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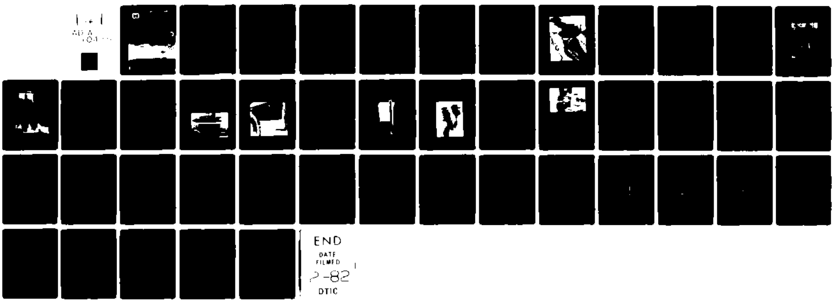

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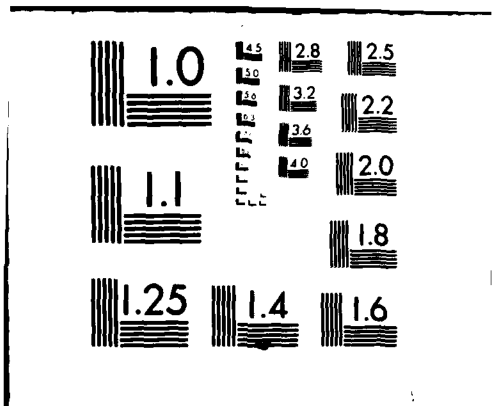

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AIR DEMAND TESTS, LIBBY DAM KOOTENAI RIVER, MONTANA

by

E. Dale Hart

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Prepared for U. S. Army Engineer District, Seattle
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Tests were conducted to determine the quantity of air drawn into one of the Libby Dam sluices following installation of a special aerator device. The test program measured air demand drawn into the test sluice through a full range of gate openings at 1-ft increments from 1 through 16 ft with essentially full pool (2447.7 ft msl).

Data reduction indicated that most of the air is drawn into the aerator

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20. ABSTRACT (Continued).

through the air vent and the equipment shaft (when open). At most gate openings the airflow rate was not constant, experiencing sudden gusts of high velocity. The largest recorded air vent flow occurred between gate openings of 7 to 12 ft (40 to 70 percent).

PREFACE

The prototype tests described in this report were conducted during October 1980 by the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the U. S. Army Engineer District, Seattle.

Acknowledgment is made to individuals of the Seattle District for their assistance in the investigation. Mr. E. D. Hart, Chief of the Prototype Evaluation Branch, was test coordinator for WES. This report was prepared by Mr. Hart with assistance from Mr. E. B. Pickett, Mr. J. E. Hall, and Dr. F. M. Neilson, under the general supervision of Mr. M. B. Boyd, Chief of the Hydraulic Analysis Division, and Mr. H. B. Simmons, Chief of the Hydraulics Laboratory, WES.

Commanders and Directors of WES during the investigation and the preparation and publication of this report were COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acre-feet	1233.482	cubic metres
cubic feet per second	0.02831685	cubic metres per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
feet per second	0.3048	metres per second
feet per second per second	0.3048	metres per second per second
inches	25.4	millimetres
inches per second	25.4	millimetres per second
miles (U. S. statute)	1.609344	kilometres
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6894.757	pascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic foot
slugs (mass) per cubic foot	515.3788	kilograms per cubic metre
square feet	0.09290304	square metres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvins (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

Figure 1. Libby Dam and Reservoir

AIR DEMAND TESTS, LIBBY DAM, KOOTENAI RIVER, MONTANA

PART I: INTRODUCTION

Pertinent Features of the Project

1. Libby Dam (Figure 1) is located on the Kootenai River in northwestern Montana 221.9* river miles** upstream from its confluence with the Columbia River and approximately 17 river miles above the town of Libby, Montana (Figure 2). It is a multipurpose project constructed as

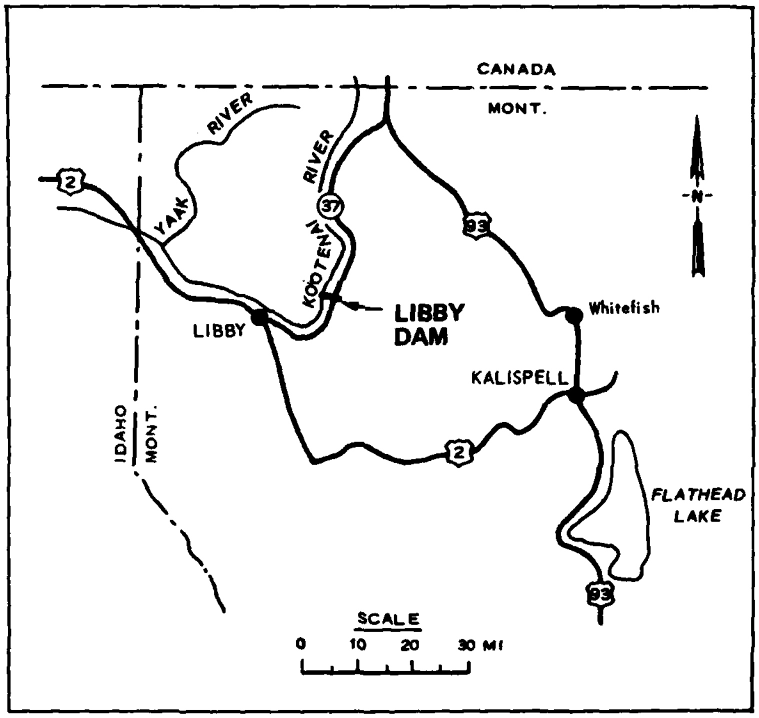

Figure 2. Vicinity map

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* Based on official river miles. Previous publications list the dam location as river mile 219.0

** A table of factors for converting U. S. customary units of measurement to metric (SI) units is given on page 3.

an integral unit of the comprehensive water resource development plan of the Columbia River Basin in the United States and Canada.

2. The completed project consists of a concrete gravity structure, a reservoir (Lake Koocanusa) having a total gross capacity of 5,870,000 acre-ft, at maximum lake elevation 2459 ft msl, and a hydropower installation of four 105,000-kw units. Four additional units are now under construction. The maximum length of the lake is 90 miles (42 of which extend into Canada). The lake provides 4,980,000 acre-ft of flood storage.

Outlet Works

3. Desired flow through the structure is accomplished by means of a two-bay ogee spillway over which flow is controlled by two 48-ft-wide by 56-ft-high tainter gates and three sluices, each 10 ft wide by 22 ft high, controlled by 10-ft-wide by 17-ft-high tainter gates. Both the spillway and sluices empty into the same hydraulic jump-type stilling basin with sloping end sill and no baffles.

Purpose and Scope of Tests

Background

4. Libby Dam became operational in March 1972. Major cavitation damage occurred in the center and right sluices in September 1973 and July 1974, respectively. Following repairs to the center sluice, the U. S. Army Engineer District, Seattle, requested the U. S. Army Engineer Waterways Experiment Station (WES) Hydraulics Laboratory to conduct field measurements to determine the pressures acting on the invert of the center sluice. Tests were conducted in 1974 and a report of findings was published in 1976 (Hart and Tool 1976). With this information as reference material, WES conducted a model study of the sluice (Dortch 1976). As a result, an aerator device was designed that would aerate the flow along the sluice boundaries without adversely affecting flow conditions.

5. The recommended aeration system installation, completed by the Seattle District in the summer of 1980, consists of a slot in both sidewalls and the floor of each sluice as shown in Plate 1. Observation during initial sluice operation revealed, as expected, a significant increase in air demand above the premodified condition. The Seattle District requested a proposal to measure the air demand during operation of the modified sluices.*

Purpose

6. The center sluice of the project receives air indirectly from the outer sluice air vents through crossover passages (Plate 1). Tests were conducted to determine the air drawn into one of the outer sluices as a result of the addition of the aerator. This information would be used to design an independent air vent for the center sluice. A portion of one of the aerators is shown in Figure 3.

Scope

7. The test program measured air demand in the right sluice with a full range of gate openings at 1-ft increments from 1 through 16 ft with essentially full pool (2447.7 ft msl). The test sluice and air vent are shown in Figure 4. The 4- by 4-ft crossover vent to the center sluice, shown in Plate 1 and Figure 5, was blocked to prevent airflow from the other two sluices. Air-demand measurements included the air supplied: (a) by the 7- by 5-ft vent, (b) by the 3.5-ft-diam equipment shaft, and (c) along the roofline of the sluice itself. Separate tests were accomplished with the equipment shaft open and closed. In addition, pressure drops from the atmosphere to the sluice chamber were measured; measurement points are shown in Table 1 and Plate 1.

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* NPSEN-HH-HC, letter to WES, subject: "Libby Dam, Prototype Air-Demand Tests," 26 June 1980.

Figure 3. Sluice aerator slot

Figure 4. Test sluice and air vent (looking upstream)

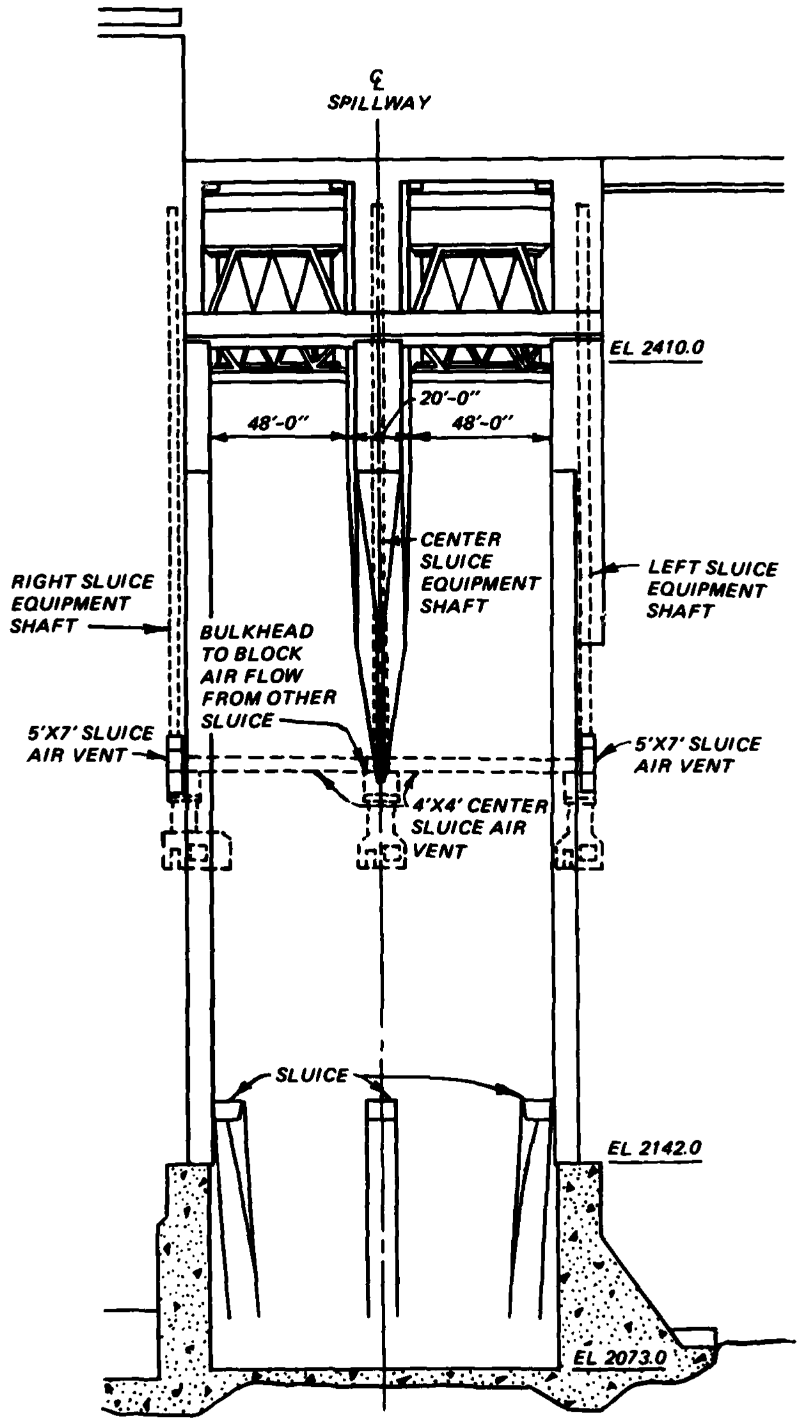


Figure 5. Air vent system, looking upstream.

PART II: TEST FACILITIES, EQUIPMENT, AND PROCEDURES

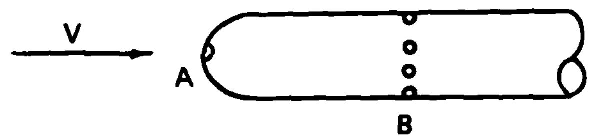
Test Facilities

Air velocity

8. Pitot tube differential pressures were measured at the locations listed in Table 1 and shown in Plate 1 for determining the air velocities in the air vent, equipment shaft, and sluice. For calculating average velocities, the average differential pressure recordings from the oscillograms were used. The largest pitot tube differential pressure observed on either the digital multimeter display or the oscillogram was used in calculating the maximum recorded velocity at each pitot tube for each gate opening. Typical oscillograms are shown in Plates 2 and 3.

9. Pressure probes, such as the pitot tube, rely upon a unique relationship that exists between pressure and velocity. This relationship, discussed in detail in cited references (Rouse 1962, Bryer and Pankhurst 1971), is presented here in mathematical form:

$$\Delta p = p_s - p_o = \frac{\rho V^2}{2}$$



or

$$V = \sqrt{\frac{2\Delta p}{\rho}} = k\sqrt{\Delta p} \qquad (1)$$

where

Δp = pressure difference between positions A and B

p_s = stagnation pressure, position A

p_o = pressure of the undisturbed flow, position B

ρ = mass density of air at ambient temperature

V = point velocity of the air being measured

10. Because air is compressible, higher densities and temperatures will occur at the pitot tube position A, the point of maximum pressure. The resulting effect on the differential pressure being recorded is directly proportional to the air velocity. For Mach numbers less

than unity, this effect is considered negligible (Vennard 1954). The Mach number is a ratio of the air velocity to the propagation velocity of a pressure wave in the same medium. For a point velocity of 156 fps (see Table 2, Test 9), the Libby tests Mach number is less than 0.2. Therefore, the compressibility effect was not considered in converting the measured differential pressures to point velocites.

11. A typical arrangement of the pitot tube, differential pressure transducer, and electrical cables is shown in Figure 6. The transducer is a Validyne DP9 differential pressure transducer with a range of 0 to 0.5 psid. Specifications for all transducers used in the test program are presented in Table 1. Pitot tubes used in the tests were calibrated in a wind tunnel at the National Space Technology Laboratories (NSTL), Bay St. Louis, Mississippi. The calibration provided a correction coefficient for the pitot tubes used in the study.

12. The theoretical coefficient (k) of Equation 1 is $\sqrt{2/\rho}$. The

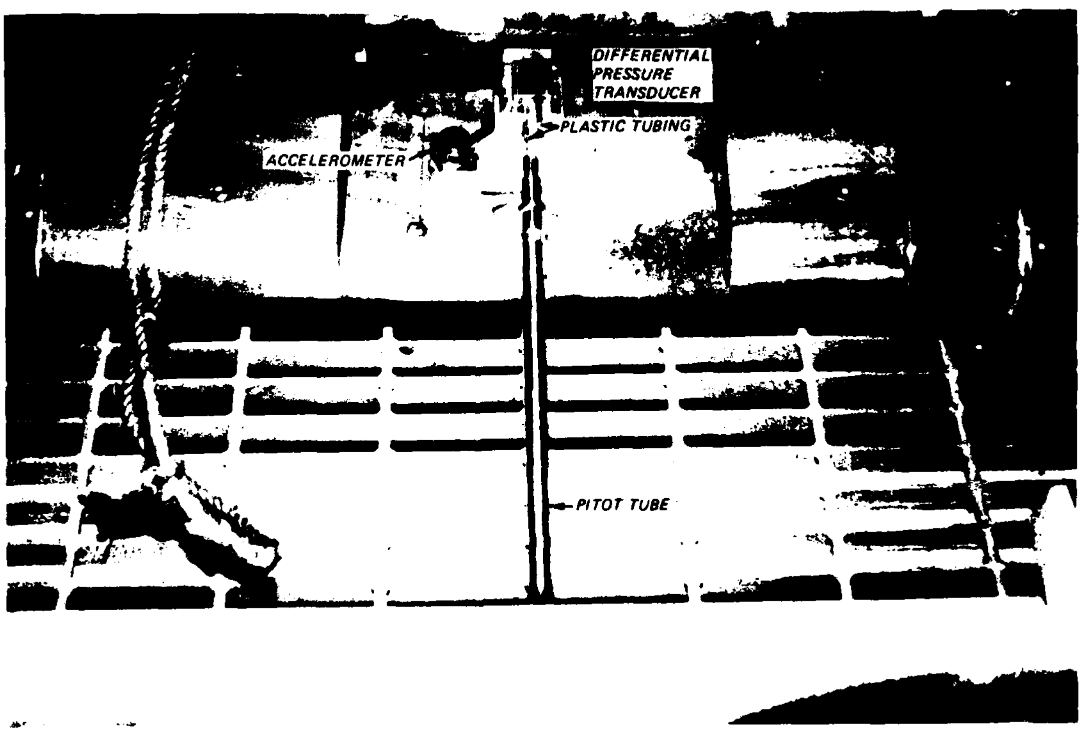


Figure 6. Equipment shaft strut (panel removed) and instrumentation

average temperature during the field tests was 41°F giving a value of $\rho = 0.00247 \text{ lb-sec}^2/\text{ft}^4$. Therefore

$$k = \sqrt{\frac{2 \times 144}{0.00247}} = 341.47 \quad \frac{\text{in.-ft}}{\text{sec } \sqrt{\text{lb}}}$$

where Δp (Equation 1) is in psi. The calibrated pitot tube coefficient was calculated to be 351.90 based on information provided by NSTL. A graph comparing the coefficients is presented in Plate 4. The test section of the wind tunnel is shown in Figure 7.

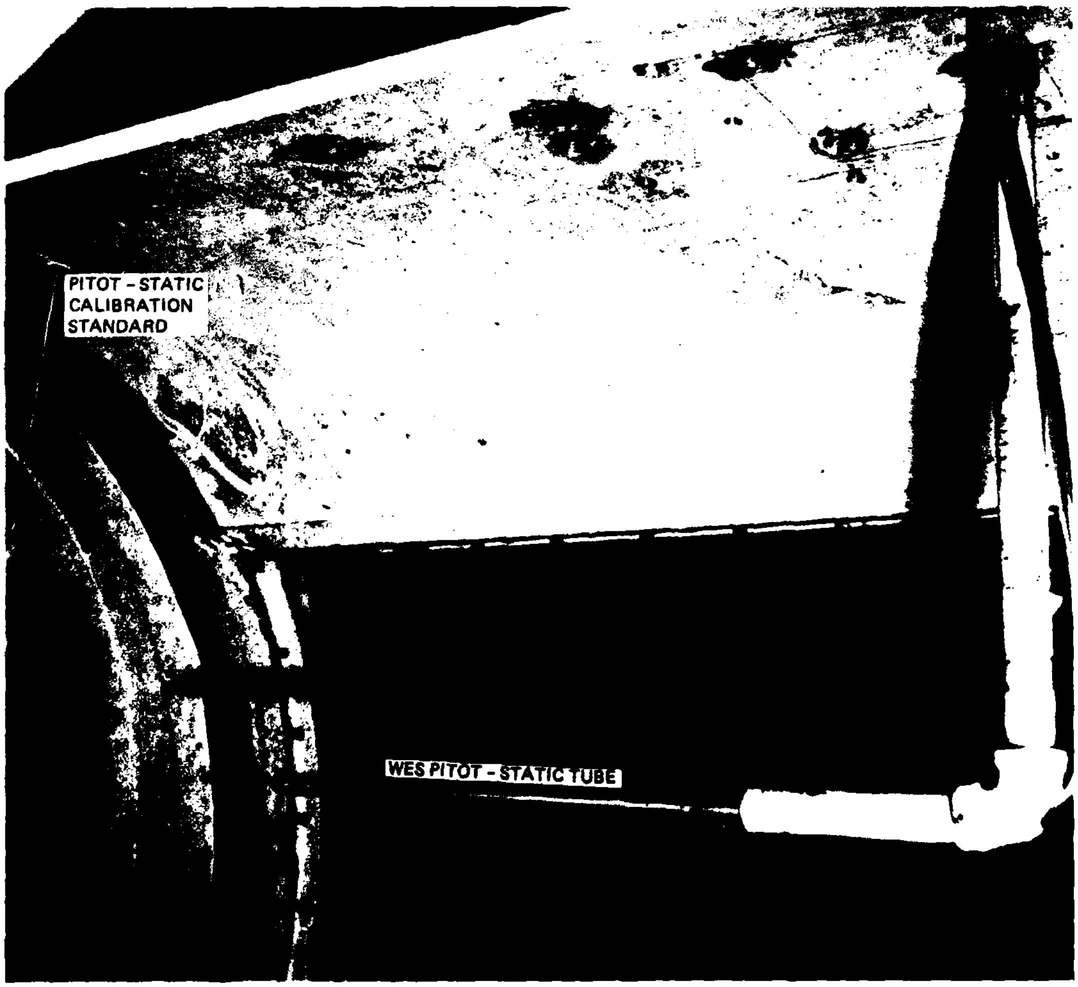
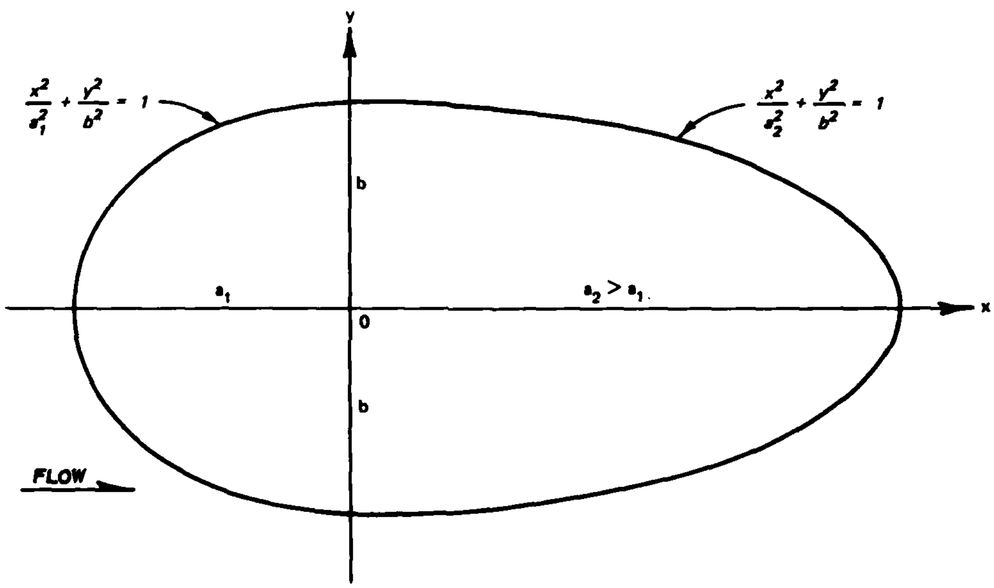


Figure 7. Wind tunnel test section

Struts

13. The streamlined struts were fabricated from mahogany. A typical strut cross section is shown in Figure 8. The cross section of each consisted of two ellipses joined at their minor axes. The downstream major axis (a_2) was longer than the upstream (a_1). The minor axes (b) were identical. The struts consisted of two halves, divided along the major axis. Sections of each inner side of the strut were grooved to accommodate the pitot tubes, pressure transducers, accelerometers, and cables, as in Figure 6.



Strut Location	Cross-Section Dimensions, in.		
	a_1	a_2	b
Air vent	5.00	8.50	2.38
Equipment shaft	4.00	5.50	1.75
Sluice	3.00	3.00	1.25

Figure 8. Strut cross section

14. Strut brackets were fabricated to attach to the walls and encase the strut ends. After bolting the brackets in place, shims and setscrews were used to hold the strut securely in place. Electrical cables that exited from one end of the strut were attached to anchor bolts every foot through the area of high velocity. Figure 9 shows the air vent strut in place with brackets and secured cables.

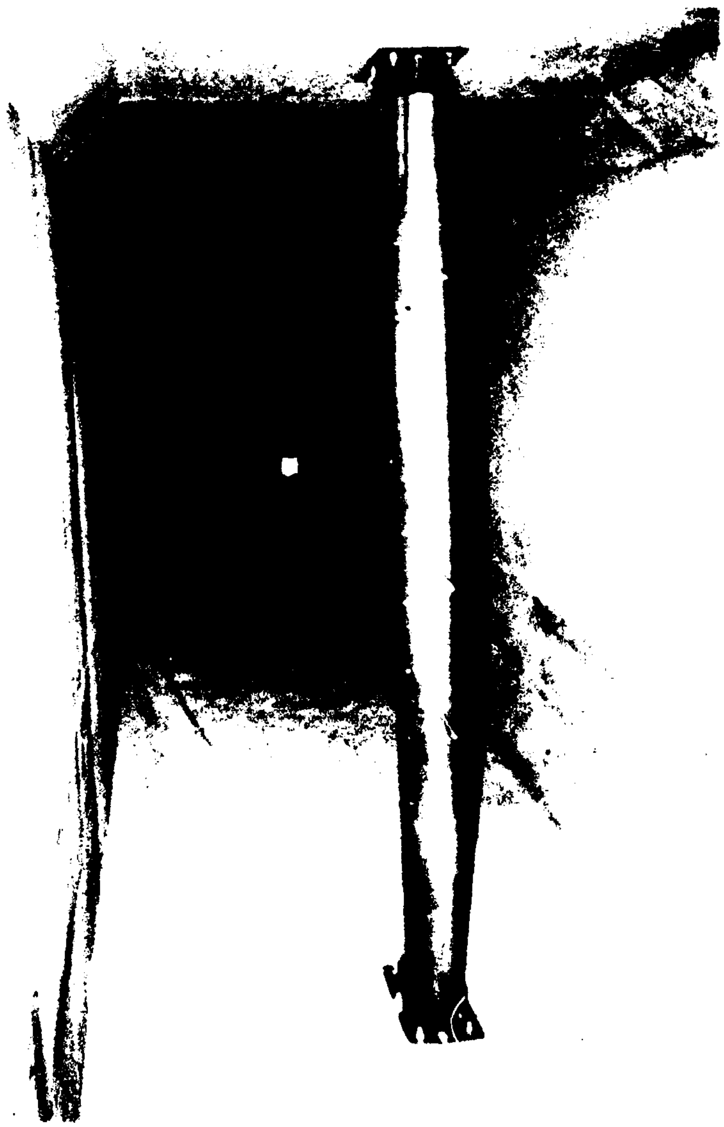


Figure 9. Air vent strut and pitot tubes

Transducer locations

15. The pitot tube and acceleromenter arrangements are presented in Table 1 and Plate 5. The equipment shaft pressure transducer (ES1) and accelerometer (ESA) were located in the center of the strut. The distance ratios (y/r) from the air vent strut center line to the pitot tubes are shown in Plate 5. The sluice strut was attached to the sluice roof as shown in Figure 10 and Plate 1. The pitot tubes were located 6 and 13.5 in. from the roof; this was necessary to keep them dry during the higher gate openings.

Figure 10. Sluice strut and pitot tubes

Strut acceleration

16. Computations indicated the possibility of the struts vibrating at or near their natural frequency. For this reason, a ±5 g accelerometer was placed in the center of the air vent and equipment shaft struts (AVA and ESA, respectively). The accelerometers were secured with wood screws and their cables led out of the struts through the pressure transducer cable passageway grooves.

Differential pressure

17. Pressure in the gate chamber was measured with a differential pressure transducer (GC1, Table 1, Plate 1). The purpose was to measure the drop in pressure from the atmosphere to the aerator which caused the airflow through the air vent, equipment shaft, and sluice. The transducer was placed on the handrail of the gate chamber walkway a short distance from the aerator.

Other Measurements

18. Other recorded data consisted of upper pool elevation, air temperature, barometric pressure, gate opening, and water discharge. These data were provided by project and District personnel. Water discharge was determined from computed discharge rating curves.

Recording Equipment

19. The recording equipment consisted of: (a) WES-fabricated model 03 bridge amplifiers to condition the strain gage transducers (GC1, AVA, ESA) output signal, (b) a WES-fabricated channel selector, (c) a Validyne CD12 recorder for providing an analog output signal, (d) a Fluke 8300A digital multimeter for displaying the Validyne recorder output voltage digitally (AV1, AV2, AV3, AV4, ES1, SL1, and SL2), and (e) a CEC model 5-124, 7-in. direct print oscillograph capable of reproducing up to 18 channels of data at chart speeds of 1/4 to 64 ips. Chart speeds of 4, 16, and 64 ips were used during the Libby tests. Figure 11 shows the equipment setup at the recording station.

Figure 11. Test recording equipment

Test Procedures

20. Tests were conducted on 22 October 1980. Data for each gate opening were recorded on the oscillograph chart and also read from the multimeter and recorded manually. The procedure was the same for all tests and consisted of the following:

- a. Record step calibrations.
- b. Record test number, date, time, and gate opening.
- c. Raise gate to desired opening; allow flow to stabilize.
- d. Set channel selector.
- e. Set zero and gain on Validyne recorder.
- f. Record data on the oscillograph chart and manually.
- g. Repeat steps d-f until all data channels are recorded.
- h. Record upper pool elevation, barometric pressure, and air temperature.
- i. Record step calibrations.

Notes were made on the oscillograms during the tests for reference during data reduction and analysis.

PART III: TEST RESULTS AND ANALYSIS

Air Discharge

21. Point velocities in the equipment shaft, air vent, and sluice were calculated by the methods previously described. Conditions at each measurement station were different, necessitating different methods of coverting the calculated point velocities to average velocities in their respective conveyance system. These methods and results are described below. In addition, the pressure drop data measured at the gate chamber were used to approximate losses through the equipment shaft and air vent.

Equipment shaft

22. Rouse (1962) shows that when the Karman-Prandtl velocity distribution equations for smooth and rough surfaces are each solved for the mean velocity and then subtracted from their original form, an identical expression results. With a slight adjustment of coefficients, the derived equation was found to agree very closely with experimental data. This final form, which presents the mean velocity ($\overline{V}$) as a function of the maximum (center line) velocity (V_m) and the resistance coefficient (f), is

$$\overline{V} = \frac{V_m}{1.43\sqrt{f} + 1} \tag{2}$$

23. Provided the Reynolds Number ($\Re$) is sufficiently high, the velocity distribution in a circular duct should be typical of fully developed turbulent flow at a distance of about 50 diameters or more downstream of the entrance. The equipment shaft strut was located 49 diameters downstream of the entrance (top of the dam) and $\Re$ was equal to or greater than 7×10^5 (Tables 2 and 3). Therefore, Equation 2 is applicable for converting the measured center-line velocities to mean equipment shaft velocities.

24. The Corps of Engineers (OCE 1980) recommends a surface roughness height (k) value of 0.0020 for circular concrete conduits. For a 3.5-ft-diam conduit, this corresponds to a resistance coefficient (f)

value of approximately 0.019. Since this is a design recommendation, a further review was conducted. The k value range for concrete is given in most references as 0.001 to 0.01 ft. This corresponds to f values for this study of 0.015 and 0.026, respectively. Albertson et al. (1961) state "the average value of k should be utilized unless additional information is available." The average value of f then is 0.0205.

25. A value of $f = 0.021$ was used in the computations. It is noted that using the above extreme values of f and a center-line velocity of 100 fps, the average velocity differs by only 4 percent. The flow rate was then determined by multiplying the average velocities by the equipment shaft area (9.62 ft^2). Plate 6 presents the average equipment shaft discharge values for each gate opening. Table 4 also presents the average as well as maximum computed discharges. Tables 2 and 3 present the observed maximum and average equipment shaft point velocities which were used in the air discharge computations.

Air vent

26. Point velocities were measured at four vertical locations in the air vent as shown in Plate 5. The strut was located 57 ft downstream of the vent entrance or 9.8 equivalent diameters (D_e = 5.75 ft). The strut was situated in this forward position in an attempt to minimize back-pressure effects in the relatively short vent (15.4 D_e) which exits at a right angle into the gate chamber.

27. Because of the short distance from the entrance (and after reviewing the data), the velocity distribution was assumed to be essentially constant from wall to wall. The mean velocity, then, was assumed to be the average value of the four measurements. To determine the degree of validity of this assumption, the standard deviation (σ) of the velocities for each gate opening was computed. The average of this value divided by the average of the means ($\overline{V}$) gives the coefficient of variation (CV) (Miller and Freund 1977), i.e.,

$$CV = \frac{\overline{\sigma}}{\overline{\overline{V}}} \qquad (3)$$

28. For the Libby air vent measurements, the value of CV was

determined to be 0.080 and 0.095 for the average and maximum recorded point velocities, respectively. In other words, on the average, the respective standard deviations were 8.0 and 9.5 percent of the mean. This implies that the assumption of uniform velocity distribution at the strut is reasonable. These mean velocities were multiplied by the air vent area (34.5 ft^2) to determine the discharge. Air vent discharge versus gate opening is presented in Plate 6 with the equipment shaft open and closed. Note that the discharge is approximately the same in each case. Table 4 presents the average and maximum computed air vent discharges. The maximum values are approximately 20 percent and 25 percent greater than the average values with the equipment shaft open and closed, respectively. Tables 2 and 3 present the observed maximum and average air vent point velocities which were used in the air discharge computations. The four point velocities used in each computation were not recorded simultaneously. Plate 7 presents the air to water discharge ratio as a function of the Froude number plotted on the Hydraulic Design Criteria Chart 050-1.

29. Sudden gusts of high-velocity air occurred during many gate openings. To estimate the relative difference between a gust velocity and the recorded high velocities the gust peak of AV4, test 26 (Table 2 and Plate 2), was compared with the average of the recorded maximum velocities of AV1, AV2, and AV3, same test. These values are 139.0 and 103.0 fps, respectively. This indicates that the gust velocity was 35 percent greater than the average of the recorded nongusting maximum velocities.

Sluice

30. After the aerators were installed, spray was observed being drawn back into the sluices at their exit portals. Therefore it was determined that airflow in the sluice should be monitored also. The sluice air velocity was measured near the roof as shown in Plate 1. As stated previously, this was necessary to ensure that the strut and encased transducers cleared the discharging water at all gate openings. It was assumed that a bidirectional velocity profile existed in the sluice, i.e., the pressure differential causing air near the roof to move upstream and shear at the air-water interface causing downstream flow of the lower portion. This is similar to the theoretical study of flow between two

parallel plates (Schlichting 1968). In this case, one wall is at rest (sluice roof) and the other wall moves at velocity U (water-surface velocity).

31. Use of this theoretical approach for computing sluice discharge was complicated by the fact that the velocity data (SL1, SL2) indicated that (a) there was very little airflow at the measurement point for gate openings of 11 ft and less, and (b) the measured flow oscillated in both directions at the higher gate openings. Figure 12 presents an illustration of this phenomenon. For these reasons, it is believed that very little of the air entering the sluice exit actually reached the aerator, instead was drawn back out by shear along the air-water interface.

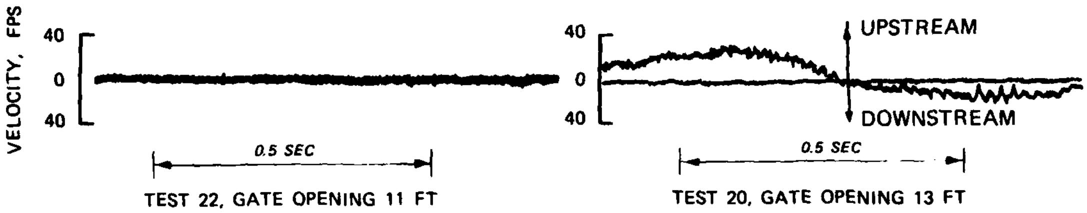


Figure 12. Sluice airflow (SL2)

Pressure Differential

32. The pressure differential between the atmosphere and the gate chamber was measured with a differential pressure transducer located near the aerator (GC1), which is shown in Plate 1. These data were used, with the velocity measurements, to approximate losses through the air vent and equipment shaft. The Bernoulli equation (Rouse 1962) may be used to evaluate the total energy loss from the entrances to the gate chamber as follows:

$$\rho \frac{V_e^2}{2} + p_e = \rho \frac{V_c^2}{2} + p_c + \rho \frac{V_m^2}{2} K \qquad (4)$$

where

ρ = density of air, slugs/ft^3

V_e = entrance velocity, ft/sec
p_e = entrance pressure, lb/ft^2
V_c = chamber velocity, ft/sec
p_c = gate chamber pressure, lb/ft^2
V_m = measurement point (air vent or equipment shaft) velocity, ft/sec
K = loss coefficient

Assuming $V_e << V_c << V_m$ Equation 4 reduces to $\Delta p = \rho \left(Q_m^2 \Big/ 2A_m^2\right) K$

$$\therefore \quad Q_m^2 = \frac{2A_m^2}{\rho K} \Delta p \quad \text{or} \quad Q_m = K' \sqrt{\Delta p} \tag{5}$$

where

$$K' = A_m \sqrt{\frac{2}{\rho K}} \tag{6}$$

where

$Q_m = V_m A_m$
A_m = *conveyance system cross section at the measurement location*
Δp = pressure differential between the atmosphere and the gate chamber

33. Using the field data, the values of Q_m, $\sqrt{\Delta p}$, and K' (Equation 5) for each gate opening were computed for both the equipment shaft and the air vent flows. A plot of the individual data points with their corresponding averaged K' value is presented in Plate 8. With this information the apparent total loss coefficient (K) through each system can be determined with Equation 6. For the equipment shaft and air vent, the values are:

$$K_{ES} = \frac{2(9.62)^2}{(0.00247)\ (176.0)^2} = 2.4 \qquad K_{AV} = \frac{2(34.5)^2}{(0.00247)\ (572.1)^2} = 2.9$$

34. These K values are the sum of the loss coefficients for each conveyance system. The primary individual losses contributing to

the total were assumed to be the entrance, friction, and exit losses. Assigning values of 0.5, 0.02 L/D (conveyance system length to diameter ratio), and 1.0 to these losses, respectively, the sums were determined to be:

$$K_{ES} = 2.59 \qquad K_{AV} = 1.82$$

The equipment shaft coefficient seems reasonable while the air vent value is lower than the computation based on the test data. The additional losses may be due to the combined sudden expansion, 90-deg turn, and grating (el 2265.63, Plate 1) at the top of the gate chamber.

Strut Vibrations

35. The aformentioned accelerometers were placed in the equipment shaft and air vent struts to monitor their vibrations. Prior to the tests, each was struck lightly with the butt of the hand and the response recorded. These recordings are shown in Figure 13. During the entire test program, the air vent strut (AVA) vibrated very near its natural frequency. The maximum recorded peak-to-peak displacement was 5×10^{-3} in. at a frequency of 56 Hz and a gate opening of 10 ft. The equipment shaft strut (ESA) maximum displacement was 7.5×10^{-4} in. at 130 Hz (9-ft gate opening).

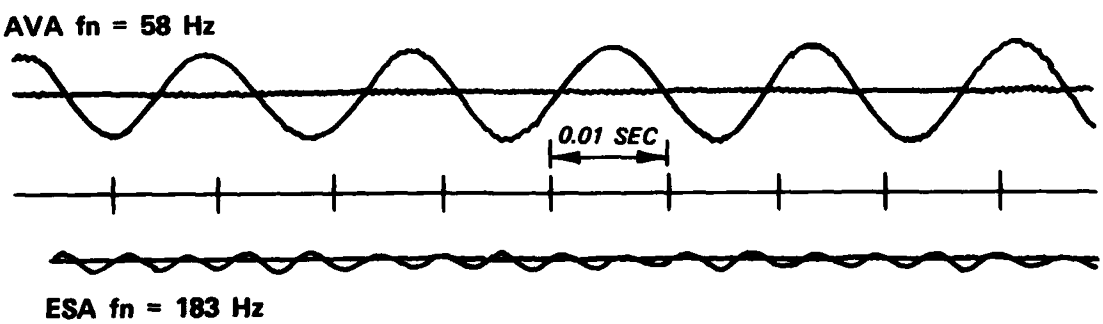


Figure 13. Air vent strut (top) and equipment shaft strut (bottom) "tap" response

Measurement Errors

36. The maximum error in pressure differential determination from the records or the digital multimeter is estimated to be approximately 7 percent. This value is based on the following estimated errors.

- a. The step calibrations were read to within ± 0.02 in. over a 1-in. deflection for an error of 2 percent.
- b. The oscillogram traces were read to within ± 0.02 in. over a deflection of 0.4 in. for an error of 5 percent.
- c. It is estimated that the digital multimeter was read with an error of ± 5 percent.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

37. The following determinations, conclusions, and recommendations result from literature review, field observations, and analysis of the reduced data of the Libby Dam air demand tests.

- a. Measurements indicate that practically all of the air is drawn into the aerator through the air vent and equipment shaft (when open).
- b. The air vent draws approximately the same amount of air whether the equipment shaft is open or closed.
- c. The maximum measured airflow values of the air vent exceeded the average values by approximately 20 and 25 percent with the equipment shaft open and closed, respectively.
- d. Observations were made of air being drawn into the exit portal of the sluice at many gate openings. Air in the sluice oscillated in both directions at the measurement point, indicating it may not have reached the aerator.
- e. A reasonable approximation of the loss coefficients through the equipment shaft and air vent is 2.5 and 2.9, respectively.
- f. Since the spillway location precludes duplicating the existing air vent geometry, a loss coefficient for the proposed center sluice air vent cannot be approximated directly from these measurements. If the surface finish is similar to the equipment shaft and air vent tested, 0.02 would be a reasonable approximation of the friction coefficient to be used in estimating friction losses.
- g. At most gate openings the airflow rate was not constant, experiencing sudden gusts of high velocity. This instability should be considered in the air vent design.
- h. Because of g, future air demand tests should consist of simultaneous recording of all channels on magnetic tape in order to fully analyze the gusting phenomenon.
- i. Model results (Dortch 1976) indicate that an increase in air demand will occur during combined spillway-sluice flow. This should be considered if combined flow is anticipated.

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Table 1

Instrumentation

	Instrument		Instrument Location*			Cable	
Code	Type	Range	Description	Sta**	El	Length, ft	Parameter
AV1	Validyne DP9	0.5 psid	Air vent strut	0+85.7	2279.0	320	Point velocity
AV2	Validyne DP9	0.5 psid	Air vent strut	0+85.7	2277.0	320	Point velocity
AV3	Validyne DP9	0.5 psid	Air vent strut	0+85.7	2276.0	320	Point velocity
AV4	Validyne DP9	0.5 psid	Air vent strut	0+85.7	2274.0	320	Point velocity
AVA	CEC 4-202	±5 g's	Air vent strut	0+85.7	2277.0	320	Strut transverse vibration
ES1	Validyne DP9	0.5 psid	Equip. shaft strut	0+40.5	2300.5	320	Point velocity
ESA	CEC 4-202	±5 g's	Equip. shaft strut	0+40.5	2300.5	320	Strut transverse vibration
SL1	Validyne DP9	5 psid	Roof of sluice	0+84.0	2206.5	420	Point velocity
SL2	Validyne DP9	0.5 psid	Roof of sluice	0+84.0	2205.9	420	Point velocity
GC1	CEC 4-312	0-15 psia	Gate chamber handrail	0+54.0	2219.5	250	Absolute pressure

* See Plate 1

** Scaled from drawings.

Table 2

Air Vent and Equipment Shaft Maximum Recorded Point Velocities

Test No.	Gate Opening ft	Air Vent AV1 fps	Air Vent AV2 fps	Air Vent AV3 fps	Air Vent AV4 fps	Air Vent Avg fps	Air Vent $\Re \times 10^6$*	Equipment Shaft ES1 fps	Equipment Shaft Avg fps	Equipment Shaft $\Re \times 10^6$*
1	1.0	20.8	38.6	20.8	38.5	29.7	1.16	35.2	29.1	0.70
2	2.0	26.1	38.6	27.3	26.1	29.5	1.16	35.2	29.1	0.70
3	3.0	28.4	41.6	32.4	33.4	33.9	1.33	45.2	37.4	0.90
4	4.0	43.9	54.5	43.4	40.1	45.5	1.79	61.9	51.3	1.22
5	5.0	55.6	72.1	66.8	67.7	65.6	2.58	103.8	86.0	2.06
6	6.0	77.0	85 5	89.7	92.4	86.2	3.39	95.1	78.8	1.88
7	7.0	101.4	101.4	81.0	92.4	94.0	3.70	106.2	87.9	2.10
8	8.0	115.6	96.4	109.6	98.2	105.0	4.13	153.4	127.1	3.05
9	9.0	126.9	116.7	110.2	102.0	113.8	4.48	156.0	129.2	3.10
10	10.0	108.5	120.0	103.2	100.8	108.1	4.25	126.9	105.1	2.52
11	11.0	93.8	90.4	81.8	92.4	89.6	3.53	116.7	96.7	2.32
12	12.0	80.2	87.6	84.0	86.9	84.7	3.33	126.9	105.1	2.52
13	13.0	85.5	93.1	73.0	73.8	81.3	3.20	110.2	91.2	2.19
14	14.0	84.0	87.6	91.2	84.0	86.7	3.39	118.8	98.4	2.36
15	15.0	82.5	94.4	80.2	81.8	84.7	3.33	111.3	92.2	2.21
16	16.0	72.1	79.5	74.7	69.5	73.9	2.91	98.9	81.9	1.96
17	16.0	77.9	79.5	73.8	73.0	76.0	2.99	--	--	--
18	15.0	84.8	97.7	86.2	88.3	89.2	3.51	--	--	--
19	14.0	80.2	91.1	95.7	93.1	90.0	3.54	--	--	--
20	13.0	81.0	95.7	77.1	85.5	84.8	3.34	--	--	--
21	12.0	86.2	94.4	99.8	105.0	96.4	3.80	--	--	--
22	11.0	104.4	140.8	98.3	97.7	110.3	4.34	--	--	--
23	10.0	100.8	133.5	96.4	118.8	112.9	4.44	--	--	--
24	9.0	121.9	134.0	114.6	123.0	123.4	4.86	--	--	--
25	8.0	98.3	112.4	102.0	113.5	106.6	4.20	--	--	--
26	7.0	102.0	108.5	98.9	139.0	112.1	4.41	--	--	--
27	6.0	81.8	89.0	82.4	98.3	87.9	3.46	--	--	--
28	5.0	77.1	77.0	72.0	73.8	75.0	2.95	--	--	--

* $\Re = \frac{\bar{V}L}{\upsilon}$ where $\bar{V}$ = average velocity, fps; L = conduit diameter, feet; and $\upsilon = 1.46 \times 10^{-4}$ ft^2/sec.

Table 3

Air Vent and Equipment Shaft Average Point Velocities

Test No.	Gate Opening ft	Air Vent AV1 fps	AV2 fps	AV3 fps	AV4 fps	Avg fps	$\Re \times 10^6$*	Equipment Shaft ES1 fps	Avg fps	$\Re \times 10^6$*	ΔP GC1 psf
1	1.0	20.8	38.6	20.8	38.5	29.7	1.17	35.2	29.1	0.70	--
2	2.0	26.1	38.6	27.3	26.1	29.5	1.16	35.2	29.1	0.70	--
3	3.0	28.4	41.6	32.4	33.4	33.9	1.33	45.2	37.4	0.90	--
4	4.0	43.9	54.5	43.4	40.1	45.5	1.79	58.9	48.8	1.17	6.8
5	5.0	52.2	68.6	63.9	57.8	60.6	2.39	79.4	65.8	1.57	14.6
6	6.0	65.8	68.6	78.7	78.7	73.0	2.88	91.7	76.0	1.82	17.9
7	7.0	77.9	89.7	76.3	78.7	80.6	3.17	98.3	81.4	1.95	26.2
8	8.0	86.2	89.0	86.2	81.8	85.8	3.38	144.2	119.4	2.86	34.7
9	9.0	86.2	93.1	82.5	94.4	89.1	3.51	102.6	85.0	2.04	29.5
10	10.0	87.6	82.5	83.3	84.8	85.8	3.38	111.2	92.1	2.21	28.5
11	11.0	75.4	78.7	70.4	65.8	72.6	2.86	95.1	78.8	1.89	19.3
12	12.0	72.1	73.8	73.0	74.7	73.4	2.89	96.3	79.8	1.91	15.3
13	13.0	73.0	72.1	65.8	63.0	68.5	2.70	98.2	81.3	1.95	19.7
14	14.0	74.6	77.9	80.2	67.7	75.1	2.96	103.1	85.4	2.05	24.1
15	15.0	70.4	78.4	70.4	70.4	72.4	2.85	104.4	86.5	2.07	22.8
16	16.0	66.8	72.1	63.9	61.9	66.2	2.61	89.0	73.7	1.77	10.6
17	16.0	70.4	73.8	69.5	66.7	70.1	2.76	--	--	--	19.0
18	15.0	72.1	77.9	74.6	72.1	74.2	2.92	--	--	--	21.6
19	14.0	71.2	79.4	76.3	75.5	75.6	2.98	--	--	--	21.6
20	13.0	73.8	73.0	67.7	71.3	71.4	2.81	--	--	--	16.8
21	12.0	73.0	87.6	81.8	68.6	77.8	3.06	--	--	--	27.1
22	11.0	80.2	86.2	74.6	77.1	79.5	3.13	--	--	--	21.6
23	10.0	86.2	102.6	81.0	100.2	92.5	3.64	--	--	--	24.4
24	9.0	102.0	87.6	80.2	101.4	92.8	3.65	--	--	--	41.1
25	8.0	77.7	83.0	86.5	86.2	85.3	3.36	--	--	--	28.2
26	7.0	87.6	82.5	77.1	100.2	86.8	3.42	--	--	--	25.4
27	6.0	75.5	75.5	77.9	72.1	75.2	2.96	--	--	--	16.8
28	5.0	62.9	65.8	57.8	55.6	60.5	2.38	--	--	--	13.5

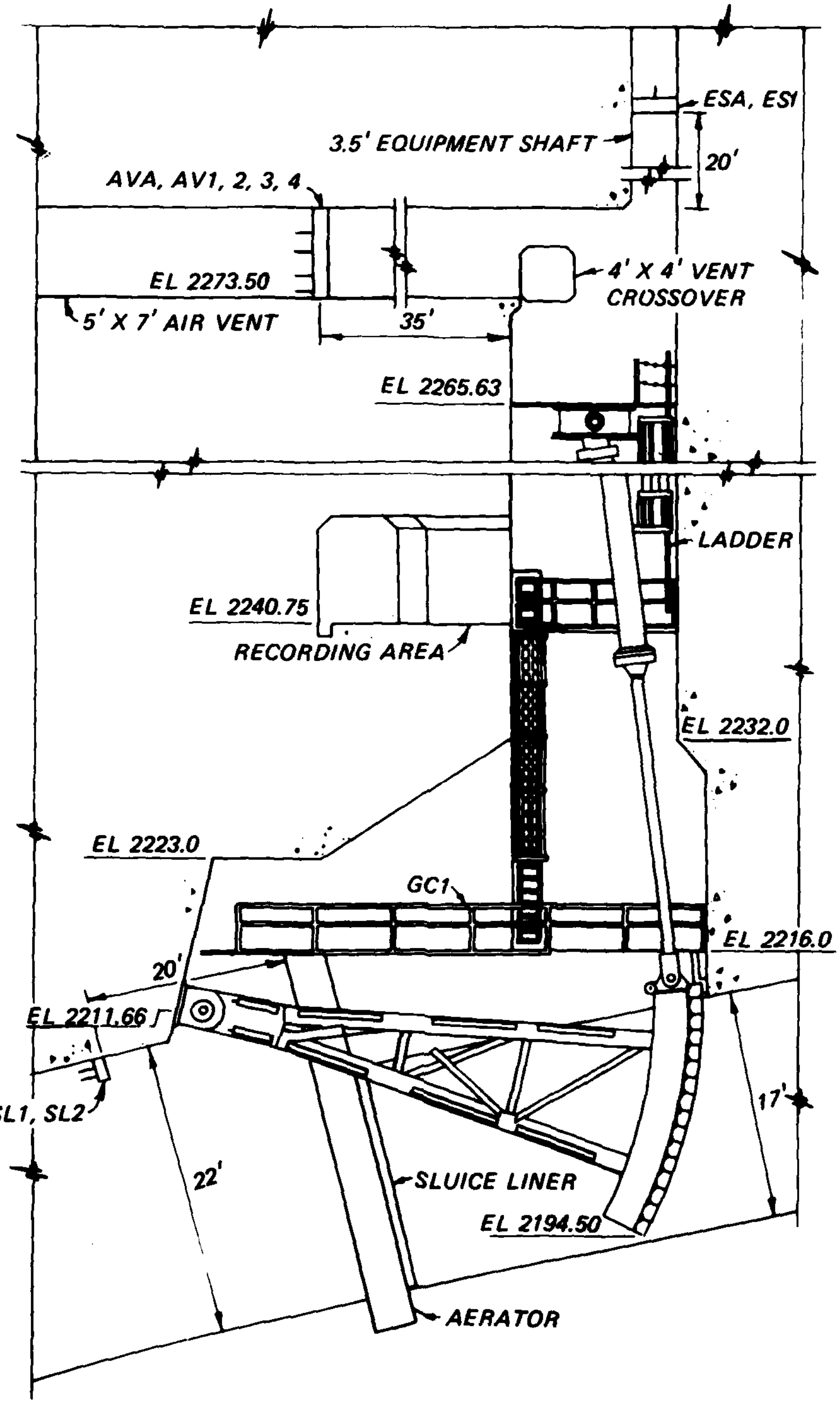
* $\Re = \frac{\bar{V}L}{\upsilon}$ where $\bar{V}$ = average velocity, fps; L = conduit diameter, feet; and $\upsilon = 1.46 \times 10^{-4}$ ft^2/sec.

Table 4

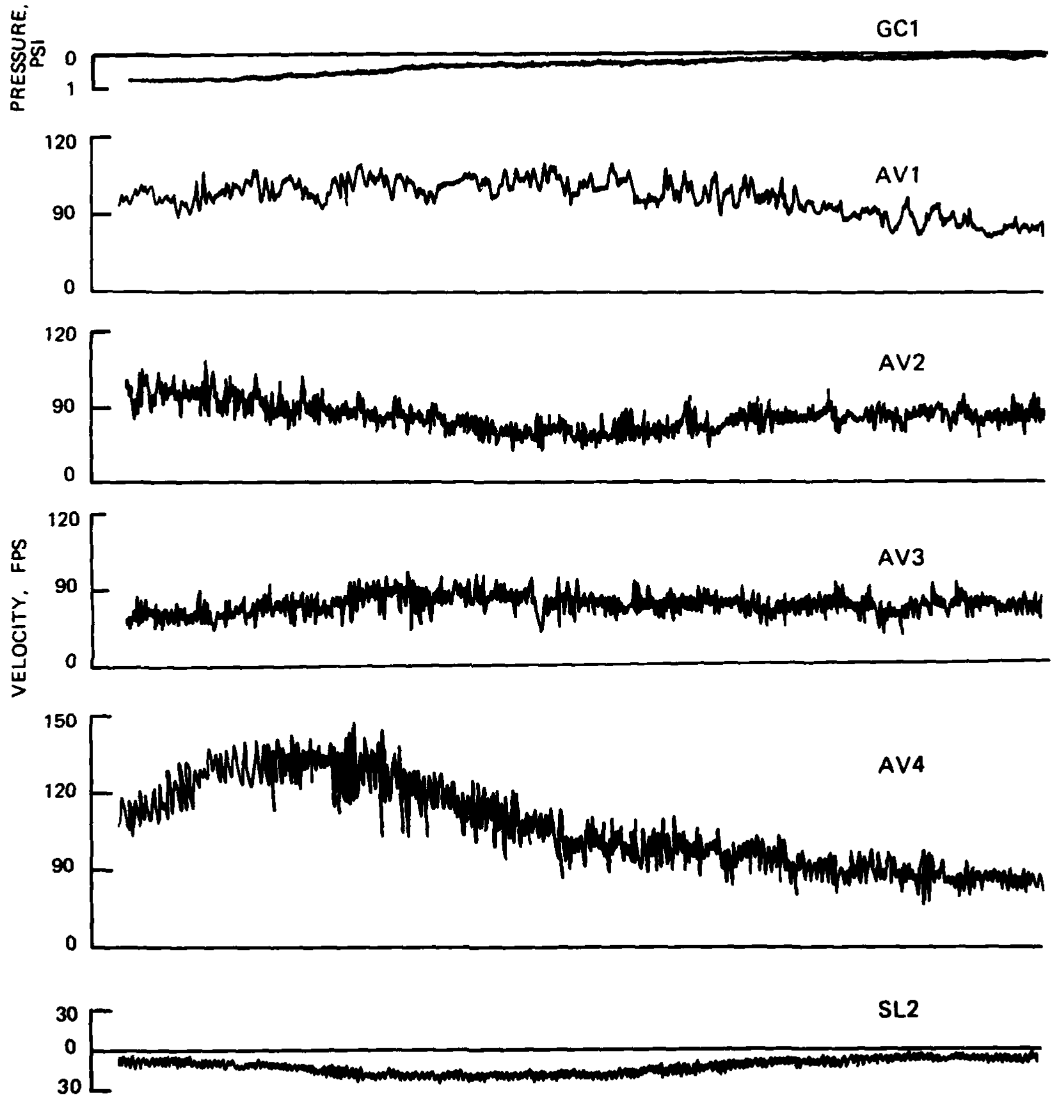
Test Conditions and Results 10/22/80

Test No.	Start Time	Air Temp °F	Gate Open ft	Water Q cfs	Mean Airflow, cfs Air Vent	Mean Airflow, cfs Eq. Shaft	Maximum Computed Airflow, cfs Air Vent	Maximum Computed Airflow, cfs Eq. Shaft
1	0850	34	1.0	780	1024	280	1024	280
2	0910		2.0	1,600	1018	280	1018	280
3	0925		3.0	2,400	1171	360	1171	360
4	0940		4.0	3,000	1570	469	1570	494
5	1000		5.0	3,800	2092	633	2261	827
6	1020		6.0	4,500	2518	731	2973	758
7	1045		7.0	5,300	2781	783	3243	846
8	1110		8.0	6,000	2960	1150	3622	1222
9	1230		9.0	6,800	3074	818	3926	1242
10	1245		10.0	7,800	2960	886	3729	1011
11	1305		11.0	8,800	2504	758	3091	930
12	1315		12.0	9,800	2532	768	2922	1011
13	1332		13.0	10,800	2363	782	2805	878
14	1343		14.0	12,000	2591	821	2974	947
15	1353		15.0	13,500	2498	832	2922	887
16	1410		16.0	15,300	2283	709	2550	788
17	1430	47	16.0	15,300	2418	--	2622	--
18	1440		15.0	13,500	2559	--	3078	--
19	1448		14.0	12,000	2608	--	3105	--
20	1458		13.0	10,800	2463	--	2926	--
21	1506		12.0	9,800	2684	--	3326	--
22	1514		11.0	8,800	2743	--	3805	--
23	1522		10.0	7,800	3191	--	3895	--
24	1530		9.0	6,800	3202	--	4257	--
25	1542		8.0	6,000	2873	--	3678	--
26	1550		7.0	5,300	2995	--	3867	--
27	1601	42	6.0	4,500	2594	--	3032	--
28	1610		5.0	3,800	2088	--	2588	--

Pool elevation 2447.70, atmospheric pressure 13.91 psi.



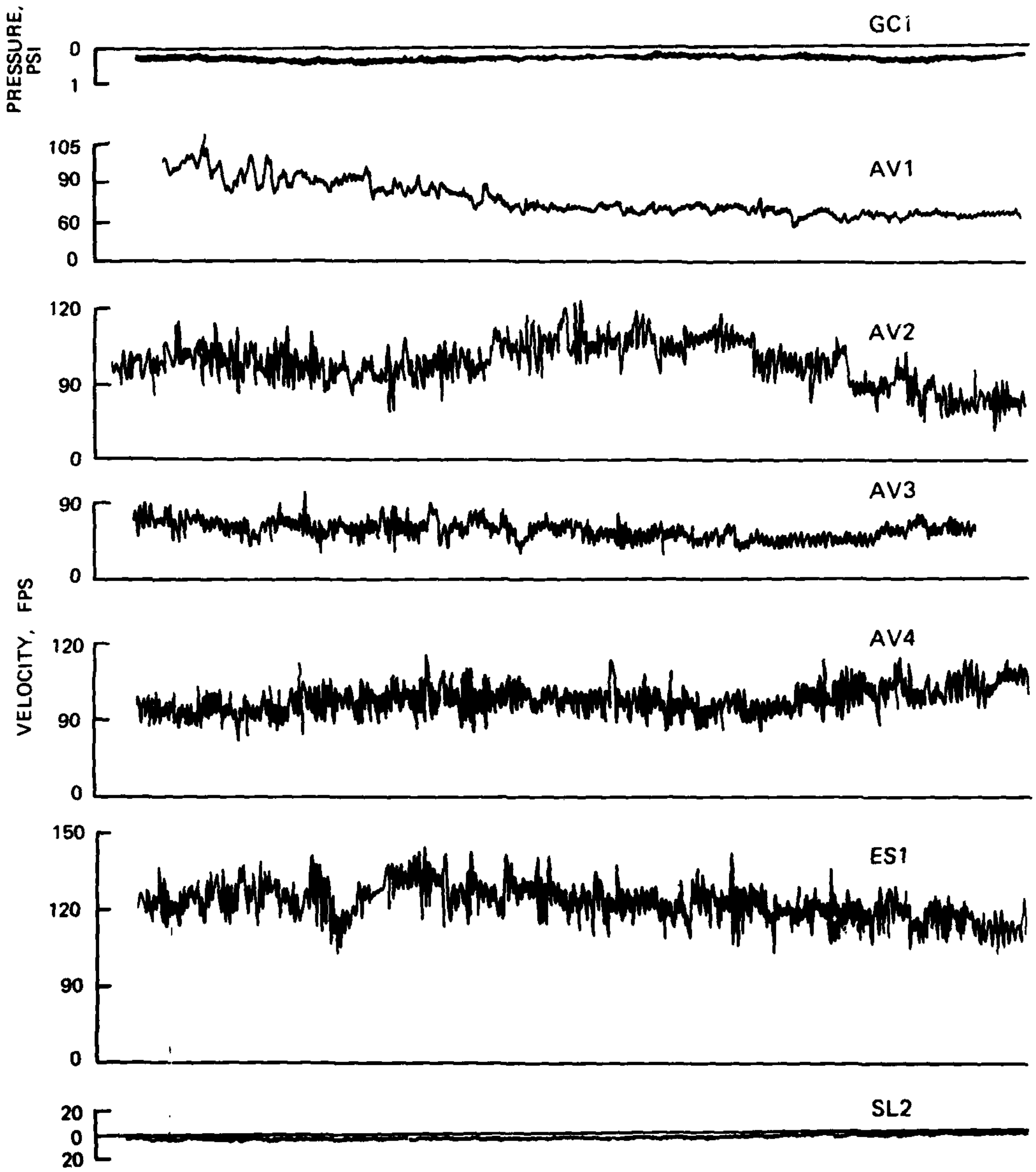
AIR DEMAND TESTS
INSTRUMENTATION



NOTE: (1) EQUIPMENT SHAFT OPEN.

(2) VELOCITY SCALES CONVERTED FROM RECORDED PSID DATA: $V = 351.9\sqrt{\Delta p}$

POINT VELOCITIES
TEST 26, GATE OPENING 7.0 FT
CHART SPEED 4 IPS



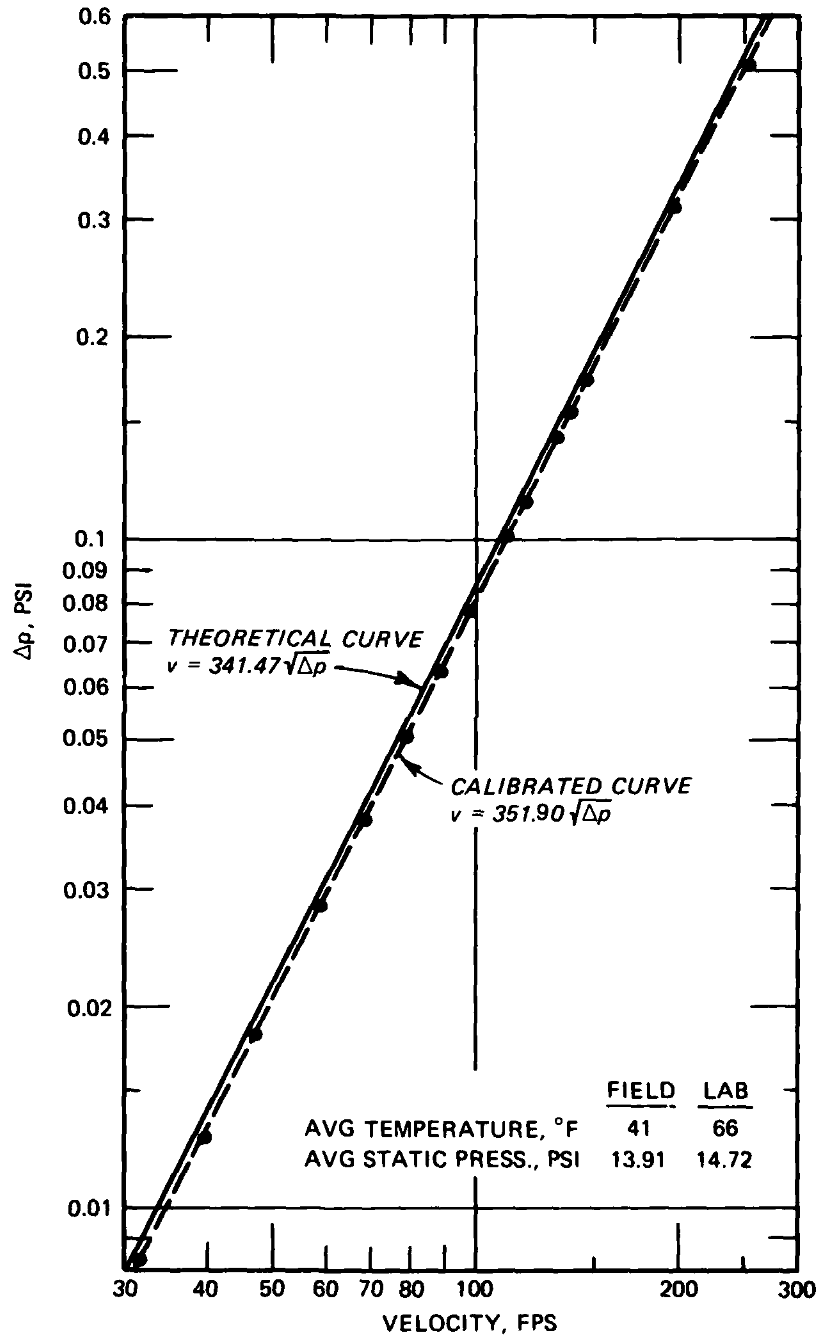
NOTE: (1) EQUIPMENT SHAFT OPEN.

(2) VELOCITY SCALES CONVERTED FROM RECORDED PSID DATA: $V = 351.9\sqrt{\Delta p}$

POINT VELOCITIES

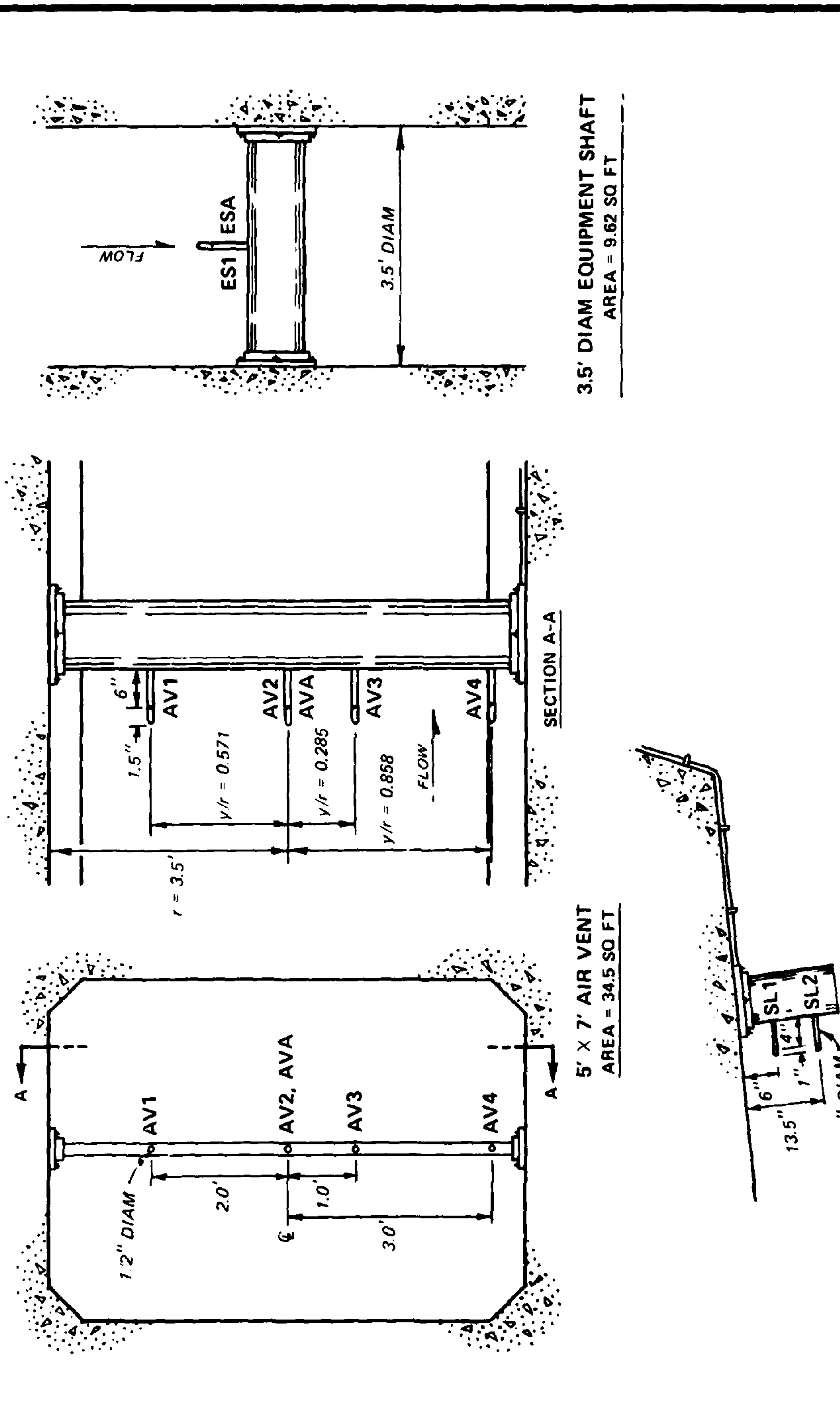
TEST 9, GATE OPENING 9.0 FT

CHART SPEED 4 IPS

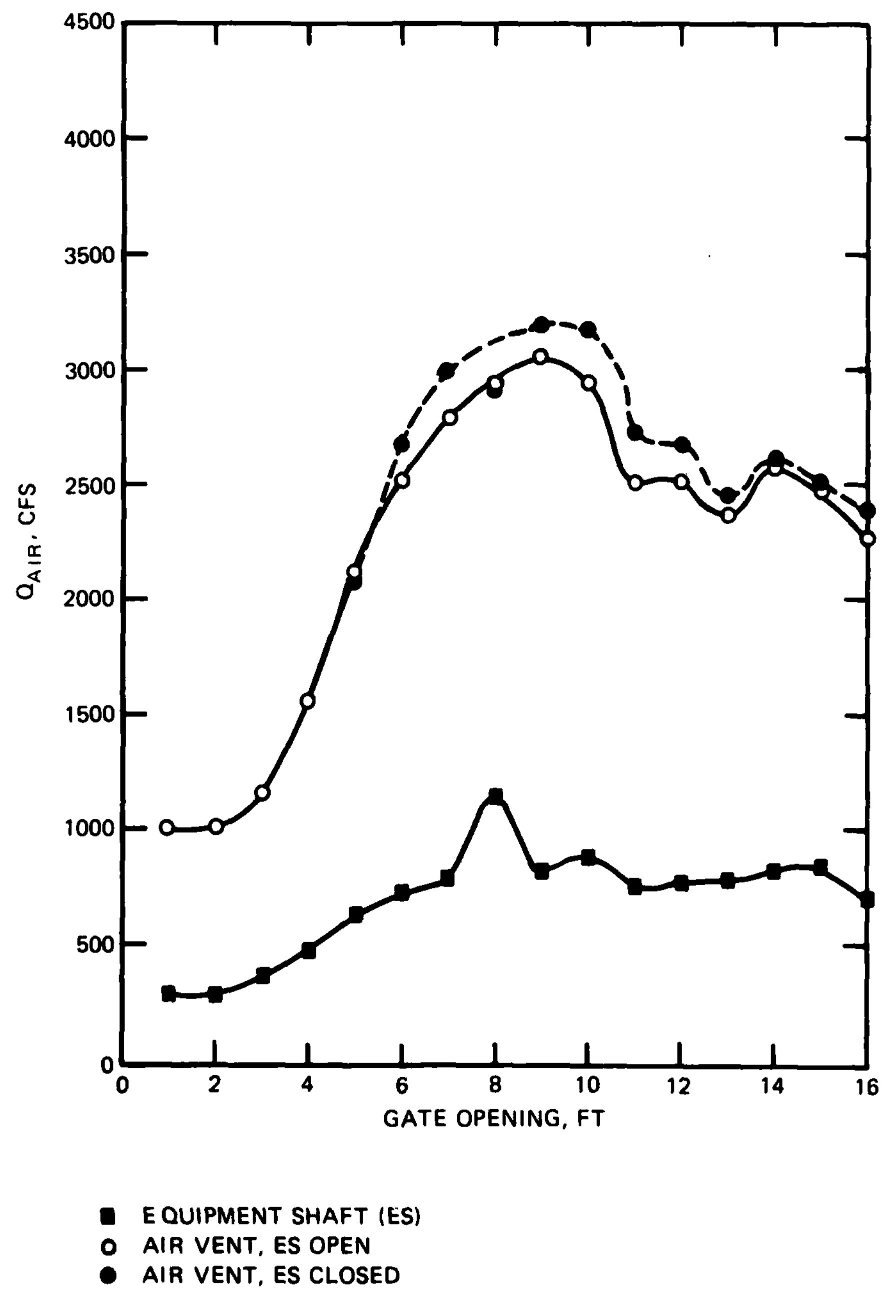


PITOT TUBE CALIBRATION

PLATE 4

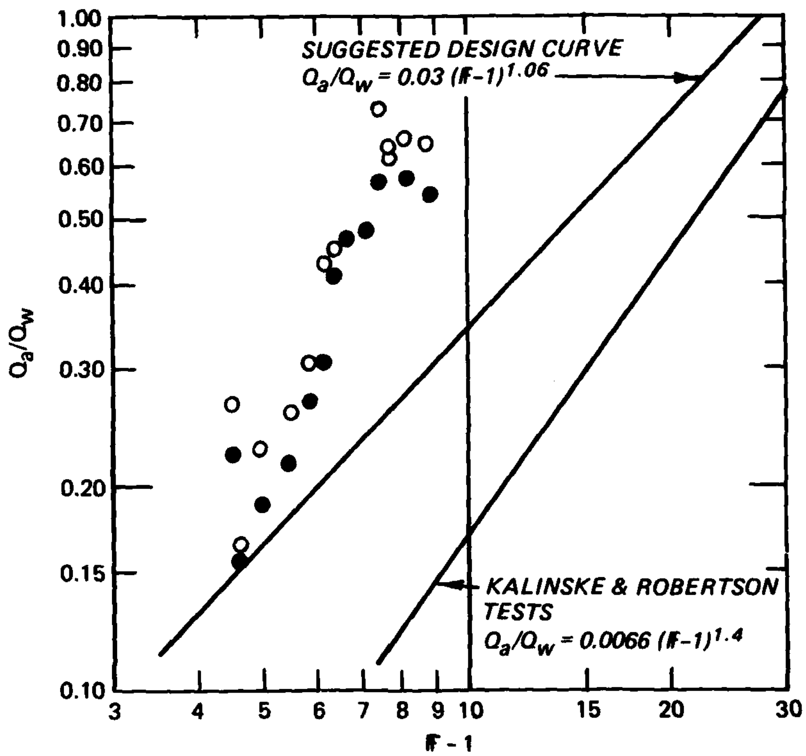


AIR DEMAND TESTS
VELOCITY PROBE LOCATIONS



AVERAGE AIRFLOW VERSUS GATE OPENING

PLATE 6



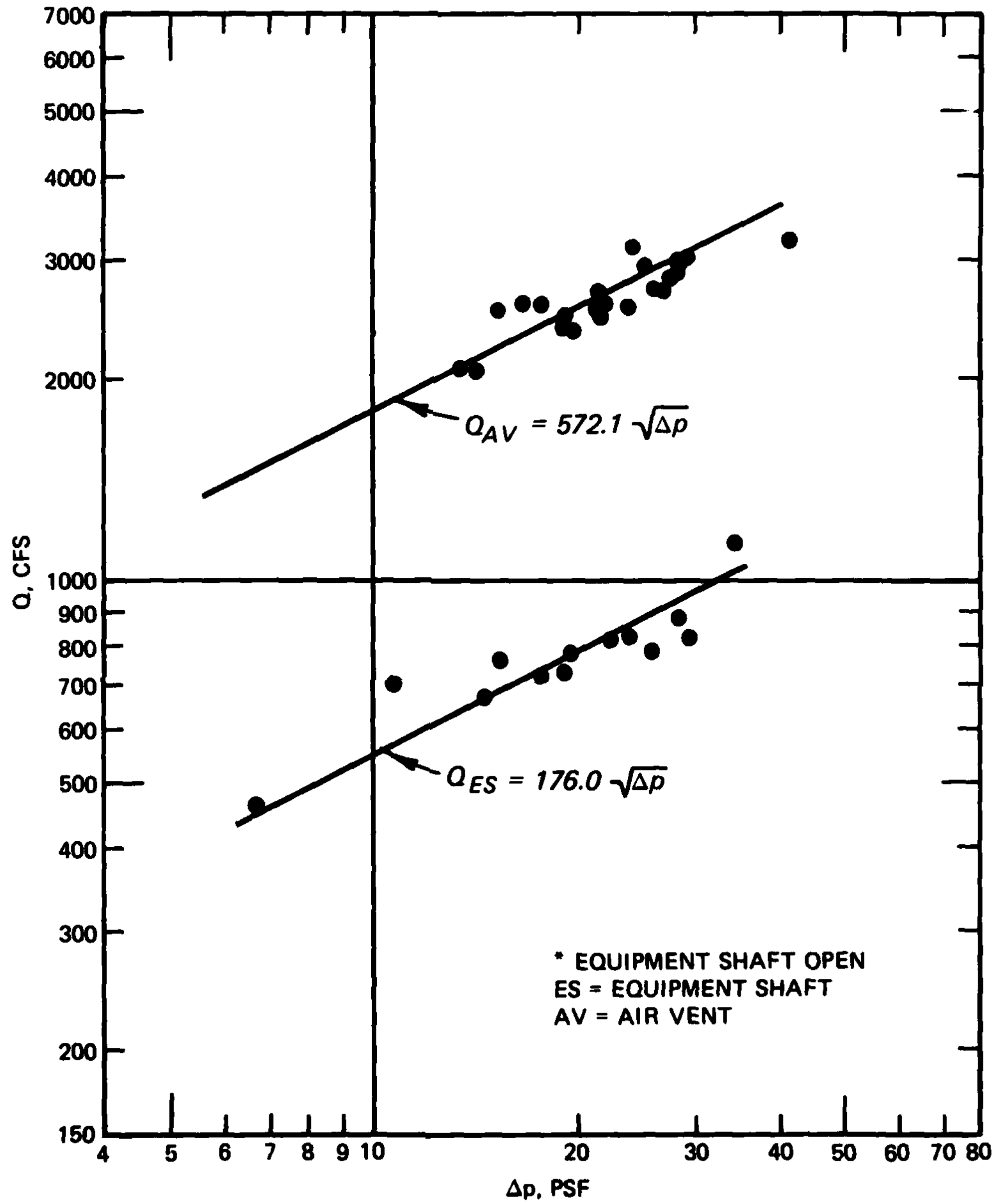
LIBBY DATA, EQUIPMENT SHAFT CLOSED

● AVERAGE AIR VENT FLOW
○ MAXIMUM MEASURED AIR VENT FLOW

NOTE: $\mathbb{F} = V/\sqrt{gy}$ (FROUDE NUMBER)
V = WATER VELOCITY AT VENA CONTRACTA, FPS
y = WATER DEPTH AT VENA CONTRACTA, FT
Q_a = AIR DEMAND, CFS
Q_w = WATER DISCHARGE, CFS

AIR DEMAND

FROM HDC 050-1



AIR DISCHARGE VERSUS PRESSURE DIFFERENTI/'.

PLATE 8

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Hart, Dale E.
Air demand tests, Libby Dam, Kootenai River, Montana / by E. Dale Hart (Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1981.
28, [4] p., 8 p. of plates : ill.; 27 cm. -- (Miscellaneous paper / U.S. Army Engineer Waterways Experiment Station ; HL-81-6)
Cover Title.
"December 1981."
Final Report
"Prepared for U.S. Army Engineer District, Seattle."
Bibliography: p. 28.

Hart, Dale E.
Air demand tests, Libby Dam, Kootenai River : ... 1981.
(Card 2)

1. Hydraulic gates. 2. Libby Dam (Mont.). 3. Water--Aeration. I. United States. Army. Corps of Engineers. Seattle District. II. U.S. Army Engineer Waterways Experiment Station. Hydraulics Laboratory. III. Title IV. Series: Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; HL-81-6.
TA7.W34m no.HL-81-6