CAVITATION AND VIBRATION STUDIES FOR A CYLINDER GATE DESIGNED FOR HIGH HEADS

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James W. Ball, Hydraulic Research Engineer
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A paper to be presented at the Eighth Congress of the International Association for Hydraulic Research, Montreal, Canada, August, 24-29, 1959

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SUMMARY

This paper discusses hydraulic problems encountered in the design of a 20-foot 4-inch diameter, 12-1/2-inch thick, 9-foot high cylinder gate which will control the flow from the base of a 300-foot deep, 18-foot diameter vertical shaft into a 21-foot diameter pressure tunnel. Hydraulic model studies were made to ascertain the vibration possibilities of the gate cylinder, to investigate the pressure intensities on various parts of the gate, and test changes in design directed toward the elimination of any conditions tending to induce cavitation and vibration. The problems considered and the solutions obtained are explained in detail.

INTRODUCTION

A cylinder gate 20 feet 4 inches in diameter, 12-1/2 inches thick and 9 feet high is located in the Eucumbene-Tumut Tunnel at the base of an 18-foot diameter vertical shaft 270 feet below the riverbed at the confluence of the Tumut and Happy Jacks Rivers. This tunnel system and shaft are a part of the Snowy Mountains Hydro-Electric Scheme in the Snowy Mountains of Southeastern Australia, near Cooma, about 260 miles southwest of Sydney, Figure 1. The gate which is in an enlarged section or chamber in the tunnel about three-quarters of the distance between the storage reservoir, Lake Eucumbene, and the power reservoir, Tumut Pond, (Figure 2) will control flows into the tunnel for storage in Lake Eucumbene when the combined flow of the Tumut and Happy Jacks Rivers

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exceeds the needs at Tumut Pond. The gate will be operated to keep the 300-foot deep shaft under pressure and prevent air being entrained and carried into the tunnel system. The tunnel will always be under pressure, and the gate will operate with differential heads up to 277 feet, depending on the amount of water being diverted to storage and the water elevation in the storage reservoir.

The gate is suspended and operated by three 4-1/2-inch diameter steel stems which extend upward 330 feet to the hoists at the shaft inlet (Figure 3).

The fact that the gate will not be readily accessible and the requirements that it operate under high heads and discharge large quantities of water (up to 9,000 cfs) made it imperative that unbalanced forces, vibration and cavitation be an acceptable minimum. Hydraulic model studies were made to develop a design having these characteristics. Items of particular concern in this paper are:

(a) Magnitude and distribution of pressures on gate seat and possibility of cavitation occurring

(b) Magnitude and distribution of pressure in water passages between gate top seal and frame seal rings and possibility of cavitation occurring

These items are discussed in the order given, and the discussions contain brief descriptions of the test facilities used in each case.

STUDY OF GATE SEAT

Description of Hydraulic Model

The model used for an overall evaluation of the proposed design was constructed on a geometric scale of 1:18. The model of a preliminary design included short sections of the main tunnel, the gate chamber, the cylinder gate, and a portion of the vertical shaft (Figure 4). A 12-inch inside diameter metal pipe represented the 18-foot diameter vertical shaft. The cylinder gate was fabricated of brass (Figure 5), the gate chamber of transparent plastic, and the tunnel sections of 14-inch diameter heavy gage sheet metal pipe. A valve was placed on the storage reservoir end of the tunnel section to control the back pressure on the model gate.

Because high velocities would pass over the flow surfaces of the prototype gate lip and seat, it was important that the configuration of these parts not induce reductions in pressure to cause vapor pressure and cavitation. Piezometers were, therefore, placed at strategic points on the gate and its seat.

Pressures on Gate Seat

Hydraulic tests of preliminary design. Pressures on the preliminary gate model were above atmospheric except on the seat where subatmospheric pressures of approximately 18 feet prototype were indicated for a discharge representing 5,400 cfs and a gate opening of 1.15 feet (Piezometer 38, Figure 6). The discontinuities formed by the steps in the seat caused a tendency toward flow separation with severe subatmospheric pressures. The seat was not considered satisfactory. Also at small gate openings only, many air bubbles injected into the water model flowed downward along the vertical side of the gate pedestal. The cause of this flow condition was not understood until a similar flow action was observed later on an air model.

The dismantling and machining of several successive gate seat shapes for the hydraulic model would have been time consuming and expensive. Accordingly, a low cost two-dimensional air model constructed of wood to a 1:4 scale was utilized to expedite the study of the seat shape (Figure 7).

Description of air model. The air model consisted of a 40- by 30- by 6-inch plywood box with an inlet transition at one end and a sliding panel in one side to represent the gate cylinder at various openings (Figure 8). The seat, shaped of wood, was placed in the end of the box opposite the entrance which was attached to a 10-inch centrifugal air blower. The 6-inch length of seat in the air model represented a 2-foot long section of the prototype.

Air Tests of Gate Seat

Preliminary design. The jet from the prototype gate was submerged by water in the gate chamber. The air model in which the jet discharged into atmosphere represented this condition. There was one difference, however; the air jet was not confined by walls representing the gate chamber, and thus currents adjacent to the gate were not the same as in the water model. This fact was brought out in the tests.

Preliminary tests were first made to correlate results between the air and water models. The pressure relationship (Pressure Factor) $\frac{h_A-h_B}{H_T-h_B}$ was used, where

H_T = total head in shaft, pressure plus velocity head, feet

h_A = piezometric head in critical area of gate seat, feet and

h_B = pressure head into which gate jet discharges, feet

At first, the comparison was rather unsuccessful (Curves A and B, Figure 9), but later an incomplete but satisfactory correlation was obtained.

When the air model was operated at gate openings to approximately 0.5-foot prototype, the jet could be forcibly deflected from a horizontal direction to a downward direction across the gate seat base, where it would remain (X to Y, Figure 9), a condition which it was believed would have occurred naturally if the gate chamber confinement had been represented in the model. This flow condition was believed to be similar to that observed on the water model when bubbles of air flowed down the face of the gate pedestal. The air downstream and adjacent to the gate seat was rarefied by the deflected jet and a pressure indicating cavitation occurred at the gate seat. The jet remained in the downward direction until aeration was supplied to relieve the negative pressure. Cognizance was taken of this critical range of openings in subsequent tests which concerned several seat shapes. A shortening of the base on the downstream side of the gate seat in the air model (the equivalent of decreasing the pedestal diameter) to provide better circulation underneath the jet resulted in a minimum pressure factor of approximately -0.47, which was only slightly greater than for the water model. The gate openings for the minimum pressure factors differed by approximately 1.0-foot prototype (Curve C, Figure 9). Although the air model did not give the same results as the water model, it would give more conservative results and thus was considered satisfactory for indicating the feasibility of various seat shapes.

Air tests of seat, 1-1/4-inch wide, with vertical upstream face and 45° sloped downstream face. The shape (Shape 2, Figure 7) was satisfactory for all except the smaller gate openings, 0 to 0.5 foot. In this range of gate opening, the jet could be forcibly deflected downward where it would remain and cause a subatmospheric pressure on the seat surface equal to approximately 0.9 of the total upstream head.

Air tests of seat, 9 inches high with 20° sloped upstream face and 60° sloped downstream face. A wedge-shaped gate seat was tried (Shape 3, Figure 7). Pressures on this seat were above atmospheric, and the jet was always stable in a horizontal position. Although acceptable from a hydraulic standpoint, the shape was undesirable because the gate must seat on a 20° sloping surface. Machining and setting of the prototype gate and seat to provide a satisfactory sealing surface would be difficult because of the angle of the seat. A soft material such as babbitt or rubber recessed in the slope would be undesirable because of the possibility of being deformed by the gate lip or loosened and removed by the flow of high velocity water.

It was concluded that the upstream edge of the seat must be rounded and that a vertical or nearly vertical downstream face should be placed close to the edge of the gate pedestal. These factors were taken into account in selecting a gate seat for further study.

Air tests of seat with two radii curve upstream of seat surface and vertical downstream face. The upstream edge of a 9-1/2-inch high gate seat was rounded on a compound curve composed of radii of 2-1/8 and 6-1/2 inches (Shape 4, Figure 7). A 2-3/8-inch flat section tangent to the 6-1/2-inch radius formed a horizontal seating surface. The total width of the gate seat was 7-1/8 inches, and the downstream face was vertical. Severe subatmospheric pressures occurred on the downstream side of the seat at openings up to 0.6 foot, when the jet was forcibly deflected downward and remained in that position (Piezometer 6, Figure 10).

The width of the gate seat was increased to 10 inches in an attempt to provide continuous circulation under the jet. When forcibly deflected downward, the jet still continued to flow in that direction so the width was increased to 11 inches. When the jet was deflected downward and the deflecting force removed, the jet would return immediately to the horizontal position where pressures were satisfactory. As a seat width of 11 inches made the fastening of the prototype gate seat to the gate pedestal difficult, a lesser width was structurally desirable. The air model results were conservative because of the severe method used to deflect the jet during the tests and because relatively more aeration was required on the air model than on the water model. Therefore, a gate seat width of 10 inches (Figure 10) was selected for further tests in the hydraulic model.

Hydraulic tests of seat with two radii curve upstream of seat surface and vertical downstream face. No subatmospheric pressures were detected on the

10-inch wide gate seat in the water model when the upstream edge was rounded on a compound curve of 2-1/8- and 6-1/2-inch radii (Figure 11); nor did water flow down the face of the pedestal as observed for the preliminary gate seat design.

Pressures measured on the seating surface were satisfactory because they changed gradually and were positive for all discharges. Since there were no subatmospheric pressures on this design, the seat shape was considered cavitation-free and satisfactory.

STUDY OF GATE TOP-SEAL

The Seal Problem

Because the cylinder gate at the base of Junction Shaft will not be readily accessible, studies were made to minimize maintenance and inspection. One of the studies concerned the seal between the gate cylinder and frame at the top of the gate.

Because of operating requirements and conditions, it was not necessary that the gate be droptight when closed; thus the upper seal was designed to eliminate the surface contacts present with high pressure rubber seals. A small clearance or gap was left between the inner surface of the cylinder gate and the outer surface of the bottom of the lower gate frame. This spacing formed an annular passage between the frame and gate seal rings (Detail A, Figure 3). Water under differential heads up to 277 feet will flow through this passage from the shaft to the tunnel.

With the gate closed or nearly closed, the flow passage between the gate and frame seal rings was 1/16 inch wide. As the gate opened past the frame seal ring, the width increased to 1/2 inch, the space between the frame seal ring and the gate skin-plate surface. As it was impracticable to study the flow and cavitation characteristics of this passage on the 1:18 scale model, a separate sectional model to a larger size was constructed.

Description of Seal Model

A full-scale, 1-foot long straight section of the frame seal ring and gate seal ring was constructed and installed in a gate-like facility (Figure 12). The equipment consisted of a hydraulic lift for positioning the seal surfaces, a housing with transparent plastic windows for observation, and an outlet pipe with a valve for controlling the downstream pressure on the gate seal gap. Although the gate moved with respect to the frame, it was expedient on the model to accomplish the same relative motion by moving the frame seal ring with respect to the fixed gate seal ring. Piezometers were located in both shapes to study critical pressure areas. Pressure heads to a maximum of 160 feet of water upstream from the 1/2- and 1/16-inch flow passages were supplied by two 12-inch centrifugal pumps in series.

Hydraulic Tests on Preliminary Design

Cavitation in flow passage. Preliminary tests with low back pressures indicated that cavitation would occur in the 1/2- and 1/16-inch flow passages of the gate seal. For gate openings greater than the frame seal ring width, a vapor pocket formed in the 1/2-inch flow passage downstream from the 1/4-inch radius near the bottom of the frame seal ring. The vapor pocket extended downstream along the frame seal ring boundary to connect with a second pocket that formed in an offset of the frame seal ring boundary (Figure 13).

A vapor pocket formed also in the 1/16-inch flow passage between the two seal ring surfaces at gate openings smaller than the frame seal ring width and extended downstream from the passage along the frame seal boundary (Figure 18).

Cavitation index. As the laboratory pump facilities could not supply full prototype differential head (277 feet), a cavitation parameter was used to indicate the possibility of cavitation in the prototype. This parameter was the cavitation number or index, K, a dimensionless pressure relationship which could be varied by regulating the back pressure on the flow passage to determine K_i, the value of K at which cavitation is incipient. The values of K_i are the same for two passages of the same size and shape; thus, the value obtained from the model could be applied directly to the prototype to determine its cavitation potential. A cavitation index may be of several different forms, but that used for analyzing the pressure conditions in the 1/2-inch flow passage was:

$$K = \frac{h_b - h_v}{h_o - h_b}$$

where:

h_b = back pressure representing the gate recess pressure (feet of water)

h_v = vapor pressure in feet of water (atmosphere as datum)

h_o = pressure representing that in the 18-foot diameter shaft (feet of water)

The numerator of this equation is a measure of the pressure head available to prevent cavitation in the flow passage. The denominator is a measure of the differential head producing the velocity through the flow passage.

As vapor cavities formed in the passage and the cavitation envelop enlarged to decrease the effective area of the passage, the cavitation index and discharge capacity decreased. Because of this fact, the discharge coefficient was used with the cavitation index to define K_i.

The coefficient of discharge, C, for the flow passage used in this case was:

$$C = \frac{Q}{A \sqrt{2g\,(h_o - h_b}}$$

where Q = model discharge (cfs)

A = area 1/2- by 12-inch space (square feet)

h_o = pressure head representing shaft pressure (feet of water)

h_b = pressure head representing gate recess pressure (feet of water)

and g = 32.2

As the transition from flow in which no cavitation occurred to flow with cavitation was gradual, exact values of K_i were not readily obtainable; however, by a plot of K vs C, approximate values could be determined for a study of a particular design (Figure 14). For values of K from 0 to 0.8, a vapor pocket formed along the boundary and across the width of preliminary shape frame seal (Figure 13). Cavitation was negligible for values of K greater than 0.8, with only small vapor pockets due to local roughness forming in the modelbefore a change in the flow pattern was indicated by the index curve, thus K_i = 0.8. A cavitation index of 0.45, computed for the prototype, was in the cavitation range (Plot A, Figure 14). The shape was unsatisfactory and an electric analog was utilized to extend the study to determine a curved boundary that would be free from cavitation.

Electric Analog Study of 1/2-Inch Flow Passage

Description of analog test facility. The electric analog utilized for obtaining a cavitation-free shape for the 1/2-inch flow passage consisted of a graphite-coated paper cutout, a potentiometer with dial reading to 1/10 of 1 percent, a precision galvanometer, and a 22-1/2-volt battery (Figure 15).

The cross-section shape for the 1/2-inch seal passage was cut from graphite-coated paper. Electrodes of aluminum foil were clamped to the paper with sponge rubber strips backed with plyboard. The contact of the electrode with the graphite coating was checked by measuring an equipotential line near the electrode. Contact was considered good when the distance of the line from the electrode was uniform for potentialswithin 1 or 2 percent of the electrode potential.

Once good contact was obtained, it was necessary to establish only the potential drop between points along the boundary to study the pressure change along the boundary. A probe with two points, one electrically insulated from the other, provided an accurate stepwise measurement of the boundary length and the potential drop between points. The change of potential between equal increments of boundary length indicated changes in velocity and pressure. This factor was used to investigate the tendency toward cavitation pressures at the flow surfaces.

Frame seal boundary with 1/4-inch radius at upstream edge--Preliminary design. The potential drop along the preliminary frame seal boundary was plotted against the developed length of the boundary to indicate the rate of change of the velocity at the boundary as the water flowed through the passage (A, Figure 16). For the passage to be free of isolated regions of low pressure, the velocity of the water must increase gradually to a maximum in the 1/2-inch flow passage. Thus, the passage shape must be such that the slope of the potential drop $\frac{(\Delta\varphi)}{\Delta S}$ versus distance (S) curve increases to the maximum at the uniform section of the analog which represented the 1/2-inch flow passage. A higher velocity and lower pressure on the boundary than at the uniform section would be indicated by a slope steeper than that for the uniform section.

The ratio of the maximum slope $(\Delta\varphi_1/\Delta S_1)$, to the slope at the uniform section $(\Delta\varphi_2/\Delta S_2)$ was used with the data from the water model to predict cavitation. The velocity at the 1/4-inch radius was related to the velocity in the uniform section by

$$\frac{V_1}{V_2} \doteq \frac{\Delta\varphi_1/\Delta S_1}{\Delta\varphi_2/\Delta S_2} \qquad \text{(D), Figure 16} \qquad (1)$$

The pressure change from S_1 to S_2 from the Bernoulli equation is $h_1 - h_2 = \frac{V_2^2}{2g} - \frac{V_1^2}{2g}$, losses assumed negligible. By substituting for V_1

$$h_1 - h_2 \doteq \left[1 - \frac{\Delta\varphi_1/\Delta S_1}{\Delta\varphi_2/\Delta S_2}\right] \frac{V_2^2}{2g} \qquad (2)$$

The slope of the potential drop curve indicated that the maximum velocity along the boundary would be 1.4 times the velocity in the uniform section. The observed vapor pocket at the 1/4-inch radius in the water model (Figure 13) coincided with the region for the steepest slope on the analog potential drop curve (Curve A, Figure 16).

For cavitation to occur along the boundary, any negative value of h_1 in Equation (2) must equal or exceed the vapor pressure of water (minus 27 feet of water referred to atmospheric at an elevation 5000 feet above seal level). With $V_1/V_2 = 1.4$

$$h_1 \doteq h_2 + \left[1 - (1.4)^2\right] \frac{V_2^2}{2g} \qquad (3)$$

When data for $K < K_1$, obtained from the water model and used in Plot A, Figure 14, were substituted into Equation (3), negative values of h_1 greater than 27 feet were obtained, thus indicating that cavitation would occur. For $K > K_1$, the computed values of h_1 would have negative values smaller than vapor pressure or positive. This would signify the absence of cavitation. From the foregoing, it was concluded that the electric analog was useful to predict cavitation pressures on a boundary and that the method could be used successfully to determine the cavitation potential of other shapes.

Frame seal boundary with two radii curve at upstream edge. A frame seal ring boundary consisting of two radii (3/4 and 1-3/4 inches) was next studied as a means of obtaining a continuously increasing velocity from the shaft to the uniform 1/2-inch section of the seal flow passage (B, Figure 16). The analog study gave a ratio of 1.2 for the maximum boundary velocity to the uniform section velocity for the area near the point of tangency of the 1-3/4-inch radius and the wall of the 1/2-inch flow passage (Curve B, Figure 16). This seal ring shape was an improvement over the preliminary design, but vapor pressure was indicated for a velocity head of approximately 61 feet, which was much less than the 250 feet which might exist for a 4.5-inch gate opening in the prototype. The shape was unsatisfactory.

Frame seal boundary with three radii curve at upstream edge. A compound curve of 3 radii (0.555, 1.182, and 2.39 inches, C, Figure 16) was next investigated. This curve was more gradual and approximated an ellipse with a minor axis of 0.88 inch and a major axis of 1.50 inches.

The slope of the potential drop curve for this design progressively increased along the boundary and reached a maximum at the 1/2-inch width in flow passage indicating that the maximum velocity was in the 1/2-inch flow passage (Curve C, Figure 16). Since no subatmospheric pressure was indicated, the frame seal on the water model was machined to this shape.

Hydraulic Tests on Frame Seal Ring Boundary with Three Radii Curve at Upstream Edge

Cavitation index. Cavitation did not occur along the flow passage boundary with the 3-radii curve in the 1-foot-long sectional water model for the maximum available laboratory pressure of 160 feet of water, thus, K_i for this part of the design could not be determined.

Cavitation at frame seal offset. Cavitation still persisted in an offset in the frame seal boundary downstream from the 1/2-inch flow passage (Plot B, Figure 14). The offset was increased from 1/2 inch to 1 inch in an attempt to raise the pressure at the jet contraction (F, Figure 14).

Severe cavitation occurred at the 1-inch offset for a gate opening of 2-9/16 inches, where the jet from the 1/2-inch flow passage was deflected across the offset by the sloping face of the gate seal ring. The computed index for this prototype opening was near the cavitation region (Plot D, Figure 14). The offset in the frame seal ring was filled to extend the frame seal ring surface and provide a larger offset. This change moved the offset to the upper edge of the frame seal ring and increased it to approximately 2 inches at the six 7-1/2-inch-wide upper gate guides and to 6-1/2 inches between the guides. The offset of 2 inches at the guides was considered sufficient because no cavitation and no decrease in coefficient resulted for this distance in the model. Approximately 70 feet of back pressure will be available for gate openings greater than 4-1/2 inches with a minimum water level in Lake Eucumbene. The cavitation index for this condition is 0.45, which is out of the cavitation range (Plot E, Figure 14). The lower frame seal boundary with a 3-radii curve and 4-1/4-inch tangent would, therefore, be cavitation-free and satisfactory (Figure 17).

Hydraulic Tests on Gate Seal Ring Boundary

Cavitation potential--Preliminary design. With the preliminary gate seal ring (F, Figure 14) the gap between the gate seal ring and the final frame seal ring at gate openings less than 4-1/2 inches was 1/16 inch.

A vapor cavity formed within and extended downstream of the 1/16-inch flow passage (Figure 18). The passage between the frame and gate seal rings at the small gate openings formed a short tube in which the contraction and expansion of flow within the passage was sufficient to produce vapor pressure.

The gate seal ring shape was modified in an attempt to eliminate the conditions causing the short tube flow. The 1/4-inch face of the gate seal was reduce to 1/16 inch. A flow contraction formed at the upstream end of the passage and expanded along the 45° chamfer to cause cavitation (Figure 19). As cavitation was not eliminated from the design, the gate seal was unsatisfactory.

Cavitation potential--Revised design. A modification based on the results of the tests on the frame seal ring was made to the gate seal ring to eliminate the vapor cavity in the 1/16-inch passage. The 45° chamfer on the inner diameter of the gate seal ring was eliminated to cause the jet to separate from the boundary and increase the pressure in the contraction region. The gate seal ring was kept 1-1/4 inches thick, but had a 1/8-inch vertical face down from the top surface at the inner diameter and a 30° chamfer at the bottom (Figure 17).

The length of flow passage was 1/8 inch, or equal to the minimum length of a short tube when based on the 1/16-inch gap between the frame and gate seal rings. The minimum flow section was now at the exit of the flow passage at the top of the gate seal ring, and cavitation would, therefore, not occur within the passage. The acceptability of this design was based on this factor, and no tests were made of this particular shape.

Pressures on gate seal ring--Small gate openings. Pressures were measured on the 30° chamfered surface of the gate seal ring to investigate any condition that might induce a vertical movement of the gate as the gate is raised and the clearance between the frame and gate seal rings increases abruptly from 1/16 to 1/2 inch.

The pressure factor vaired on approximately a straight-line relationship from 0.11 to 0.85 between gate openings of 4 and 4-3/4 inches (Figure 20). The pressure on the 30° chamfered surface would change at a rapid rate from the shaft pressure to the gate recess pressure in the 3/4 inch of gate movement.

Any tendency for movement of the gate by pressure fluctuations in the shaft or gate chamber may be accentuated at gate openings between 4 and 4-3/4 inches because of the rapid rate at which the seal pressure changes with opening in this range of gate travel. No movement was noted in the gate seal model, but the tendency for movement with the somewhat rigidly supported model would be less than for the prototype gate supported by three 330-foot-long stems. However, friction from the guides should prevent movement of the gate cylinder from this source.

CONCLUSIONS

It is extremely important to shape any water passage or flow surface in which high velocity flow is involved so that severe reductions in pressure, which might induce vapor pressure and cavitation, do not occur. The flow surfaces of the seat and the flow passage of the top seal of the Junction Shaft Gate are examples.

The preliminary gate seat design would have induced cavitation and resulted in severe vibration of the gate. The seat shape developed by model studies will not have areas of low pressure to cause cavitation, provided the field installation is identical to that developed from the model studies, and it is free of objectionable local irregularities sometimes produced in fabrication and installation. The air model used in the cylinder gate study served as an expeditious and economical means of developing a cavitation-free gate seat shape.

Cavitation would have occurred at the gate top seal of the preliminary design. At small openings (below about 2 inches) there would have been cavitation in the space between the gate seal ring and the frame seal ring, while at large openings (greater than about 2 inches) cavitation would have occurred in the flow passage between the skin plate of the gate and the frame seal ring near the leading edge of the latter. The design developed by model studies will be free of cavitation insofar as the shape of the flow passage and flow surfaces are concerned, provided there are no detrimental irregularities produced during fabrication and installation. The electric analog, using graphite-coated paper, served as an expeditious and economical means of determining the flow surface profile which would not contain low pressures to cause cavitation.

The abrupt change in pressure on the 30° chamfered surface of the gate seal ring, which takes place at an opening between 4 and 4-3/4 inches as the gate is raised or lowered, and the flow control transfers from the gate seal ring to the frame seal ring or vice versa, may tend to induce small movements in the gate. This will be particularly true if the gate is slightly eccentric to the frame seal ring and/or the horizontal plane of the gate seal ring is different from that of the frame seal ring. Friction at the gate guides should overcome this tendency, and no serious vibrations should result.

ACKNOWLEDGMENTS

The series of studies discussed in this paper were made over a period of several months, and several Australian engineers took part in the work. Angus McKinnon helped in planning and testing during the initial part of the program, and Milton Chappel took part in later tests and analyses. Other Australian engineers and officials observed many of the model tests and discussed the results. The Snowy Mountains Hydro-Electric Authority kindly granted permission to use the model study results in this paper. Special credit is due Bureau of Reclamation Engineer Jack C. Schuster, who supervised the various tests and analyzed the test data.

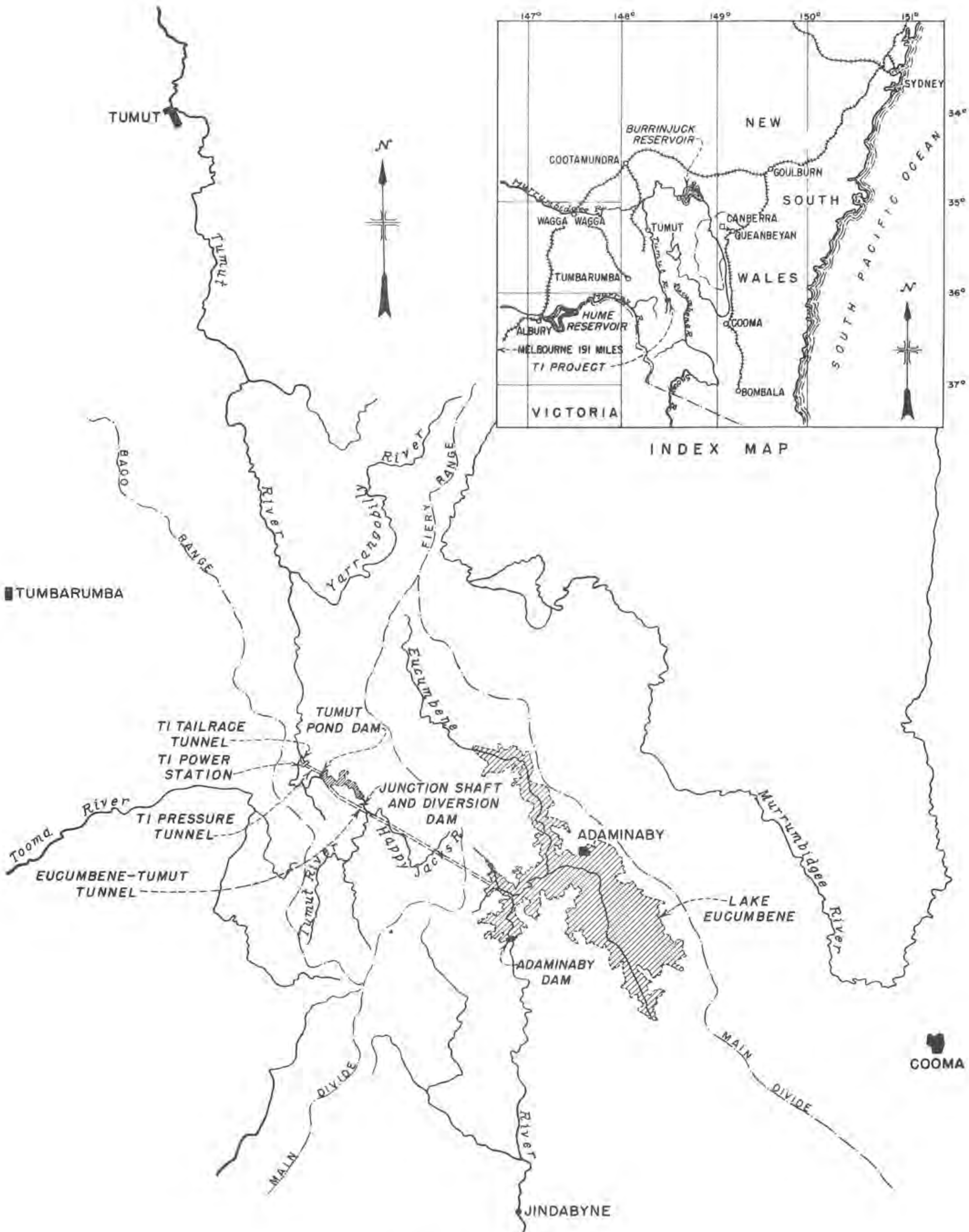


FIGURE I. LOCATION MAP
EUCUMBENE-TUMUT TUNNEL-T-I PROJECT, AUSTRALIA

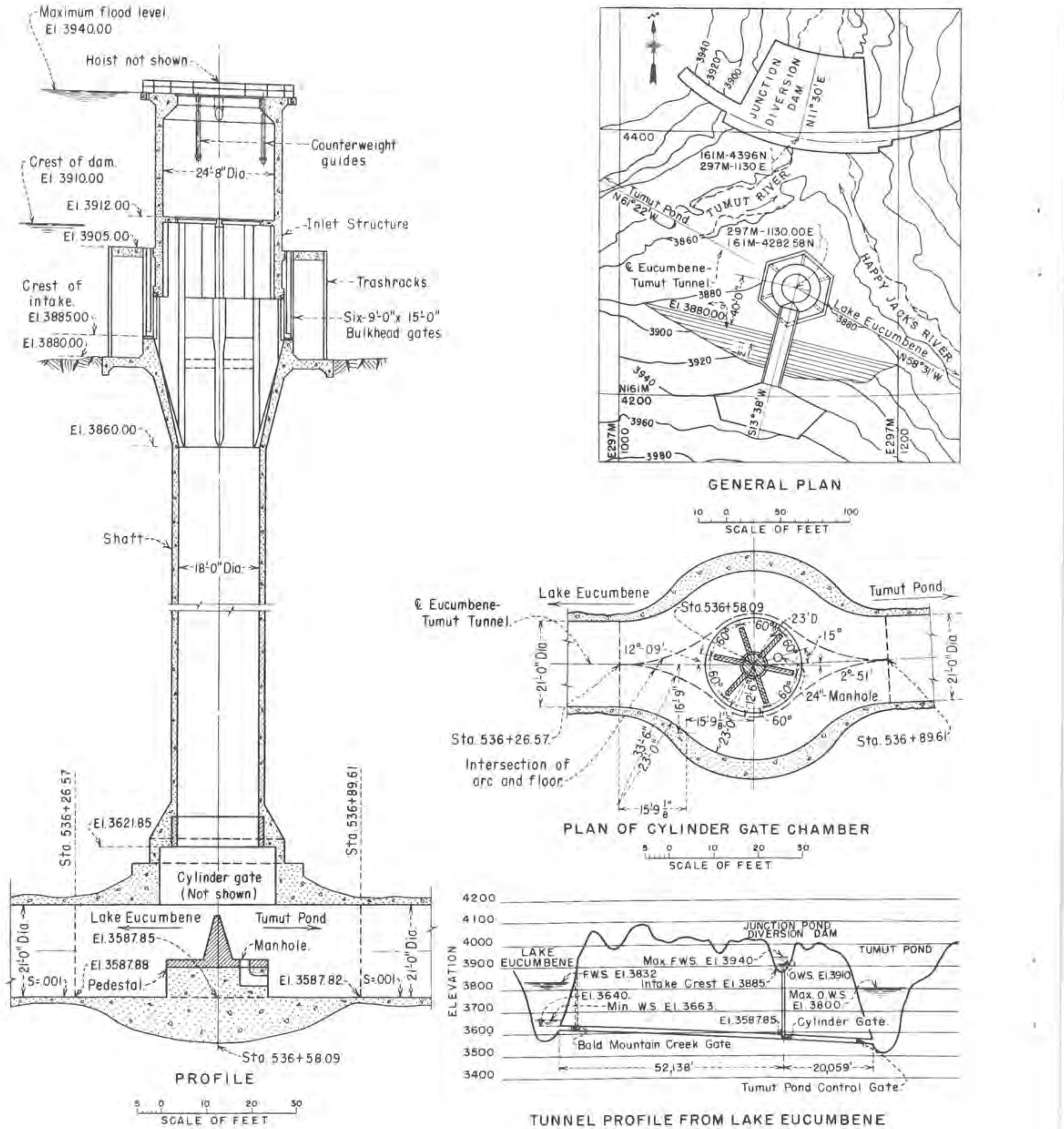


FIGURE 2. EUCUMBENE–TUMUT TUNNEL INTAKE SHAFT

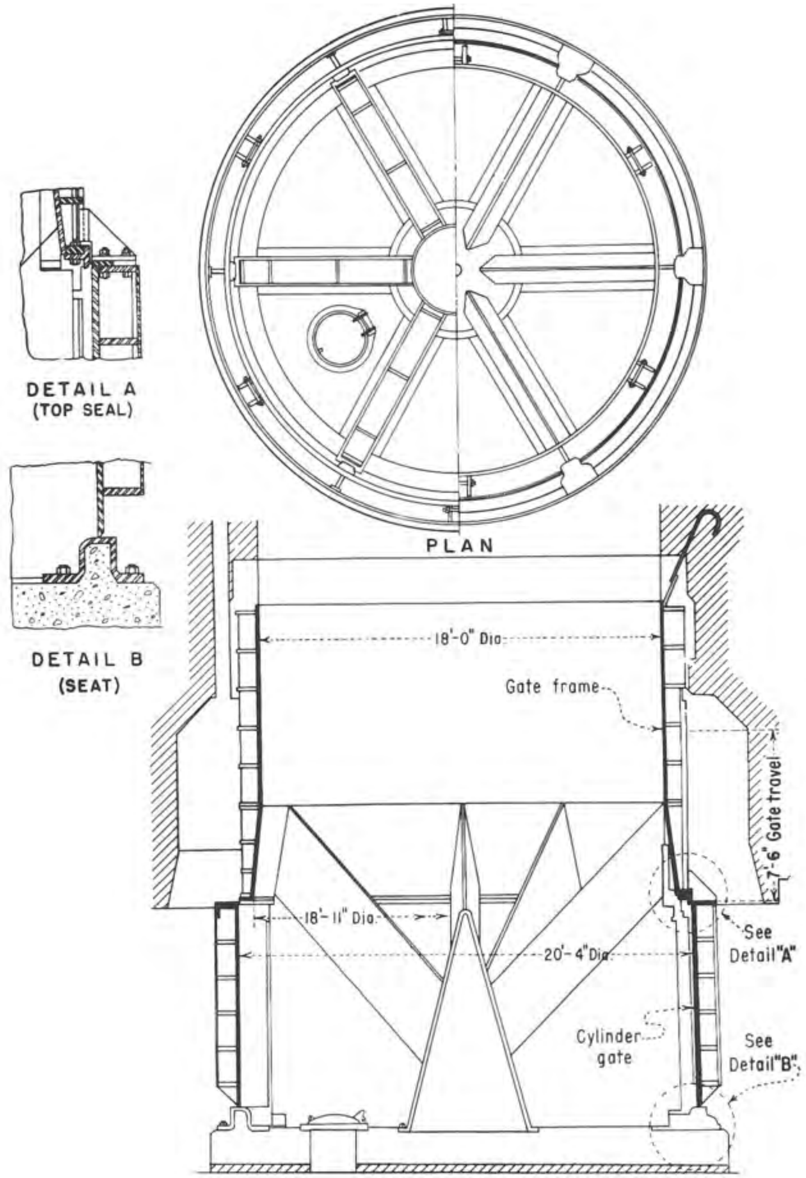


FIGURE 3. CYLINDER GATE AND FRAME

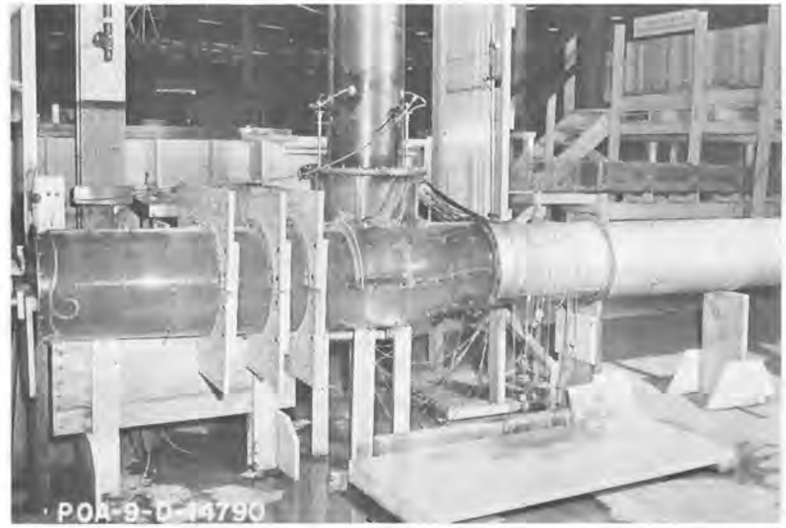


Fig. 4 Model Junction Shaft Cylinder Gate, Gate Chamber and Tunnel Sections 1:18 Scale POA-9-D-14790

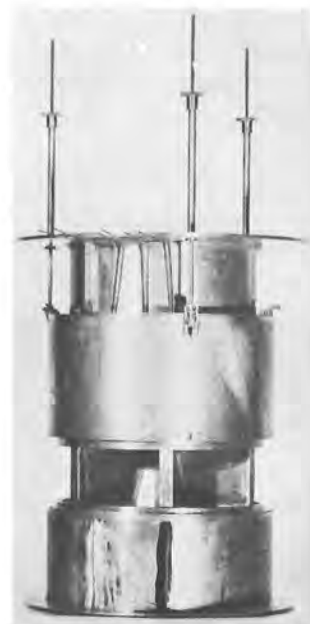


Fig. 5 Assembled 1:18 Scale Model of Cylinder Gate POA-9-D-14791

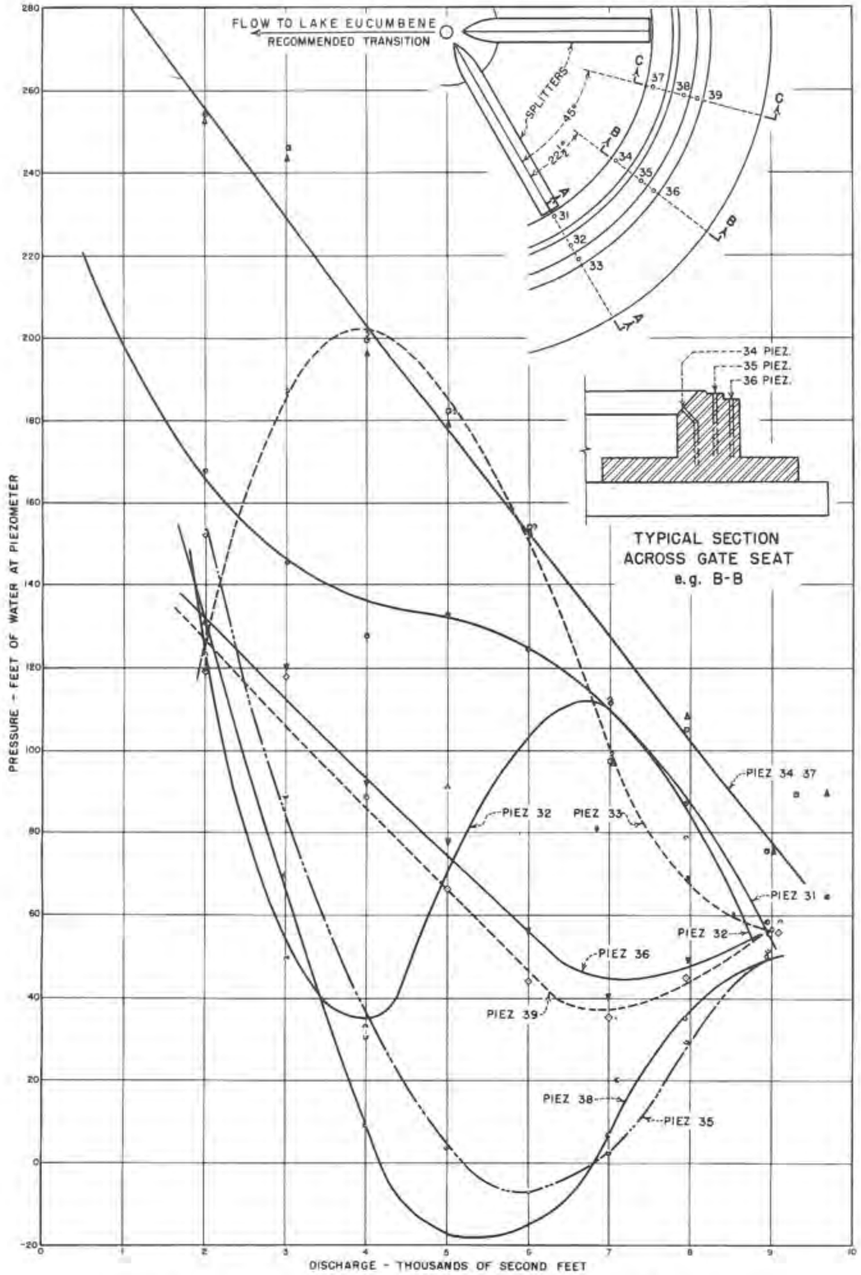


FIGURE 6. PRESSURES ON PRELIMINARY DESIGN GATE SEAT
1:18 SCALE HYDRAULIC MODEL

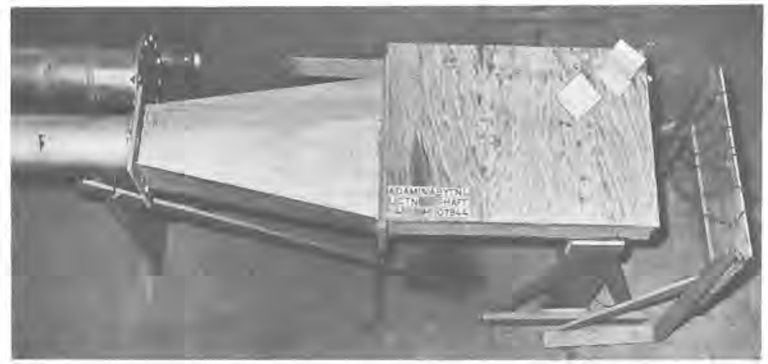
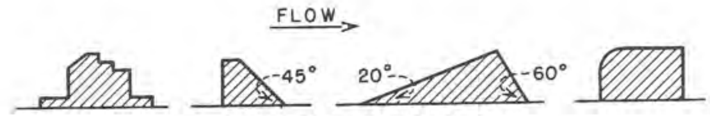


Fig. 7 1:4 Scale Air Model Installation
POA-9-D-14789



GATE SEAT SHAPES

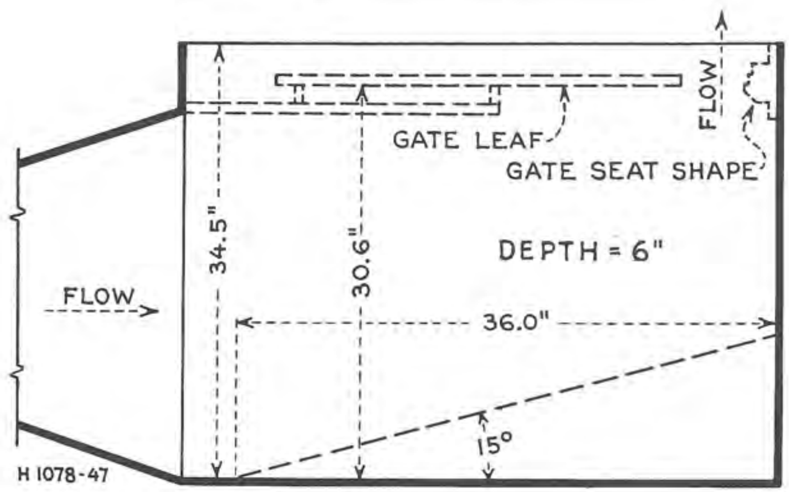


FIGURE 8. PLAN OF AIR MODEL FOR TESTING GATE SEAT SHAPE

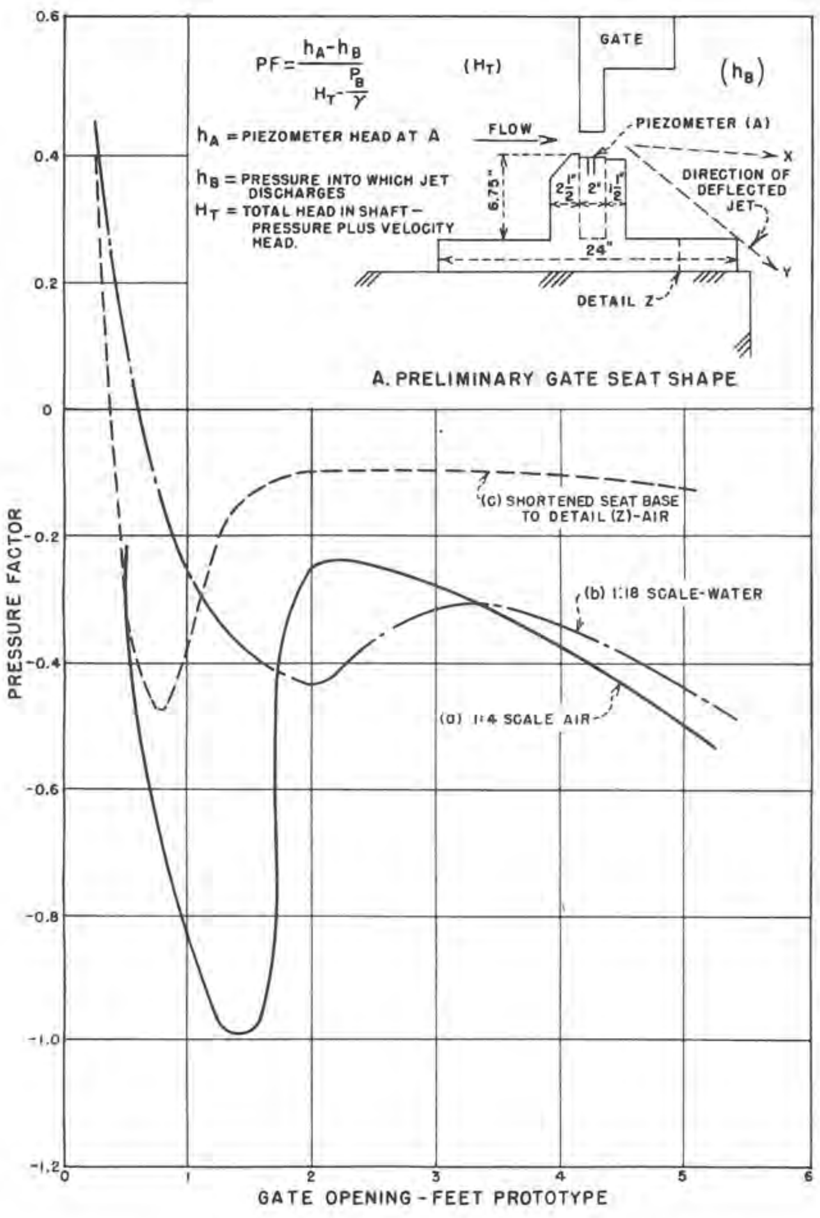


FIGURE 9. PRESSURE FACTORS FROM WATER AND AIR MODELS FOR PRELIMINARY DESIGN GATE SEAT

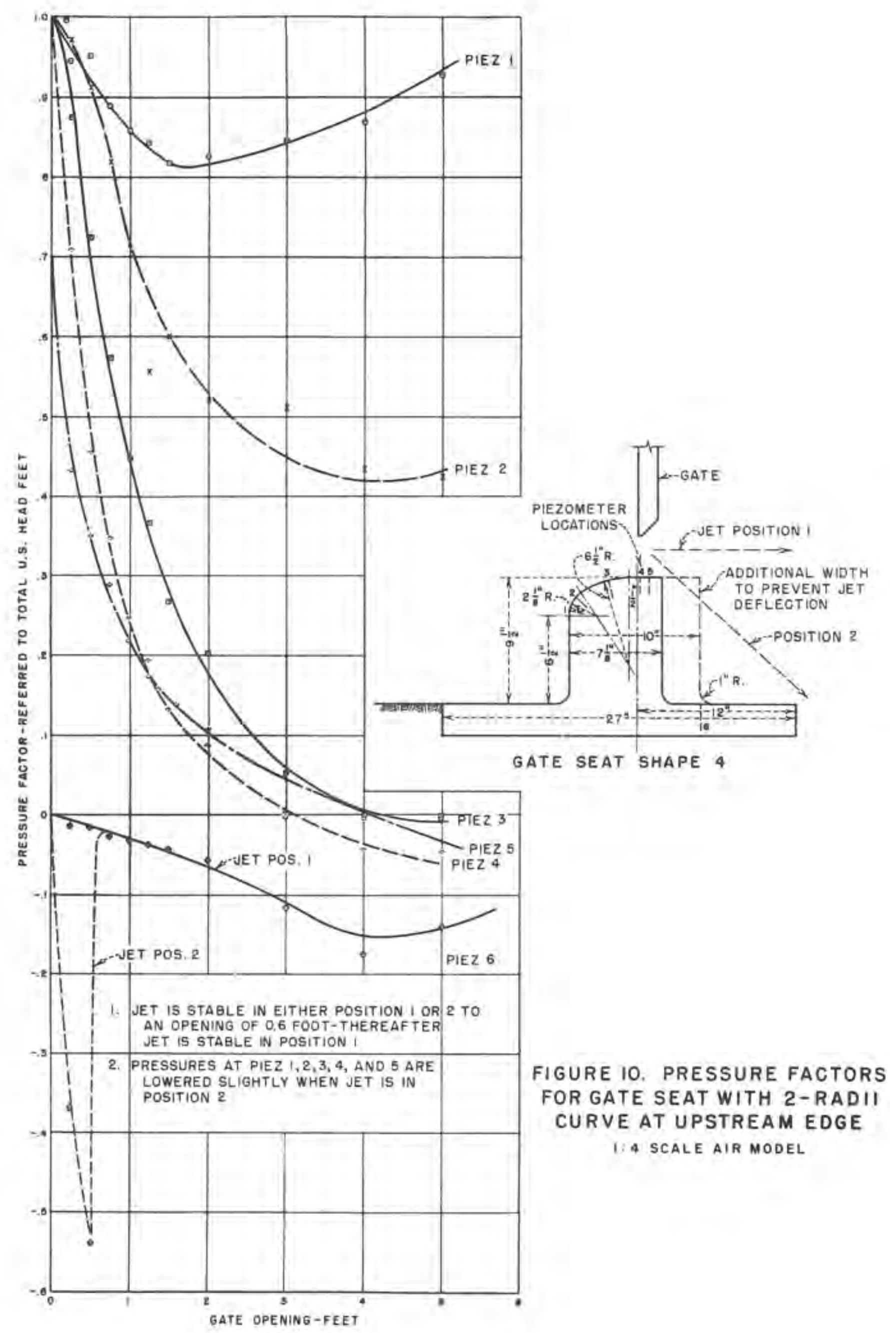


FIGURE 10. PRESSURE FACTORS FOR GATE SEAT WITH 2-RADII CURVE AT UPSTREAM EDGE

1:4 SCALE AIR MODEL

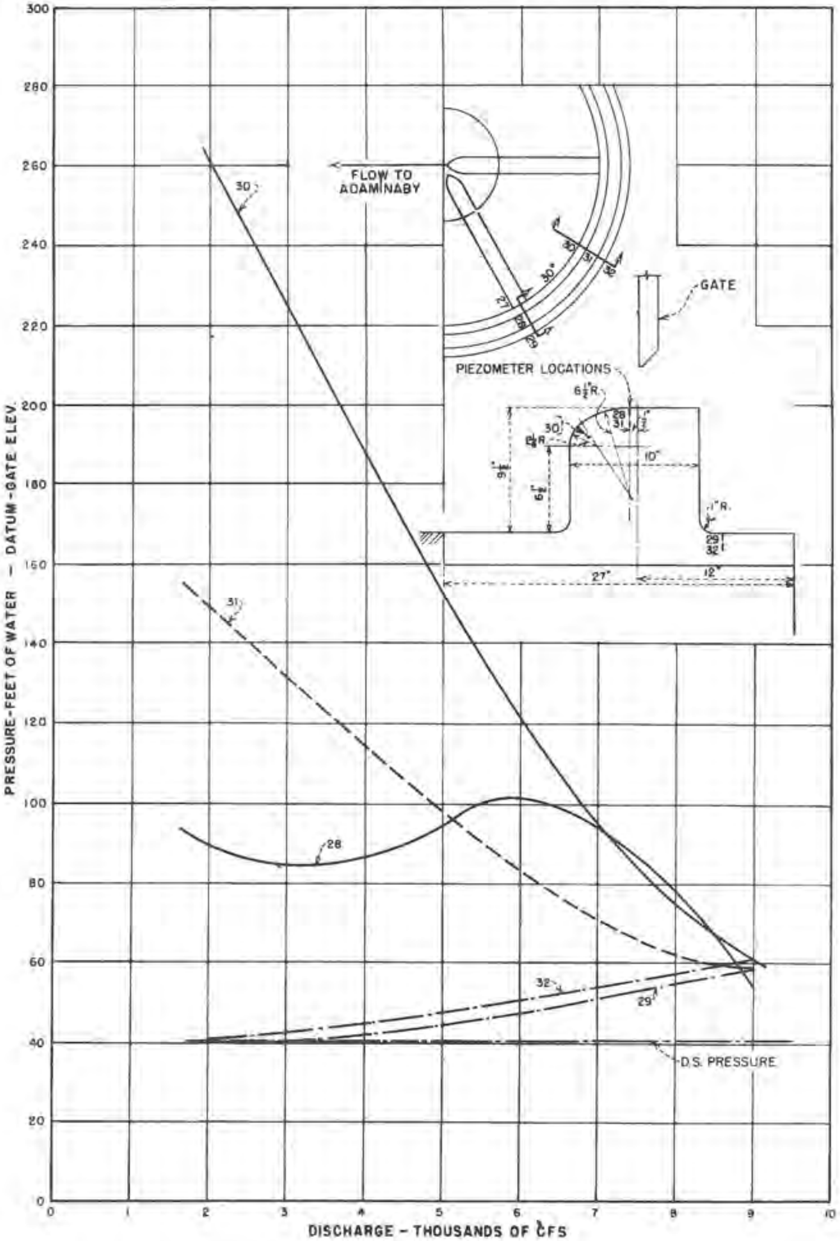


FIGURE 11. PRESSURES ON RECOMMENDED GATE SEAT DESIGN WITH 2-RADII CURVE AT UPSTREAM EDGE

1:16 SCALE HYDRAULIC MODEL

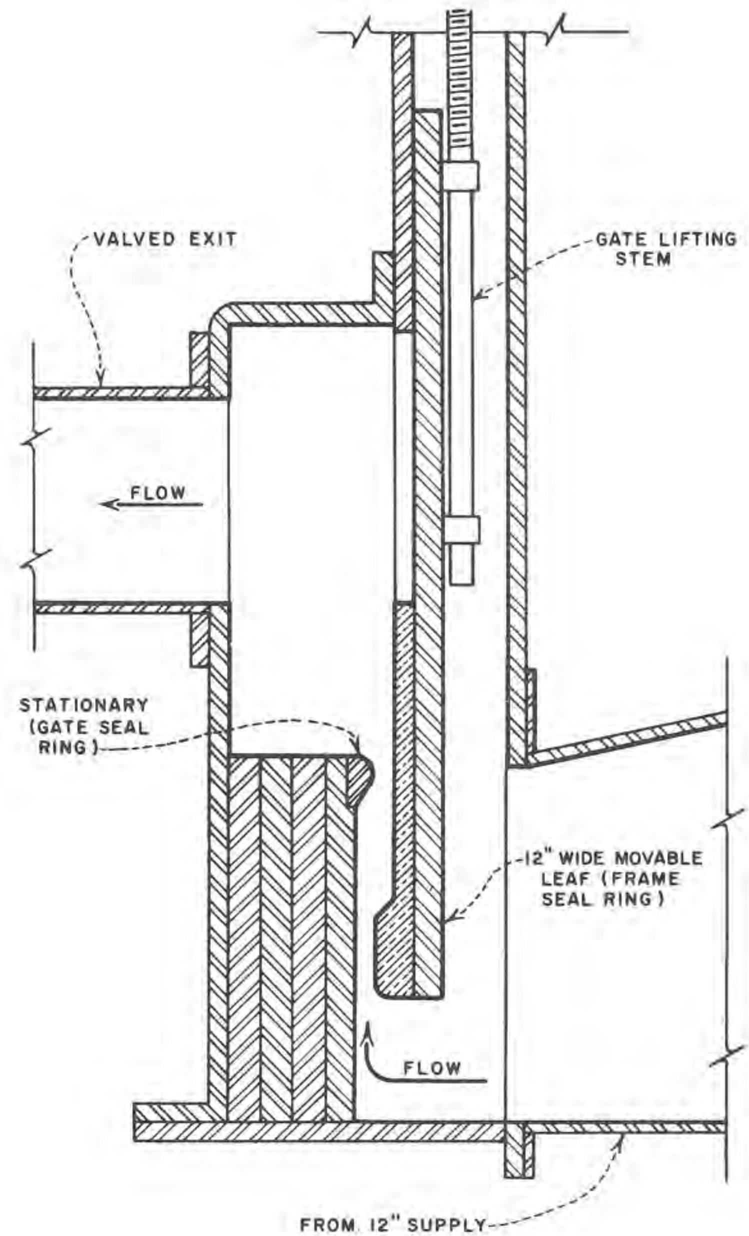


FIGURE 12. SECTIONAL DIAGRAM OF GATE TOP SEAL IN TEST FACILITY

Fig. 13 Cavitation Vapor Pocket - Preliminary Design top gate frame seal ring Cavitation Index, K, =0.53 PX-D-14787

Fig. 15 Electric Analog Facility using graphite-coated paper to represent top seal flow passage.
(1) Potentiometer (2) Galvanometer
(3) Battery (4) Probe (5) Detail Seal Passage Cross Section 10 times prototype size (6) Boundary Curve 4 times prototype size. PX-14788

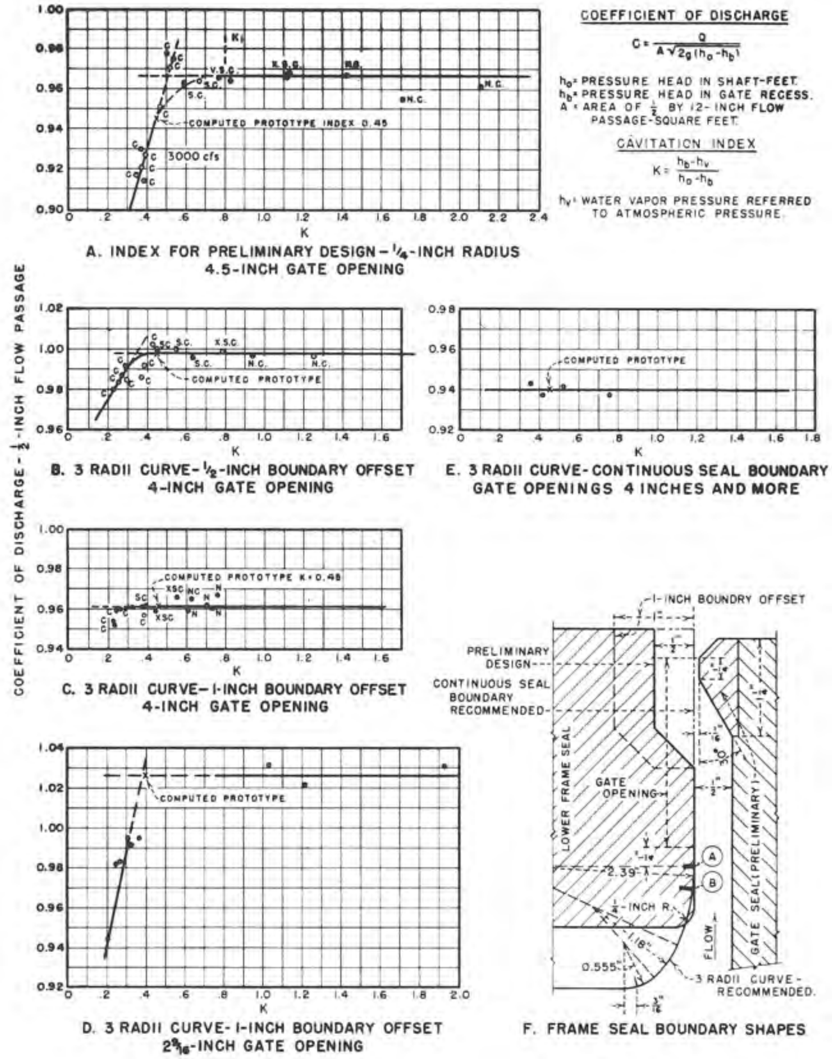


FIGURE 14. CAVITATION INDEX FOR VARIOUS GATE FRAME SEAL RING BOUNDARY SHAPES

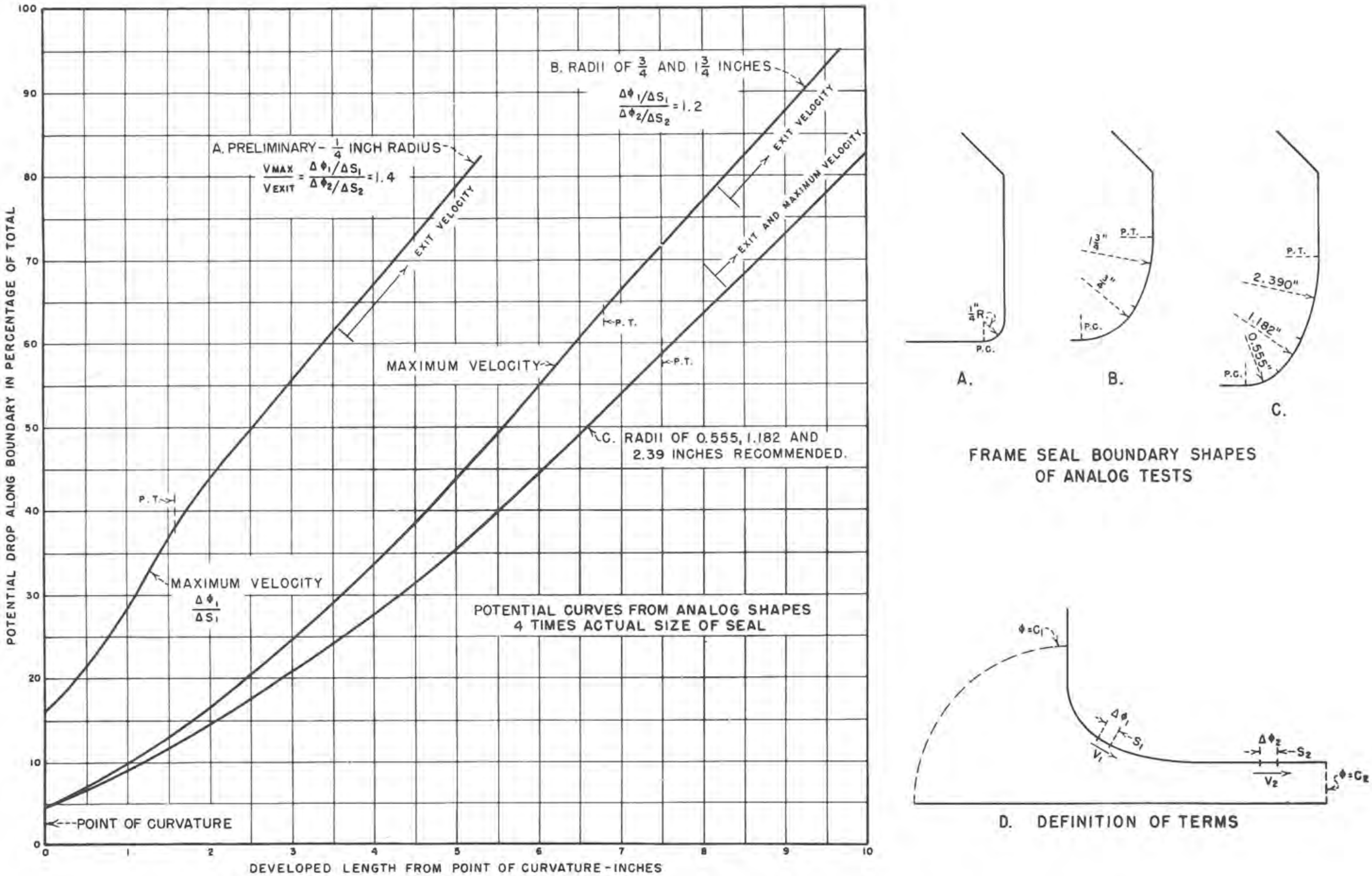


FIGURE 16. POTENTIAL DROP CURVES FOR VARIOUS BOUNDARY FRAME SEAL RING SHAPES FOR GATE TOP SEAL FLOW PASSAGE
ELECTRIC ANALOG

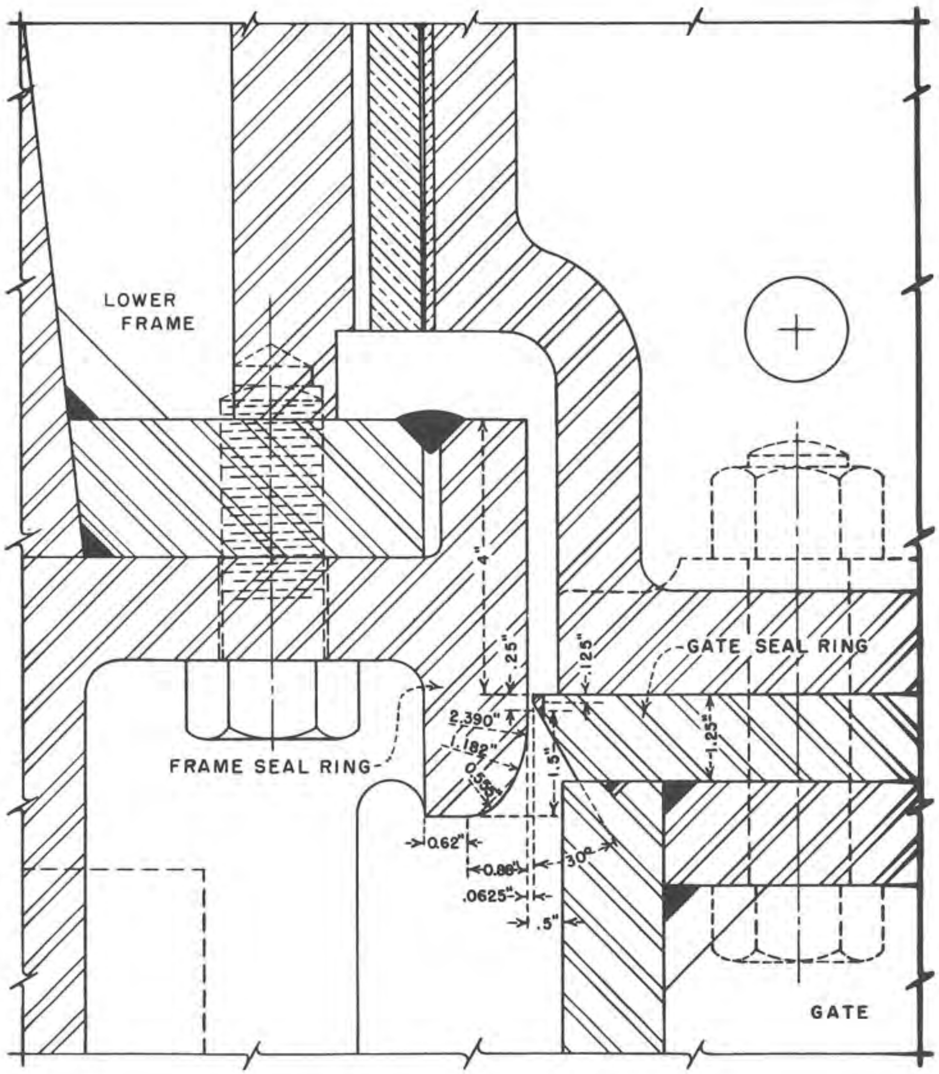


FIGURE 17. RECOMMENDED CYLINDER GATE TOP SEAL

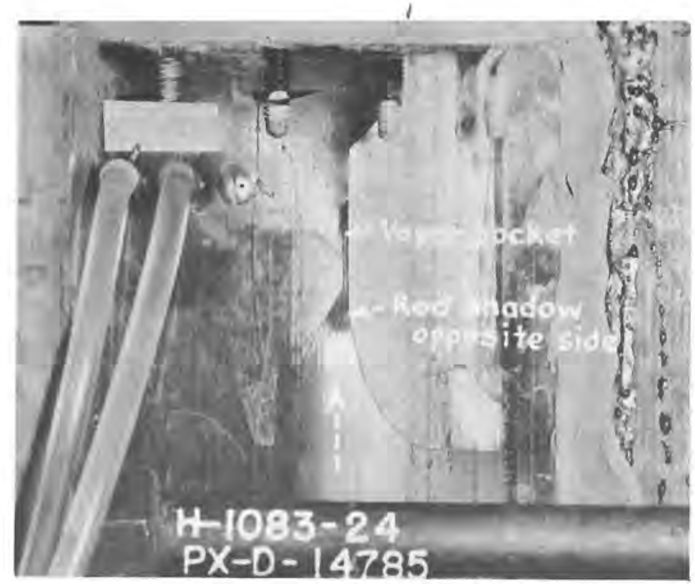


Fig. 18 Vapor Pocket in 1/4-inch long flow passage (width of flat face on gate seal ring) PX-D-14785

Fig. 19 Vapor Pocket downstream from 1/16-inch long flow passage (width of flat face on gate seal ring) PX-D-14786

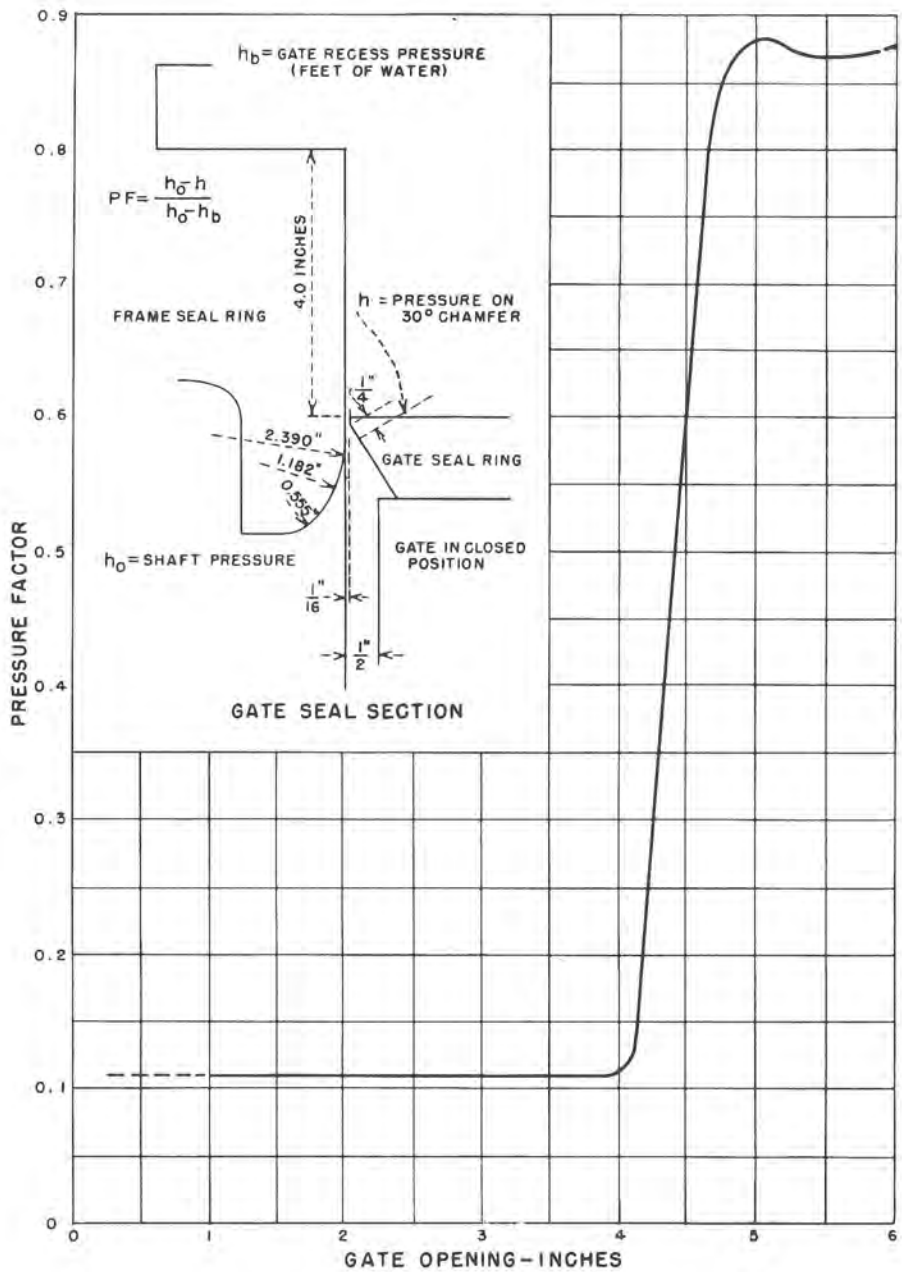


FIGURE 20. PRESSURE CHANGE ON 30 DEGREE CHAMFERED SEAL RING SURFACE FOR SMALL GATE OPENINGS