R-93-04

EMERGENCY CLOSURES OF GUARD GATES WITH UNBALANCED HEADS

HIGH-PRESSURE SLIDE GATES

April 1993

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Denver Office
Research and Laboratory Services Division
Hydraulics Branch

7-2090 (4-81)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. R-93-04	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE EMERGENCY CLOSURES OF GUARD GATES WITH UNBALANCED HEADS HIGH-PRESSURE SLIDE GATES		5. REPORT DATE April 1993 6. PERFORMING ORGANIZATION CODE D-3752
7. AUTHOR(S) K. Warren Frizell		8. PERFORMING ORGANIZATION REPORT NO. R-93-04
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bureau of Reclamation Denver Office Denver CO 80225		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. 13. TYPE OF REPORT AND PERIOD COVERED
12. SPONSORING AGENCY NAME AND ADDRESS Same		14. SPONSORING AGENCY CODE DIBR

15. SUPPLEMENTARY NOTES

Microfiche and hard copy available at the Denver Office, Denver, Colorado.

16. ABSTRACT

The Bureau of Reclamation Hydraulic Laboratory studied closure of high-pressure slide gates under unbalanced head conditions. The gates in question were guard or emergency gates in dam outlet works. The studies included a scale hydraulic model of the Cedar Bluff Dam outlet works and laboratory tests on a 4-inch air vacuum-release valve. Field tests at Silver Jack Dam outlet works and Tieton Dam outlet works provided prototype verification. We developed a mathematical model which evaluates air valve sizing and calibrated it using the laboratory and field results. Along with Reclamation's Dam Safety Office, Mechanical Branch, and Operations and Maintenance Engineering Branch, a standard test procedure was developed to field evaluate hoist loading on the gates and perform an overall evaluation of the outlet to ensure safe testing. The test procedure is safe and can easily be performed during routine Reclamation field examinations.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- gate closure/ unbalanced head/ automatic air valve/ hydraulic model study/ field study/ method of characteristics/ SEED and RO&M inspections/ gate hoist capacity/ pipeline collapse/ slide gates/ guard gates

b. IDENTIFIERS-- Cedar Bluff Dam/ north-central Kansas/ Silver Jack Dam/ Montrose, Colorado/ Tieton Dam/ Yakima, Washington

c. COSATI Field/Group   COWRR: SRIM:

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 40
	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. PRICE

R-93-04

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by

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ACKNOWLEDGMENTS

Many people have been involved in the successful completion of these studies. In particular, the staff at the Colorado River Storage Project Power Operations Curecanti Field Division assisted with the Silver Jack field tests, and the Yakima Project Office staff assisted with Tieton field tests. Denver Office personnel from the Dam Safety Office, Mechanical Branch, Operations and Maintenance Engineering Branch, Concrete Dams Branch, and Hydraulics Branch were instrumental in developing the test procedures which have now been instituted for emergency closures of high-pressure slide gates with unbalanced heads. Special mention goes to Jim Wadge (USBR retired) for his active role in promoting the awareness that this type of testing needed to be done but in a safe and efficient manner.

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GLOSSARY

A - pipe area

A_G - open area of gate

B - characteristic impedance

C^+ - positive characteristic

C^- - negative characteristic

C_d - discharge coefficient

C_{in} - inflow air valve discharge coefficient

C_{out} - outflow air valve discharge coefficient

D - pipe diameter

H - hydraulic gradeline elevation

$\overline{H}$ - barometric head

H_o - steady-state head across gate

H_{Res} - reservoir head

ΔH - instantaneous drop in hydraulic gradeline across a gate

Q - volumetric flow rate

Q_o - steady-state flow rate

R - Universal gas constant

T - temperature

V - velocity in pipe

a - acoustic wave speed

f - friction coefficient

g - gravitational acceleration

m - mass

$\dot{m}$ - mass flow rate

p - pressure in pipe

p' - p/p_o

t - time

v - volume

x - distance along pipe

z - elevation

γ - specific weight of liquid

τ - dimensionless gate opening

Δ - change in quantity

INTRODUCTION

Many Reclamation (Bureau of Reclamation) projects have outlet works structures with inadequate air venting to allow for safe closure of the guard gate under unbalanced head conditions. In addition, the ability of the gate hoist system to close the guard gate under unbalanced head conditions needs to be verified. In order to upgrade these facilities and develop a standardized test procedure for use during Reclamation field examinations [SEED (Safety Evaluation of Existing Dams and RO&M (Review of Operation and Maintenance)], the Hydraulics Branch performed several investigations. These included a 1:12 scale hydraulic model of Cedar Bluff Dam outlet works, laboratory tests of a 4-inch air vacuum-release valve, field studies on the Silver Jack Dam outlet works and Tieton Dam outlet works, and development of a mathematical model which can evaluate and size automatic air valves. Many guard gates on Reclamation outlet works structures are slide gates. These studies summarize investigations on slide gates only and any recommendations should pertain only to slide gates.

INVESTIGATIONS

Model Study: Cedar Bluff Dam Outlet Works

Cedar Bluff Dam in north-central Kansas features a single conduit, gated outlet works structure that delivers water for irrigation and other downstream requirements. Typical of many other Reclamation outlet works, the guard gate is in a chamber, several hundred feet upstream from the control gate (fig. 1). The guard gate normally operates only under balanced head conditions. On occasion, the guard gate might need to be closed while the control gate is partially or fully open. Air must be supplied to the pipeline between the two gates to prevent damage or collapse of the pipe due to low pressures. This study observed the outlet works operating with an unbalanced head. The air demand and pressures downstream from the guard gate were the major topics which we investigated.

1. The model. - We constructed a 1:12 scale Froudian model of the Cedar Bluff Dam outlet works in the Reclamation hydraulics laboratory. The main feature of the model was a variable speed, motor operated guard gate (fig. 2). The laboratory system supplied water to the model. A free-surface constant head tank with an overflow weir, provided a continuous head equivalent to the maximum design water surface. The head tank was connected to the guard gate structure by an 8-inch-diameter pipe. Several piezometers were located in the gate structure for pressure measurements. Downstream from the guard gate we included a scaled air vent (fig. 3). The pipeline between the guard gate and the control gate was clear acrylic plastic pipe to help observe flow. The control gate was an adjustable slide gate.

A microcomputer-based data acquisition system read data from the instrumentation and recorded, analyzed, and plotted results. Quantities measured included:

- Guard gate discharge measured with a strap-on acoustic flowmeter
- Guard gate position, using a string transducer
- Pressures on the gate leaf and surrounding chamber surfaces, using a differential pressure transducer and scanivalve
- Air demand downstream of the guard gate, using an orifice plate and differential pressure transducer

- Dynamic pressure fluctuations in the pipeline between the guard gate and the control gate, using piezoelectric pressure transducers

2. The study. - We tested two guard gate closure rates and five downstream control gate positions. Prototype closure rates of 1- and 2-ft/min were scaled in the model. For each closure rate, control gate positions of 20, 40, 60, 80, and 100 percent were tested. The test procedure consisted of setting a control gate position, establishing steady-state flow conditions, and then closing the guard gate. As the guard gate was closed, the computer polled the instrumentation, recording all quantities as a function of time.

3. Results. - Air demand for the various unbalanced head conditions tested are shown in figure 4. These curves are for the scaled 1-ft/min closure rate. At the scaled 1-ft/min rate, the hydraulic jump exited the pipeline before the guard gate closed for all control gate settings tested. However, at a scaled 2-ft/min closure rate, the guard gate closed before the jump exited the pipeline. The air demand curves reflect this condition (fig. 5). At the point where the air demand began to diminish, the curve intercepted the axis (0-percent gate opening), indicating a residual airflow. When this occurred, a wave travelled up the pipeline and hit the downstream face of the guard gate leaf.

Pressures measured on the gate showed the bottom of the gate leaf at vapor pressure during much of the length of gate travel (fig. 6).

4. Discussion. - The main topic of interest – air demand – is a difficult quantity to evaluate in a hydraulic model due to scale effects which exist in modeling air-water flows. Scale effects in these types of flows are generally due to the inability to reproduce the fine scale turbulence levels present in prototype flows. This is especially noticed in free surface aeration. The air demand in this case is driven by the hydraulic jump moving down the conduit. Since the air demand is caused by a phenomenon which can be modeled with some confidence, the quantities of air predicted should be accurate as long as the air valve and vent system losses are modeled correctly.

The closure rate at most field sites is 1-ft/min at maximum and probably slower depending on reservoir levels and temperature. The length of the pipeline between the guard gate and the control gate along with the closure rate determines whether the jump will exit the pipeline before the guard gate closes.

Pressures on the gate leaf and in the surrounding gate frame were scaled by Froude number. The vapor pressure of the fluid and the atmospheric pressure were not scaled in the model. Scaled pressures from the model lower than vapor pressure were not meaningful. However, the low pressures measured in the model correlate with cavitation damage that has occurred on gates of this design in the field. The pressures on the gate leaf point out shifts in control with change in gate position. The short tube effect, typical with most gates at small openings, is magnified by the curved floor section in the gate frame.

The dynamic pressure fluctuations measured in the model should pose no problems to the prototype conduit. The fluctuations were highest in the hydraulic jump; otherwise, the levels were insignificant. Several researchers (Toso, 1987) have proved that scaling the dynamic pressure amplitude and frequency for the case of a hydraulic jump can be successfully accomplished in a hydraulic model.

Laboratory Tests: 4-Inch Air Vacuum-Release Valve

We tested a typical 4-inch air combination-release valve in the hydraulic laboratory under a variety of conditions. In most pipeline applications, these air valves are designed to evacuate accumulated air. However, when the relief of low pressures is important, the valve's inflow characteristics become important. Of specific interest was the coefficient of discharge for the valve. Knowing the C_d, we can size the air valve to alleviate low pressures in the pipeline.

1. **Test setup.** - There were two configurations used to test flow through the air valve. An air test facility consisting of a large centrifugal fan circulated air through the valve which was installed inside an air plenum (fig. 7). Flow to the valve was measured with an in-line orifice meter. Two pressure transducers sensed the pressure difference across the valve. Temperature and barometric pressure were also recorded. Due to limitations in the airflow rates with this setup, more tests were required. These tests consisted of mounting the air valve on a large vacuum chamber [LAPC (low ambient pressure chamber)] located in the Hydraulic Laboratory. In this configuration, the air valve was mounted on a standpipe on the exterior of the chamber. An inline orifice meter measured the discharge. The valve was isolated from the chamber by a quarter-turn butterfly valve. The butterfly valve was closed while a vacuum was pulled in the chamber. When the desired negative pressure in the chamber was reached, we opened the butterfly valve, allowing air to flow into the chamber through the air valve, relieving the lower pressure in the chamber.

   Operation and maintenance characteristics of the air valve were evaluated on a test stand in the laboratory (fig. 8). The valve was cycled by opening and closing a motor-operated butterfly valve. Water was supplied with a portable pump, and the water level in the standpipe leading up to the air valve oscillated due to the opening and closing of the butterfly valve. Pressure transducers on the standpipe and the air valve body measured minimum seating pressures and the frequency of seating failures. Disassembly of the air valve for inspection of the internal parts was performed after this series of tests.

2. **Results.** - The air inflow characteristics of the air vacuum-release valve appear in figure 9. The first test arrangement did not allow adequate air capacity to determine a meaningful discharge coefficient for comparison with the manufacturer's data. The LAPC tests, however, revealed an average discharge coefficient of 0.4 (fig. 10). The manufacturer's curves for a similar valve indicate a value of 0.44 for C_d. The discharge coefficient measured in the laboratory used the pressure differential measured at the lower drain tap. Since this tap is near the bottom flange, losses in the valve between this tap and the flange were negligible.

   The minimum internal seating pressure to prevent leakage was 3 lb/in^2. The valve continued to remained tightly sealed as the pressure was reduced to 1.5 lb/in^2. Below this pressure, leakage occurred. The valve was cycled 580 times with no observed operation failure. A thorough inspection of the valve after these tests showed no wear on the seat or float. The inner metallic surfaces had a light coating of rust (fig. 11). All moving parts were in good condition.

3. **Discussion.** - We tested automatic air valves from two different manufacturers. The valves conformed to the manufacturers' published data concerning airflow capacities. No problems in seating were noted during the cycling tests although leakage could occur if internal valve pressures drop below 3 lb/in^2. Valve maintenance should be minimal and easy due to very few moving parts and good accessibility.

Prototype Tests

1. Silver Jack Dam outlet works. - Two fields tests were conducted in October 1986 and May 1987 on the outlet works at Silver Jack Dam on the Cimarron River near Montrose, Colorado. The outlet works has a 2.75- by 2.75-foot guard gate feeding a 38-inch-diameter pipeline, which bifurcates and terminates with two 2.25- by 2.25-foot control gates (fig. 12). The guard gate is a typical 45° gate leaf with no upstream skinplate (fig. 13). The guard gate was equipped with an automatic 4-inch air vacuum-release valve. Silver Jack Dam outlet works was selected for testing due to its small pipeline. The strength of the conduit was adequate to withstand vapor pressure in the pipe without the possibility of collapse. The site also met other test requirements such as type of control gate, downstream channel capacity, and water availability.

a. The tests. - Tests included measuring the downpull and uplift forces on the guard gate under balanced and unbalanced head conditions. A sample of the proposed standard guard gate test emergency closure procedure was run. In addition, air demand through the 4-inch air valve was measured for three unbalanced head conditions. During these tests, pipeline pressures (both static and dynamic) were monitored along with accelerations on the steel pipeline between the guard gate and the control gates.

b. Results. - The following summarizes the test results .

October 6-10, 1986. - A set of measurements was made on the gate for balanced head conditions. The net force for gate operation was determined from monitoring pressures in the hydraulic cylinder of the guard gate. A positive net force is in the downward direction (fig. 14). The force during opening was the submerged weight of the gate and stem (2,500 pounds). In the closing direction, the weight of the gate was sufficient to close the gate.

We also performed the proposed standard guard gate emergency closure test. The guard gate was opened to approximately 20 percent and then closed again under totally unbalanced head (with the downstream pipeline initially dewatered.) This test procedure allowed the hoist cylinder to be operated under maximum loading conditions without requiring operation of the automatic air valve since the air demand was satisfied by the fully open control gate at the end of the pipeline. Results of this test are shown in figure 15.

A series of three tests was run under unbalanced head conditions. The two control gates were set with symmetric openings of 25, 50, and 75 percent, corresponding to 33.5-, 66.9-, and 100.4-percent openings referenced to the guard gate area. In each case, the guard gate was fully opened, a steady-state flow was established, and then the guard gate was closed.

Three sets of results are presented: (a) forces on the guard gate leaf, (b) static pressures in the 38-inch pipeline, and (c) air demand at the 4-inch air valve. Gate hoist loading (fig. 16) can be explained by looking at the gate leaf area exposed to the flow at specific gate openings. At 85 percent open, the gate leaf is subjected only to upthrust on the bottom sloping section of the gate leaf; whereas at the 60-percent opening, upthrust and downpull are nearly balanced due to the upward sloping surface entering the flow (fig. 17). Below the 60-percent opening, frictional forces dominate and increase as the gate closes.

In all cases of the unbalanced head conditions, the guard gate closed at a rate of 0.67 ft/min. Data for the 25-percent control gate settings are shown in figures 18a and b. The pipeline pressures at four different stations show the decrease in pressure from the reservoir head to a negative pressure below a 10-percent opening. The pressure did not recover, meaning that the hydraulic jump had not exited the pipeline before the guard gate closed. The air demand data showed the air valve opening and drawing air at about a 21-percent guard gate opening. The air demand, however, fluctuated wildly and did not reach expected levels. After the guard gate closed, the air demand continued for a time, reinforcing the fact that the hydraulic jump was still in the pipeline at the time of closure.

The data for 50-percent control gate openings are shown in figures 19a and b. The pipeline pressures again decrease with the closing of the guard gate. The stations further downstream (stations 6+19 and 7+39) also showed the initial frictional losses at the increased discharge. The crown pressure at station 4+35 nearly reached full vapor pressure at a 20-percent gate opening and did not fully recover before the gate was closed. Again, the hydraulic jump was still in the pipeline or was just exiting at the moment of closure. The air demand began at a guard gate position of 44 percent and was again very sporadic and much lower than anticipated.

The data for 75-percent control gate openings (fully unbalanced) are shown in figures 20a and b. The pipeline pressures were similar to those seen in the previous test, with the pipeline exposed to vapor pressure at a 40-percent guard gate opening. The pressure recovered, indicating the hydraulic jump exited the pipeline before the gate movement was completed. The air demand began at a guard gate position of 62 percent. As with the previous tests, the air demand fluctuated wildly and was much lower than anticipated.

May 26-29, 1987. - These additional tests resulted from the need to better understand the air demand data which were acquired during the first test series. The predictions of air demand for Silver Jack were much higher than measured. The first thought was that there was a problem with the transducer measuring the pressure differential across the air valve. The second tests included air demand measurements along with guard gate position and several pipeline pressures and accelerations. Audio and video recordings were made in the gate chamber to help determine what was occurring throughout the tests. As a result of a higher reservoir head and colder temperatures, the guard gate closure rate was not as fast as the previous test – only 0.34 ft/min.

The tests began with a guard gate closure at 25-percent control gate settings (figs. 21a and b). Again, there were low airflow rates and high negative pressures. The 50- and 75-percent control gates tests were run (figs. 22a and b and figs. 23a and b) and continued to show low airflow rates and high negative pressures. The instruments were rechecked and the video tape was viewed. The video showed only a very weak airflow into the valve with a strong blowback out of the pipeline visible near the end of the gate closure. This blowback occurred as the hydraulic jump exited the downstream end of the pipeline, allowing air to rush in and relieve the lower pressures inside the pipe. The weak airflow with a pressure differential of nearly 11 lb/in^2 could only be caused by a blockage of the airflow path.

The gate was closed and the downstream gate frame and air piping were inspected. By looking up into the air piping area from inside the pipeline, it was evident that a layer of silt had deposited on top of the downstream gate frame (fig. 24). Fourteen 1-inch-diameter holes were counted in the crown of the downstream gate frame. The average open diameter of the holes was estimated to be 0.5 inch. The silt reduced the flow area from 11 to about 2.7 in^2. The holes were cleared of as much of the silt as possible before resuming the testing. Specifications No. 860-D-85 called for sixteen 1.125-inch-diameter holes in the downstream gate frame for air-venting purposes (as opposed to the fourteen 1-inch-diameter holes observed).

We cleaned the air vent and reran a closure test with a 50-percent control gate opening. Data showed there was a large increase in airflow, and the maximum negative pressures in the pipeline were reduced from −11 to −6 lb/in^2 (figs. 25a and b). Finally, a test with 75-percent control gate openings (fully unbalanced) was run with similar results (figs. 26a and b).

c. Discussion. - The field investigations were extremely valuable in evaluating the closure of a guard gate under unbalanced head conditions (emergency). Of particular interest were the much slower closure rate and the plugging of the air manifold in the downstream gate frame. The slow closure rate was actually a benefit since it reduced the transient pressures to a minimum and allowed the hydraulic jump to fully exit the pipeline under most unbalanced head conditions. Plugged air passages are a much more serious concern and should be considered at all similar Reclamation structures. With a properly sized automatic air valve, collapse of the downstream pipeline is still a possibility if the air passages become plugged with debris. This debris can be deposited through normal operation as noted by the silt deposits found at Silver Jack Dam. Thorough and frequent inspections of the air passages should be made to ensure the integrity of the structure.

2. Tieton Dam Outlet Works. - In August of 1989, we tested the outlet works at Tieton Dam on the Tieton River near Yakima, Washington. The dam is an earthfill embankment with a concrete core wall and a height of 319 feet (fig. 27). The outlet works feature two 5- by 6-foot emergency/guard gates. The gate leafs are Reclamation's pre-1940 design (fig. 28). Each guard gate was equipped with a 6-inch and an 8-inch automatic air valve (fig. 29). The structure is regulated with two 60-inch jet-flow gates located about 500 feet downstream from the guard gates. Two separate 72-inch steel pipes connect the guard gates with the regulating gates.

a. The tests. - All tests, conducted August 28-30, 1989, were run on the right gate, while the left gate provided 900 ft^3/s of uninterrupted flow to the river below the dam. Two balanced head tests were run. During these tests, the jet-flow gate remained closed and the guard gate was operated from closed to open to closed. Hoist loads were determined from Bourdon gauges on the hydraulic cylinder. The balanced tests differed only in the location from where the hydraulic system was operated. It was possible to operate the guard gates from both the gate chamber and the top of the dam. There were three unbalanced tests. During these tests, the jet-flow gate was open and the guard gate was opened to a 20-percent (1.2-ft) opening and then closed. Two tests were completed by operating the guard gate from the gate chamber. The third unbalanced test attempted to operate from the top of the dam; however, the gate would not open.

b. Results. - The results will be presented for each test run. Test 1 was a balanced head test in which the guard gate was operated from the gate chamber. The gate was operated through a full cycle at a rate of 0.63 ft/min. Figure 30 shows the hoist load during the gate movement, note the submerged weight of the gate is roughly 8,000 pounds. During closing, the weight of the gate was sufficient to close the gate.

Test 2 was also a balanced head test; however, the hydraulic system used to operate the guard gate was located on top of the dam. The gate movement slowed to a rate of 0.45 ft/min. The reduction in speed between this test and test 1 was due to the increased losses in the much longer hydraulic lines. Hoist loading was similar to test 1 (fig. 31).

The first unbalanced test was test 3 and the hydraulic system was operated from the gate chamber. The gate was opened to about 20 percent (1.2 ft), held there for a time and then closed. The rate of opening was 0.24 ft/min while the closure rate was 0.58 ft/min. The difference in these rates is largely due to variations in loading during opening and closing. Hoist loadings are shown in figure 32. Air pressure in the throat of the 6-inch air vacuum-release valve is shown in figure 33.

During test 4, the unbalanced test operated from the top of the dam, the hydraulic hoist system would not open the guard gate. Two attempts were made. Each time, the gate barely cracked open and then stopped.

The final test, test 5, was operated from the gate chamber. The rates of opening and closing again differed, 0.26 ft/min for opening and 0.56 ft/min for closing. These results are comparable to those from test 3. Hoist loading, measured with a pressure transducer on the hydraulic cylinder, is shown in figure 34. The air pressure in the 6-inch air vacuum-release valve was also similar to that reported for test 3 (fig. 35).

c. Discussion. - From an analysis detailed in Hydraulics Branch TR-89-34, the hydrodynamic forces acting on the gate were extracted from the data (fig. 36). These forces include upthrust, downthrust, and downpull. The maximum hydrodynamic force (–48,000 pounds) occurred at a gate opening of about 5 percent. About 14.5 percent of this force was due to a vapor cavity which formed on the bottom of the gate leaf. The remainder of the force was due to downthrust acting on the top of the gate leaf and reduction of the hydrostatic upthrust acting on the gate leaf bottom.

The air demand is satisfied by the two automatic air valves. The collapse pressure of the conduit was calculated to be -7 lb/in^2 or 6.7 lb/in^2 (absolute). The steady-state computer model by Peters indicated that the air vent pressure would be -3.47 lb/in^2 at 20 percent open. This assumed both vents in operation. The measured air vent pressure in the 6-inch air valve for a 20-percent opening (closing cycle) was -2.46 lb/in^2 or 11.2 lb/in^2 (absolute).

The inability to operate the guard gate from the top of the dam pointed out a problem in the hydraulic operating system. The hydraulic system was plumbed to the top of the dam to satisfy a SEED recommendation. However, when this was done, the new system was not installed properly. Modifications to the system were recommended in the travel report.

Mathematical Model

To evaluate existing outlet works for air valve sizing and pipeline reinforcement, a computerized mathematical model was developed. In the past, site-specific models and a generalized steady-state model have been used to size air valves and make further recommendations. Due to the available laboratory model and prototype results described above, a more complete and descriptive mathematical model was developed.

1. The model. - The model uses a computational technique known as the Method of Characteristics (Wylie, 1978). This method is generally used for transient analysis. Computationally it is a relatively simple method to program. The major difficulty in applying this method is in the development of special boundary conditions which describe real world problems. The characteristics method is based on simplified equations of motion and continuity (symbols are defined in the Glossary).

$$0 = g\left(\frac{\partial H}{\partial x}\right) + \frac{\partial V}{\partial t} + \frac{f}{2D}V|V| \tag{1}$$

$$0 = \frac{\partial H}{\partial t} + \frac{a^2}{g}\left(\frac{\partial V}{\partial x}\right) \tag{2}$$

Through a linear combination of these two equations, they can be converted from two partial differential equations to two total differential equations:

$$\frac{g}{a}\left(\frac{dH}{dt}\right) + \frac{dV}{dt} + \frac{f(V|V|)}{2D} = 0 \tag{3}$$

$$\frac{-g}{a}\frac{dH}{dt} + \frac{dV}{dt} + \frac{f(V|V|)}{2D} = 0 \tag{4}$$

where equation 3 is valid when dx/dt = +a and equation 4 is valid when dx/dt = −a. The grouping of each of these equations with validating conditions gives the commonly referred to C^+ and C^- equations. Visualizing the solution in the *xt* plane, solutions of the equations dx/dt = ±a, gives two straight lines (assuming a is constant) or characteristic lines, along which equations 3 and 4 are valid (fig. 37). The development of these equations into a model is done by integrating equations 3 and 4 along the C^+ and C^- lines. The pipe is divided into N reaches, each Δx in length with a time step given by Δt = Δx/a. This basic finite difference formulation yields two equations for the pressure head at point P:

$$C^+: H_p = H_A - \frac{a}{gA}(Q_P - Q_A) - \left(\frac{f\Delta x}{2gDA^2}\right)Q_A|Q_A| \tag{5}$$

$$C^-: H_P = H_B + \frac{a}{gA}(Q_P - Q_B) + \left(\frac{f\Delta x}{2gDA^2}\right)Q_B|Q_B| \tag{6}$$

The solution requires that we compute H and Q for each grid point for the time duration desired. At the interior grid points, the two equations are solved simultaneously for the unknowns Q_{Pi} and H_{Pi}. Equations 5 and 6 can then be written as:

$$C^+: H_{Pi} = C_P - \frac{a}{gA}(Q_{Pi}) \tag{7}$$

$$C^{-}: H_{Pi} = C_M + \frac{a}{gA}(Q_{Pi}) \tag{8}$$

where:

$$C_P = H_{i-1} + \frac{a}{gA}Q_{i-1} - \left(\frac{f\Delta x}{2gDA^2}\right) Q_{i-1}|Q_{i-1}|$$

$$C_M = H_{i+1} - \frac{a}{gA}Q_{i+1} + \left(\frac{f\Delta x}{2gDA^2}\right)Q_{i+1}|Q_{i+1}|$$

Elimination of Q_{Pi} from equations 7 and 8 gives a direct solution for H_{Pi}:

$$H_{Pi} = \frac{(C_P + C_M)}{2} \tag{9}$$

After the first time step, the end (or boundary) points begin influencing the interior points; so for a complete and accurate solution at any time step, the appropriate boundary conditions must be applied.

2. Boundary conditions. - To solve real world problems, we need to specify appropriate boundary conditions. The guard gate closure problem has boundary conditions which are straightforward except for the automatic air valve. Details of the boundary conditions used in this model are:

a. End conditions. - The ends of the pipeline can yield only one valid characteristic equation. Therefore, an auxiliary condition that specifies Q_P, H_P, or some relation between them must be given.

(1) Reservoir at upstream end with specified elevation. - This case gives $H_{P1} = H_{Res}$, so Q_{P1} can be determined by a direct solution of equation 10:

$$Q_{P_1} = \frac{(H_{P_1} - C_M)}{\left(\frac{a}{gA}\right)} \tag{10}$$

Here the subscript 1 refers to the upstream or reservoir section with the other unknowns dependent on known values from the previous time step.

(2) Gate at the downstream end. - A gate at the downstream end of the system is simulated with the orifice equation for flow through the gate:

$$Q_P = C_d\, A_g\sqrt{2g\Delta H} \tag{11}$$

where C_d is the discharge coefficient, A_g is the area of the gate and ΔH is the instantaneous drop in hydraulic gradeline across the gate. In terms of the model parameters:

$$Q_{P_{NS}} = -\frac{a}{gA}\left(\frac{(Q_o\tau)^2}{2H_o}\right) + \sqrt{\left(\frac{a}{gA}\left(\frac{(Q_o\tau)^2}{2H_o}\right)\right)^2 + 2\frac{(Q_o\tau)^2}{2H_o}(C_P)} \tag{12}$$

$$H_{P_{NS}} = C_P - \frac{a}{gA}(Q_{P_{NS}}) \tag{13}$$

where τ is the dimensionless gate opening, given by:

$$\tau = \frac{C_d\, A_G}{(C_d\, A_G)_o} \tag{14}$$

with $\tau = 1$ for a fully opened gate and $\tau = 0$ for a closed gate. The coefficients of discharge are dependent on the type of gate leaf you want to simulate.

b. Change in pipe diameter. - A change in the pipeline diameter can be handled by matching conditions at an intersecting node. This same method can be used to simulate a simple series connection. Continuity of discharge and pressure head are enforced at the connecting point:

$$Q_{P_{1,e}} = Q_{P_{2,1}} \tag{15}$$

$$H_{P_{1,e}} = H_{P_{2,1}} \tag{16}$$

Solving these equations simultaneously along with equations 7 and 8 gives:

$$Q_{P_{2,1}} = \frac{C_{P_1} - C_{M_2}}{\left[\left(\frac{a}{gA}\right)_1 + \left(\frac{a}{gA}\right)_2\right]} \tag{17}$$

The rest of the unknowns are solved for directly.

c. Guard gate in-line. - The boundary condition for the closing guard gate is handled similarly to the control gate at the pipeline end. Basically, continuity is applied at the gate forcing:

$$Q_{P_{2,1}} = Q_{P_{1,e}} = \frac{Q_o\tau}{\sqrt{H_o}}\sqrt{H_{P_{1,e}} - H_{P_{2,1}}} \tag{18}$$

If flow is in the positive direction, this equation can be combined with equations 7 and 8 to yield a quadratic equation and be solved for:

$$Q_{P_{1,e}} = -C_v(B_1 + B_2) + \sqrt{C_v^2(B_1 + B_2)^2 + 2C_v(C_{P_1} - C_{M_2})} \tag{19}$$

where $C_v = Q_o^2\tau^2/2H_o$ and B_1 and B_2 refer to (a/gA) for the sections upstream and downstream of the gate. If flow happens to reverse directions, all the signs in the above equation are simply reversed as well. Once the flow is known, equations 7 and 8 can be used to find the hydraulic gradeline.

d. Automatic air valve. - This condition allows for the inflow of air when the line pressure at an air valve drops below atmospheric. When the pressure in the pipeline increases above atmospheric, trapped air can escape at a much slower rate; however, water is not permitted to escape. When the head drops below the pipeline elevation, the air valve opens and flow enters according to the ideal gas law:

$$pv = mRT \tag{20}$$

This equation must be satisfied at the end of each time increment as long as the pressure stays reduced. In terms of the model parameters, equation 20 becomes:

$$p\left[V_i + \frac{1}{2}\Delta t(Q_i - Q_{PX_i} - Q_{PP_i} + Q_{Pi})\right] = \left[m_o + \frac{1}{2}\Delta t(\dot{m}_o + \dot{m})\right]RT \tag{21}$$

The characteristic equations are:

$$C^+ : H_{Pi} = C_P - B(Q_{PPi}) \tag{22}$$

$$C^- : H_{Pi} = C_M + B(Q_{Pi}) \tag{23}$$

In addition, the relationship between p and H_p is:

$$p = \gamma(H_P - z + \bar{H}) \tag{24}$$

The substitution of equations 22 and 23 into 21 gives:

$$p\left(V_i + \frac{1}{2}\Delta t\left[Q_i - Q_{PXi} - \frac{(C_M + C_P)}{B} + \frac{2}{B}\left(\frac{p}{\gamma} + z - \bar{H}\right)\right]\right) = \left[m_o + \frac{1}{2}\Delta t(\dot{m}_o + \dot{m})\right]RT \tag{25}$$

which is solved at the end of each increment when an air cavity is present in the pipeline. The airflow rate $\dot{m}$ used is not known but is a function of p', given by one of the following:

$$\dot{m} = A_{2i}p'2 + A_{1i}p' + A_{0i} \qquad 0.528 \le p' \le 1.0$$

$$\dot{m} = MDC = C_{in}A_o(0.686)\frac{P_o}{\sqrt{RT_o}} \qquad p' < 0.528$$

$$\dot{m} = D_{2i}p'^2 + D_{1i}p' + D_{0i} \qquad 1.0 < p' \le 1.894$$

$$\dot{m} = -0.686C_{out}\,A_o p_o\frac{p'}{\sqrt{RT}} \qquad p' > 1.894$$

The solution of equation 25 is then simply a quadratic when one of these forms for $\dot{m}$ is used.

The proper zone of p' is selected in the program and the solution stepped forward. If none of the conditions are satisfied, there is no cavity.

3. Two test runs were completed: (a) Cedar Bluff Dam outlet works and (b) Silver Jack Dam outlet works. These are two sites covered by either model or prototype data. The results are shown below.

a. Cedar Bluff Dam outlet works. - The computer simulation of Cedar Bluff Dam used prototype dimensions and a closure rate of 1 ft/min. A comparison of scaled model data and the computer output is shown for air demand during the gate closure, for two levels of imbalance (60 and 100 percent) (fig. 38).

b. Silver Jack Dam outlet works. - The computer simulation of Silver Jack Dam used prototype dimensions and a closure rate of 0.33 ft/min. A comparison of prototype field data taken during test 2 and the computer output is shown for air demand during the gate closure for two levels of imbalance (66.9 and 100.4 percent) (fig. 39).

4. Discussion. - The computer code, while still in a development stage, provided satisfactory simulations of both problems attempted. The simulation of the Cedar Bluff outlet works compared well with model data acquired in the laboratory study. The simulation of the Silver Jack outlet works was not as good. However, as the coefficient of discharge was lowered so that the partially plugged air intake was more closely simulated, the results moved closer to the actual field measured values. Some work still needs to be done on the code to make it more user friendly and improve data input/output. The basic features are coded and have been shown to operate satisfactorily for the two calibration runs.

CONCLUSIONS AND RECOMMENDATIONS

Investigations in this report provide additional understanding of the guard gate emergency closure problem for slide gates. The model tests provided a good aid in comprehending a very complex phenomena. The model tests allowed for prediction of prototype behavior with good confidence. The prototype tests reiterated these findings and also pointed out some important maintenance considerations that could lead to design changes. The possibility of modifying the air intake manifold in the downstream gate frame needs review, and existing manifolds should be inspected and cleaned. The mathematical model should provide the tool needed to evaluate existing and new structures. Based on the mathematical model results, recommendations on air valve sizes and/or pipeline reinforcement can be provided.

As the result of these investigations, a standard field test was developed for slide gates. This test evaluates the gate hoist capacity and operation under unbalanced head conditions. This procedure could be done during a regular SEED inspection or RO&M examination.

The following is the proposed guard gate test procedure for slide gates separated by more than five pipe diameters from the regulating gate:

1. Prior to testing, the structure should be reviewed and preparations made for monitoring gate position and pressures in the hydraulic system. An evaluation using the mathematical model should be done. Modifications should be made which are reflective of the computer model results (i.e. air valve requirements, stiffener rings, etc.). Once the modifications are complete, the test may be performed.

2. The field test is primarily for determining the adequacy of the guard gate hoists to perform under unbalanced head conditions. A general inspection of the facility should be made to verify the condition of the structure. At this time, the automatic air valve should be inspected, along with the air passages leading to the inside of the pipeline. In particular, the manifold plate in the top of the downstream gate frame should be inspected for clogging. The guard gate should be exercised through a full cycle in the balanced mode. The regulating gate should then be opened and the conduit between the guard and regulating gates dewatered.

3. The guard gate is then opened to a 10-percent opening. The hydraulic system pressures as well as the gate position should be monitored. Once the gate has reached the 10-percent level, the gate can then be closed. If during guard gate operation a problem is encountered, close the regulating gate and then close the guard gate under balanced conditions.

This test procedure will identify the maximum static loading and frictional forces on the gate leaf. Also within the gate travel specified, the maximum hydrodynamic forces are generally reached (depending specifically on gate leaf configuration). We recommended that a guard gate not be fully opened then closed under an unbalanced head just for testing purposes. The above test procedure should confirm acceptable operation of the hoist mechanism under maximum loading conditions. With proper sizing and maintenance of the automatic air valve and associated vent piping and manifold, no problems should be expected in case of an actual emergency closure.

Additional studies should be conducted to evaluate the capability for other types of guard gates, such as ring follower gates and fixed wheel gates, to close under unbalanced head.

SUMMARY

Model and prototype studies show that venting the pipeline between the guard gate and the control gate with an automatic air valve is an effective method for reducing the magnitudes of negative pressures generated when closing the guard gate under unbalanced head conditions. Usually, the pressures can be

increased enough to prevent collapse of the pipeline; however, some sites may need additional stiffeners as well as the automatic air valve to prevent damage.

The prototype 4-inch air vacuum-release valve that we tested in the laboratory performed up to the manufacturer's claims. Slightly more airflow was measured at the same pressure differentials than was reported in the manufacturer's literature. Operation and maintenance of the valve pose no problem. While maintenance on the air valve itself is minimal, the air passages leading from the valve to the pipeline need to be clear and free of obstructions.

Field investigations showed that the air manifold in the downstream frame of the guard gate is a particular area where fouling can occur. If these passages (usually 1- to 1.125-inch-diameter holes) become restricted, the air valve is rendered useless and the outlet works pipeline may be in danger of collapsing if the guard gate is closed under unbalanced head.

A standardized guard gate emergency closure test procedure for slide gates was developed and tested. This procedure allows for testing at the maximum loading of the gate hoist while requiring only minimal air demand.

The computer model showed good agreement with the data collected in the model tests of Cedar Bluff Dam outlet works and the prototype tests at Silver Jack Dam outlet works.

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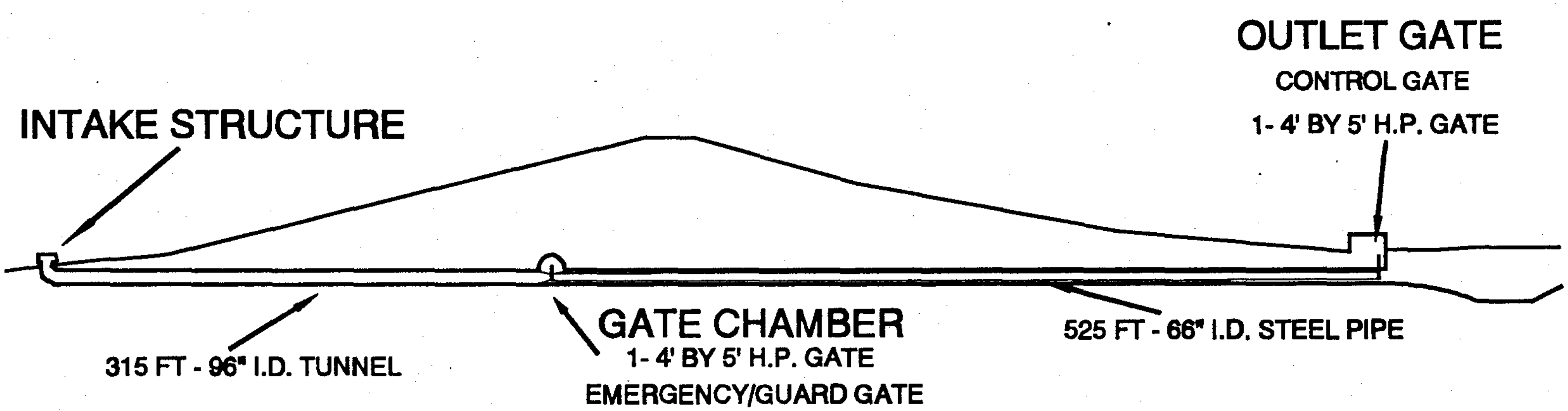


Figure 1. - Outlet works layout of Cedar Bluff Dam.

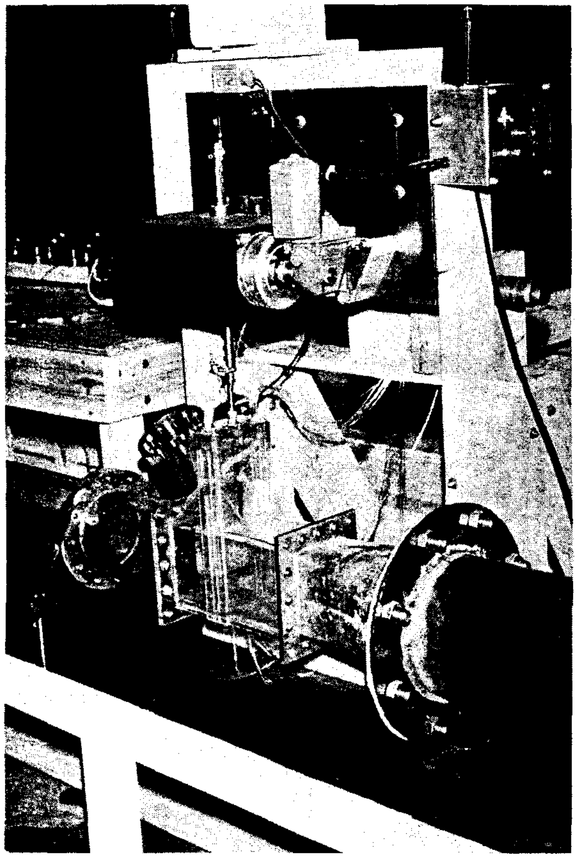


Figure 2. - Motor-operated guard gate in the 1:12 scale hydraulic model of Cedar Bluff outlet works.

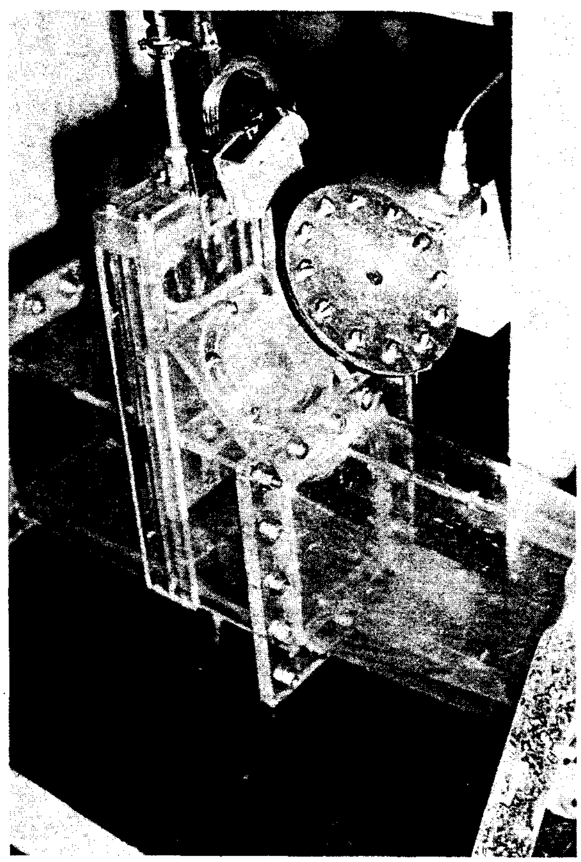


Figure 3. - Detail of model air vent configuration, showing the orifice plate.

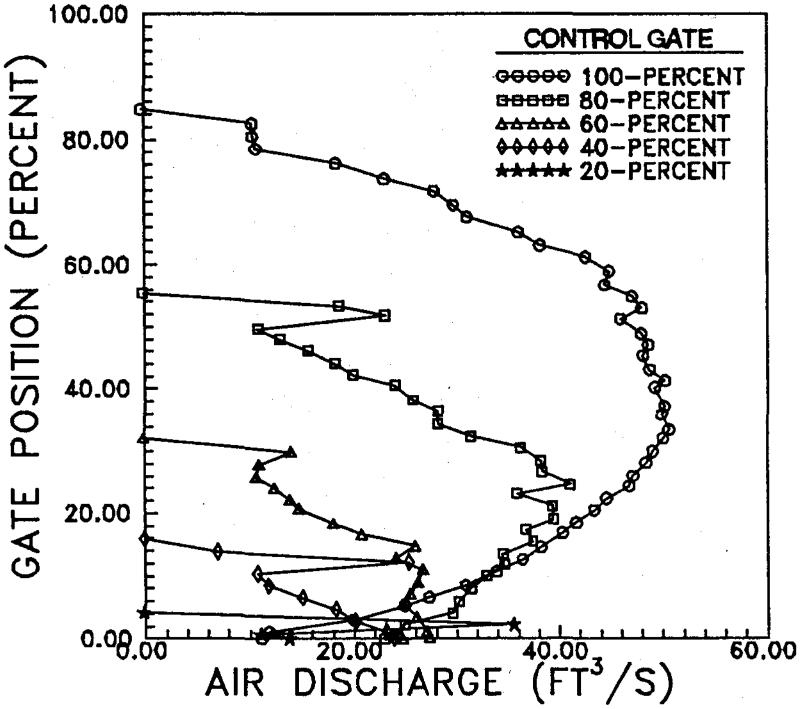


Figure 4. - Air demand for a 1-ft/min gate closure rate (Cedar Bluff model).

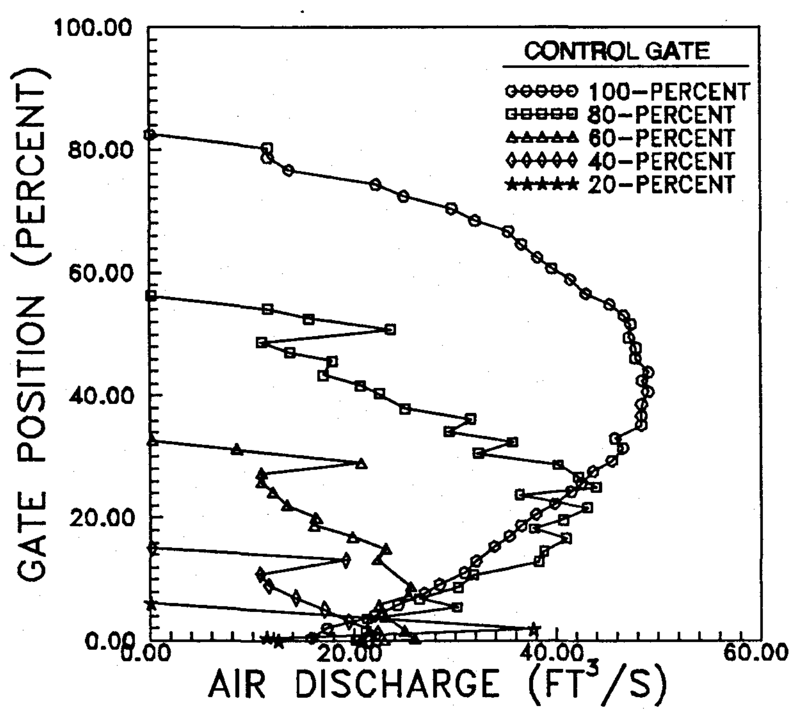


Figure 5. - Air demand curves for a 2-ft/min gate closure gate (Cedar Bluff model).

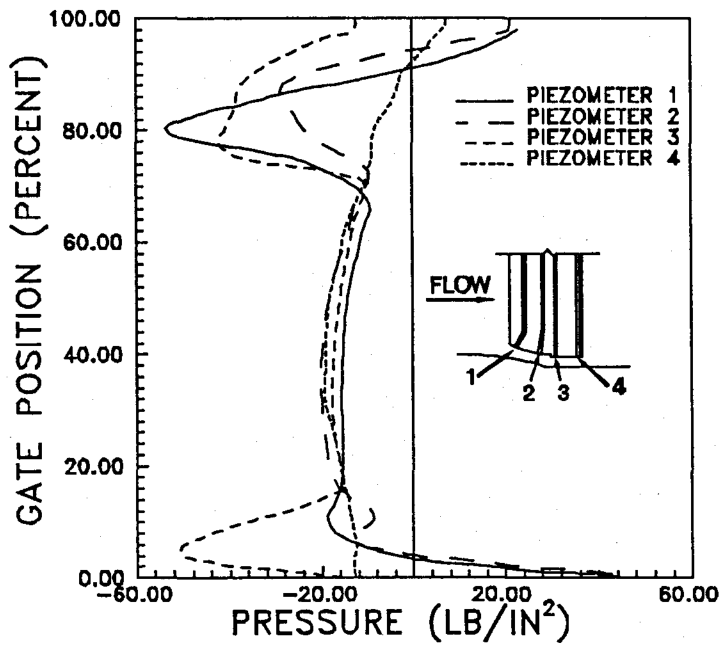


Figure 6. - Pressures on the centerline of the gate leaf bottom (Cedar Bluff).

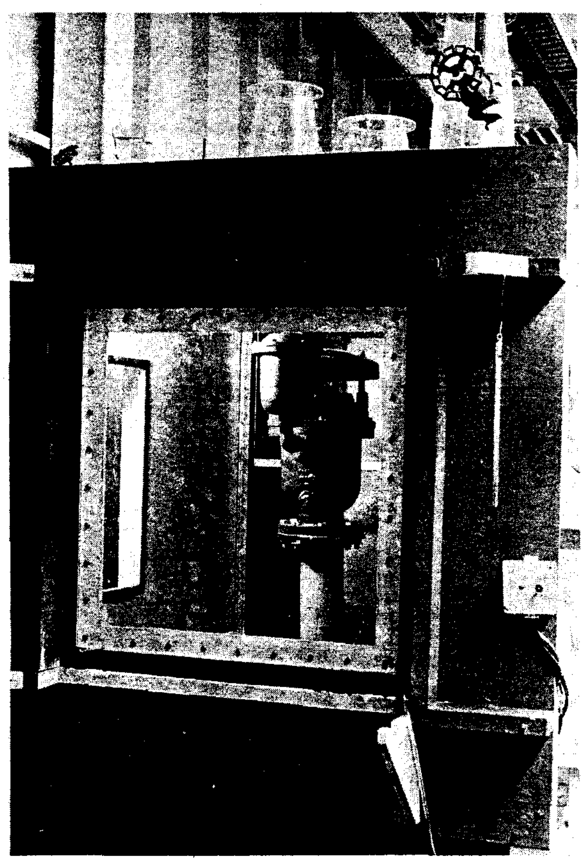


Figure 7. - 4-inch automatic air valve in the plenum.

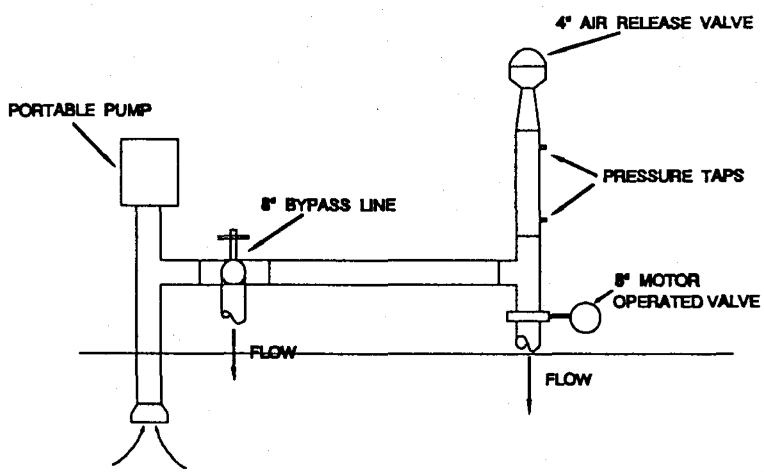


Figure 8. - Schematic of the standpipe used to cycle the valve for operational tests.

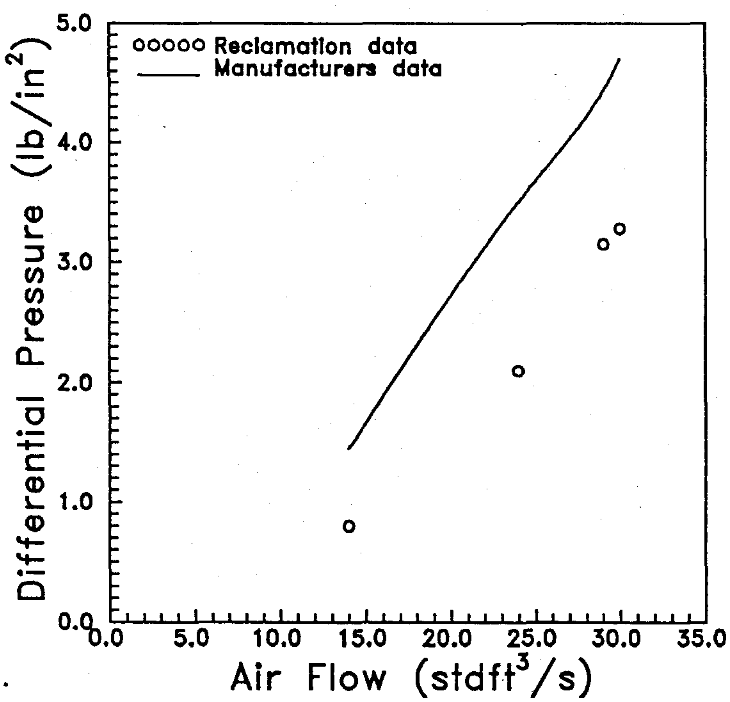


Figure 9. - Air valve characteristics, discharge versus pressure differential across the valve.

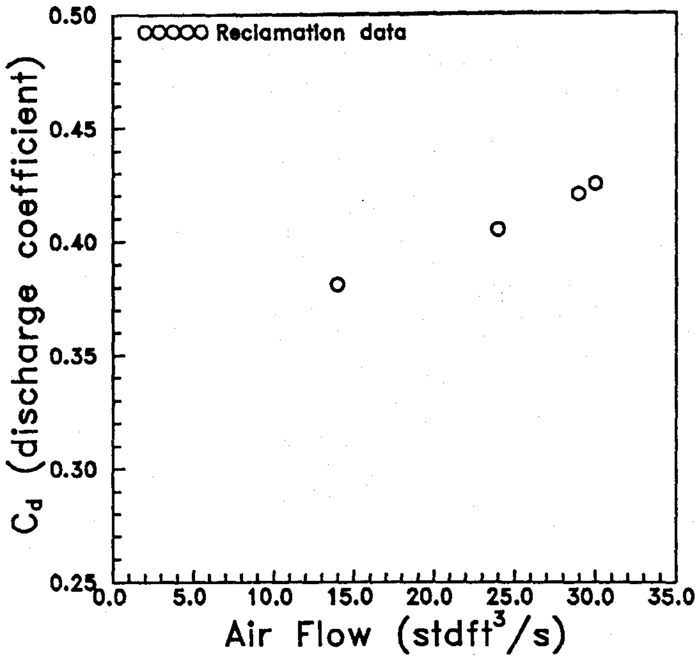


Figure 10. - Coefficient of discharge for the 4-inch air valve.

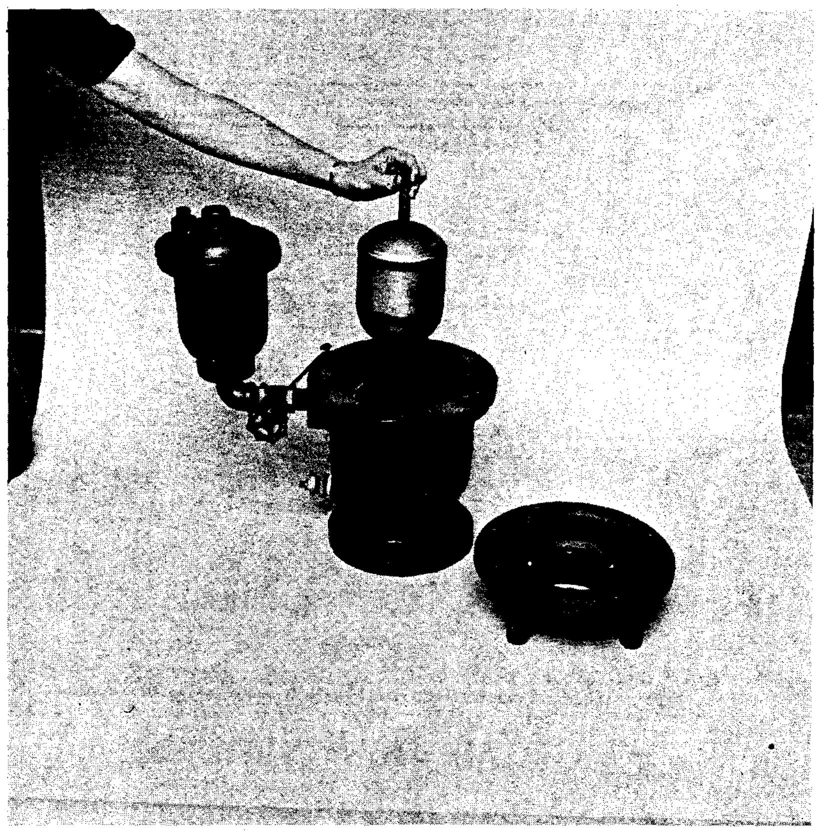


Figure 11. - Inside of the air valve after the cycling tests.

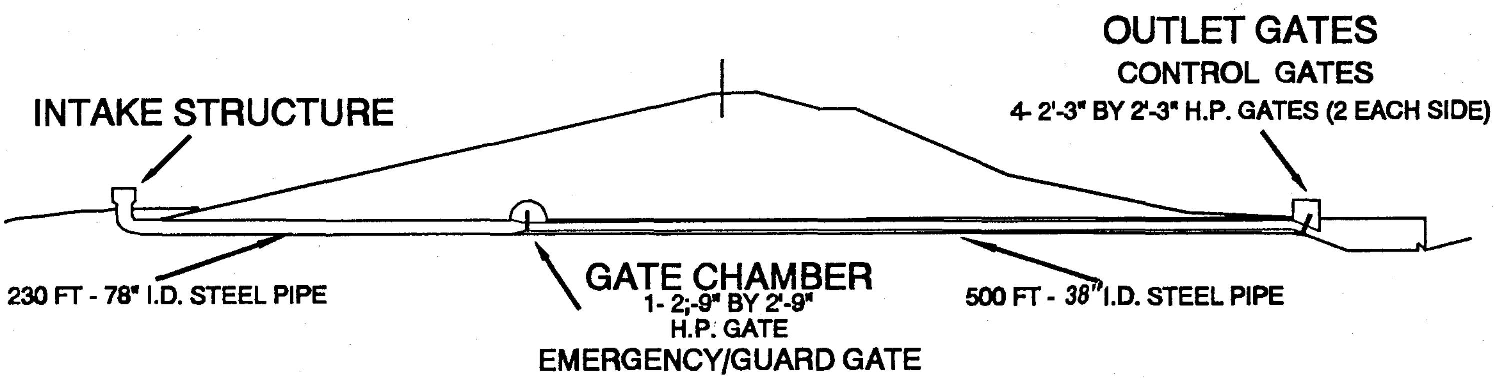


Figure 12. - Section of Silver Jack Dam outlet works structure.

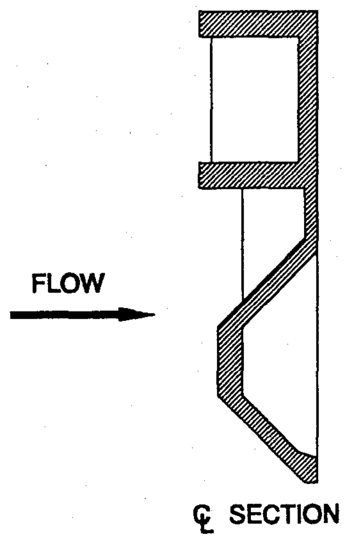


Figure 13. - Detail of the guard gate leaf (no skinplate) (Silver Jack).

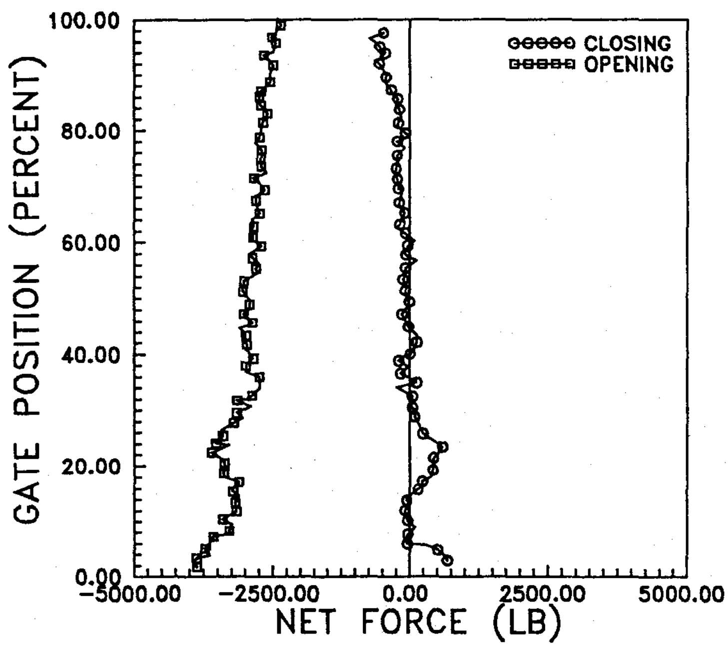


Figure 14. - Balanced head test - gate movement in both directions (Silver Jack).

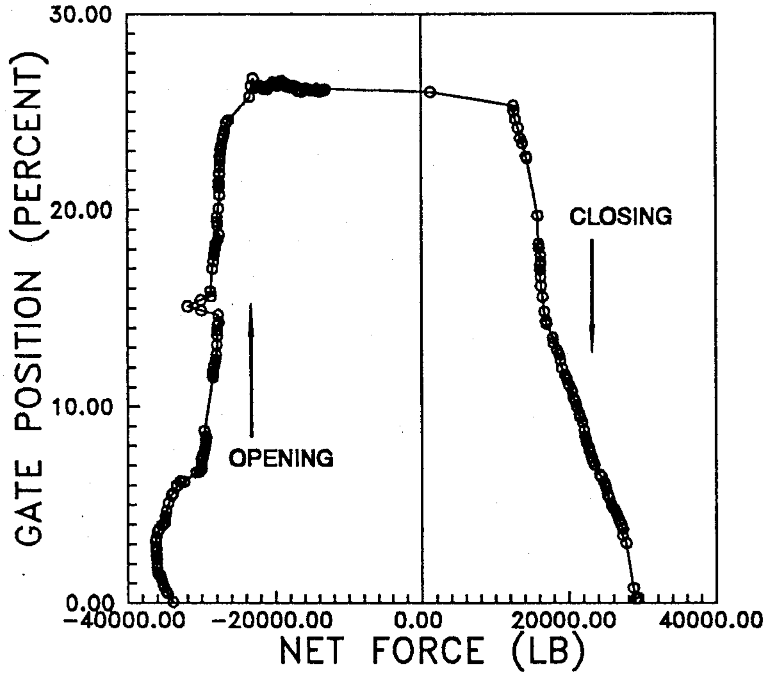


Figure 15. - Test results of the proposed standard guard gate emergency closure test (Silver Jack).

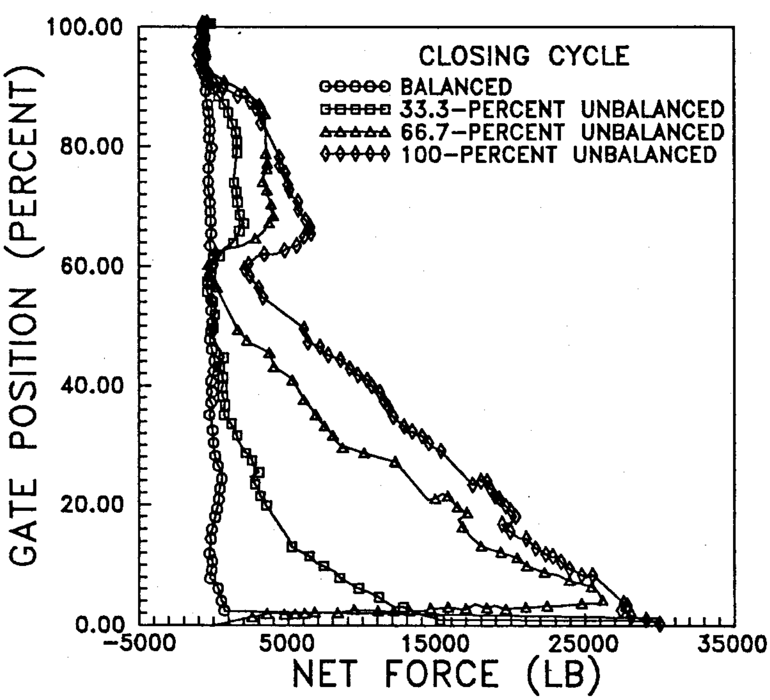


Figure 16. - Unbalanced head tests - loading on gate leaf (Silver Jack).

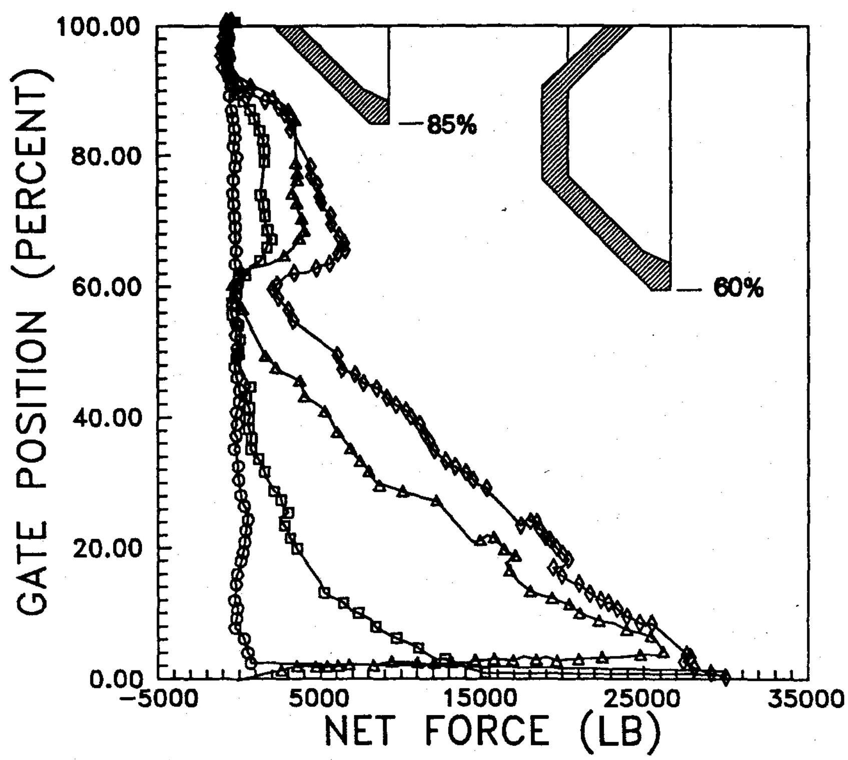
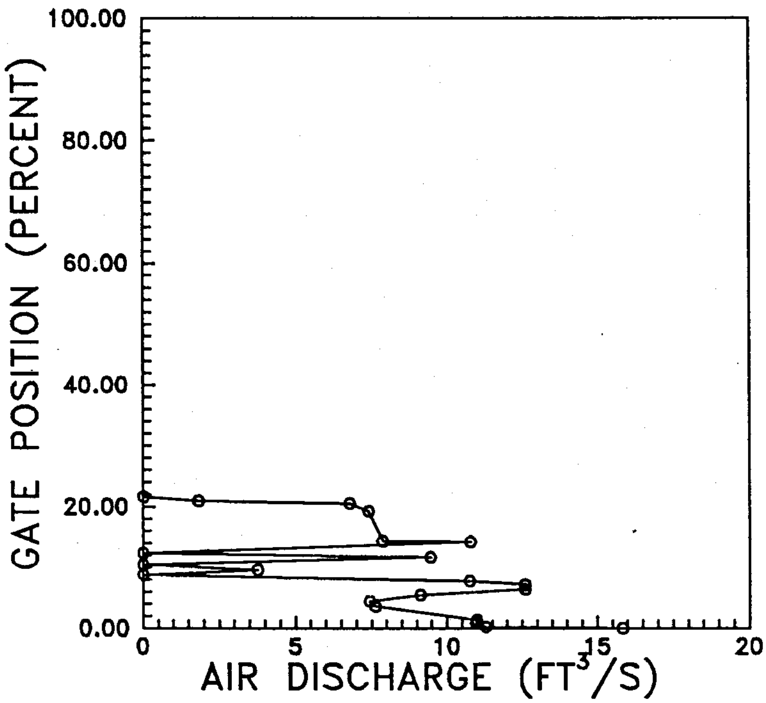
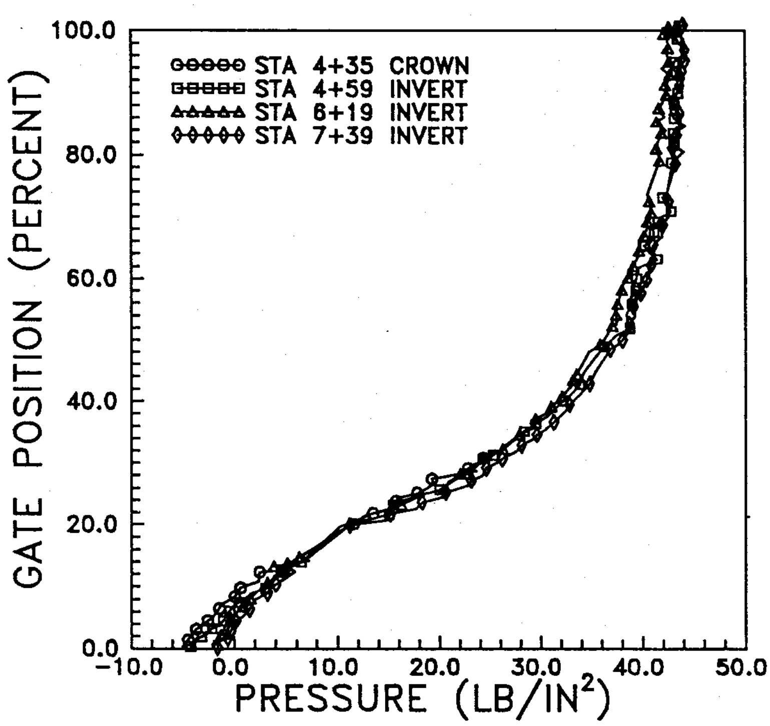


Figure 17. - Position of gate leaf relative to gate loading during an unbalanced test (Silver Jack).

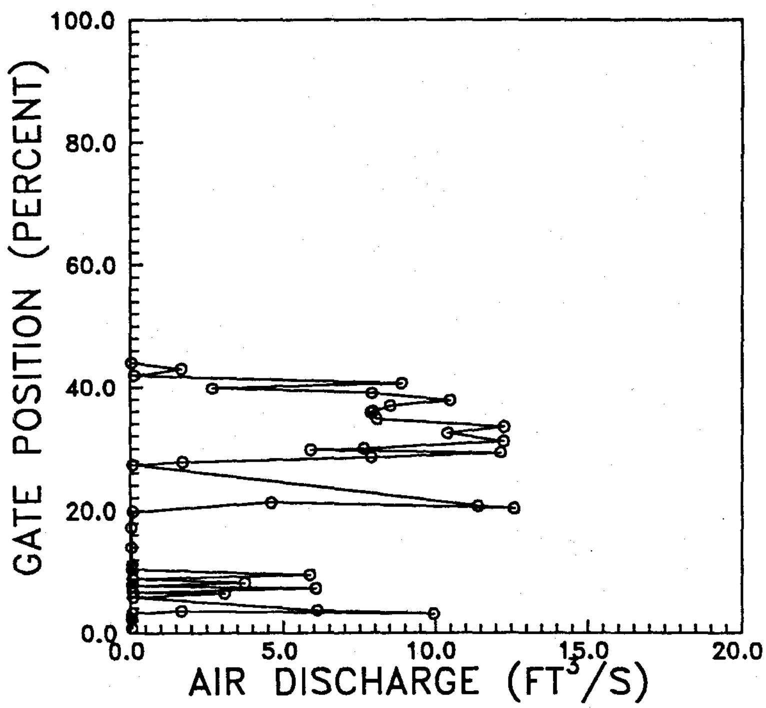


(a) Air demand.

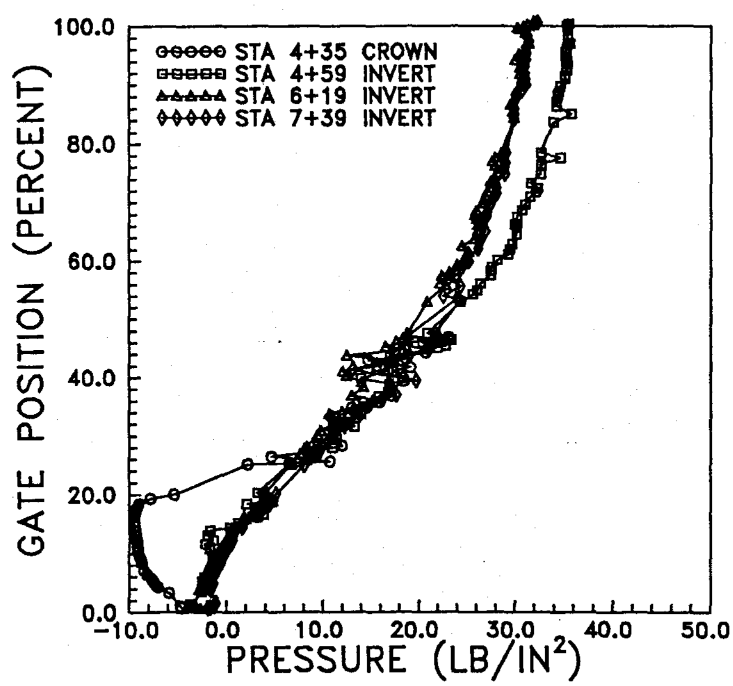


(b) Pipeline pressures.

Figure 18. - Test series 1, 25-percent control gate position (Silver Jack).

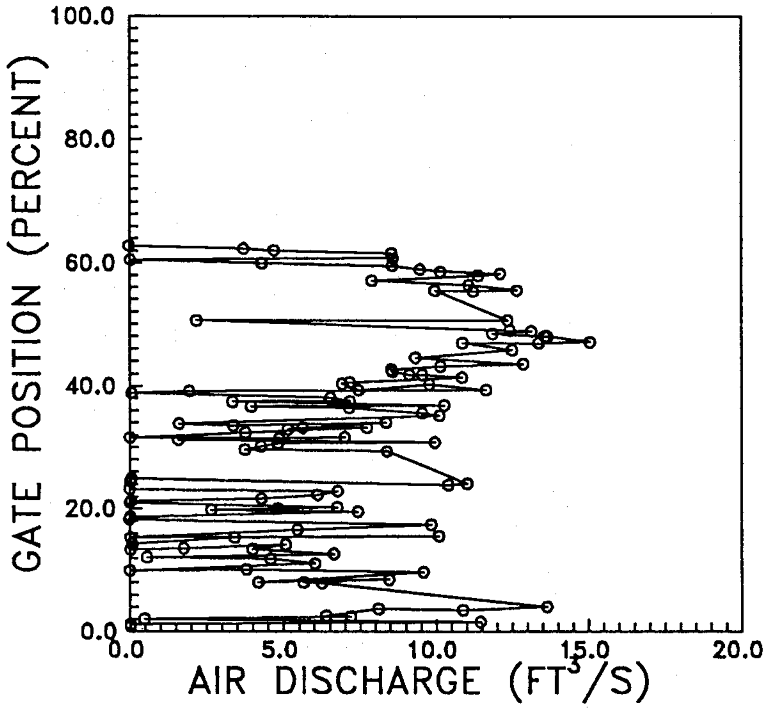


(a) Air demand.

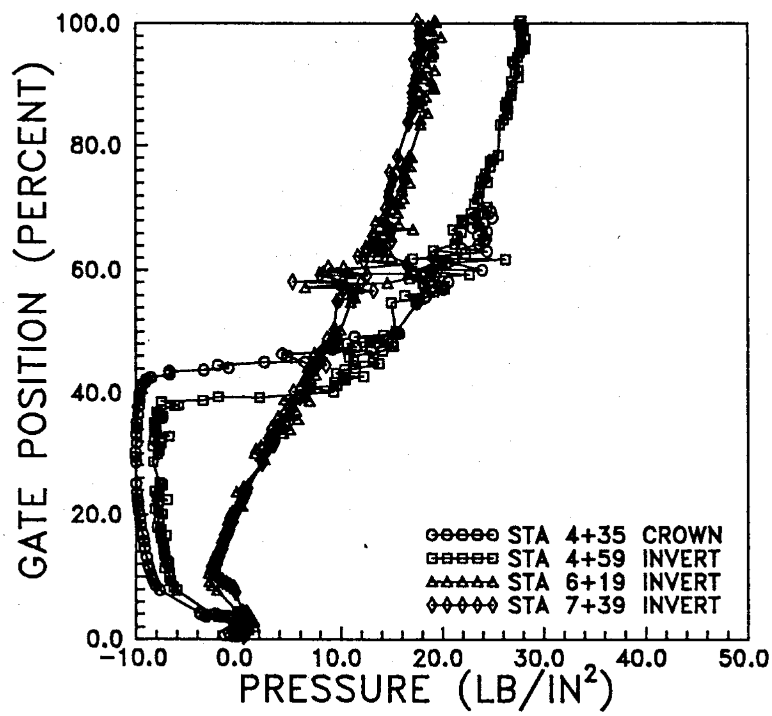


(b) Pipeline pressures.

Figure 19. - Test series 1, 50-percent control gate position (Silver Jack).

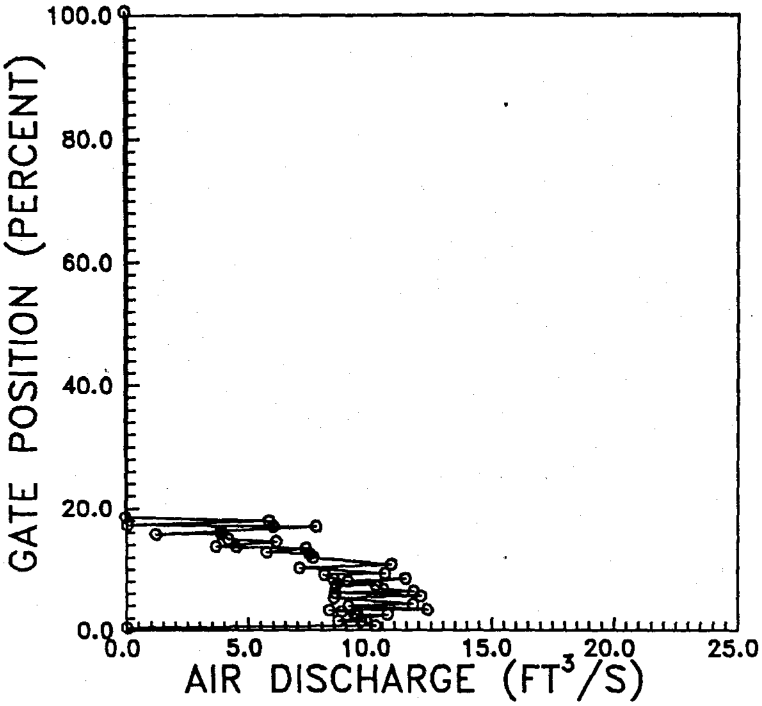


(a) Air demand.

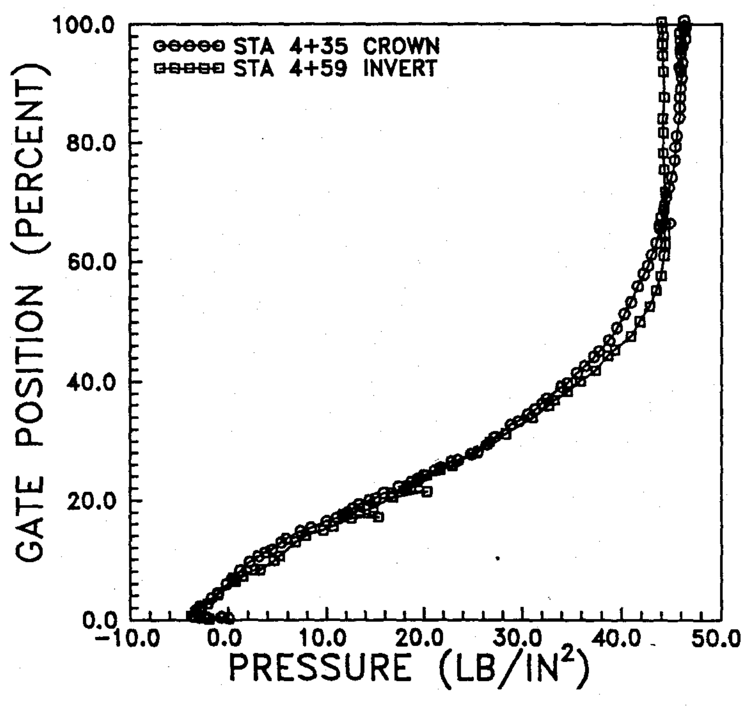


(b) Pipeline pressures.

Figure 20. - Test series 1, 75-percent control gate position (Silver Jack).

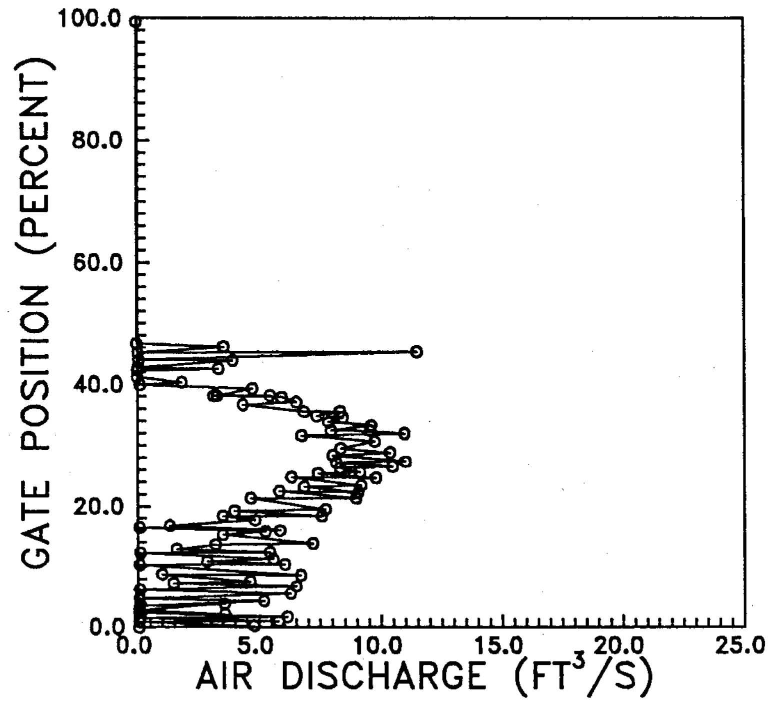


(a) Air demand.

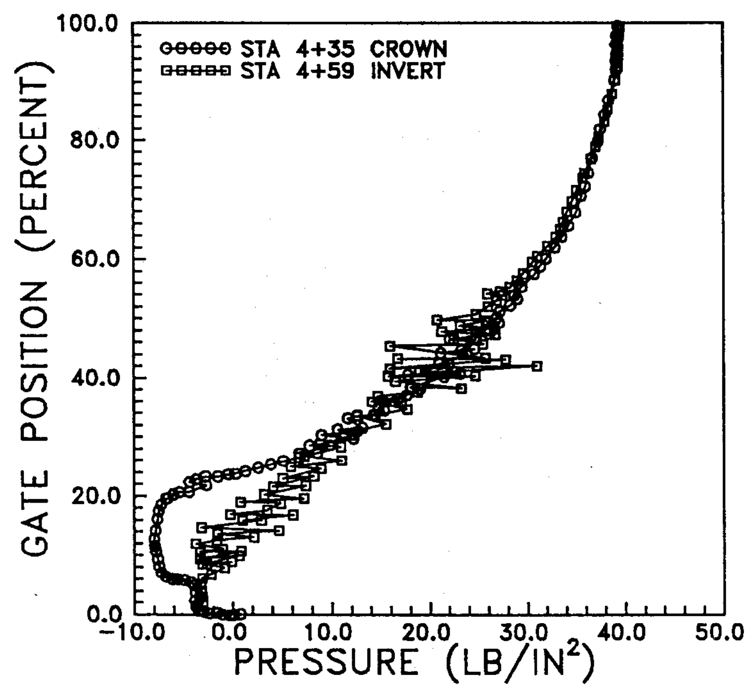


(b) Pipeline pressures.

Figure 21. - Test series 2, 25-percent control gate position (Silver Jack).

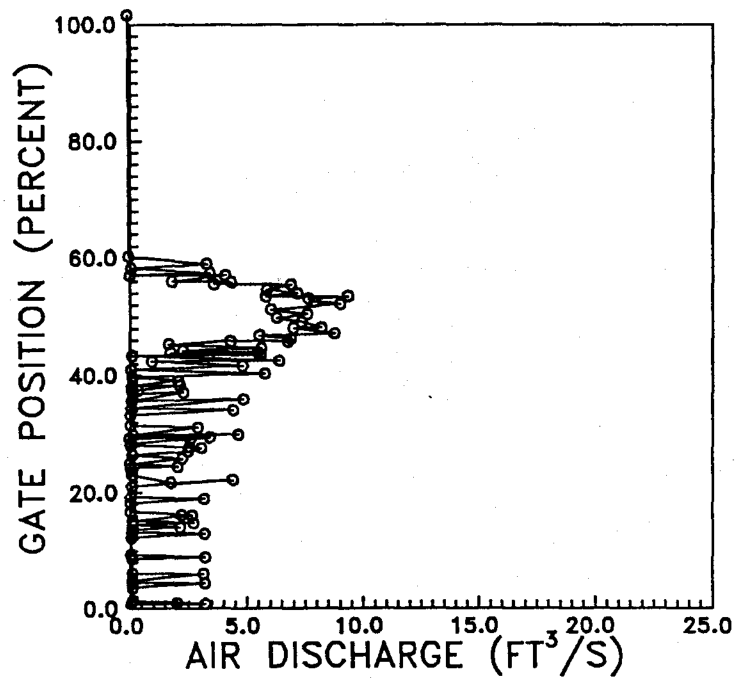


(a) Air demand.

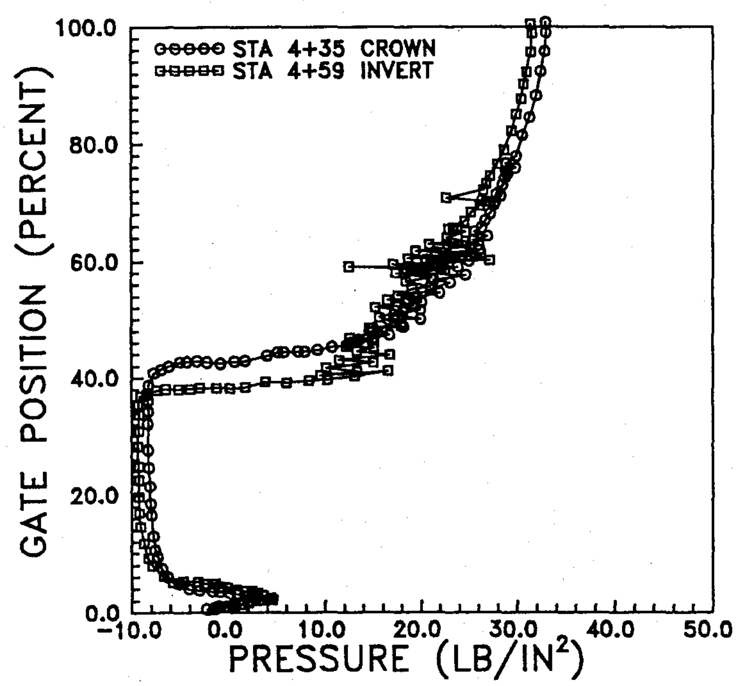


(b) Pipeline pressures.

Figure 22. - Test series 2, 50-percent control gate position (Silver Jack).

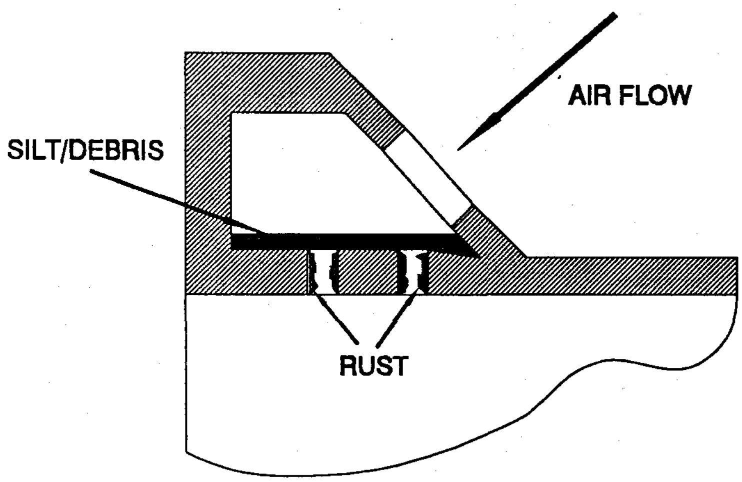


(a) Air demand.

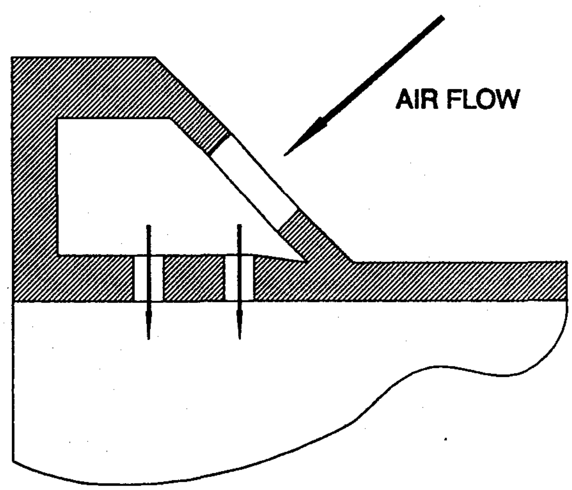


(b) Pipeline pressures.

Figure 23. - Test series 2, 75-percent control gate position (Silver Jack).

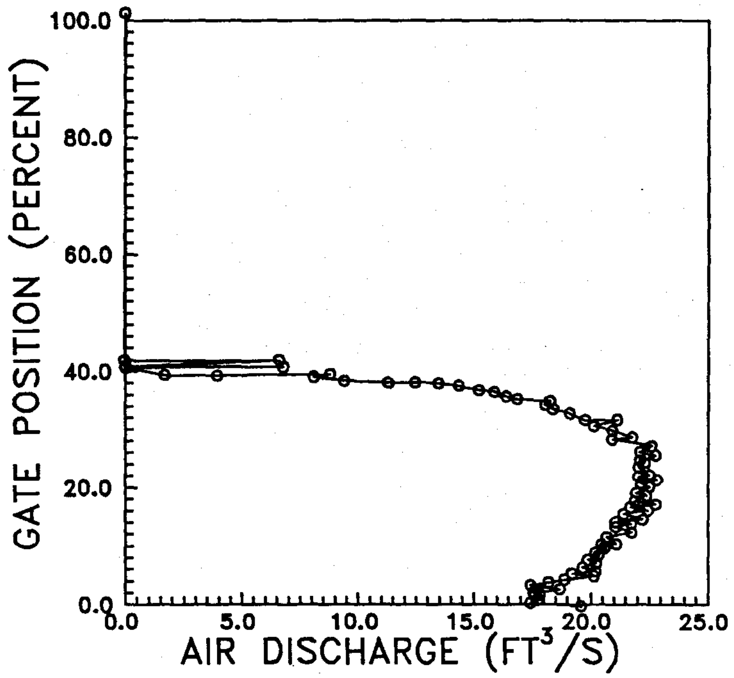


(a) Possible means of plugging vent holes.

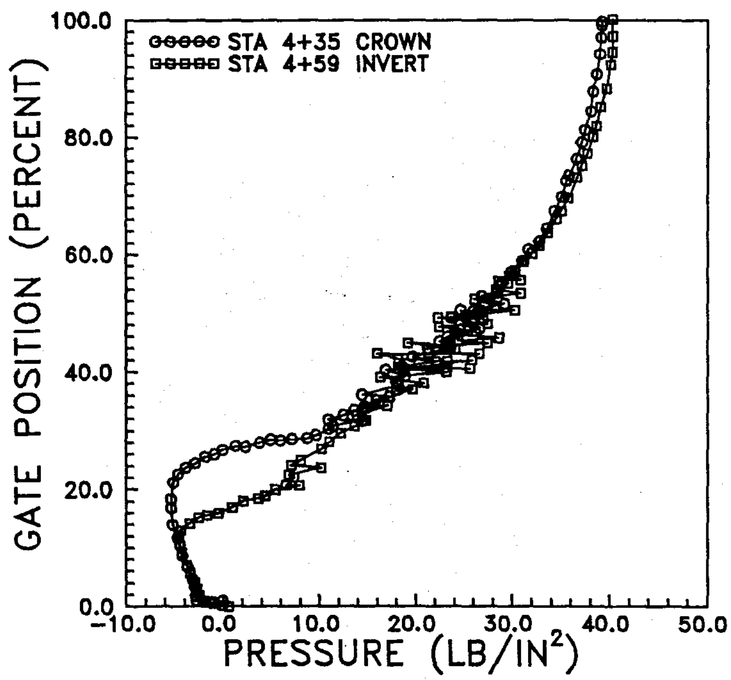


(b) Normal operation.

Figure 24. - Section through downstream gate frame in the area of the air intake (Silver Jack).

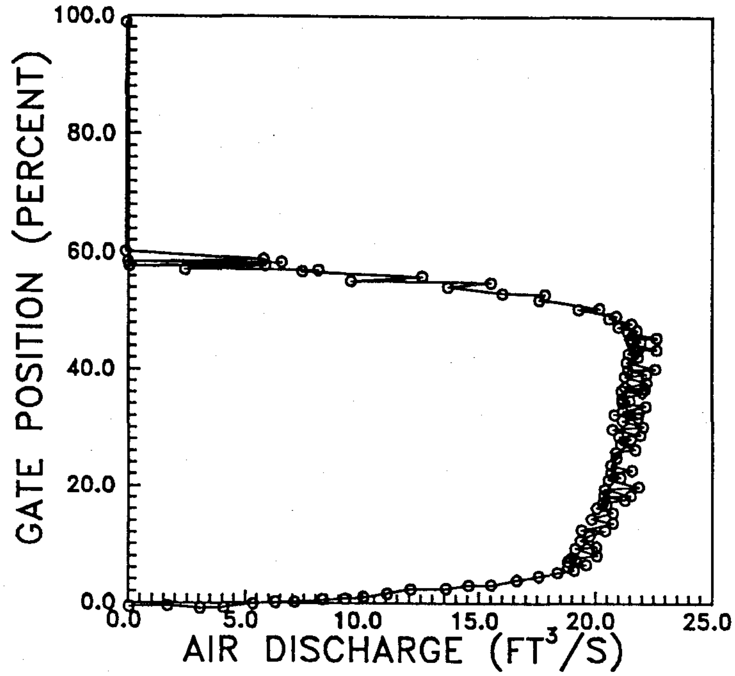


(a) Air demand.

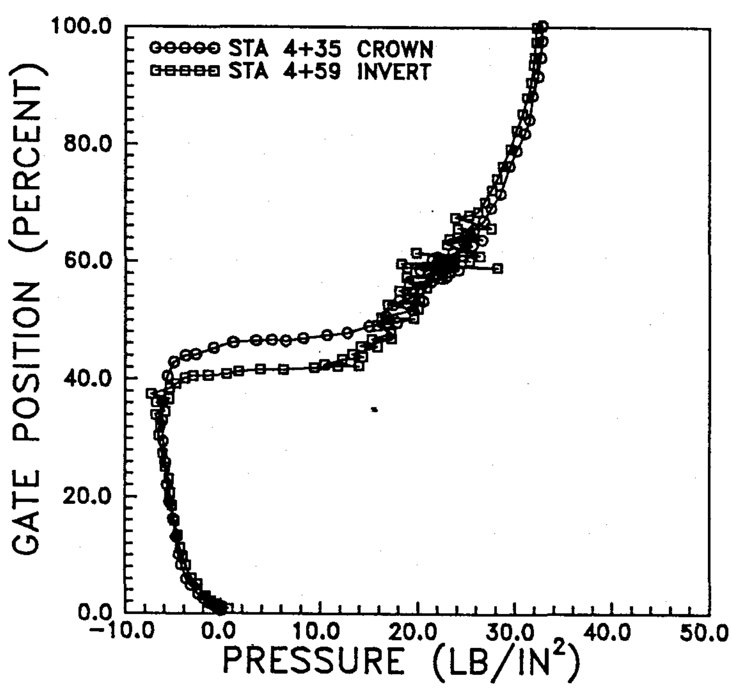


(b) Pipeline pressures.

Figure 25. - Test series 2, 50-percent control gate position, holes cleaned (Silver Jack).



(a) Air demand.



(b) Pipeline pressures.

Figure 26. - Test series 2, 75-percent control gate position, holes cleaned (Silver Jack).

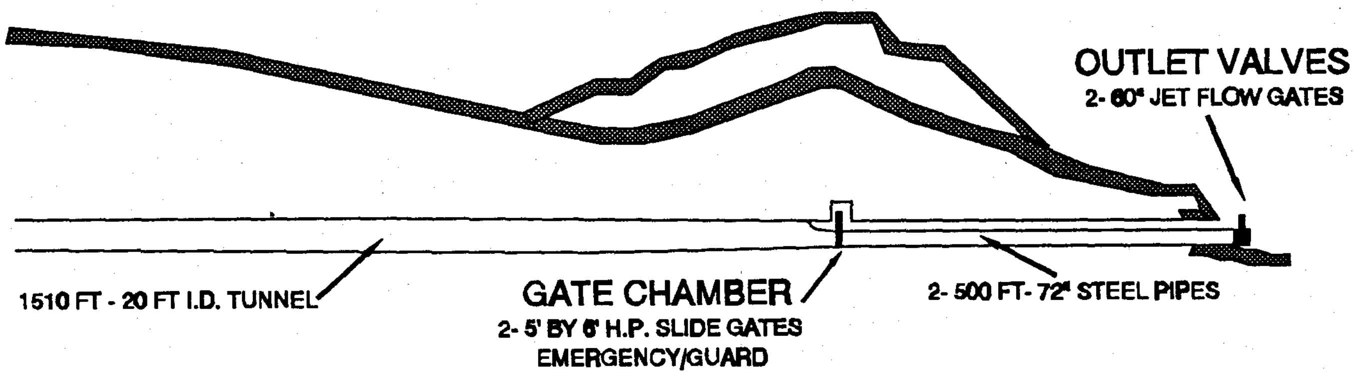


Figure 27. - Plan of Tieton Dam outlet works.

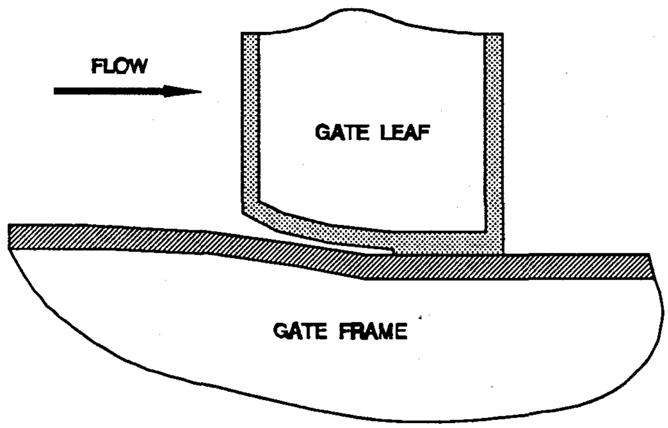


Figure 28. - Pre-1940s slide gate design, seating detail.

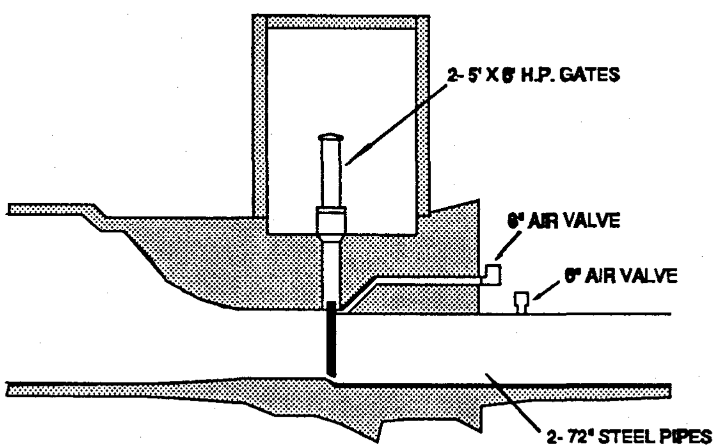


Figure 29. - Air valve protection at Tieton Dam.

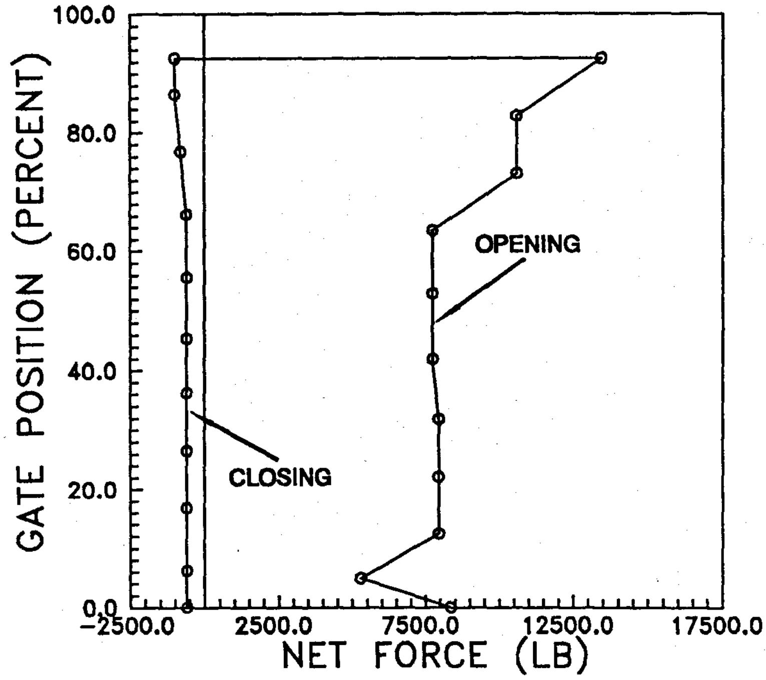


Figure 30. - Test 1, balanced head, gate chamber operation (Tieton).

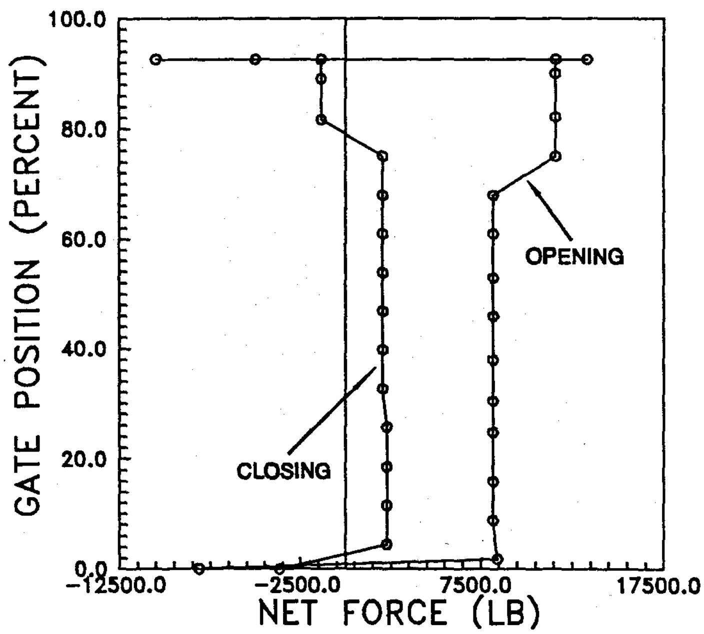


Figure 31. - Test 2, balanced head, top-of-dam operation (Tieton).

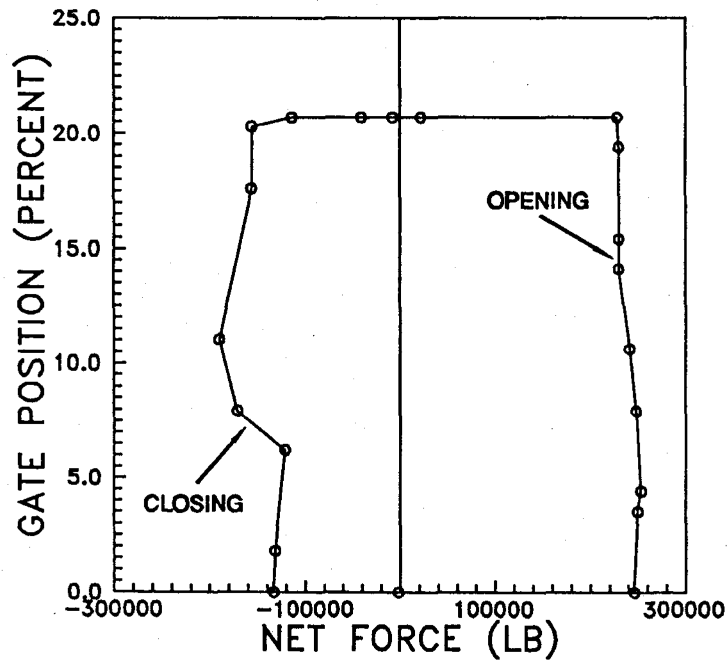


Figure 32. - Test 3, hoist loads, unbalanced test, gate chamber operation (Tieton).

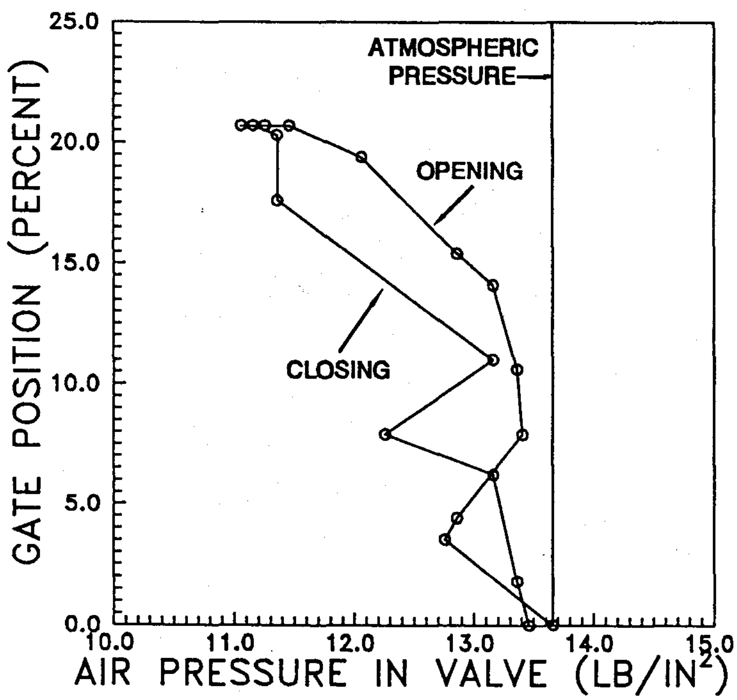


Figure 33. - Test 3, air demand, 6-inch-air vacuum-release valve (Tieton).

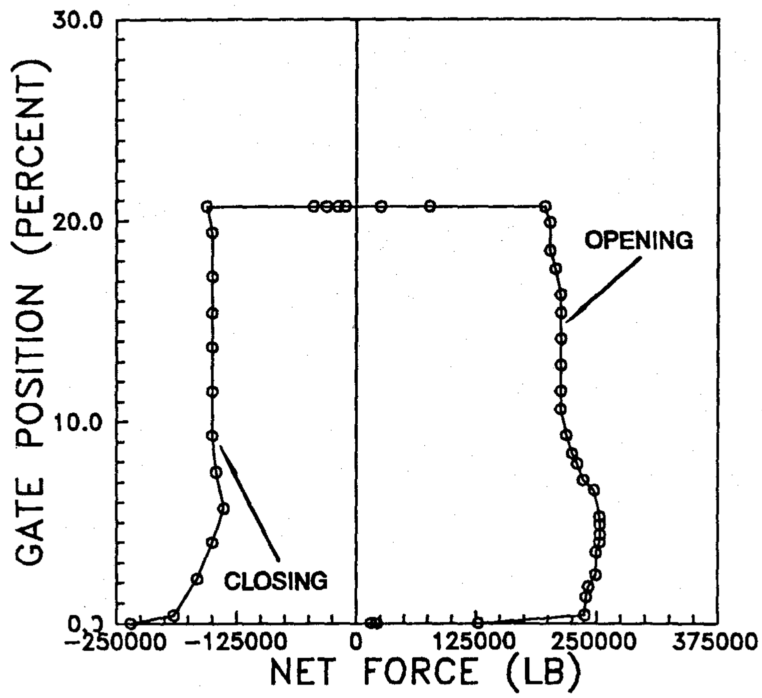


Figure 34. - Test 5, hoist loads (pressure transducer), unbalanced test, gate chamber operation (Tieton).

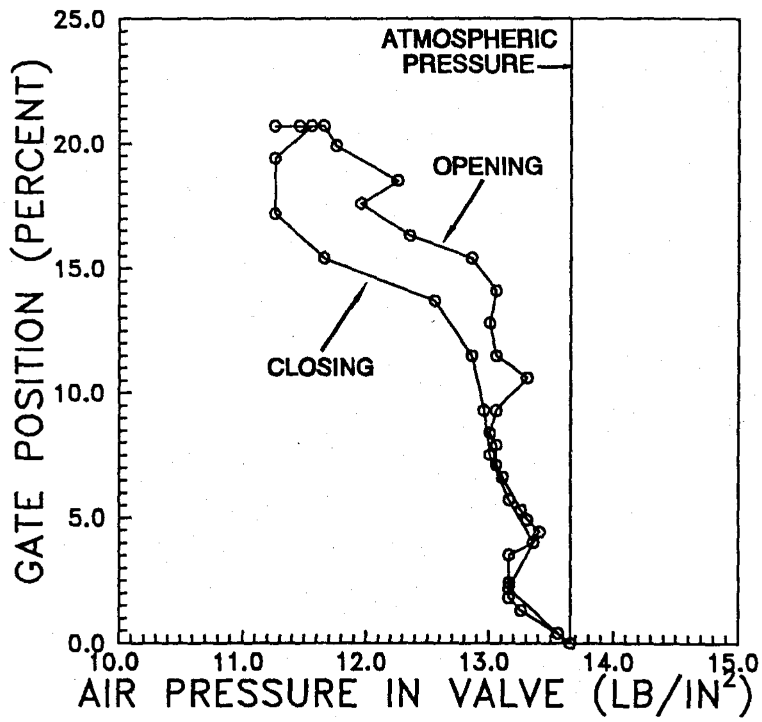


Figure 35. - Test 5, air demand, 6-inch air vacuum-release valve (Tieton).

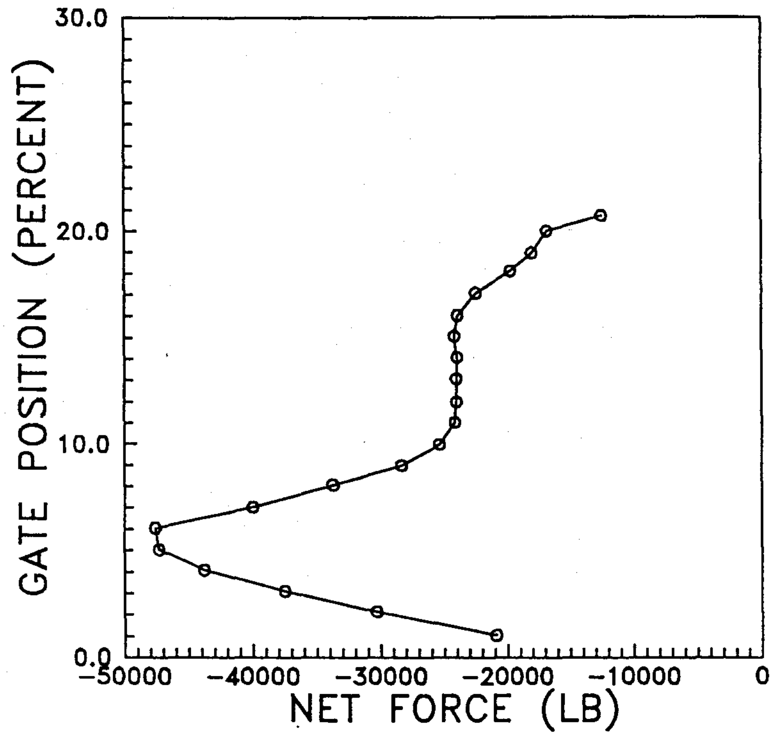


Figure 36. - Hydrodynamic forces acting on the guard gate (Tieton).

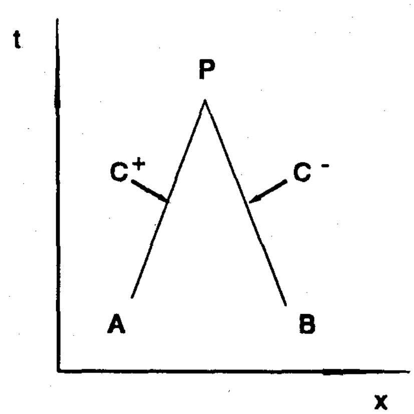


Figure 37. - Characteristic lines on the xt plane.

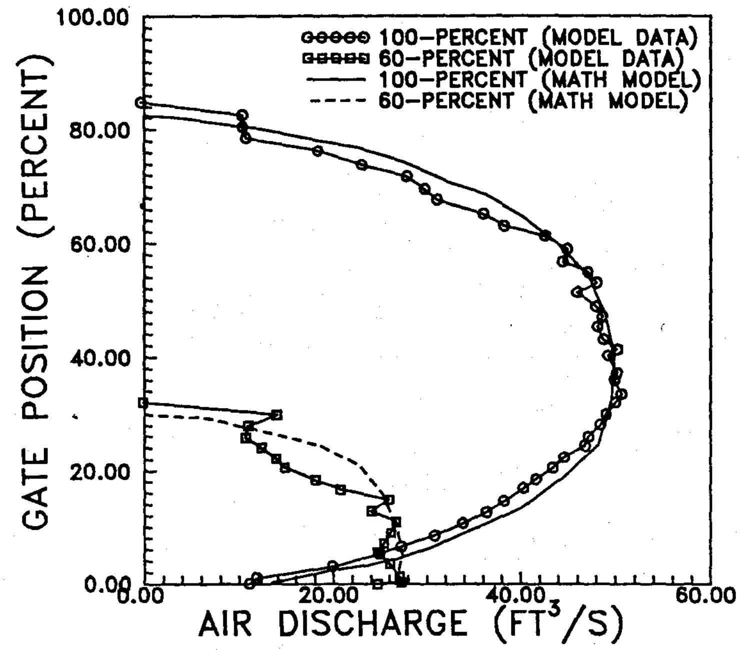


Figure 38. - Cedar Bluff Dam, physical model computer model comparison of air demand during emergency closure of the guard gate.

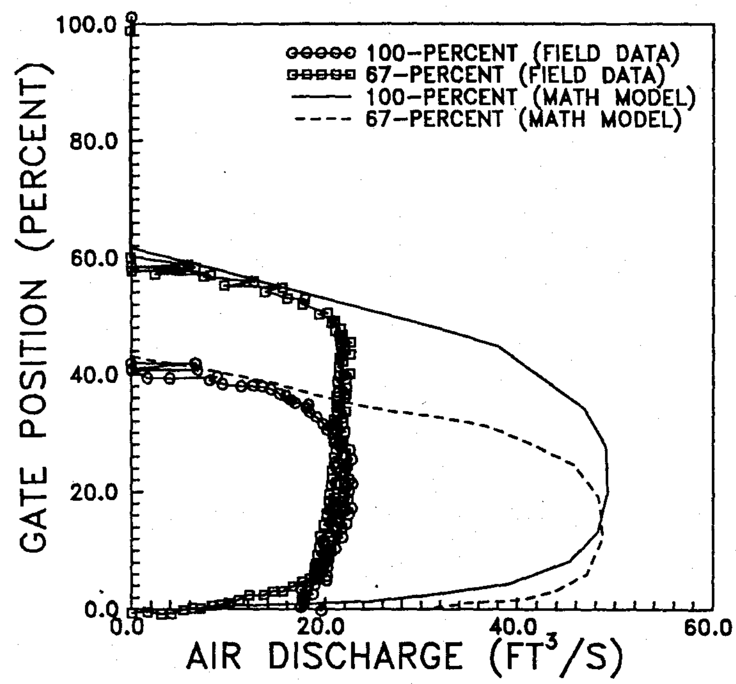


Figure 39. - Silver Jack Dam, prototype-computer model comparison of air demand during emergency closure of the guard gate.

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-7923A, PO Box 25007, Denver Federal Center, Denver CO 80225-0007.