two possibilities exist:

1. Avoid operating the valves near 50% open by using multiple valves or
2. Use compressed air injected into the pipe near the downstream flange

The first alternative decreases the amount of cavitation damage per valve but causes damage to more than one valve and also increases the possibility of operator breakdown.

The second alternative is more promising. Tests have been conducted at Colorado State University in which air was injected, under pressure, through the pipe below the valve. Under most flow conditions the cavitation was completely eliminated or significantly reduced. If it becomes necessary to use the ball valves temporarily this method should be considered.

## VII

### ALTERNATIVES

As a result of the field testing, the examination of the present conditions and future requirements of the outlet works, and a review of the past operating difficulties, several alternative solutions to the existing difficulties have been developed. Four or five of the most suitable solutions are presented and discussed in detail. Other alternatives are merely mentioned as possible solutions. The following discussion includes:

1. Proposed expansion of the air supply system
2. Modifications needed in the downstream chamber and conduit system
3. Proposed modifications in the valve vault

#### Air Supply System

In a preceding section the deficiencies of the present air supply system were explained. The general conclusion was that an expansion of the present system is very much needed. The following recommendation is offered as the most economical and practical solution to the problem.

For discharges above 200-300 cfs, the adit tunnel should be used for additional air supply. In doing this it will be necessary to make two minor additions to the system.

First, a second set of access doors to the adit tunnel, which swing in, should be installed. These doors, or gates, should be fabricated of wire mesh, or some similar material which would allow for free passage of air while restricting access to the valve vault. In winter, when discharge demands are small and the danger of freezing exists, the adit tunnel would be closed and not be used to supply air.

Second, additional air inlet ports into the downstream chamber are needed. It is suggested that a port of approximately 8 ft.<sup>2</sup> area be placed near the top of the west side of the chamber, connecting it with the duct work of the present air supply system. In addition, air intake ports with a total area of about 16 ft.<sup>2</sup> should be provided into the chamber. These ports would best be located at the top of the bulkhead wall separating the valve vault and the downstream chamber. This would allow for partial

submergence of the chamber at maximum discharge without spilling water into the vault. Also, the air intake to the hollow jet valve should be opened directly into the chamber.

### Downstream Chamber and Conduit

The hydraulics of the system are well suited to the required task. Consequently, it is believed that modifications in the downstream conduit system are not warranted. The only problem which exists is the possibility of choking at the large discharges.

However, two alternatives are presented for consideration as methods of eliminating choking at large discharges. These are:

1. Installation of a roto-disc valve at the exit of the 8-foot diameter tunnel to maintain backpressure on the valves at high discharges. To accomplish this it would be necessary to make major modifications in the downstream chamber so it could be pressurized.
2. Enlarge the downstream conduit so it would not cause submergence at large discharges.

Since the normal discharge of the outlet works over the past ten years has been less than 700 cfs (max. of 893), and the field tests indicated no choking at this discharge, it is believed that modifications to eliminate the possibility of choking for the highly uncommon larger flows above 700 cfs would not be economical.

If the downstream conduit is not pressurized or enlarged to eliminate choking, the possibility exists of the valves becoming partially or completely submerged at large discharge. The present downstream chamber is not capable of submergence.

Weakening of the bulkhead wall between the valve vault and the downstream chamber caused by replacement of the original 48-inch needle valve with the present 36-inch hollow cone valve has occurred. To correct this difficulty the following recommendations are proposed:

1. Conduct a complete structural examination of the wall to insure that it will withstand a static pressure in the chamber of 12 - 14 feet of water, plus an allowance for surging.
2. If the wall is structurally sound, repairs to make it waterproof will be necessary after the selected valves are installed.

## Modifications in the Valve Vault

The heart of the problem is selecting suitable valves and the development of an operating procedure which will enable the system to supply the demand requirements and operate as free as possible of cavitation damage and maintainance problems. Of highest priority is selecting a system which will meet all system demands, require a simple operating schedule, allow adequate safety and back-up in case of breakdown of a throttling valve--and yet not be overdesigned. Consideration was also given to the unfortunate, but often existing fact that adequate funds are not always available to construct the system which is hydraulically the best. Consequently, alternate solutions are listed in decreasing order of preference which will each meet the system requirements, but do not have the overall reliability and safety features of the first alternative.

The first three alternatives listed have been selected so as to satisfy completely the requirements of 1200 cfs at 37 ft. head. Other alternatives are listed which would allow for more economical solutions if the demand requirements can be relaxed. For each alternative the following information is presented to aid in the selection of the final choice:

1. Type and size of valves
2. General operating procedures
3. Operating capabilities and limitations
4. Advantages and disadvantages
5. Cost estimate

### Alternative #1

The first system, and the one most highly recommended, consists of 2 - 48-inch needle valves and 2 - 42-inch ball valves, The needle valves would be installed in positions number two and three and would be the primary valves for discharge regulation. The ball valves would be installed in positions one and four, and would be used only as low head outlet when the discharge from the two needle valves is inadequate to meet the demand.

General operating procedures:- The discharge records of the outlet works for the past ten years of operation were used as a guide to develop a general operating procedure. These records indicate that one 48-inch needle valve will supply all required discharges normally encountered. Only very seldom has there been a discharge required which could not be satisfied by a single 48-inch needle valve. The following ideas are presented as guidelines in developing a detailed operating plan.

1. The needle valve to be located in position 3 will be the primary throttling valve. Only in the event of a breakdown of valve #3, or a discharge in excess of that which can be supplied by valve #3 alone, will the second needle valve be employed.
2. Alternate service of valves #2 and #3 should be avoided. This will insure that in case of emergency there is always at least one operable throttling valve available for use.
3. The ball valves in positions 1 and 4 should never be used for control. The only time that they would be required, in order to supply the maximum discharge of 1200 cfs, would be for heads less than 138 feet. Above 138 feet the two needle valves will meet this requirement.
4. In the event that a ball valve is needed to meet this requirement it should only be operated 100% open. Any throttling to adjust the flow rate should be done with one of the needle valves.
5. Unseating and seating of the ball valves upstream of the two needle valves should be attempted only when the needle valves are closed and pressure across the ball valves is equalized with the by-pass valve.

Operating capabilities and limitations: - It is desired that all but the very unusual discharge requirements be satisfied without the use of the ball valves. Again referring to the records of the past ten years, the extremes in head and discharge were as follows: the minimum head experienced was 150 feet and the maximum discharge less than 900 cfs. The normal minimum reservoir head is about 200 feet.

Figure 9 is an estimated plot of discharge versus reservoir head for one and two 48-inch needle valves in operation. It can be seen that a discharge of 800 cfs can be supplied at a head of approximately 63 feet by the two needle valves. A head of about 138 feet is needed to pass 1200 cfs through the two needle valves. Consequently, the only time that either ball valve would be needed is for maximum discharge at heads below 138 feet. Under this condition little, if any, cavitation damage to the ball valves would ever occur, and the torque required to unseat the ball would be relatively small.

The needle valve system has the distinct advantage of being able to operate as a free discharge system or with a submerged discharge. Since at maximum flow some submergence of the

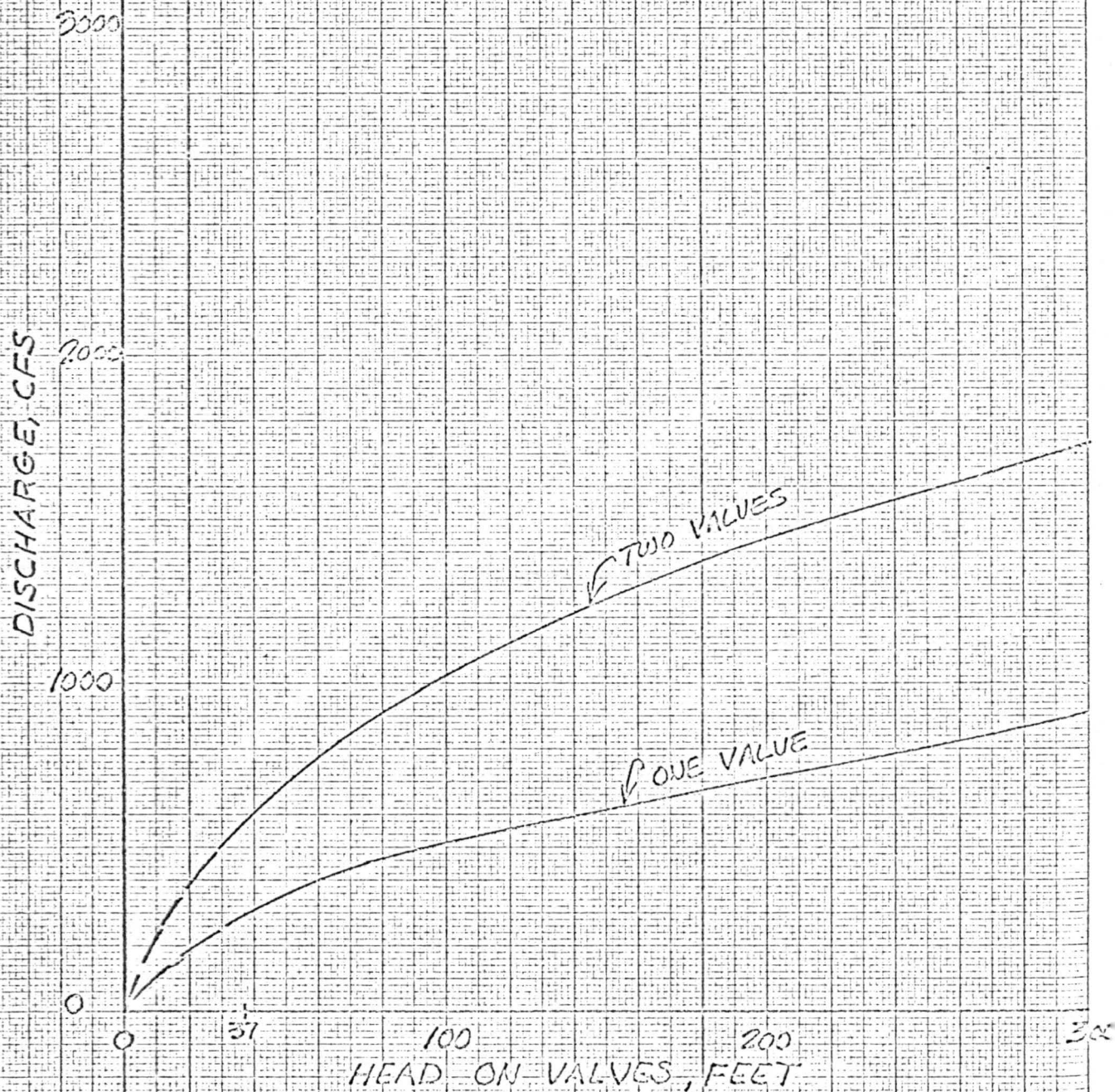


FIG. 9. DISCHARGE-HEAD CURVES FOR 43-INCH NEEDLE VALVES WIDE OPEN

GROSS DAM

valves is expected, this factor is important. Past experience with the needle valve submerged or as a free discharge valve verifies its reliability. (References 1 - 11)

Advantages and disadvantages: - The advantages of the needle valve system are summarized below:

1. The system will pass the required 1200 cfs at 37 feet of head.
2. The ball valves will never be used to throttle the flow.
3. A second throttling valve is always available in the event one becomes inoperable.
4. None of the ball valves will ever be required to unseat against a head in excess of 138 feet, except in an extreme emergency.
5. The system can operate either with free discharge or submerged.

The only disadvantage to this system is the relatively high cost of the needle valves.

Cost estimate: -

Purchase 2 - 48-inch needle valves	\$120,000
Repair one ball valve	10,000
Enlarge air supply system	5,000
Installation of valves	10,000
Modify bulkhead wall	5,000
Total	<u>\$150,000</u>

It is strongly recommended that the valve manufacturers be required to supply, with their valves, reliable information on: discharge coefficients, cavitation characteristics and operating torque.

Alternative #2

The second system to be suggested consists of 2 - 48-inch hollow cone valves plus 2 - 42-inch ball valves.

General operating procedure: - The general installation and operation of this system would be similar to alternative #1 for the needle valves. One hollow cone valve would be installed in position #2 and would serve as the primary control valve. The

second hollow cone valve would be placed in position #3 and would be used only in the event of a breakdown of #2 or for additional discharge.

The only advantage of this alternative relative to alternative #1 is a cost savings. The major disadvantage is the hollow cone valves have not yet been used successfully under submerged discharge conditions. Consequently, it is recommended that a modest model study be considered as an integral part of this alternative. The purpose of the model study would be to give qualitative information on the performance of the valves as they become submerged and evaluate the operating conditions where vibrations would be minimum.

The capabilities of this system, which are discussed in the next section, are such that the hollow cone valves would be required to operate with submergence only for extremely large discharges and relatively low heads. Calculations indicate that a head in the downstream chamber of 4 feet above the 8-foot tunnel is required to pass 1200 cfs through the 8-foot tunnel. This calculation is actually very conservative because it was calculated ignoring the dynamic effect of the jets from the valves. It is therefore probable that the valves will not be submerged for all discharges under high head. It is quite possible, however, that the valves will become partially or completely submerged for large discharges at smaller heads.

Based on the operating requirements for the past ten years, which lists the maximum discharge delivered of 893 cfs, and on the present capabilities of the downstream river and canal system, it seems only remotely possible that a discharge sufficient to cause submergence will be delivered in the future. But since the possibility does exist, it is necessary to verify the operation of the valves with a model study if this alternative is selected.

Operating capabilities and limitations: - For this system, as for alternative #1, it is desired that the ball valves not be used except under emergency conditions. The capabilities of the system with one and two hollow cone valves in operation is approximated in Fig. 10. At a head of 58 feet the two valves can deliver over 800 cfs. The maximum discharge of 1200 cfs can be delivered by the two valves at a head of about 130 feet. Since the reservoir has never been below 150 feet since its initial filling it is unlikely that the ball valves will ever be needed.

If the situation arises where the ball valves are required they should be operated only 100% open, i. e. they should not be used for throttling.

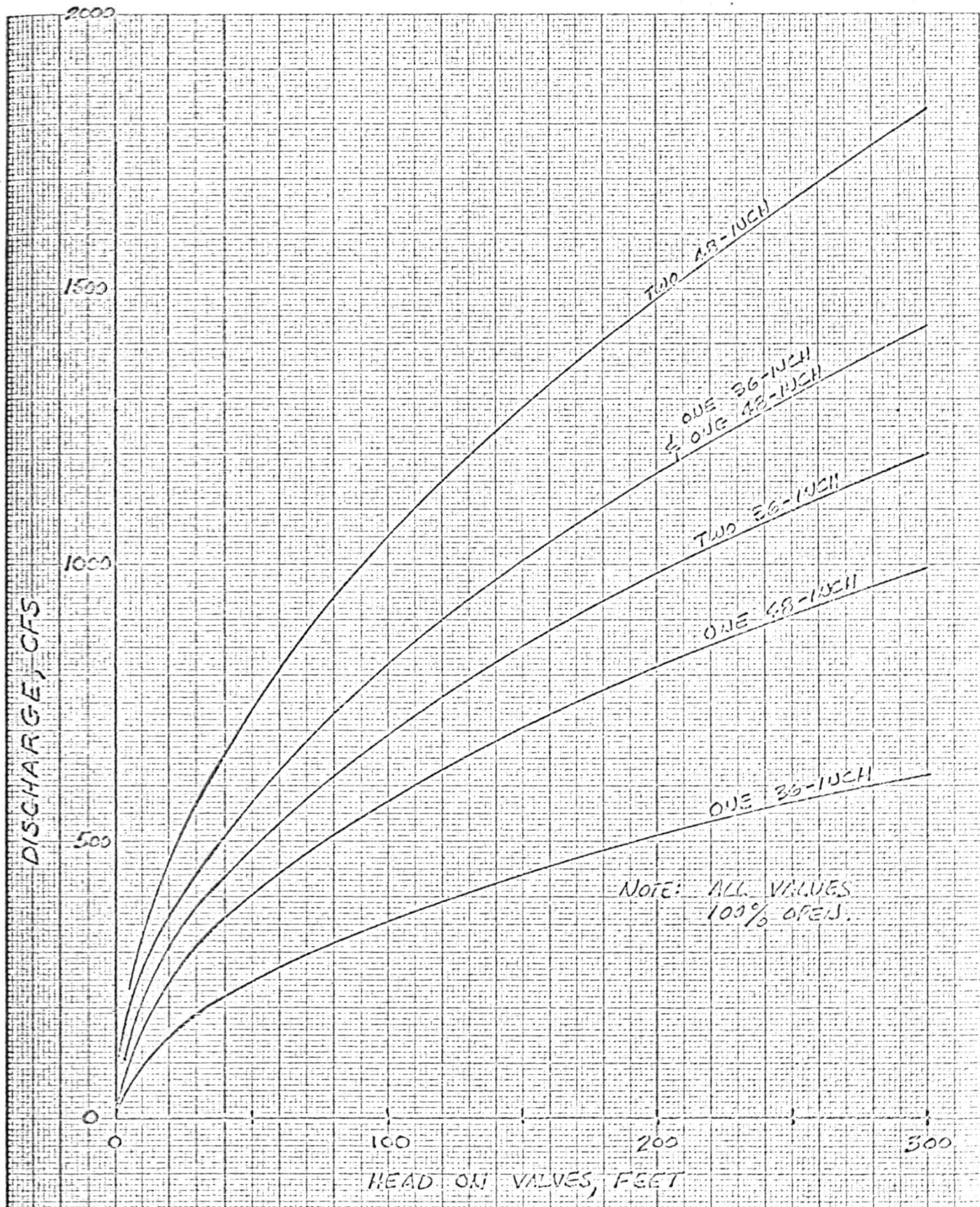


FIG. 10. HEAD-DISCHARGE CURVES FOR HOLLOW CONE VALVES AT GROSS DAM.

The only limitation of the system is the uncertainty of the performance of the valves under submerged conditions.

Advantages and disadvantages: - The advantages and disadvantages of the hollow cone valve system are summarized below:

1. The system will pass the required 1200 cfs at 37 feet of head (provided that the system can operate submerged).
2. The ball valves will never be used to throttle flow.
3. A second throttling valve is always available in the event one becomes inoperable.
4. None of the ball valves will normally be required to seat or unseat against heads in excess of 130 feet.
5. The initial cost of installation is less than alternative #1.

The disadvantage of alternative #2 is the uncertainty which exists about the performance of the hollow cone valves under partial and completely submerged conditions.

Cost estimate: -

Purchase 2 - 48-inch hollow cone valves	\$ 67,200
Repair one ball valve	10,000
Enlarge air supply system	5,000
Installation of valves	10,000
Modify bulkhead wall	5,000
Model study	10,000
Total	<u>\$ 107,200</u>

It is recommended that the valve manufacturers be required to furnish reliable information on the discharge, torque or thrust, and cavitation characteristics of their valves.

Alternative #3

The third system to be suggested consists of 1 - 48-inch needle valve and 3 - 42-inch ball valves with the 36-inch hollow cone valve to be used as a stand-by valve in case of failure of the needle valve.

General operating procedure: - The needle valve would be installed in position 3 and would be used for throttling. If a

discharge in excess of that possible from the needle valve is required the ball valve (s) would be used. When the ball valves are required they will be operated only 100% open with regulation being made with the needle valve. Since larger discharges have never been required, it is very improbable that a ball valve will ever be required for throttling in the future.

In case of a temporary breakdown of the needle valve the ball valve in position #2 would be used until the repairs could be completed. It is recommended that #2 be a stainless steel lined ball valve. If the repairs will require an extended period of time the 36-inch hollow cone valve should be installed to replace the needle valve. The installation of the needle valve should be designed to allow for rapid replacement with the 36-inch hollow cone valve.

Operating capabilities and limitations: - The general discharge throttling capabilities of the system are shown by Fig. 9 for one needle valve. The obvious limitation of this system is that only one throttling valve is present in the system at any one time. This will increase the possibility of needing the ball valves for throttling. Unless new ball valves are purchased to replace the existing damaged valves, the use of ball valves for throttling flow is questionable.

Advantages and disadvantages: - The only advantage which might be listed would be a cost savings. However, if new ball valves are purchased to increase the reliability of the system little, if any, savings would be realized. The disadvantages are listed below.

1. Only one throttling valve is present in the system.
2. In the event of breakdown of the throttling valve a ball valve must be used to throttle the flow.
3. An expensive valve must be left at the site for a stand-by valve at all times.

This solution is mentioned as a possible alternative but not recommended.

Another similar alternative would be to use a 48-inch hollow cone valve as the primary throttling valve with the 36-inch valve as a stand-by.

Each of the foregoing schemes will meet the demand requirement of 1200 cfs at 37 feet head. The following alternatives are presented as more economical solutions in the event that the requirements can be relaxed.

#### Alternative #4

This alternative is suggested as the most practical solution to the existing problems in the valve vault, provided some relaxation of the requirements can be tolerated. This scheme would consist of the present 36-inch hollow cone valve, 1 - 48-inch needle valve and 2 - 42-inch ball valves.

General operating procedures: - The existing hollow cone valve would be used as the primary control valve for free discharge. The needle valve would be installed in position #3 and serve as a stand-by control valve for free discharge and as the primary control valve for submerged discharge. It could also be used in conjunction with the 36-inch valve for large free discharges.

For submerged discharges two possibilities exist. First, the two ball valves plus the needle valve can be used with complete confidence. If it is anticipated that more discharge is required a model study could be conducted to determine if it is practical to also use the hollow cone valve under submerged conditions.

System capabilities: - If all valves are opened, the required 1200 cfs can be obtained at a head of approximately 40 feet. This is assuming that a model study is made to confirm the performance of the hollow cone valve submerged. If the 36-inch valve is not used submerged, the 1200 cfs can be obtained at a head about 65 feet.

Most normal discharges will be satisfied with only one throttling valve in operation, since the head in the reservoir is normally above 200 feet.

Advantages and disadvantages: - The main advantages are:

1. Only one 48-inch needle valve will need to be purchased, which will significantly reduce the overall cost of the modifications.
2. The present 36-inch hollow cone valve will be used in its present location, again reducing costs.
3. Two throttling valves are always present in the system.

The only disadvantage to this scheme is that the requirement of 1200 cfs at 37 feet of head is not quite possible.

Cost estimate: -

Purchase 48-inch needle valve	\$67,000
Repair one 42-inch ball valve	10,000
Enlarge air supply system	5,000
Install valves	5,000
Modify bulkhead wall	5,000
Total	<u>\$92,000</u>

Alternative #5

Other alternate solutions to the problem are also possible. These are listed below but are not discussed in any detail. Each of these solutions would meet the normal requirements of the system but will not meet the stringent requirement of 1200 cfs at 37 feet head.

1. Use 2 - 36-inch needle valves plus 2 - 42-inch ball valves. This would give complete flexibility of operating either submerged or free discharge but at reduced capacity.
2. Use 2 - 36-inch hollow cone valves plus 2 - 42-inch ball valves. This would be the most economical solution to having maximum flexibility for free discharge. Again a model study is recommended for submerged discharge conditions.
3. Use one 36-inch needle valve, the existing 36-inch hollow cone valve and 2 - 42-inch ball valves.

Summary cost estimates for Valves

1 - 48-inch needle valve	\$ 67,000
2 - 48-inch needle valves	120,000
1 - 48-inch hollow cone valve	33,600
1 - 36-inch hollow cone valve	24,200
1 - 42-inch ball valve	23,000
1 - 42-inch ball valve with stainless steel lining	32,000

Bypass Valve

It is also suggested that consideration be given to modifying the 12-inch bypass line. For small discharges (less than about 30 cfs) it is not practical to use a 36- or 48-inch valve due to the difficulty of controlling the flow accurately, the increased chance of cavitation damage, erosion, and general wear on the valve.

## Free Discharge Structure

The second, general solution considered was the possibility of abandoning the present valve vault and constructing a new outlet works at the end of the box flume, which would be a free discharge outlet.

After a brief consideration of the extensive changes necessary, the costs involved, and the advantages involved it was concluded that such an undertaking was not warranted. The cost estimate based on a cursory study was \$300,000.

APPENDIX

## References

1. Albertson, M. L., Tullis, J. Paul and Thomas, Charles W., "Hydraulic and Cavitation Characteristics of Valves," Colorado State University, Department of Civil Engineering, Hydro-Machinery Laboratory Report No. 1, 2 Vol. Report to Metropolitan Water District through Bechtel Corporation, June 1967.
2. Darvas, L., "Laboratory Investigation Into the Cavitation Characteristics of Needle Valves," Manly Hydraulic Laboratory, Metropolitan Water and Sewerage and Drainage Board, Sydney, Australia, Aug., 1965.
3. O'Brien, T., "Needle Valves with Abrupt Enlargements for the Control of a High Head Pipeline," Annual Engineering Conference Papers, 1966 Conference of the Institution of Engineers, held at Newcastle, New South Wales.
4. Skinner, M.M. and Tullis, J. Paul, "Results of the Testing of a 12-inch Ball Valve and a 12-inch Butterfly Valve with a Downstream Expansion," Colorado State University, Department of Civil Engineering, CER66-67MMS-JPT26. Report to Santa Clara Flood Control District, San Jose, California, January 1967.
5. Stierlin, K., "Pressure Reducing Plant for a Water Power Station," Escher Wyss News, Zurich, Vol. 30, No. 1, 1957.
6. Tullis, J. Paul, "Discharge Calibration and Cavitation Investigation of a 12-inch Needle Valve," Colorado State University, Department of Civil Engineering, Hydro-Machinery Laboratory Report No. 2, September 1967.
7. Tullis, J. Paul, "Torque Cavitation and Discharge Calibration of a 12 x 10-inch Larner Johnson Valve," Colorado State University, Department of Civil Engineering, Hydro-Machinery Laboratory Report No. 6, Prepared for Darling Valve and Manufacturing Company, August 1968.
8. Tullis, J. Paul and Albertson, M. L., "Needle Valves as Pressure Regulators," Presented at the ASCE Environmental Engineering Meetings, Chattanooga, Tennessee, May 15, 1968.
9. Tullis, J. Paul, Albertson, M. L. and Marschner, B. W., "Flow Characteristics of Valves," Presented at the IAHR Symposium at Lausanne, Switzerland, September 1968.

References - continued

10. Tullis, J. Paul and Skinner, M. M., 'Reducing Cavitation in Valves, "Journal of the Hydraulics Division - - ASCE, (approved for publication).
11. Yanshin, B. N., 'Hydrodynamic Characteristics of Valves and Pipeline Components, "Mashinostroenie, Moscow, 1965, available from Victor Kamkin Corp., 1410 Columbia Road, N. W., Washington, D. C., 20009.

TABLE I. WATER BOARD PERSONNEL PRESENT  
DURING FIELD TESTS

<u>Name</u>	<u>Title</u>	<u>Duty During Test</u>
John P. Parsons	Chief Design Engineer	Observing-recording flow reading
James L. Forbes	Design Engineer	Observing-recording flow reading
Henry Kneale	District Foreman	Supervising-flow readings
Robert Chambers	Ass't. District Foreman	Operating South Boulder Intake
A. C. Matthews	Maintenance Foreman	Observing valve & equipment operation
R. L. Weaver	Caretaker	Operating valves
T. H. Glazner	Ass't. Caretaker	Operating valves
R. K. Day	Mechanic	Operating valves
C. V. Davis	Equipment Operator	Operating So. Boulder Intake & ditch riding
Henry Symanski	Equipment Operator	Operating So. Boulder Intake & ditch riding

TABLE II DISCHARGE DATA

RUN NO.	TEST VALVE OPENING PERCENT			DISCHARGE CFS	PRESSURE ON NO. 2 VALVE		DIFFER. AIR PRESSURE, INCHES H <sub>2</sub> O	COMMENTS
	NO 2	NO 3	NO 4		UPSTR.	DOWNSTR.		
1	6	0	0		120.2	0	1.5	Cavitation beginning
2	8	0	0		120.2	NEG		Light Cavitation Inside Valve
3	12.5	0	0					Light Cavitation Inside Valve
4	18	0	0	29				
5	27	0	0		117	NEG	6.0	Heavy Surging in pipeline & transition; Moderate Cavitation
6	30	0	0					Beginning of heavy pounding cavitation in downstream pipe
7	38	0	0	269	114	0	9.5	Heavy pounding cavitation in downstr. pipe. Fairly heavy surging.
8	25	0	0					Light fine cavitation
9	50	0	0	389	109	4	18.0	Heavy pounding cavitation
10	62.5	0	0	537	107.5	10	28.0	Steady cavitation but reduced pounding. High noise level due to air screaming thru manhole.
11	75	0	0		79.5	10		Heavy surging. Severe pipe vibration. Noise drowns out cavitation.
12	0	0	25					Light-moderate fine grain cavitation
13	0	0	50					Heavy pounding cavitation
14	0	27	0	164				
15	0	43	0	290				8-Ft tunnel flowing full
16	0	60	0	421				
17	0	73	0	570				
18	25	25	25					Heavy surging in transition
19	25	25	25					
20	25	25	25					
21	25	59	0					
22	25	59	0					
23	50	0	50					No backup of water in transition
24	50	0	50					
25	50	0	50					
26	50	27	0					
27	50	27	0					