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Hydraulic Model Study of Submerged Jet Flow Gates
For Arrowrock Dam Outlet Works Modification

Brent Mefford, P.E.

U.S. Bureau of Reclamation

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by

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Introduction

Arrowrock Dam is part of the Boise Project in the Pacific Northwest Region. The dam is located on the Boise River near the city of Boise, Idaho. Built in 1915, the dam is a concrete thick-arch structure 315 feet high, figure 1. Outlet works structures were placed at three elevations. The low level outlets are at elevation 2966.8 feet. Five high pressure 5-foot by 5-foot sluice gates are used to control flow through the lower outlets. There are 10 midlevel outlets at elevation 3018 feet. Seven are 52-inch-diameter conduits. The remaining three are 72-inch conduits which were originally planned for use as power conduits. The upper level has ten 52-inch conduits. Flow through the middle and upper level outlets is controlled by 58-inch Ensign balanced valves mounted on the upstream face of the dam.

Lucky Peak Dam, built by the Corps of Engineers, is located immediately downstream of Arrowrock. Lucky Peak Reservoir has a normal water surface elevation of 3035 feet and a maximum of 3060 feet. Both the lower and midlevel outlets at Arrowrock Dam are frequently submerged by Lucky Peak Reservoir.

Background

During the time period from 1916 to 1921, the middle and upper level outlets at Arrowrock were used for flood control releases for extended periods. [1] An annual inspection in 1921 found considerable cavitation damage in the Ensign valves and downstream concrete conduits. Patching of the damage was required in both the middle and upper level outlets. In 1949 the Bureau's hydraulic laboratory conducted a study of cavitation problems occurring in the valves and downstream conduits. [2] A hydraulic model of one outlet was built and tested to determine the feasibility of making minor alterations to the Ensign valve seat rings to reduce the cavitation potential. The study concluded that under maximum heads only major modifications to the valve, or applying back pressure to the valves by placing a restriction in the downstream conduit could prevent severe cavitation. The study recommended placing wedge shaped restrictions on the downstream end of the midlevel conduits. The restrictions would reduce both the cavitation potential and discharge capacity. As a result of the study, wedge shaped restrictions were installed on the conduit crown at the exit of each 52-inch midlevel outlet.

In December 1985 the Hydraulics Branch was requested to model the installation of jet flow gates on the midlevel outlets. During the study two different outlet works design schemes were tested.

The initial design called for the removal of the midlevel Ensign balanced valves on the seven 52-inch conduits, installing steel liners, and mounting 48-inch jet flow gates on the downstream dam face. Project construction cost estimates developed from the feasibility study exceeded available funding. Subsequently a second lower cost outlet works design was proposed by the Region based on a value engineering study of the project.

The second design called for rehabilitating only the three midlevel 72-inch-diameter power conduits. The rehabilitation design was similar to the first design, except the size of the outlets increased. Sixty-eight-inch-diameter jet flow gates were proposed for the larger conduits.

History of Submerged Jet Flow Gates

Laboratory studies of submerged jet flow gates have been conducted for outlet works at Crystal and Teton Dams. [3,4] These studies resulted in a jet flow gate design which included a narrow gate slot and a 3-diameter expansion in the downstream gate body. The expansion prevented the cavitating jet exiting the valve from impinging on the gate body. Even with the expanded body style, laboratory testing indicated cavitation pitting would occur on the gate leaf guides. The guides were mounted 1.25 diameters apart. At partial openings, vortices trailing from the intersection between the gate leaf and the orifice caused the cavitation pitting. To prevent damage the guide spacing in the Crystal Dam style gate was widened to 1.53 diameters. Model tests of the wider gate leaf design were not conducted.

Two 48-inch submerged jet flow gates were installed at Crystal Dam in 1976. The gates have operated without damage. Reports of high levels of acoustic noise and vibration in the powerplant and dam during operation were investigated by Maytum and Isbester. [5] A combination of cavitation and turbulent flow downstream of the submerged gates created a noticeable increase in the noise and vibration levels. Vibration levels measured on the structure were determined to not be structurally damaging.

Part I - Model Study of the 52-inch Outlets

Model studies were conducted to determine if the jet flow gates would operate satisfactorily for both free and submerged conditions. Tests were conducted to investigate cavitation in the shear layer around the jet under submerged conditions and to observe operation of the gates at partial submergence. A 1/15 Froude scale sectional model of the downstream face of Arrowrock Dam was placed in the LAPC (low ambient pressure chamber), figure 2. Three 48-inch-diameter Crystal Dam style jet flow gates were constructed out of Plexiglas for use in the model, figure 3. The gates were mounted on 10.5-foot centers (prototype). By conducting the tests in the LAPC both Froude number and cavitation number scaling could be applied between model and prototype. Atmospheric pressure within the chamber was scaled at 1/13. A different model scale ratio was used to scale atmospheric pressure because the absolute vapor pressure of water cannot be scaled.

Test results. - Flow conditions were observed for two patterns of gate operation, tailwater elevations from 3018 to 3060 feet and gate openings from 10 to 100 percent. The two patterns of gate operation used in the model were: (1) three gates operating at equal openings, and (2) two outside gates operating equal with the center gate closed.

No detrimental flow conditions were observed as a function of the gate operation pattern or partial submergence. Air entraining vortices were present in the model along the downstream face of the dam for tailwater elevations between 3020 and 3060 feet. Although vorticity patterns in the sectional model are not representative of the prototype, air entraining vortices will occur in the prototype for a range of tailwater elevations above 3020 feet. Air entraining vortices do not affect the gate operation, although they are generally an undesirable flow condition. Under submerged conditions cavitation occurring in the shear layer of the jet exiting the gate appeared stable and free of all boundaries. The cavitation at partial gate openings started at the intersection of the gate leaf and orifice, similar to the findings of Isbester.[4]

During the study the incipient cavitation index, σ, and the coefficient of discharge for the submerged gate were also determined. Data for each as a function of gate opening are given in the appendix.

Part II - Model Study of the 72-inch Outlets

As an alternative to modifying all seven 52-inch midlevel outlets the second design only involved the three 72-inch power outlets. The 72-inch conduits exit the dam near the left abutment at elevation 3018. At the intersection with the downstream face of the dam the 72-inch conduits lie on 14.5-foot centers. The design proposal required the installation of 68-inch-diameter jet flow gates on each of the conduits. The 14.5-ft (2.55 gate diameters) span between the conduit centerlines is less than the 3-diameter minimum spacing required for the Crystal style jet flow gate.

Isbester [4] investigated the jet flow gates using 2- and 3-diameter downstream expansions. Cavitation in the 2-diameter expansion impinged on the boundary during operation at partial gate openings. Increasing the expansion to 3 diameters was found to prevent cavitation from reaching the boundary. To determine if a gate expansion of less than 3 diameters could be used for the Arrowrock power conduits, model tests were conducted of gate expansions between 2.25 and 2.75 diameters.

Tests were again conducted in the LAPC. Only the center outlet in the model was used for the tests. Downstream gate body expansions of 2.25, 2.50, and 2.75 diameters were tested. Each expansion was tested in lengths of 2.0, 1.5, and 1.0 gate diameters. A piezometer tap was placed on the invert of each expansion 10.5 inches (prototype) upstream from the end. The piezometer tap was used to determine when the jet exiting the gate was impinging on the invert of the gate expansion. Jet impingement results in a component of the velocity adding to the hydrostatic pressure. A ratio greater than 1 between the measured pressure and the hydrostatic pressure reflected the presence of the jet on the boundary. Tests on each gate geometry were conducted for the same flows and ambient pressure conditions.

Test results. - The jet impinged on the boundary at small gate openings for all three lengths of the 2.25-diameter expansions tested, figure 4. The cavitating jet also fluctuated in the vertical indicating a surging in the flow about the jet. Flow conditions using the 2.5-diameter expansion were improved. Some jet impingement at small gate openings was apparent for the 1.5- to 2.0-diameter expansion lengths, figure 5. The jet cleared the 2.50- by 1.0-diameter expansion at all gate openings. Visually the jet appeared steady with cavitation occurring away from the gate boundary. Jet impingement on the 2.75-diameter expansion only occurred at 10 percent gate opening for the 1.5 and 2.0 expansion lengths, figure 6. The 1.0-diameter-long expansion was clear of the jet at all gate openings.

Conclusions

The Crystal style jet flow gate can be operated from free to fully submerged discharge without cavitation damage. By limiting the length of the downstream gate body expansion to 1 diameter, the size of the expansion can be reduced from 3 diameters to 2.5 diameters. During submerged operation acoustic noise and vibration levels in the structure will increase due to cavitation and flow turbulence downstream of the gates.

Acknowledgments

Rotation engineers Brian Becker, Joe Martino, Jonathan Meers, and Rod Johanson were each instrumental in designing the models and acquiring data during the studies.

References

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2. Colgate, D., "Hydraulic Model Studies of the Ensign Balanced Valves--Arrowrock Dam," HYD-258, April 1949.

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4. Isbester, T. J., "Hydraulic Model Studies of the Teton Canal Outlet Works Energy Dissipator," REC-ERC-74-16, October 1974.

5. Maytum, C. D., and Isbester, T. J., "Noise and Vibration Tests at Crystal Dam and Powerplant, Montrose Construction Office and Crystal Dam and Powerplant," Travel Report TR-78-37, December 1978.

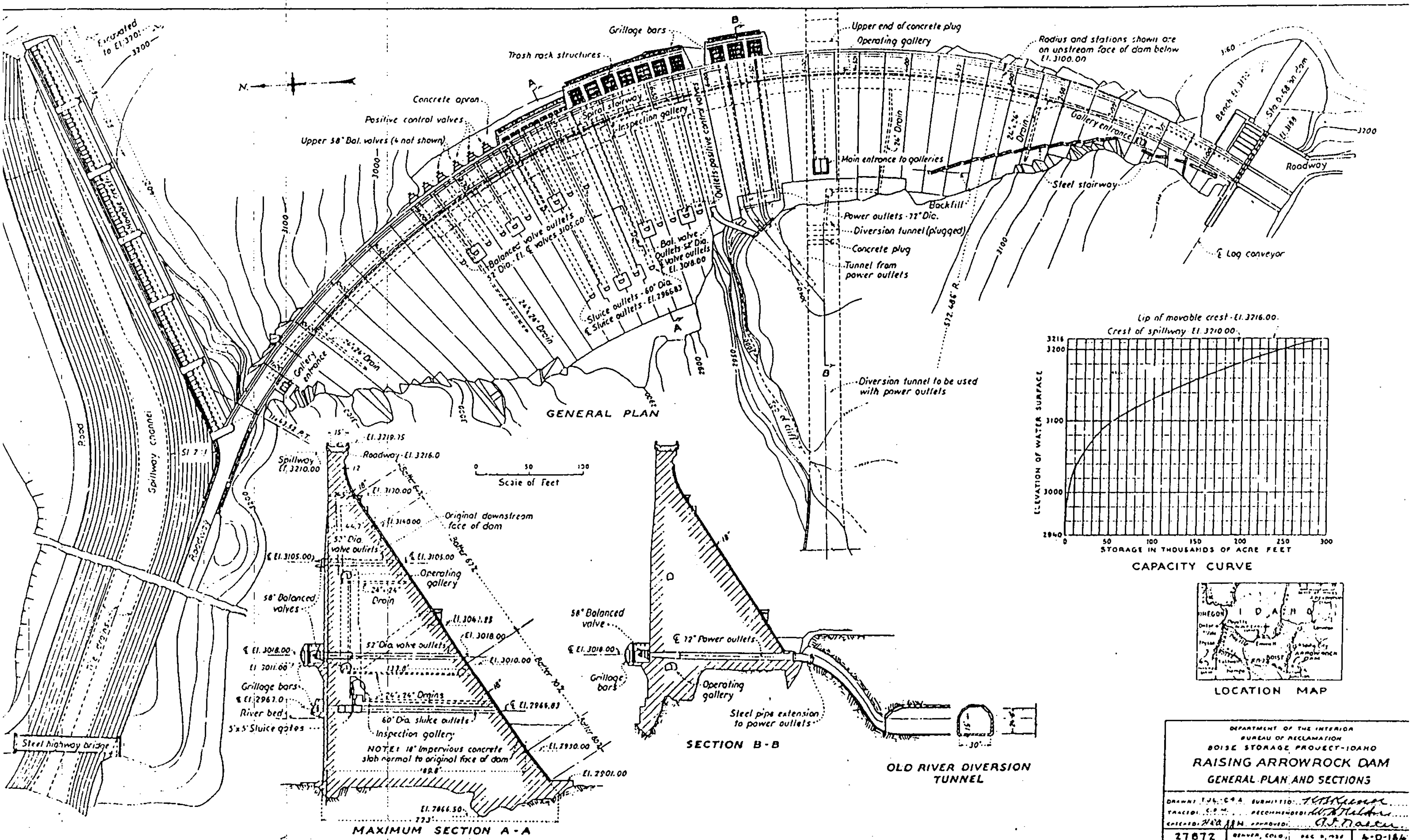
GENERAL PLAN
MAXIMUM SECTION A-A
SECTION B-B
OLD RIVER DIVERSION TUNNEL
CAPACITY CURVE
LOCATION MAP
Scale of Feet
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOISE STORAGE PROJECT-IDAHO
RAISING ARROWROCK DAM
GENERAL PLAN AND SECTIONS
27872
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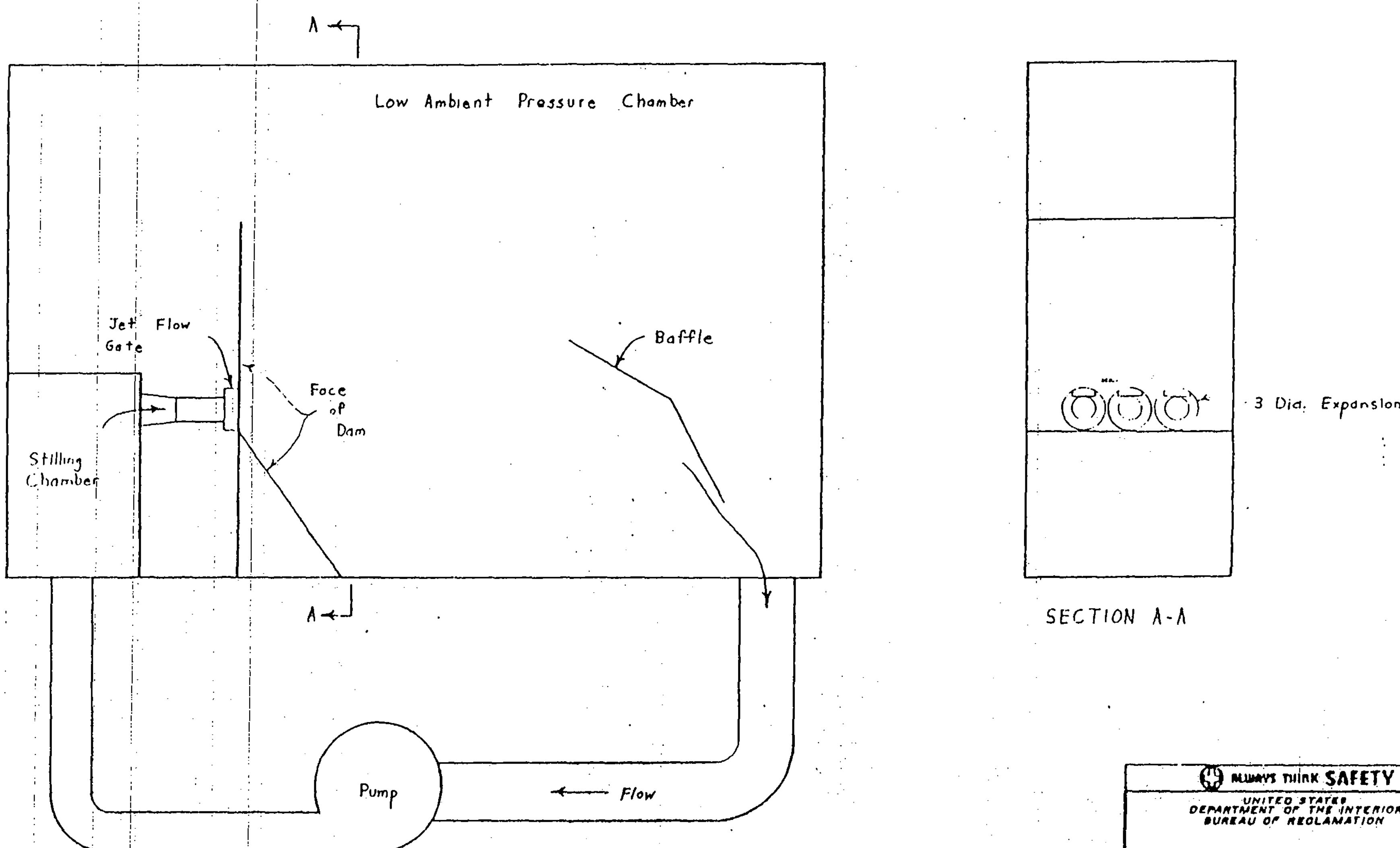
Figure 1



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UNITED STATES
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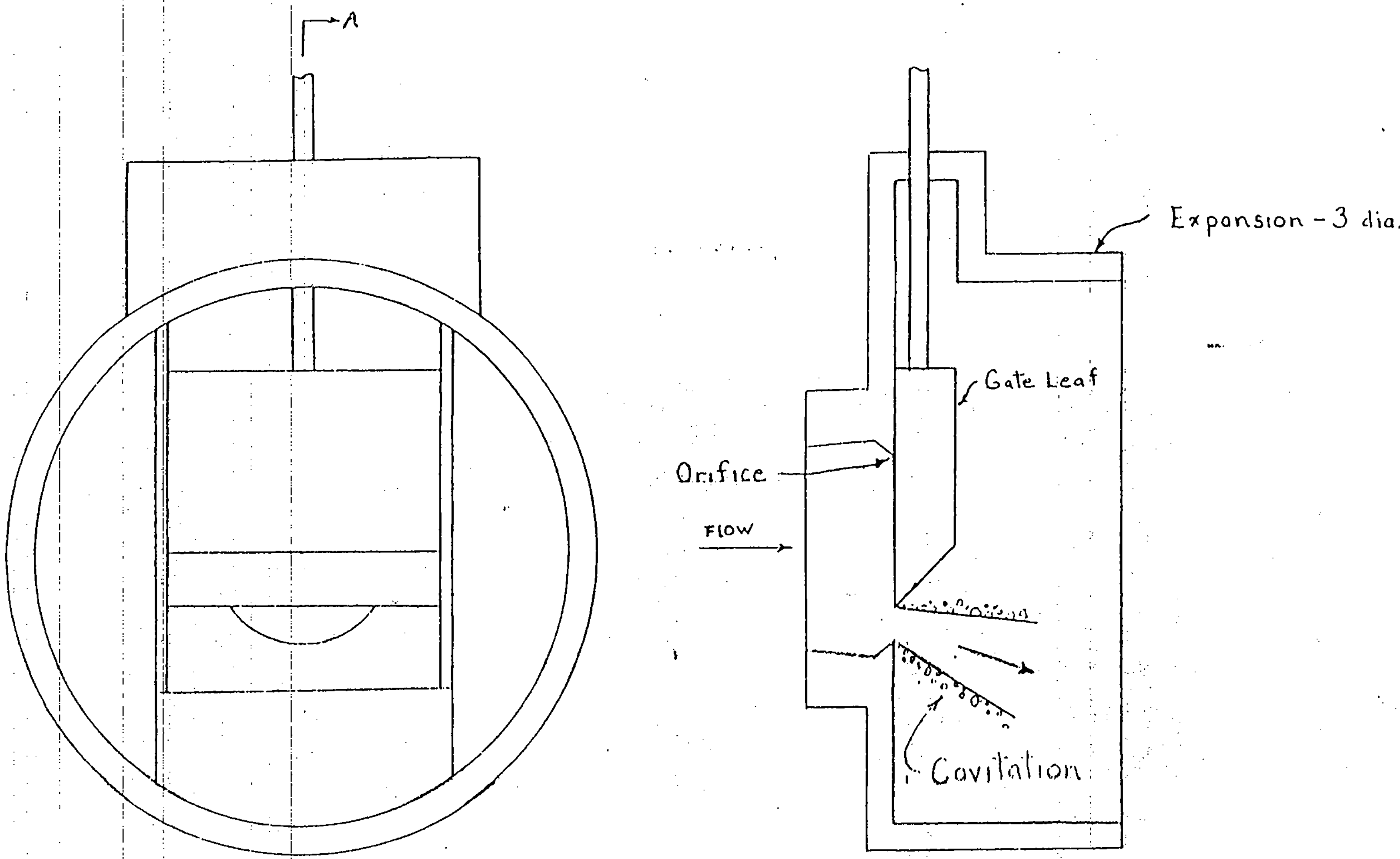
BUREAU OF RECLAMATION

DESIGNED ________ TECHNICAL APPROVAL ________
DRAWN ________ SUBMITTED ________
CHECKED ________ APPROVED ________

Figure 2. - Arrowrock Jet Flow Gate Model Test Facility.

$10\frac{1}{2}" \times 18"$



Jet Flow Gate

Section A-A

Figure 3

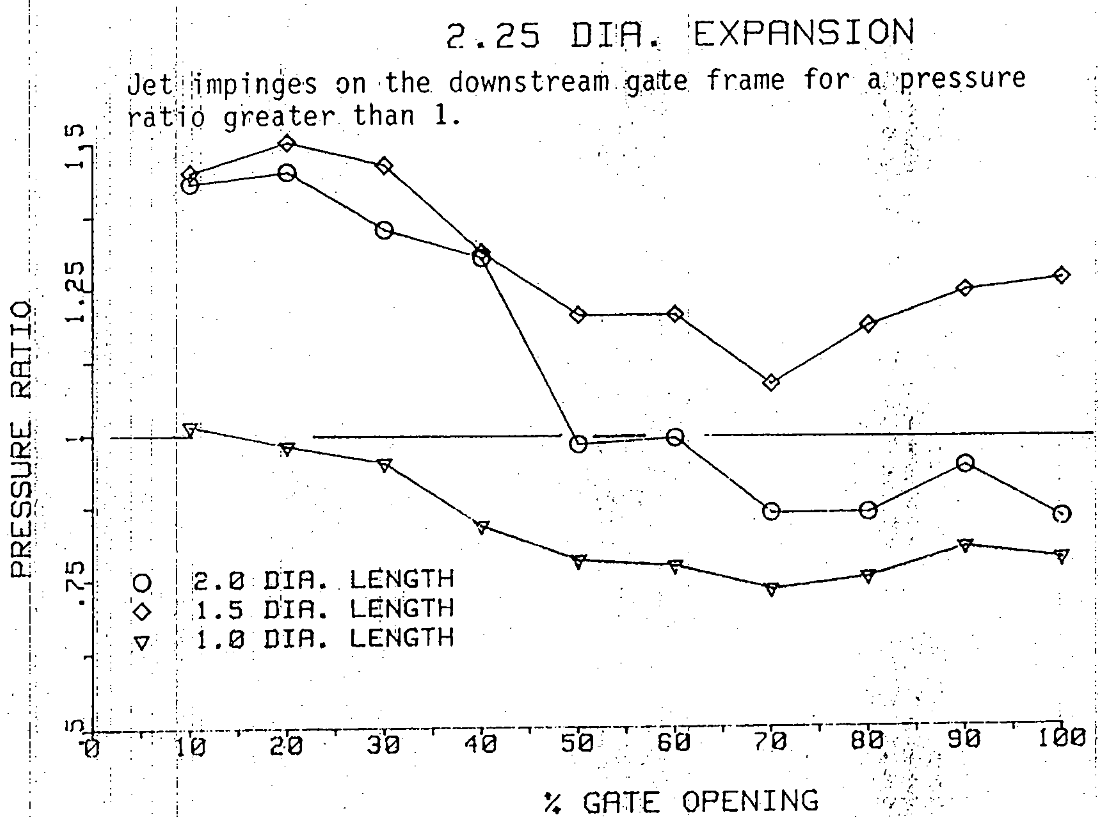

2.25 DIA. EXPANSION
Jet impinges on the downstream gate frame for a pressure ratio greater than 1.
PRESSURE RATIO
1.5
1.25
1.
.75
.5
0
10
20
30
40
50
60
70
80
90
100
% GATE OPENING
2.0 DIA. LENGTH
1.5 DIA. LENGTH
1.0 DIA. LENGTH

Figure 4

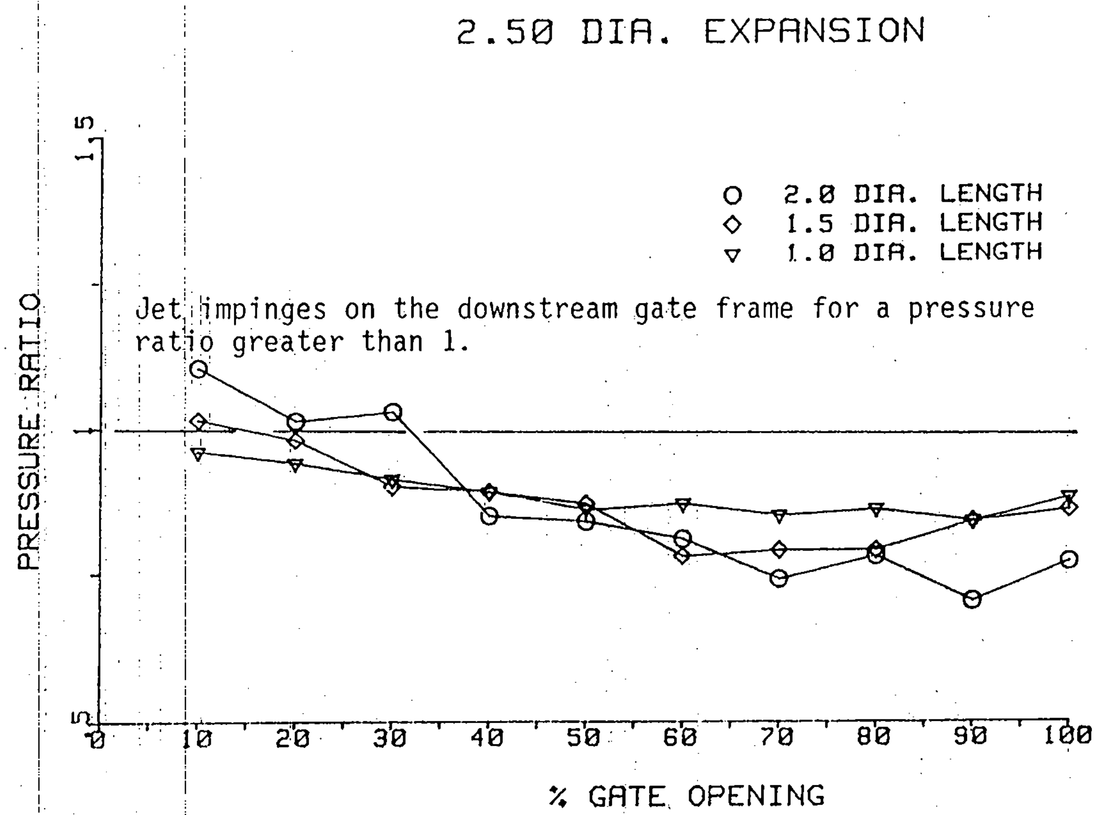

2.50 DIA. EXPANSION
2.0 DIA. LENGTH
1.5 DIA. LENGTH
1.0 DIA. LENGTH
Jet impinges on the downstream gate frame for a pressure ratio greater than 1.
PRESSURE RATIO
1.5
.5
0
10
20
30
40
50
60
70
80
90
100
% GATE OPENING

Figure 5

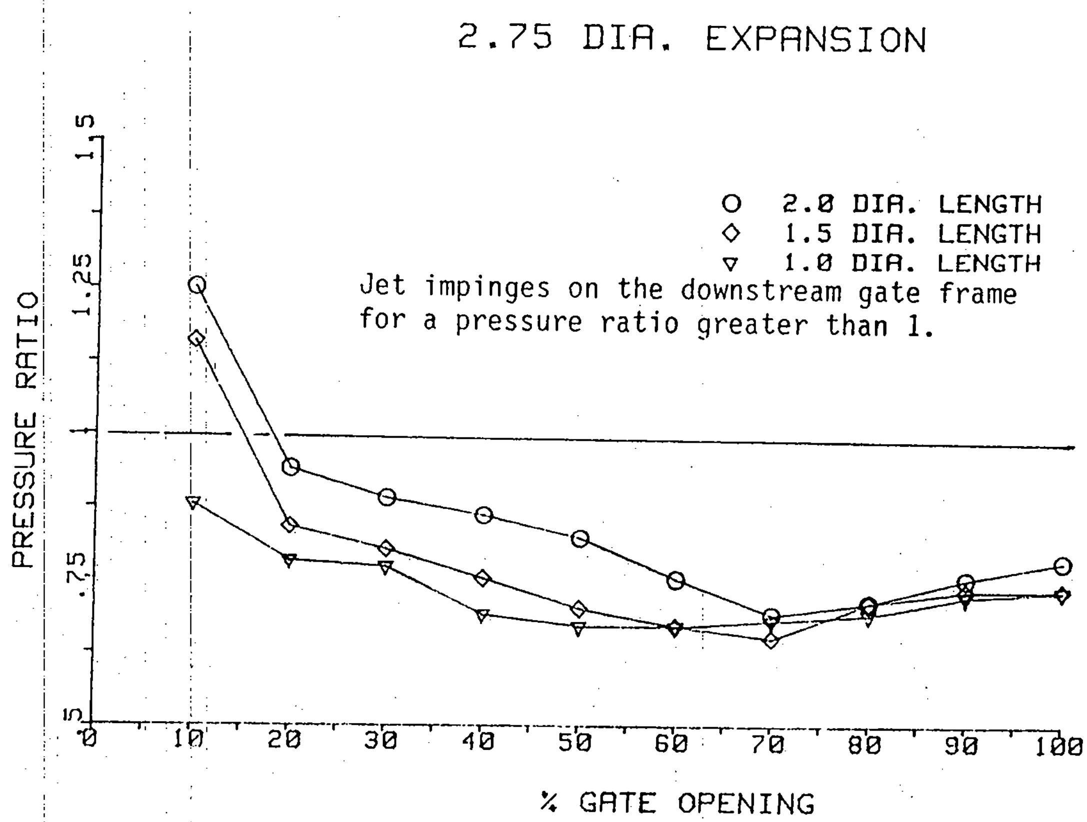
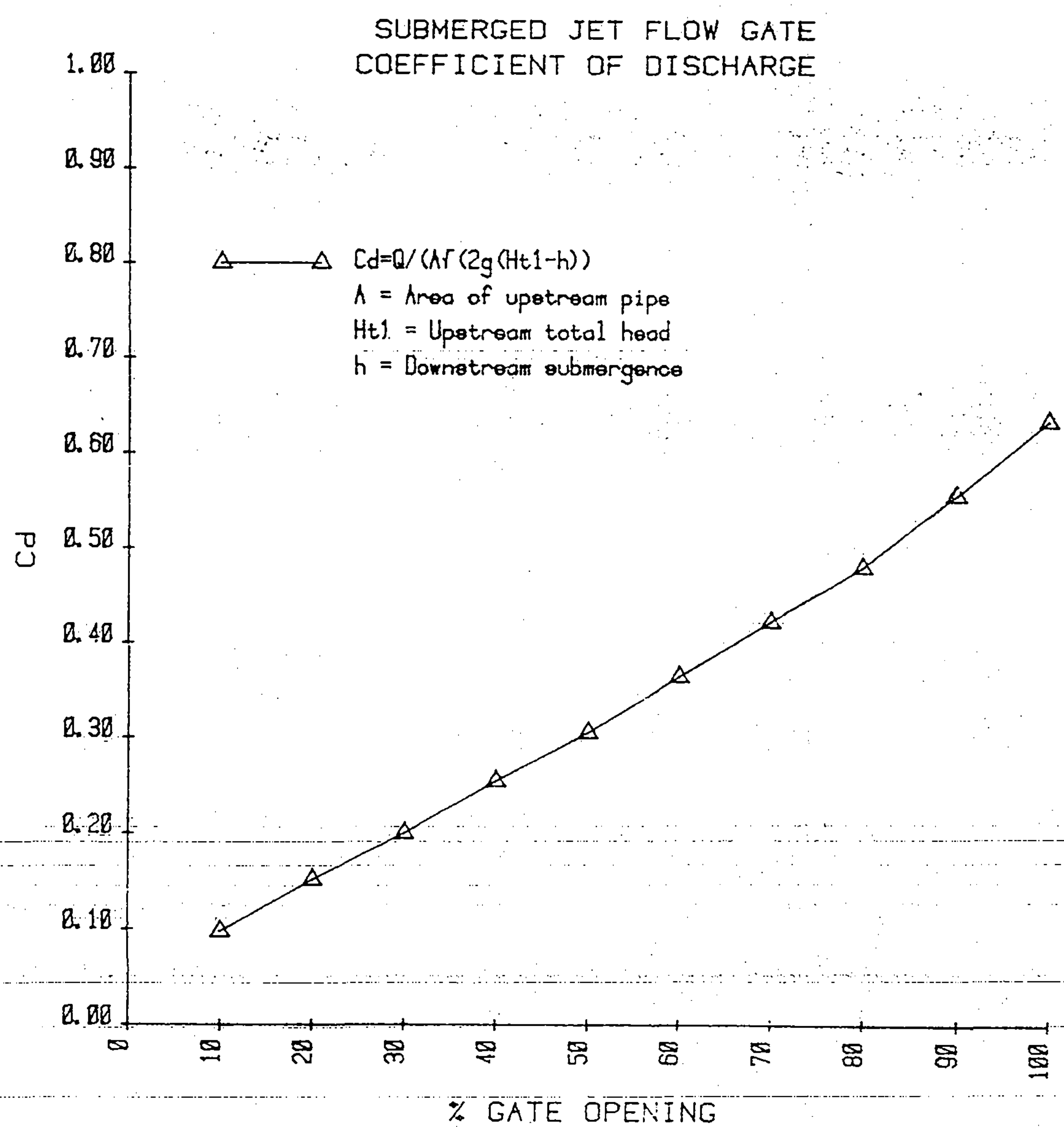
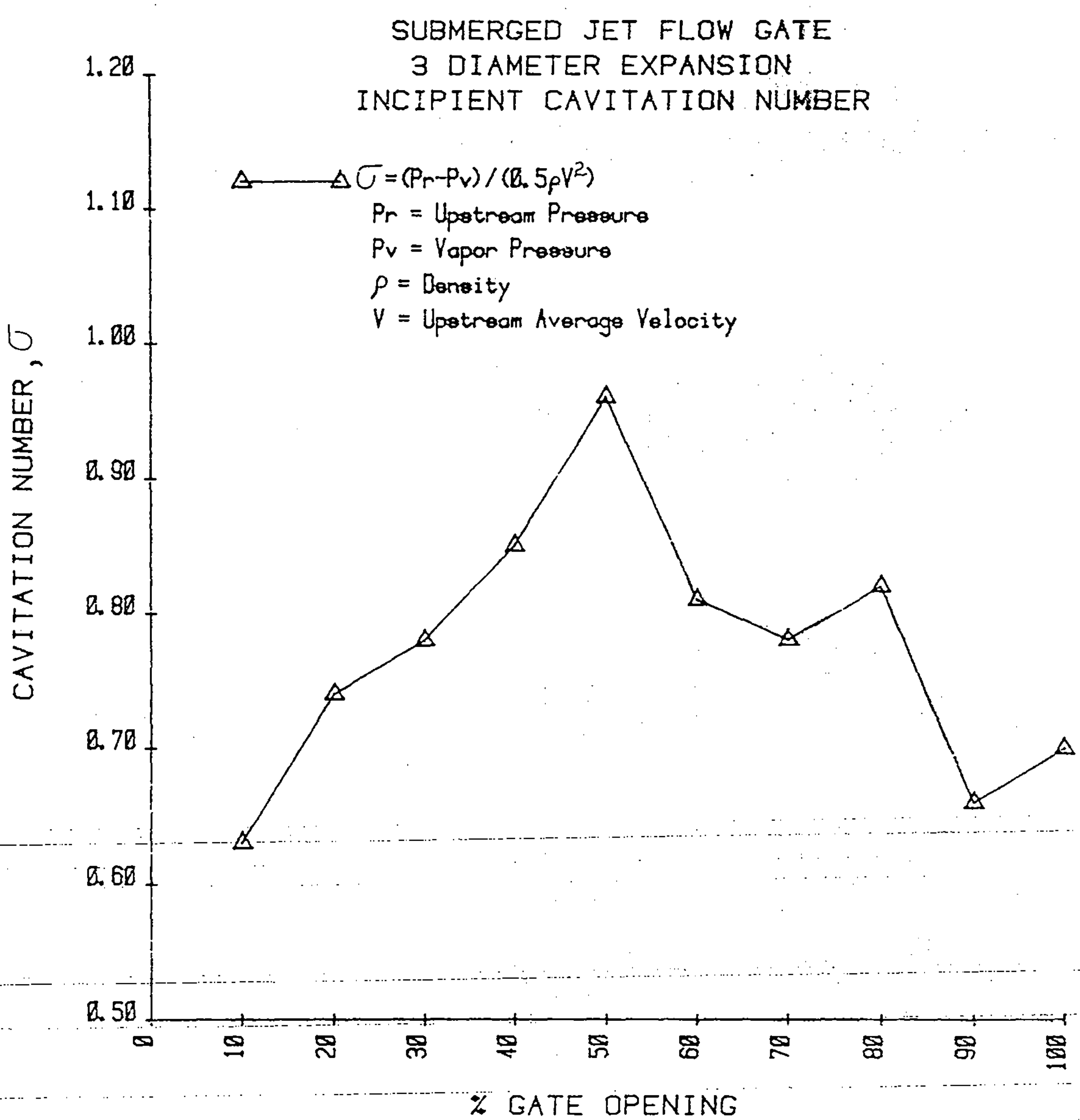

2.75 DIA. EXPANSION
2.0 DIA. LENGTH
1.5 DIA. LENGTH
1.0 DIA. LENGTH
Jet impinges on the downstream gate frame
for a pressure ratio greater than 1.
PRESSURE RATIO
1.5
1.25
.75
.5
0
10
20
30
40
50
60
70
80
90
100
% GATE OPENING

Figure 6

APPENDIX



SUBMERGED JET FLOW GATE
COEFFICIENT OF DISCHARGE
Cd=Q/(A√(2g(Ht1-h))
A = Area of upstream pipe
Ht1 = Upstream total head
h = Downstream submergence
Cd
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
% GATE OPENING



SUBMERGED JET FLOW GATE
3 DIAMETER EXPANSION
INCIPIENT CAVITATION NUMBER
σ = (Pr-Pv) / (0.5ρV²)
Pr = Upstream Pressure
Pv = Vapor Pressure
ρ = Density
V = Upstream Average Velocity
CAVITATION NUMBER, σ
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0
10
20
30
40
50
60
70
80
90
100
% GATE OPENING