TECHNICAL REPORT NO. 2-810

ACOUSTIC FLOWMETER PROTOTYPE EVALUATION TESTS

by

E. B. Pickett

January 1968

Sponsored by

U. S. Army Engineer District
Huntington

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ARMY-MRC VICKSBURG, MISS.

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FOREWORD

The tests reported herein were conducted for the U. S. Army Engineer District, Huntington, with substantial field support at Oahe Dam by the Missouri River Division and Omaha District. Some of the planning and analyses was accomplished under the Corps of Engineers Engineering Study ES 805, "Hydraulic Prototype Tests." The U. S. Army Engineer Waterways Experiment Station is responsible for coordinating this hydraulic prototype testing program for the Corps.

The study was conducted in the Hydraulics Division of the Waterways Experiment Station under the direction of Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division, and Mr. F. B. Campbell, Chief of the Hydraulic Analysis Branch. This report was prepared by Mr. E. B. Pickett, Chief of the Prototype Section, assisted by Messrs. C. J. Huval, E. D. Hart, W. C. Blanton, R. A. Yates, M. Dorl, P. M. Smith, and J. V. Dawsey, Jr.

Acknowledgment is made to the many individuals of the Huntington District who participated in the design, installation, and testing of the acoustic flowmeter facility at Summersville Dam (see Appendix A), and to personnel of the Missouri River Division and Omaha District who assisted in the tests at Oahe Dam. A representative of the U. S. Geological Survey made the dye dilution measurements. Special acknowledgment is made to personnel of the Westinghouse Underseas Division for participation in the Oahe tests, excellent cooperation in all phases of the Summersville project, and much of the acoustic flowmeter descriptive information appearing in this report.

Coordination of the flowmeter installation and testing operations at Oahe and Summersville Dams and analyses of the test data were accomplished by the Waterways Experiment Station. Most of the test measurements with electrical instruments were made by the Instrumentation Branch, Waterways Experiment Station, in which Mr. G. C. Downing participated extensively throughout the acoustic flowmeter development effort.

COL Alex G. Sutton, Jr., CE, and COL John R. Oswalt, Jr., CE, were Directors of the Waterways Experiment Station during the investigation and preparation and publication of this report. Mr. J. B. Tiffany was Technical Director.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
miles	1.609344	kilometers
square feet	0.092903	square meters
cubic feet	0.0283168	cubic meters
gallons	3.78533	liters
inches per second	2.54	centimeters per second
feet per second	0.3048	meters per second
cubic feet per second	0.0283168	cubic meters per second
feet per second per second	0.3048	meters per second per second
pounds per square inch	0.070307	kilograms per square centimeter
Fahrenheit degrees	5/9*	Celsius or Kelvin degrees

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use $K = (5/9)(F - 32) + 273.16$.

SUMMARY

Prototype tests of an acoustic flowmeter system were made in a 24-ft-diam power penstock at Oahe Dam to evaluate the system prior to permanent installation in the outlet works at Summersville Dam. Comparative discharge measurements included acoustic, penstock pressure-momentum (Gibson), turbine model test ratings, scroll-case pressure differential (Winter-Kennedy flowmeter), and surge tank volume changes. The acoustic flowmeter measurements were very consistent and many of the comparisons were within 1%. The location of the measuring section for a single-path acoustic flowmeter must be selected to give a known or measurable relation between the flow pattern of the whole section and that along the acoustic path.

ACOUSTIC FLOWMETER PROTOTYPE EVALUATION TESTS

PART I: INTRODUCTION

Background

1. The increasing development and control of major streams have greatly increased the need for more accurate and easily used means of measuring the outflow of control structures, especially the outflow of large conduits and power units. As a part of the search for such metering devices, the U. S. Army Engineer Waterways Experiment Station has participated in the development of acoustic flowmeters for use in pressure conduits. This activity has included laboratory investigations and participation with industry in developing and adapting such equipment for use in hydraulic structures.

Advantages

2. The primary advantage of an acoustic flowmeter is the absence of projections into, or constriction of, the flow. Being recessed in the conduit walls, the flowmeter elements are protected from damage and the accumulation of suspended material and do not contribute any head loss to the system. The response of an acoustic flowmeter to changes in the flow is very rapid, and the measured signal is linear over a wide range of flow rates. Also, it is not affected by electrical conductivity or by small concentrations of suspended solids or entrained air.

Limitations

3. Possible limitations of the acoustic flowmeter may be its dependence upon the velocity distribution in the conduit, the effects of wide variations in the velocity of sound through the fluid, severe attenuation by high concentrations of entrained air, and the relatively high cost of presently available equipment. However, the variation in velocity of sound and high concentrations of entrained air are not expected to be significant problems in most hydraulic structures. If generally accepted by engineers, the cost per unit would normally be

expected to decrease with increased production.

Basic Principles

Acoustic signal

4. Several types of acoustic, or ultrasonic, flowmeters have been developed,[1-13] which use the velocity of sound through the fluid to measure the velocity of flow. The basic principle of the acoustic flowmeter is shown schematically in fig. 1.

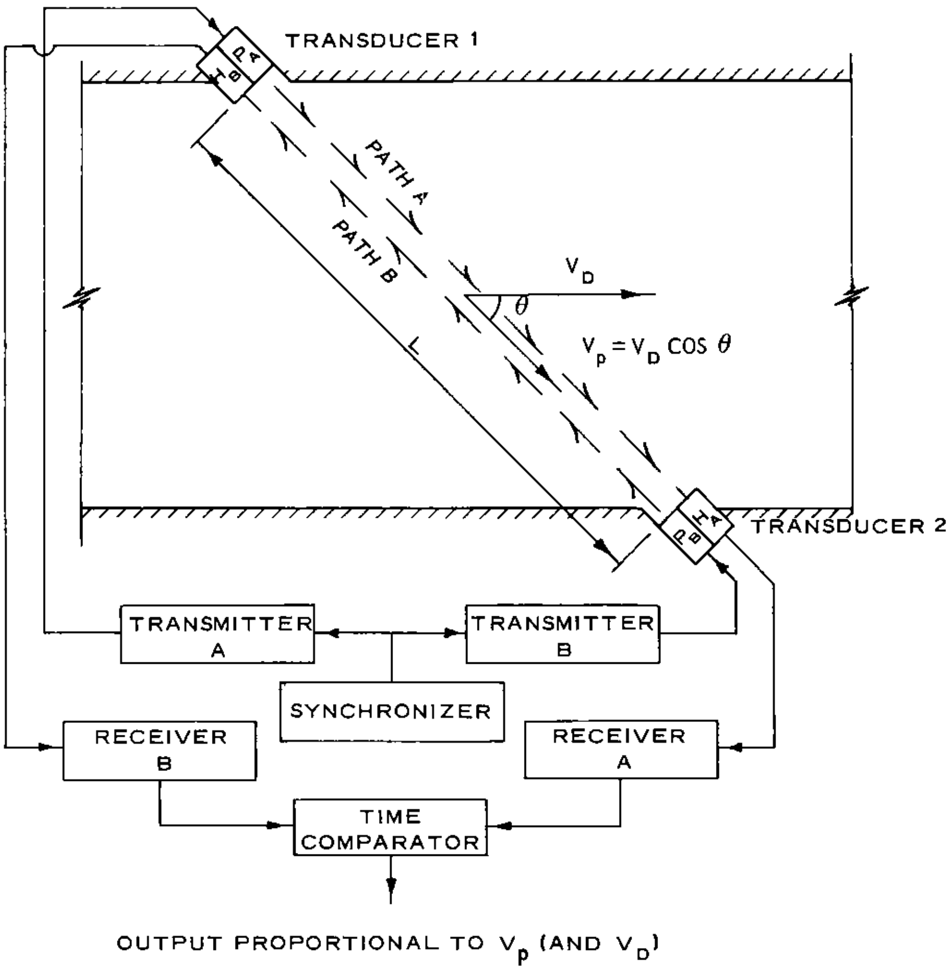

Fig. 1. Acoustic velocity measurement principle

5. In the system shown in fig. 1, a sound signal is transmitted from projector P_A in transducer 1 along path A to hydrophone H_A in transducer 2. The transit time T_A is

$$T_A = \frac{L}{C + V_p}$$

where

L = length of acoustic path between transducers 1 and 2 (the transducers should be flush with the inside surface of the conduit, or the path length and transit time appropriately adjusted)

C = speed of sound in the fluid

V_p = velocity component of fluid along an acoustic path in, and parallel to or diagonally across, the flow

Similarly, a signal travels from P_B to H_B along path B, with a transit time of

$$T_B = \frac{L}{C - V_p}$$

The difference in transit times ΔT is

$$\Delta T = \frac{2L\ V_p}{C^2 - V_p^2}$$

and where V_p is very small compared with C,

$$\Delta T = \frac{2L\ V_p}{C^2}$$

This approximation introduces an error of only 0.00047% for 10-fps* fluid velocity and 0.0047% for 100-fps fluid velocity when the speed of sound in the fluid is 4600 fps. The projectors and hydrophones are shown as separate units of each transducer in fig. 1; however, with proper cycling of the operation, a single unit can be used in each transducer and both transducers can be energized by a common transmitter.

6. The difference in transit times ΔT may be measured between individual sound pulses or the phase difference between continuous signals of frequency f transmitted simultaneously in both directions. The phase difference $\Delta\phi$ is

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* A table of factors for converting British units of measurement to metric units is presented on page ix.

$$\Delta\phi = \Delta T\omega = \frac{2L\,V_p\,\omega}{C^2}$$

where $\omega = 2\pi f$. It should be noted that a steady motion of the fluid advances or delays all cycles of the sound waves uniformly without changing the frequency. This differs from the Doppler effect in which the pitch (frequency) of the sound is changed as the transmitter and receiver move toward or away from each other without a change in the sound wave velocity between them.

Flow velocity

7. The average flow velocity on a diameter across the conduit, V_D , is

$$V_D = \frac{V_p}{\cos\theta} = \frac{C^2}{2L\cos\theta}\,\Delta T$$

where θ = angle of path relative to the conduit axis. This average flow velocity V_D includes the proportionate influence of all variations in the flow velocity along the path across a diametric plane of the conduit.

8. If the measuring section is at a location where the velocities are the same at every point in the conduit cross section, such as may be almost the case in the intake, the average conduit velocity $\overline{V}$ equals the average diametric velocity V_D . Also, $\overline{V}$ equals V_D where the flow pattern can be considered two-dimensional, as through a wide, thin slot where V_D is measured across the short dimension of the slot. In all cases the flow streamlines should be parallel through the measuring section.

9. Fully developed laminar flow through a circular conduit has a parabolic velocity distribution and the average conduit velocity $\overline{V}$ is three-fourths of the average diametric velocity V_D .

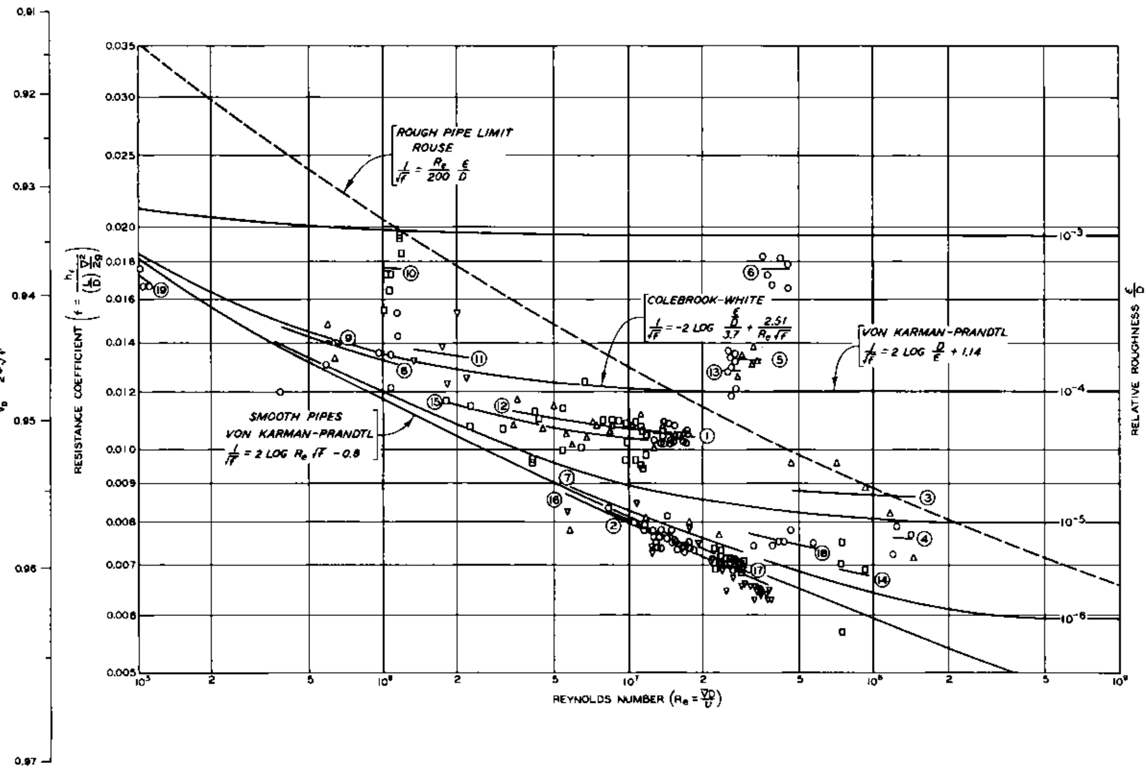
10. Generally, all flows to be measured will be turbulent with Reynolds numbers greater than 5000. The velocity distribution for fully developed turbulent flow in a circular conduit may be expressed as a function of the surface resistance coefficient, f , and the relative distance from the wall, y/r_o , by the equation

$$\frac{v}{\overline{V}} = \sqrt{f}\left(2.15 \log_{10} \frac{y}{r_o} + 1.43\right) + 1$$

This equation is applicable to both smooth and rough pipes and was derived from data for Reynolds numbers up to 3,240,000.[14] The relation between the average conduit velocity $\overline{V}$ and the average diametric velocity V_D for axisymmetric flow is then found to be

$$\frac{\overline{V}}{V_D} = \frac{2.00}{2.00 + \sqrt{f}}$$

The interrelations of resistance coefficient, Reynolds number, and this ratio of $\overline{V}$ to V_D are shown in fig. 2. The data points shown in fig. 2



h_f = resistance loss, ft

L = conduit length, ft

D = conduit diameter, ft

ϵ = absolute roughness, ft

$\overline{V}$ = average conduit velocity, fps

ν = kinematic viscosity, ft^2/sec

g = gravitational acceleration, ft/sec^2

V_D = average diametric velocity, fps

Fig. 2. Interrelations of resistance coefficient, Reynolds number, relative roughness, and ratio of average conduit velocity to average diametric velocity.[15] See table 1 for identification of data points

are from a number of prototype measurements listed in table 1.[15]

11. The variation of the ratio of $\overline{V}$ to V_D for any given conduit probably will be only 0.1 to 0.2% and only 1 to 2% for a considerable range of resistance coefficients and Reynolds numbers. The ratio of $\overline{V}$ to V_D for other velocity distributions could be obtained experimentally in model or prototype with boundary probes or cross struts for each conduit, or possibly estimated within 1 to 2% from theoretical evaluations of the velocity distribution. The resistance coefficient of the metered conduit could be determined from piezometric measurements of the hydraulic grade line or approximated from measurements of the surface roughness.[15]

12. Measured velocity distributions in Tunnel 10 at Fort Randall Dam[16] indicate a ratio of $\overline{V}$ to V_D of approximately 0.969 and an f value of approximately 0.0085. The ratio is somewhat higher than the value of 0.956 indicated by the equation given above, and 0.955 in fig. 2 (data group (3)). This difference in values of $\overline{V}/V_D$ could result either from experimental error or from a slightly less than fully developed turbulent flow velocity profile in the tunnel. The small difference in f values from references 15 and 16 resulted from analyses of the test data by different techniques.

13. Unpublished velocity data obtained with cross struts in the penstock of Oahe power plant Unit 1 (see paragraph 34) indicated $\overline{V}/V_D$ values of 0.968 at the acoustic flowmeter location and 0.961 at a location 143 ft downstream. Assuming a hydraulically smooth boundary for the vinyl-coated Oahe penstocks, fig. 2 shows f values from 0.007 to 0.009 for the range of Reynolds numbers experienced during the tests described herein. The corresponding range of $\overline{V}/V_D$ is 0.960 to 0.955. A value of 0.96 was selected for the acoustic flowmeter tests described herein.

Flowmeter Development for Corps Use

14. Published reports in 1955 by Swengle, Hess, and Waldorf[6,8,10] described the ultrasonic measurement of flow in a 16-ft-wide by 25-ft-high turbine intake at the Safe Harbor power plant. It was believed that the method could be adapted to the measurement of discharge in the rectangular

sluices common to many Corps of Engineers dams. At about this same time the U. S. Geological Survey began investigating the application of the ultrasonic method to the measurement of open channel discharge.

Rod-type transducer system

15. A system utilizing rod-type transducers covering the full height of each side of a 5.67- by 10-ft rectangular sluice at Sutton Dam was designed in 1956 by the Waterways Experiment Station. Consultant services were obtained from Messrs. R. C. Swengle and W. B. Hess and some assistance by Mr. L. Batchelder from the equipment manufacturer. Installation of the embedded anchorages for the flowmeter in a sluice at Sutton Dam was completed in 1958. The dam was essentially completed in 1959 and the project reached full operational status in early 1961. A small-scale test of the system was made in an 8- by 12-in. model sluice in 1960 and the transducers for Sutton Dam were delivered by the fabricator early in 1961.

16. Tests of the rod-type transducers were made at Sutton Dam in June 1961. A good signal could be transmitted across still water, but acoustic noise practically obliterated the 10 kHz* signal during operation of the sluice and prevented measurement of the phase shift. Part of the problem was believed to have been a strong acoustic radiation from the housings of the transducers that energize the rods. Improvement of this detail, an increase of frequency to 20 kHz, and a number of other alterations should be incorporated in any revised system of this type. Some indication has been given that the effects of nonuniform velocity distribution across the conduit are negligible.[10] However, the rather severe modification of the velocity distribution at the location of the Sutton flowmeter by partial openings of the control gate just downstream will require considerable study and evaluation.

Point-type transducer system

17. The use of small "point-type" transducers in a system to measure the average flow velocity along the beam path, instead of across the entire flow section, was described by Kritz in 1955.[9] This system is

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* 1 Hz = 1 cycle per second.

particularly applicable to a circular conduit in which the velocity distribution is axisymmetric. It also could be used near a rectangular conduit intake where the velocity distribution is essentially uniform across the entire section. On the basis of anticipated commercial development of such systems, the installation of embedded anchorages and cable conduits was recommended at several Corps projects where accurate discharge measurements would be needed for operation or prototype tests. Summersville Dam was among these projects, for both purposes.

18. Two small transducers of this type were tried in connection with the Sutton Dam tests at frequencies between 10 kHz and 200 kHz. The results were essentially the same as those of the rod-type system: a good signal in still water, but lost in acoustic noise with flow. However, it was believed that a higher frequency system might permit good phase-shift measurements. In 1961 a manufacturer of underseas acoustic instruments investigated the use of phase-shift measurement for an acoustic flowmeter but did not recommend a system. In 1964 the same manufacturer proposed a system involving the measurement of actual time differences in sound pulse travel rather than phase shift, using instrument components recently developed for underseas uses. This equipment was proposed for the Summersville installation, subject to successful performance in the tests described herein.

Purpose of Tests

19. As indicated above, the manufacturer of an acoustic water-velocity-measuring system that was found very successful in underseas applications considered the equipment adaptable to accurate metering of conduit flows. For a part of the acceptance of such a system by the Waterways Experiment Station for installation at Summersville Dam (see Appendix A), it was decided to field-test the flowmeter in a large circular tunnel with a well-established rating. Neither the manufacturer nor the Waterways Experiment Station had such a field facility. Consequently, the Missouri River Division and Omaha District cooperated in furnishing a suitable test site at Oahe Dam power plant (see fig. 3).

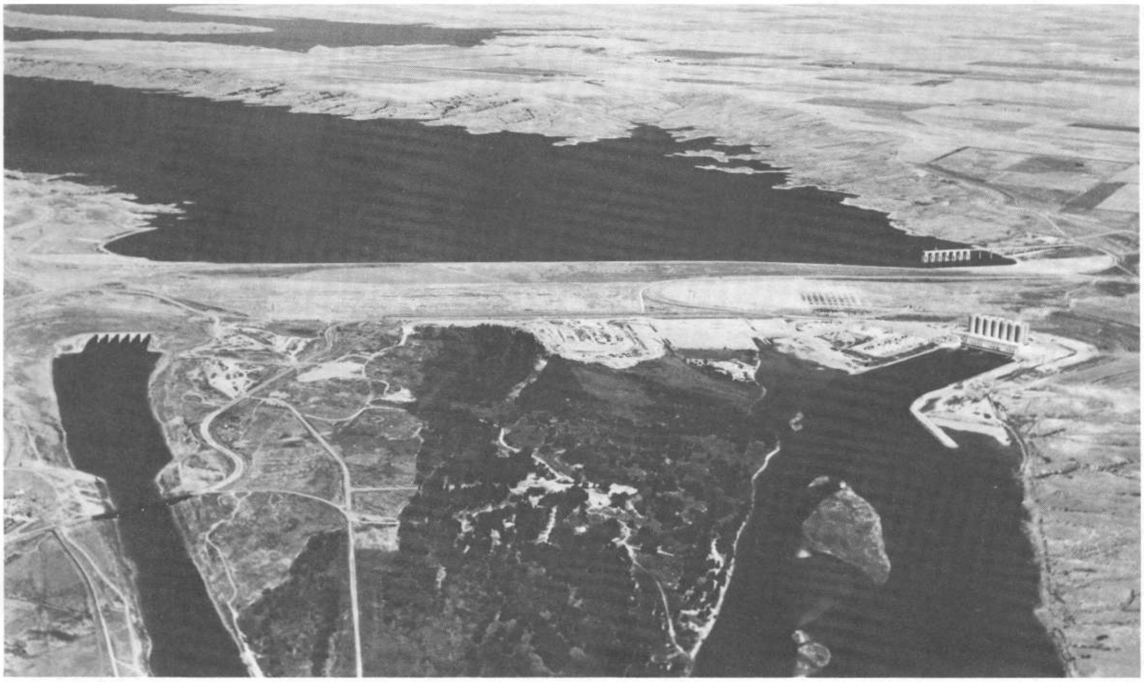


Fig. 3. Oahe Dam, Missouri River, S. Dak., outlet works at left, power plant at right

20. The penstock of Unit 1 of the Oahe power plant was of adequate size and had been carefully rated in recent prototype transients tests. It was long enough to ensure fully developed turbulent flow and had convenient external access. The effects of a few mild bends in the penstock upstream from the measuring section also could be evaluated by the use of several acoustic paths across the flow for comparison with available velocity distribution data.

PART II: "LEADING EDGE" ACOUSTIC FLOWMETER SYSTEM

Operation Principle

21. The "leading edge" acoustic flowmeter system proposed for Summersville Dam measures the difference in transit time between two pulses by measuring the difference in arrival times of the leading edges of two simultaneously transmitted, short, high-frequency (about 1.5 MHz) pulses from the projection transducers. This system is considered less sensitive to local disturbances in the flow than systems using the phase-shift principle. Only the leading edge of the received signal is important. Local disturbances may attenuate the signal, but they do not affect its speed through the fluid. The system also has provisions to automatically compensate for changes of speed through the fluid.

22. The arrival of the first pulse of each pair triggers a digital counter which measures the time to the arrival of the second pulse. This cycle of measurements is repeated at a high rate (about 80 Hz) and the time values can be averaged over a selected period (between a few seconds and about a minute). The output of this time-measuring system can incorporate the sound wave velocity, path length, path angle, and conduit area to give the discharge in either digital or analog form.

Possible Errors

23. The manufacturer has given the following maximum possible errors of the instrument as assigned to each possible source:

Assumption of linear equation ($\Delta T = 2L\, V_p / C^2$)	0.05%
Correction for speed of sound in water	0.07%
Use of a common transmitter	0.01%
Use of matched-gain receivers	0.05%
Resolving power of digital circuits	0.19%
Installation correction (angle and path length)	0.10%
Accuracy of digital-to-analog converter	0.10%
Meter error	0.50%

24. Since some of these errors will be positive and others negative, the standard square-root-of-the-sum-of-the-squares method was used to compute the overall system error of 0.56%. As can be seen from the tabulation, the largest single contributor to total error is the inherent inaccuracy of available panel meters. Therefore, if a more accurate system should be desired, each meter could be calibrated in its system using known fluid velocities. The linear response of this flowmeter system is believed to be more reliable, easier to process, and less susceptible to aging and to drift in accuracy than nonlinear systems in which the indicated quantity on the meter (velocity or discharge), M , is related to the flow velocity, V , by one of the following equations

$$M = K_1 V^n + K_2 \quad \text{or} \quad M = K_3 \sin (K_4 V + K_5)$$

where n is an exponent and the K's are constants.

Towing Basin Test

25. A leading edge system similar to the acoustic flowmeter was tested for the manufacturer in the U. S. Navy David Taylor Model Basin in December 1962. The results of one of the test runs are given in fig. 4. The system was towed through still water up to a speed of about 6 knots. The following were determined from the test data:

Root-mean-square error of data from linearity = 0.015 fps

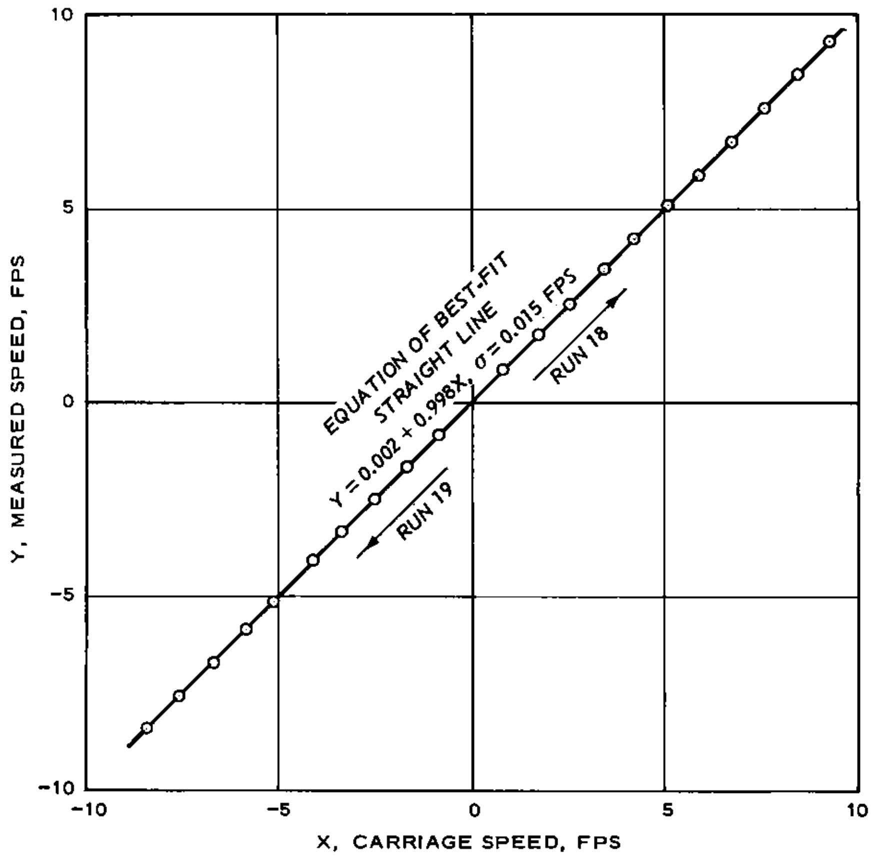
Calibration error = 0.2%

Zero offset = 0.002 fps

Equipment Tested at Oahe

System console

26. All of the electronic equipment for the system was housed in the equipment cabinet shown in fig. 5. The front panel contains only the indicating meters, on-off switches, path selector switch, self-test switch, and associated indicator lights. The indicating meters of ranges



Run 18				Run 19			
Carriage Travel from West				Carriage Travel from East			
(1) Carriage Speed		(2) Measured	(2)-(1)	(1) Carriage Speed		(2) Measured	(2)-(1)
knots	fps	fps	fps	knots	fps	fps	fps
0.5	0.84	0.87	+0.03	-0.5	-0.84	-0.83	-0.01
1.0	1.69	1.70	+0.01	-1.0	-1.69	-1.68	-0.01
1.5	2.53	2.53	0.00	-1.5	-2.53	-2.53	0.00
2.0	3.38	3.37	-0.01	-2.0	-3.38	-3.36	-0.02
2.5	4.22	4.20	-0.02	-2.5	-4.22	-4.20	-0.02
3.0	5.07	5.05	-0.02	-3.0	-5.07	-5.05	-0.02
3.5	5.91	5.89	-0.02	-3.5	-5.91	-5.89	-0.02
4.0	6.76	6.73	-0.03	-4.0	-6.76	-6.74	-0.02
4.5	7.60	7.60	0.00	-4.5	-7.60	-7.62	+0.02
5.0	8.45	8.45	0.00	-5.0	-8.45	-8.45	0.00
5.5	9.29	9.29	0.00	--	--	--	--

Fig. 4. Results of towing basin test

Fig. 5. Electronic equipment console and one pair of transducers used in Oahe tests

0 to 50 fps and 0 to 100 fps, the path selector switch, and path indicator lights for this particular unit were those assembled initially for the Summersville Dam installation. However, the system was readily adapted to the Oahe test with slight internal modifications of the circuits. To give more accurate data a digital voltmeter was used in lieu of the panel meters during the Oahe tests.

27. One pair of transducers and certain components of the circuitry are custom-wired for each flowmeter path. A single digital processing system is connected to the path to be measured by setting the path selector switch. The receiver-transmitter circuit drawer and the digital circuit drawer are accessible through a door in the back of the console. Controls used to initially adjust the system are located inside the cabinet and accidental changing of the settings is prevented by locking devices on the controls and on the console door. The console also includes a blower system for ventilation of the electronic equipment.

Transducers and adapters

28. The approximately 1/2-in.-diam transducers were supplied by the manufacturer in waterproofed adapters for installation through the 1-1/8-in.-thick steel walls of the Unit 1 penstock at Oahe Dam (see plates 1 and 2). These adapters were of a ball-and-stem configuration, as shown in fig. 6

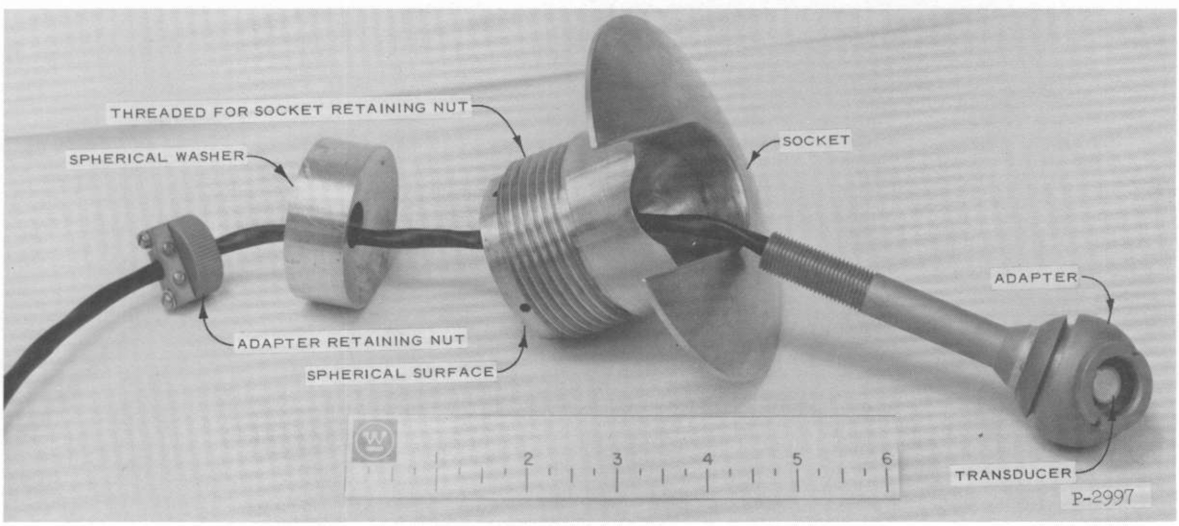


Fig. 6. Ball-and-stem adapter and socket assembly for installing transducer in Oahe penstock (socket assembly gaskets, washers, and nuts not shown)

and plate 3, and were fitted into the socket assembly furnished by the Waterways Experiment Station. This ball-and-socket arrangement permitted angular adjustment up to 5 degrees for aligning the transducers. Ordinarily, the transducer and adapter would be fully recessed. However, restrictions on hole size (2-3/8-in. diam) and alignment through the penstock wall and on welding special fittings to the wall resulted in an assembly that projected about 5/8 in. into the 24-ft-diam conduit (see fig. 7 and plate 3). Four pairs of transducers were furnished for making measurements along four diametric paths spaced at 45-degree intervals.

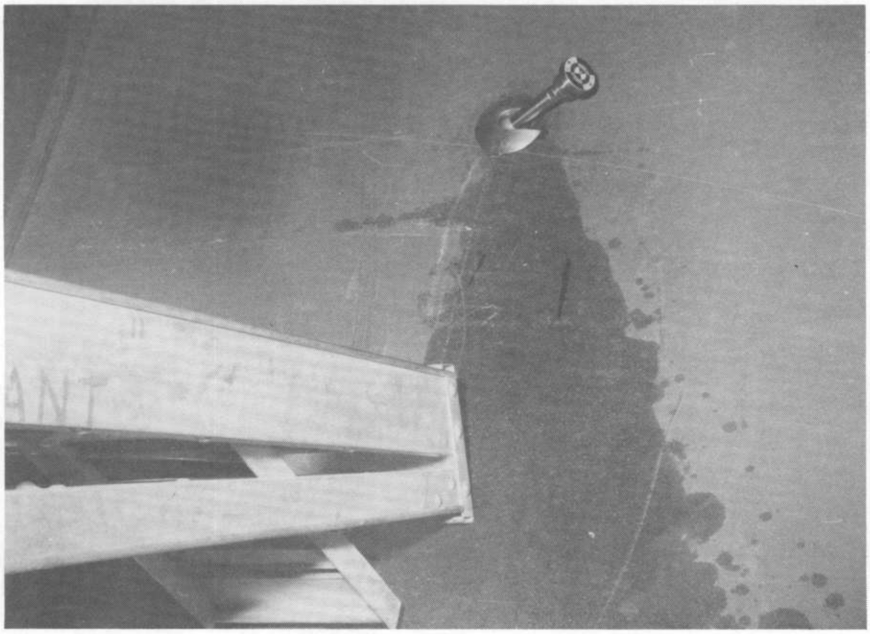


Fig. 7. Transducer installed in Oahe penstock at location U8. The temporary target attachment was used with a temporary bore scope in the transducer at the opposite end of the acoustic path to accurately align the transducer axes

PART III: FLOWMETER TESTS AT OAHE

Pertinent Features of the Project

29. Oahe Dam, located on the Missouri River in central South Dakota about 6 miles northwest of Pierre (figs. 3 and 8), is a rolled-fill earth embankment with a maximum height of 242 ft and a length of 9300 ft. The multipurpose reservoir created by the dam is one unit in the comprehensive plan for the development of the Missouri River basin. The reservoir is being used for flood control, irrigation, low-water regulation for navigation and sanitation, power generation, recreation, and wildlife preservation. With the pool at maximum operating level, elevation 1620,* the reservoir will have an estimated storage capacity of 23,600,000 acre-ft and will extend along the Missouri River in a northerly direction for approximately 250 miles to the vicinity of Bismarck, N. Dak. Minimum operating pool elevation is 1540, and maximum surcharge pool elevation, 1645.

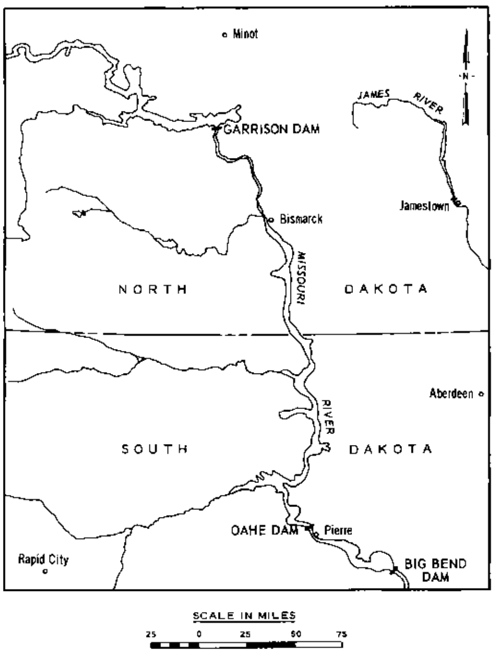


Fig. 8. Vicinity map

30. River regulation in the interest of flood control, irrigation, navigation, and sanitation is provided by six circular tunnels in the right abutment. The tunnels vary in length from 3408 to 3571 ft and have upstream diameters of 19.75 ft, central control shafts with single passages for vertical-lift gates 13 ft wide and 22 ft high, and downstream diameters of 18.25 ft. A common stilling basin dissipates the energy of flow from the six tunnels. A channel-type spillway with control gates near the upstream end is located 6000 ft landward from the right abutment of the embankment. The project layout is shown in plate 1.

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* Elevations are in feet referred to mean sea level.

31. The powerhouse at the left abutment has seven generating units rated at 85,000 kw per unit. Water for power generation is carried from the gated vertical shaft intake structure through seven tunnels 24 ft in diameter and averaging about 3600 ft long. Each tunnel is provided with dual surge tanks 70 ft in diameter and 145 ft high (Units 1-7). The surge tanks are connected to the penstock with individual risers 16 ft in diameter with 12-1/4-ft-diam orifices in each riser. The vertical-shaft, single-runner, 100-rpm, Francis-type turbines are rated at 128,500 hp for a 185-ft head and 60,000 hp for a 120-ft head. Details of the power plant are shown in plates 1 and 2.

Previous Tests in Unit 1

Gibson test

32. Performance tests of Unit 1 were made by representatives from the office of Norman R. Gibson, Consulting Engineer, on 21-22 March 1963 for pool elevation 1573 and tailwater elevation 1421 (with variations of a few tenths of a foot from these elevations). Although this was not an official acceptance test, the turbine performance was measured in accordance with the ASME Test Code for Hydraulic Prime Movers, approved May 1949, with the exception that the measuring point for the tailwater recording gage system was not located at the point of highest average tailwater level. However, the pressure-momentum type of discharge measurement of this test was independent of the tailwater level. Details of the test are given in reference 17, and the results were used in calibration of the scroll-case piezometers (Winter-Kennedy flowmeter).

Power-plant transients tests

33. Prototype tests of Unit 1 were made in June 1963 to evaluate results of a comprehensive digital computer study made by the Missouri River Division, Omaha District, and Massachusetts Institute of Technology and to determine the extent that operation corresponded to design. The general objective of the transients study is to develop an integrated solution of the entire problem of power-plant transients, with primary emphasis on governing stability.

34. Hydraulic prototype measurements of power-plant transients, including instantaneous pressure values at a number of locations in the power tunnel, the surge tank system, turbine scroll case, and draft tube were obtained simultaneously with instantaneous values of tunnel flow velocity, reservoir and tailwater elevations, turbine speed and gate opening, power output, and other elements (including governor system) in Unit 1. Pressure and water-level measurements were made with electrical pressure transducers, velocities were measured with pressure transducers connected to pitot-static tubes on cross struts in the penstock, and mechanical and electrical values were obtained with appropriate transducers. Measurements were recorded on about 100 channels of oscillograph equipment and digitized for use in the digital computer analyses by the Omaha District and Massachusetts Institute of Technology. Details of the transients study are given in references 18-20. Some of the transients test results are cited in this report.

Measurements and Instrumentation for Acoustic Flowmeter Tests

35. The acoustic flowmeter tests included electrical measuring and recording of the acoustic flowmeter signal, wicket gate angle and vibration, surge tank water-surface elevations, net head, and differential pressures between the pressure-momentum (Gibson test) piezometer rings and between the scroll-case piezometers (Winter-Kennedy flowmeter). The locations of these measurements are shown in plate 2 and the instrumentation is described in detail in the following paragraphs.

36. Additional measurements recorded by the Omaha District for studies of the governor action were generator speed, wicket gate servomotor connecting rod travel, motions of the governor dashpot pistons "R" and "M" and relay valve, and penstock pressure downstream from the surge tank risers. These measurements are indicated in plate 2, but will not be described in detail.

37. During the tests visual readings were made of the acoustic flowmeter output, manometers connected to the surge tanks and the net head piezometers, differential manometers connected to the scroll-case

piezometers (Winter-Kennedy flowmeter) and across the surge tank riser section of the penstock, and the wicket gate servomotor connecting rod position.

38. Power-plant control room recorder charts for the test period were obtained for pool and tailwater elevations, air and water temperatures, the Winter-Kennedy flowmeter, individual unit and total station power output, bus voltage, and system frequency.

39. Measurement of the penstock discharge by the dye dilution method was attempted. A solution of rhodamine B dye was injected at a constant rate from a mariotte flask at the power tunnel intake. The dilution was sampled near the acoustic flowmeter test section and analyzed with a recording fluorometer. Bottle samples also were obtained periodically for checking the continuous record. The technique has been used in similar power-plant systems to obtain very accurate discharge measurements; however, malfunction of the fluorometer or instability of the diluted dye solution nullified the results in these tests at Oahe.

Acoustic flowmeter

40. Details of the flowmeter equipment tested at Oahe are given in Part II of this report. The use of four different paths across the flow was to determine any effects of asymmetric velocity distribution resulting from several bends in the tunnel upstream from the flowmeter location (see plate 1). The location of the flowmeter section relative to the various components of the power plant is shown in plate 2. Identification and locations of the acoustic paths and transducers are given in plate 3.

41. Very careful location of the transducers was necessary to ensure that all the path lengths were as nearly the same as possible. The uniformity in length was required because only one set of circuitry was used for all four paths. Measuring the pressurized penstock, correcting for slight nonuniformity of the cylindrical shape, and locating the 2-3/8-in.-diam transducer holes were completed before the penstock was dewatered. Comparative penstock dimensions and lengths of the diagonal paths in the dewatered penstock also were measured as a final guide in locating the holes. Following the tests, another set of measurements was made of the actual transducer hole locations in the pressurized penstock. Design

dimensions for the transducer layout and final measurements of the acoustic path lengths are given in plate 3.

42. The acoustic flowmeter transducers and console were installed and operated during the tests by representatives of the manufacturer. In addition to the special effort to locate the flowmeters, as described above, the transducers were very carefully aligned with a boresight and target (see fig. 7). The system was switched from path to path and the output was recorded continuously on a light beam oscillograph supplied by the Waterways Experiment Station and manually from visual observation at short, uniform intervals from a digital voltmeter. The output of the equipment had been adjusted so that the voltage reading was equal to the average flow velocity on the diametric path, V_D .

Wicket gate position

43. The wicket gate position was indicated by an angular potentiometer on one of the wicket shafts and by scaled measurements of the wicket gate servomotor connecting rod position. An accelerometer on a wicket gate shaft lever arm was used to indicate the beginning and end of any wicket gate motion. The potentiometer and accelerometer signals were recorded on the oscillograph and visual readings were made of the connecting rod position. The wicket gate measurements were obtained for use in pressure-momentum evaluations of the discharge and to ascertain the turbine gate openings for comparisons with discharge ratings from other tests. These items are indicated by the symbols Td1(78) and Tg1(79) in plate 2.

Surge tank water-surface elevation

44. The water-surface elevations in each surge tank were measured with a ±25-psid electrical pressure transducer (reference pressure side sealed at approximately atmospheric pressure) and the signals were recorded continuously on the oscillograph. These elevations also were monitored on 12-ft-high well-type mercury manometers with readings at 15-sec intervals during the test operations. The surge tank water-surface elevations were obtained for use in volumetric-type measurements of the discharge during the surge action following complete closure of the turbine wicket gates.

45. The 1/2-in.-diam pressure transducers were mounted in

1-3/8-in.-diam, screw-in adapters. These were installed in threaded holes provided for the earlier power-plant transients tests at the locations USpBR(60) and DSpBL(66) shown in plate 2. The manometers were installed in the test recorder area and connected to the surge tanks with 3/8-in. copper tubing.

Net head

46. The pressures at the net head piezometer ring (at a 20.51-ft-average-diameter section in the tapered transition from the penstock to the scroll case) were measured with a 16-ft-high U-tube mercury manometer. Pressures in the 24-ft-diam penstock were measured just upstream from the tapered transition with a 100-psia pressure transducer (location Pp7BR(17) in plate 2) and recorded separately by the District. Computed values of the net total head were obtained from the net head piezometer readings, penstock velocity head at the net head piezometer ring, tailwater elevation, and residual velocity head in the tailrace as described in reference 17.

Penstock pressure gradient

47. Penstock pressure gradients between the surge tank risers and the turbine scroll case were obtained for use in the pressure-momentum method of measuring discharge (similar to the Gibson tests). A ±5-psid pressure transducer was connected between the piezometer rings used for the Gibson tests and the signals were recorded on the oscillograph. The approximate location of this transducer, Tp4(72), is shown in plate 2. The inside penstock surface around each piezometer was carefully sanded to eliminate local sources of pressure disturbances. Differentials between various combinations of piezometers in the rings were measured for steady flow during one of the test operations to determine possible effects of the surge tank riser entrances on local pressures at the rings.

48. Considerable high-frequency pressure fluctuation occurred in the piping between the piezometers and pressure transducer. This was believed due to vibration of the pipes and complex reflections of pressure waves in the pipes. Damping of these fluctuations was attempted with throttling valves and air cushion in the pipes, but electrical filtering of the pressure transducer signal was necessary to produce a satisfactory record. Both the unfiltered and filtered signals were recorded on one of the oscillographs.

Scroll-case pressure differential

49. The pressure differential between the outside and inside of the curved scroll-case walls was measured with a ±10-psid pressure transducer for comparison with the Leeds and Northrup Centrimax measuring and recording system used in plant operation. The differential for steady-flow operation also was monitored with a 16-ft-high, air-water differential manometer. The pressure transducer and manometer were connected to the Winter-Kennedy system[21] at the same location as the system's pressure indicating device (item Tp3(71) near the governor cabinet in plate 2). The manometer leads were closed during any transient conditions of the tests to avoid effects of any manometer surging on the pressure transducer and station recording system.

Recording

50. Signals from the transducers were amplified and recorded on a light beam oscillograph (12-in.-wide, chemically developed chart with 0.16 and 1.6 in./sec chart speeds). Part of a typical oscillogram is shown in plate 4. Duplicate records of some signals were made on a 7-in.-wide, direct-write, light-beam oscillograph for monitoring during the tests. Additional duplicate records of the acoustic flowmeter and penstock pressure differential records were made on a 12-in.-wide, pen-type recorder to determine the effects of further signal damping in the recording system. A common timing signal composed of 60 and 1 Hz pulses was used to synchronize the three records of each test.

Test Operations

51. The Unit 1 test operations consisted of short periods of steady operation for the steady-flow measurements followed by load rejections for the pressure-momentum (Gibson) tests. The tests generally included two operations at each of the following approximate wicket gate openings: 0 (static), 17 (speed-no-load), 20, 40, 60, 80, and 100%. A detailed test schedule is given in table 2.

Test conditions

52. The reservoir elevation varied between 1559.3 and 1559.0 and

the tailwater, between 1424.5 and 1419.9. Tailwater elevations depended on the total plant output, which varied with the time of day. The resulting gross head varied from 134.6 to 139.3 ft. Water temperatures were from 55 F to 53 F and outside air temperatures varied between 80 F and 67 F during the test periods on 2, 3, and 5 November 1964.

Plant operation

53. The power plant was generally operated according to the following procedure during the tests.

a. Unit 2, adjacent to Unit 1, was not operated during the tests. This was to aid in stabilizing the tailwater in the vicinity of the Unit 1 draft tube.

b. Units 3-7 were operated to give minimum plant load fluctuations. Many of these units were inoperative for tests during the low-demand period in the afternoon.

c. Unit 1 was started to speed-no-load (SNL), slowly for minimum oscillation of surge tanks, and held at SNL as required to warm the bearings. The operation was cleared with the load dispatcher. Then the unit was synchronized with and connected to the power distribution system. Load was accepted slowly to the wicket gate opening for the test and reduced on the unit selected for balancing the load change.

d. When the countdown reached "0," all of the Unit 1 load was rejected by tripping the governor shutdown solenoid and picked up rapidly by manual control on the unit selected for balancing the load change. All units operating in the system reacted to balance the sudden change but quickly returned to normal as the selected unit (No. 5 or 6) accepted the load.

e. When the measurements following the rejection were completed, items c and d above were repeated as necessary for other gate openings. After the last test of each series the plant (except Unit 1) was returned to normal operation.

Test procedure

54. The general procedure in making the tests included the following:

a. The participating personnel were briefed orally and with copies of a detailed operation schedule for the test series to be conducted.

b. The party-line phone system connecting the various areas of activity was activated, clocks were synchronized, and the electrical measuring and recording systems were made ready.

c. Electrical calibrations were made on the recorders.

d. A short record of static conditions in the Unit 1 system was made with all measuring and recording equipment.

e. Unit 1 was started to SNL and a short record was made when the operation and flow became steady.

f. Unit 1 was connected to the system and accepted load to a level equivalent to the specified wicket gate opening. Operation was held at this level for the test.

g. When flow conditions in Unit 1 reached a steady condition (no surge tank oscillation), the following measurements were obtained:

   (1) A 15- to 30-min oscillograph record at slow chart speed was made of the acoustic flowmeter signal, wicket gate angle and vibration, surge tank water-surface elevations, and differential pressures between the pressure-momentum piezometer rings and between the scroll-case piezometers.

   (2) During these steady-flow recording periods the digital voltmeter output of the acoustic flowmeter was observed and recorded at about 10-sec intervals for about 5 min on each path. In test 2 the flowmeter also was switched to successive paths every 10 sec for about 15 min, with four readings of the output in the last 6 sec of each 10-sec period. Path D3-U7 was used for the continuous record during the pressure-momentum transients measurements.

   (3) Visual readings during the steady-flow period were recorded for the pool and tailwater; the surge tank water-surface elevations, the net head, and the scroll-case differential pressures (at 15-sec intervals); and the wicket gate servomotor connecting rod position.

h. For the load rejection operation, the oscillographs were switched to a higher speed, recording from about 15 sec before to about 1 min after rejection, then were switched back to the slower speed for about 4 min additional record. The surge tank water-surface elevation manometer was read at 15-sec intervals.

i. Items e through h were repeated for succeeding tests at increased gate openings.

Data Analyses and Test Results

Acoustic flowmeter

55. The acoustic flowmeter signals indicated by the digital voltmeter and recorded on the oscillogram compared very favorably.

Consequently, the voltmeter readings were used for steady-flow comparisons; and the oscillogram traces, for the varying flow comparisons with the surge tank oscillations. Average diametric velocities for each path, obtained from averaging the 5-min sample voltmeter readings for the path, are given in lines 21-24 of table 2. Of the 19 sequential, 10-sec samples obtained in test 2 (see subparagraph 54g(2)), 11 varied less than 0.5% from the corresponding 5-min samples with an overall average variation of about 0.75%. The 10-sec samples were used for test 2f, in which the 5-min samples were not obtained. The average of the path velocities (line 25) was multiplied by 0.96 (see paragraph 12) to obtain the average conduit velocity (line 26) and then by the penstock cross-sectional area (452.5 ft^2) for the discharge given in line 27.

56. The slight fluctuations of the acoustic flowmeter signal appearing in the oscillogram trace in plate 4 also were evident in the voltmeter readings. These are considered to be the result of fluctuations and turbulence in the flow and are generally similar to other recorded fluctuations in pressures, local velocities, power output, etc. The root-mean-square, or standard deviation, values of the voltmeter readings for these fluctuations were generally 1 to 2.5% of their respective average path velocities, with most of the extreme values between 0.5 and 3% and with the greater fluctuation percentages at the lower discharges.

Effect of velocity distribution

57. Differences in average velocities across various diametric paths had been anticipated because of the horizontal and vertical bends in the tunnel upstream from the measuring section. Consequently, four acoustic paths were provided in an effort to evaluate any such differences. The average diametric velocity for each path (lines 21-24 of table 2) relative to the average of all four paths (line 25) is shown in fig. 9. Three-fourths of the path velocities are within 1% of the overall averages and over a third are within 0.5%. Paths D2-U6 and D4-U8 possibly indicated some effects of asymmetric velocity distributions at the 20 and 40% gate openings. The low velocity indicated on both the digital voltmeter and oscillogram for path D3-U7 at 100% gate opening in test 2 appeared to be an isolated occurrence that could not be verified by records of other

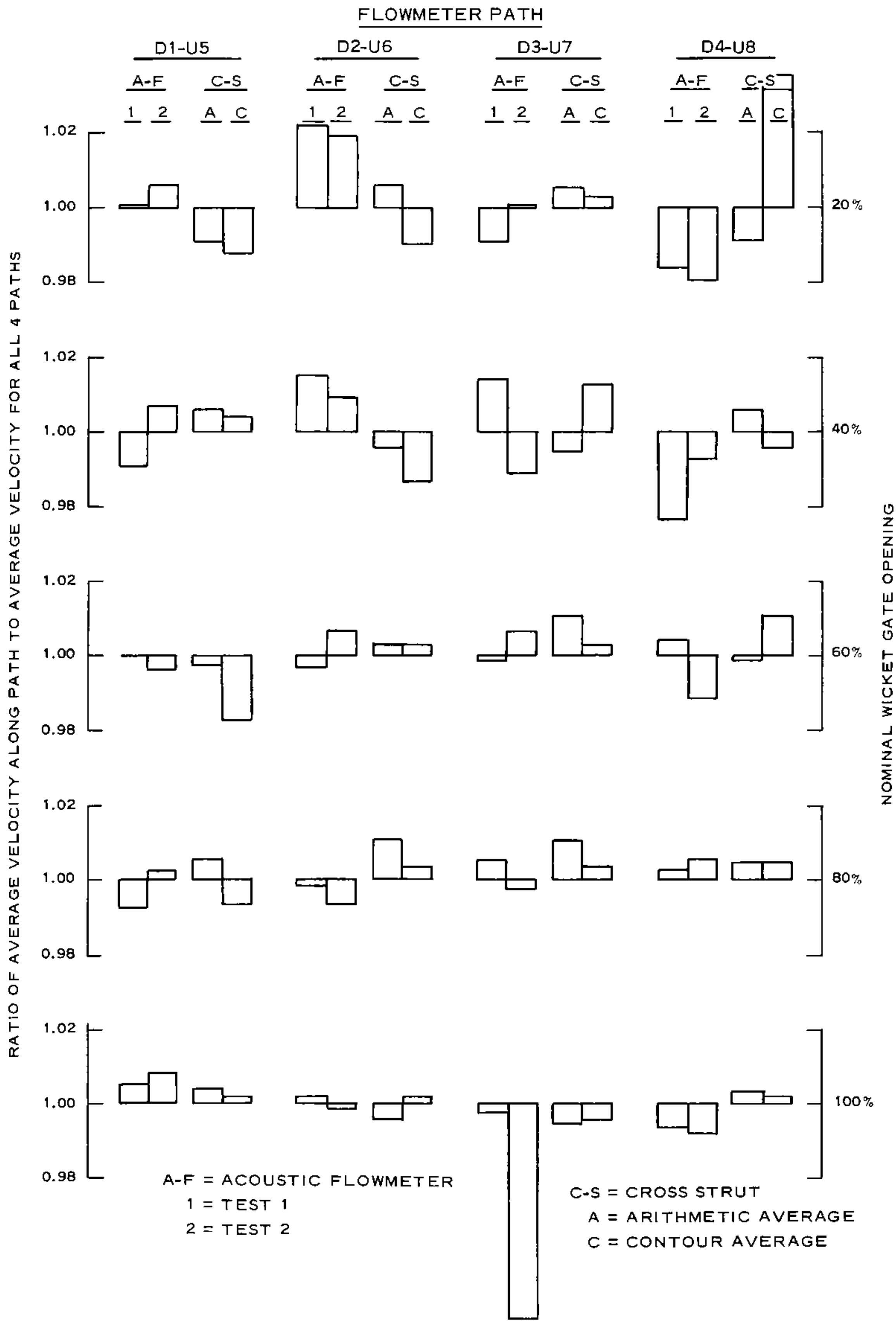


Fig. 9. Comparison of path velocities

phenomena at the same time, nor by the sequential 10-sec records. This reading was not used in computing the average velocity for that test.

58. Two sets of similar path velocity ratios interpolated from velocity measurements obtained with the cross struts in the power-plant transients tests (see paragraph 34) also are given in fig. 9. For one set, the velocities at the 13 locations shown in plate 3 were weighted according to their respective parts of the diameter and corresponding cross-sectional area, averaged arithmetically, and interpolated for the actual path locations. For the other set, velocity contours (isovels) were drawn to obtain velocity profiles for the actual path locations. Over three-fourths of these path velocities are within 1% of the overall averages and over half are within 0.5%. In general, any asymmetry in the Oahe penstock velocity distribution appears to affect the individual path velocities by less than 1%.

Pressure-momentum measurements

59. The principle of pressure-momentum measurements (Gibson tests) is outlined in many texts and the technique is described in detail in references 22-26. The data from the tests described in this report were analyzed as follows:

a. The beginning and end of the gate closure period were determined from the wicket gate angle and accelerometer traces on the oscillograms (see plate 4).

b. Average differential pressures for the measuring section in the penstock were determined from the oscillogram for periods of several seconds preceding and following the gate closure period. The average differential pressure immediately following the gate closure period was assumed to be zero. It was noted that some differential pressure was indicated during the maximum flow rates of the surge tank cycles, even though there was no flow through the measuring section. This may have resulted from secondary flow circulation induced in the measuring section by the flows entering and leaving the surge tank risers just upstream. However, the selected zero ordinate appeared to agree closely with the ordinates for subsequent periods of minimum flow rates at the peaks and troughs of the surge tank cycles.

c. The average differential pressure preceding the gate closure period was adjusted, if necessary, to represent the computed conduit resistance loss between the piezometer rings (0.05 ft at maximum discharge). These adjustments were found desirable from an analysis of differential pressures between combinations of the piezometers in the rings, which were measured during a prolonged steady-flow period. The observed variations in these differentials are attributed to effects of the surge tank riser entrances just upstream from the rings. (The maximum adjustments to the pressure-momentum differential pressure record were less than 0.5% of the differential transducer range for all but one test (0.9%). The resulting adjustments were from 0.5 to 3% of the final computed discharge for all but one test (6%).)

d. The base of the pressure-time diagram was assumed to be a straight line connecting the adjusted average differential pressure value (from c above) at the beginning and the zero pressure differential (from b above) at the end of the gate closure period.

e. The area of the pressure-time diagram was measured by planimetering and then converted to equivalent feet (pressure)-seconds (time) with the applicable oscillogram calibration factors.

f. Discharge was computed from the equation

$$Q = A_{pt}\left(\frac{A_p}{L_p}\right)g$$

where Q = discharge, cfs

A_{pt} = area of pressure-time diagram, ft-sec

A_p = cross-sectional area of penstock = 452.5 ft^2

L_p = length of penstock test section = 48.45 ft

g = acceleration of gravity = 32.17 ft/sec^2

The discharges determined by the pressure-momentum method are given in line 28 of table 2.

Turbine discharge rating

60. Turbine discharges given in line 29 of table 2 were obtained from turbine model test data adjusted on the basis of the March 1963 Gibson tests. The net total heads used with the rating are given in line 16 of table 2 and were determined by the method noted in paragraph 46. It should be noted that the 1963 tests were at a gross head of about 150 ft and the acoustic flowmeter tests were at a gross head of about 140 ft. The discharges indicated for gate openings less than 50% are from

extrapolations of the Gibson test adjustments and may not be reliable. Also, the wicket gate openings (line 19) for the Oahe turbine were derived from measurements of a similar turbine of the same manufacturer at Fort Peck Dam. However, these data are of considerable value in indicating the variation of discharge for the small differences in net head and gate opening at the same general test conditions.

<u>Scroll-case pressure differential</u>

61. Differential pressures H measured at the scroll case, Winter-Kennedy flowmeter system, were converted to discharge Q with the equation

$$Q = 1953\ H^{0.512}$$

derived from turbine model data and the physics of vortex flow. These discharges are given in line 31 of table 2 and were used in comparisons of the discharges measured by various methods.

62. Discharges also were computed with the equation

$$Q = 1977\ H^{0.515}$$

obtained from the 1963 Gibson tests and are given in line 32. The discharges indicated by the Leeds and Northrup Centrimax measuring and recording system are shown in line 33. The discrepancies between lines 32 and 33 may have resulted from small differences in the manometric and mechanical measurements of the pressure differential and from small errors in calibration adjustment of the flowmeter.

<u>Surge tank volume changes</u>

63. Volumetric-type measurements of discharge were computed from the surge tank manometer records during the surge action following complete closure of the turbine wicket gates for the pressure-momentum measurements. The change in volume between two elevations is compared in lines 34 and 35 of table 2, with the volume computed by integrating the average velocity on acoustic flowmeter path D3-U7 for the same period. The two sets of data are for different length measurement periods.

Comparison of Measurements

64. The discharges measured or determined by the acoustic flowmeter, pressure-momentum, model, and scroll-case meter methods are compared in lines 27, 28, 29, and 31 of table 2 and in plate 5. The undistorted and expanded comparisons in plate 5 have arbitrary reference curves for convenience in visual comparisons of the data points. (These curves have no physical significance.) Plus and minus 1% brackets relative to the arbitrary curve also are shown for assistance in comparing the data points.

65. The acoustic flowmeter measurements generally agree very well with the pressure-momentum test results given in this report and the model rating curve adjusted with the previous Gibson test data. The model rating curve values below 50% gate opening are not considered reliable, but they should indicate the relative effects of small variations in actual net head and gate openings for the same general test conditions.

66. The repeatability of acoustic measurements in the second series of tests two days after the first series indicates a probable high precision. Although there appears to be considerable scatter of the measurement data in plate 5 for gate openings near 100%, most of this is believed due to variations in actual net head and gate opening. Table 3A gives a comparison of acoustic measurements adjusted to common net heads. These show an average repeatability of about 0.3% with a maximum variation of about 0.7%. Further adjustment of these measurements to a common net head of 134 ft and a large-scale plot of discharge relative to gate opening showed excellent agreement of test "O" with tests 1g and 2g, indicating precision of these maximum discharge measurements well within 1%. The repeatability of all methods of measurement is compared in table 3B.

67. The scroll-case meter indicated discharges at least 3 to 4% lower than the other methods. However, that system had been calibrated at a somewhat higher head, and the local pressures at the inner piezometers may have been affected by changes in local flow patterns caused by a larger wicket gate opening for an equivalent discharge in the acoustic flowmeter tests. A 4% variation in comparative measurements of the same discharge has been experienced in other tests.[27]

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

68. These tests were an effort to evaluate the performance of an acoustic flow measuring instrument believed to be accurate within 1%, with methods and equipment generally considered to be less accurate. Also, it was necessary to restrict the tests to a relatively few during a single short period because of limited funds, personnel, and plant availability. The following conclusions have been drawn from a study of the test results and should be considered with respect to these conditions.

a. Discharge measurements made with the acoustic flowmeter were in good agreement with those obtained from pressure-momentum measurements and with rating curves derived from turbine model tests and previous Gibson tests. Much of the agreement was within 1%.

b. Flow volumes computed from a continuous record of one flowmeter path were in good agreement with several computations of the same volume obtained from measured changes of water level in the surge tanks.

c. The acoustic flowmeter measurements appear to be generally more precise relative to repeated tests at approximately the same flow conditions than those by the other methods.

d. Any asymmetry in the Oahe penstock velocity distribution generally appeared to affect the individual flowmeter path velocities by less than 1%.

e. A value of 0.96 for the ratio of average conduit velocity to average path velocity seems appropriate for the Oahe penstock and should be applicable to other long, reasonably straight conduits with fully developed turbulent flow and equivalent resistance coefficients. The ratios for conduits having different surface resistance effects should be approximated closely by the relation

$$\frac{\overline{V}}{\overline{V}_D} = \frac{2.00}{2.00 + \sqrt{f}}$$

f. The acoustic flowmeter is a distinct advance in the art of gaging discharge by the direct measurement of the average velocity along a path across the flow. Although this path velocity probably can be measured within about 0.5% of the true value, as claimed by the manufacturer, the selection of the measuring section must be such as to give a known or measurable relation between the flow pattern of the whole section and that along the acoustic path.

Recommendations

69. The following recommendations are given for any future use or testing of the acoustic flowmeter:

a. Additional evaluations of the flowmeter performance in prototype installations should be made wherever possible. Methods and equipment for comparative measurements should be selected and utilized for maximum accuracy.

b. Available traversing probes should be installed in the acoustic flowmeter transducer holes in the Oahe penstock to obtain additional velocity distribution data. These data would be of great value in evaluating the effects of asymmetry on the average and path velocities.

c. The measuring section for an acoustic flowmeter should be at a location where the velocity distribution is known or can be determined by computation or measurement.

d. Embedded anchorages and electrical conduit in concrete-walled conduits and reinforced ports in steel penstocks should be provided during construction of any projects where any use of an acoustic flowmeter is contemplated. These provisions are relatively simple to install during construction and design suggestions can be obtained from the Waterways Experiment Station and the flowmeter manufacturer.

LITERATURE CITED

1. Mousson, J. M., "Water gaging for low-head units of high capacity." Transactions, American Society of Mechanical Engineers, vol 57, Hyd-57-10 (August 1935), pp 303-316.

2. Hess, W. B., and Mousson, J. M., More Power Through Higher Operating Efficiencies of Hydro Electric Power Plants. Edison Electric Institute Bulletin, July 1941.

3. Hess, W. B., Vibration, the Criterion for Maximum Loading of Hydraulic Turbines. Paper presented at Pennsylvania Electric Association, Hydraulic Power Committee, October 1948.

4. Hess, W. B., Swengel, R. C., and Waldorf, S. K., Measuring Water Velocity by an Ultrasonic Method. American Institute of Electrical Engineers Miscellaneous Paper 50-214, October 1950.

5. ________, "Demonstrations of the principles of the ultrasonic flowmeter." Electrical Engineering, vol 73, No. 12 (December 1954), pp 1082-1084.

6. ________, "Principles and application of the ultrasonic flowmeter." Transactions, American Institute of Electrical Engineers, No. 17, Paper 55-28 (April 1955), pp 112-118.

7. Swengel, R. C., Antenna-type Transducers for Ultrasonic Flowmetering. Institute of Radio Engineers Convention Record, June 1955.

8. Swengel, R. C., and Hess, W. B., "Development of the ultrasonic method for measurement of fluid flow." Proceedings of the Sixth Hydraulics Conference, Bulletin 36, State University of Iowa, Iowa City, Iowa (1956), pp 61-74.

9. Kritz, Jack, "An ultrasonic flowmeter for liquids." Proceedings of the Instrument Society of America, vol 10, No. 11 (November 1955), pp 1-2.

10. Swengel, R. C., Hess, W. B., and Waldorf, S. K., "The ultrasonic measurement of hydraulic turbine discharge." Transactions, American Society of Mechanical Engineers, vol 77 (October 1955), pp 1037-1043.

11. Sani, Luciano, "Sulla misura delle velocità medie di una corrente liquida a mezzo di ultrasuoni modulati" (Concerning mean velocity measurement of a flowing liquid by means of ultrasonic modulations). L'Energia Elettrica, No. 3 (1957), p 237.

12. Fischbacher, R. E., "Measurement of liquid flow by ultrasonics." Water Power, vol 11, No. 6 (June 1959), pp 212-215.

13. Barron, Edger G., New Instruments of the United States Geological Survey for the Measurement of Tidal Flow. Paper prepared for presentation at ASCE Eighth National Conference, Hydraulics Division, July 1959.

14. Rouse, Hunter, Elementary Mechanics of Fluids. John Wiley and Sons, Inc., New York, N. Y., 1956.

15. U. S. Army Engineer Waterways Experiment Station, CE, Prototype Performance and Model-Prototype Relationship, by F. B. Campbell and E. B. Pickett. Miscellaneous Paper No. 2-857, Vicksburg, Miss., November 1966.

16. __________, Flow Characteristics in Flood-Control Tunnel 10, Fort Randall Dam, Missouri River, South Dakota; Hydraulic Prototype Tests, by J. V. Dawsey, Jr., C. J. Huval, and W. C. Blanton. Technical Report No. 2-626, Vicksburg, Miss., June 1963.

17. Levett, R. J., Turbine Performance Test Made for the Corps of Engineers on Unit No. 1 at the Oahe Power Plant. Unpublished letter report from Norman R. Gibson, Consulting Engineer, Niagara Falls, N. Y., June 1963.

18. Barbarossa, N. L., "Hydraulic analysis of surge tanks by digital computer." Journal of Hydraulic Division; Proceedings of the American Society of Civil Engineers, vol 85, Paper No. 1996, No. HY 4, (April 1959), pp 39-78. Discussions thereto, HY 9 (September 1959), pp 159-161; HY 10, Part 1 (October 1959), pp 143-156; HY 12, Part 1 (December 1959), pp 99-101; and vol 86, HY 5 (May 1960), pp 105-112.

19. __________, Investigation of Transients in the Garrison and Oahe Surge Systems. Paper presented at First National Water Resources Engineering Conference, American Society of Civil Engineers, Omaha, Neb., 15 May 1962 (unpublished).

20. Perkins, F. E., Eagleson, P. S., and Ippen, A. T., Hydro-Power Plant Transients, Part I, Design of a Comprehensive Field Test Program, Technical Note No. 7, Massachusetts Institute of Technology, Hydrodynamics Laboratory, Cambridge, Mass., January 1961.

21. Winter, Ireal A., "Improved type of flow meter for hydraulic turbines." Transactions, American Society of Civil Engineers, vol 99, Paper No. 1875 (1934), pp 847-872.

22. Gibson, N. R., "Experience in the use of the Gibson method of water measurement for efficiency tests of hydraulic turbines." Transactions, American Society of Mechanical Engineers, Journal of Basic Engineering, vol 81, Series D, No. 4 (December 1959), pp 455-487.

23. __________, "The Gibson method and apparatus for measuring the flow of water in closed conduits." Transactions, American Society of Mechanical Engineers, vol 45 (1923), pp 343-392.

24. __________, "Pressures in penstocks caused by the gradual closing of turbine gates." Transactions, American Society of Civil Engineers, vol 83, Paper No. 1439 (1920), pp 707-775.

25. Dickinson, W. D., and Weathers, L. C., A Discussion of the Suitability of the Gibson Method and Apparatus for Measuring the Quantity of Water Supplied to the Boulder Turbines During Efficiency Tests. U. S. Bureau of Reclamation Technical Memorandum No. 431, January 1935.

26. ASME Power Test Codes, Hydraulic Prime Movers. PTC 18-1949, United Engineering Center, New York, N. Y., 1949.

27. Hutton, S. P., and Murdoch, G. B., "Comparative flow-measurement tests at Finlarig Power Station." Water Power, vol 14, No. 10 (October 1962), pp 391-395, 404; vol. 14, No. 11 (November 1962), pp 438-444.

Table 1

Conduit Resistance Tests

Curve*			Test Section			Tests			Range of Data				
Symbol	No.	Project Name	Surface	Diam ft	L/D	Year	Age yr	No.	Velocity ft/sec	$\mathcal{R}_e$	f	Std Error	Data Source
○	1	Fort Randall penstock 1 Missouri River, S.D.	Coal tar enamel on steel	22	22			20	10.5 14.7	1.25×10^7 1.75×10^7	0.01053 0.01045	0.00023	General Design Memorandum No. G-7, 1955, U. S. Army Engineer District, Omaha
○	2	Fort Randall penstock 8 Missouri River, S.D.	Vinyl paint on steel	22	22	1956		29	6.4 14.6	8.11×10^6 1.84×10^7	0.00833 0.00739	0.00017	General Design Memorandum No. G-9, 1956, U. S. Army Engineer District, Omaha
△	3	Fort Randall tunnel 10 Missouri River, S.D.	Coal tar enamel on steel	22	29	1959		5	21.0 65.8	4.67×10^7 1.46×10^8	0.00881 0.00869	0.00098	Unpublished data, U. S. Army Engineer Waterways Experiment Station
○	4	Denison Dam tunnel Red River, Okla. and Tex.	Concrete	20	32	1947- 57		3	65.3 71.6	1.20×10^8 1.40×10^8	0.00764 0.00762	0.00034	-do-
△	5	Pine Flat Dam conduit Kings River, Calif.	Concrete	Rect 5×9	54	1952		7	61.5 68.4	2.80×10^7 3.43×10^7	0.01318 0.01317	0.00037	-do-
○	6	Pine Flat Dam conduit Kings River, Calif.	Concrete	Rect 5×9	54	1954- 58		6	80.5 91.5	3.54×10^7 4.49×10^7	0.01750 0.01750	0.00073	-do-
△	7	Ontario Power Co. tunnel, Niagara Falls, Canada	Concrete	18	361		8	5	4.0 20.0	5.88×10^6 2.94×10^7	0.00889 0.00733	0.00059	Scobey, Bulletin No. 852, 1924, USDA, Washington, D. C.
○	8	Umatilla River siphon Umatilla Project, Oregon	Concrete	3.83 3.83	2550 2565		5 2	5 2	1.4-3.2 4.0-4.2	3.80×10^5 1.14×10^6	0.01481 0.01310	0.00164	-do-
△	9	Umatilla Dam siphon Umatilla Project, Oregon	Concrete	2.5	2011		New	3	3.4 3.6	6.00×10^5 6.40×10^5	0.01406 0.01396	0.00075	-do-
□	10	Prosser pressure pipe Yakima, Washington	Concrete	2.54	896		4	7	4.9 5.8	1.01×10^6 1.20×10^6	0.01768 0.01761	0.00151	-do-
▽	11	Deer Flat conduit Boise Project, Idaho	Concrete	3.0	2427		6	5	5.4 9.1	1.32×10^6 2.20×10^6	0.01368 0.01333	0.00123	-do-
△	12	Chelan Station conduit, State of Washington	Concrete	14.0	659		New	17	1.2 14.8	3.40×10^6 1.69×10^7	0.01123 0.01056	0.00039	Fosdick, Trans. ASCE, Vol. 101, 1936
○	13	Enid Dam tunnel Yocona River, Miss.	Concrete	11.0	5	1958	6	8	37.0 38.9	2.58×10^7 2.71×10^7	0.01290 0.01290	0.00062	Unpublished data, U. S. Army Engineer Waterways Experiment Station
□	14	Oahe Dam tunnel Missouri River, S.D.	Concrete	18.25	36	1960- 62		4	36.7 44.4	7.37×10^7 9.17×10^7	0.00690 0.00682	0.00079	-do-
□	15	San Gabriel penstock Los Angeles County, Calif.	Enameled steel	4.23	118	1953		30	6.0 36.0	1.82×10^6 1.17×10^7	0.01162 0.01037	0.00066	Burke, Trans. ASCE, Vol. 120, 1955
▽	16	San Gabriel penstock Los Angeles County, Calif.	Enameled steel	10.23	49	1953		26	7.3 49.9	5.57×10^6 3.81×10^7	0.00880 0.00653	0.00031	-do-
□	17	Garrison Dam penstock Missouri River, N.D.	Vinyl paint on steel	24	32	1956	New	26	8.0 15.5	1.54×10^7 2.96×10^7	0.00761 0.00698	0.00019	Friction Loss Tests in Penstock No. 1, 1957, U. S. Army Engineer District, Garrison
○	18	Niagara-Sir Adam Beck tunnel, Canada	Concrete	45	624	1954	New	6	8.4 15.1	3.25×10^7 5.66×10^7	0.00769 0.00747	0.00019	Bryce and Walker, The Engineering Journal, August 1959
○	19	Louisville sewer model	Plastic	0.490 and 0.330	508 762	1949	New	16	1.18 4.15	4.80×10^4 1.13×10^5	0.0206 0.0168	--	Unpublished data, U. S. Army Engineer Waterways Experiment Station

* The curve symbols and numbers are those in fig. 2.

Table 2

Test Schedule and Data Summary

Line		1a	2a	1b	2b	1c	2c	1d	2d	1e	2e	1f	2f	1g	2g	0	Line
1	Approximate Gate Opening (See Line 19)	0% (Static)		17% (SNL)		20%		40%		60%		80%		100%			1
2	Test Number (Chronological)	1a	2a	1b	2b	1c	2c	1d	2d	1e	2e	1f	2f	1g	2g	0	2
3	Date (November 1964)	3	5	3	5	3	5	3	5	3	5	3	5	3	5	2	3
4	Time (a = observation; b = load rejection)	a-1110	a-1000	a-1110	a-1040	b-1220	b-1215	b-1340	b-1330	b-1510	b-1451	b-1630	b-1610	b-1830	a-1700	b-1351	4
5	Water Temperature, C	12.5	11.7	12.6	11.9	12.5	12.3	12.6	12.5	12.7	12.7	12.6	12.9	12.6	12.7	13.0	5
6	Air Temperature, C	22.0	19.5	22.8	22.0	25.0	29.8	24.0	23.8	22.8	23.3	21.5	23.0	20.0	22.6	25.0	6
7	Pool Elevation, ft msl	1559.14	1559.02	1559.15	1558.99	1559.18	1559.07	1559.19	1559.11	1559.26	1559.05	1559.29	1559.16	1559.09	1559.10	1559.04	7
8	Surge Tank Manometer, ft msl	1559.1	1559.0	Oscil	Oscil	1559.0	1558.7	1557.6	1557.4	1555.3	1554.9	1552.4	1552.2	1550.1	1549.6	--	8
9	Net Head Manometer, ft msl	1559.1	1559.0	1559.0 ± 1.0	1558.8 ± 1.0	1558.9	1558.6	1557.0	1556.6 ± 0.5	1553.5	1553.0 ± 1.0	1549.5	1549.3	1546.1	1545.8	1539.8	9
10	Tailwater, ft msl	1422.62	1422.95	1422.60	1422.60	1422.16	1422.09	1420.72	1420.48	1420.34	1419.92	1420.55	1419.90	1424.53	1420.36	1421.65	10
11	Gross Head, ft (L7 - L10)	136.5	136.1	136.6	136.4	137.0	137.0	138.5	138.6	138.9	139.1	138.7	139.3	134.6	138.7	137.4	11
12	Head Loss Along Penstock, ft (L11 - L13 - L14)	0.0	0.0	0.0	0.0	0.0	0.2	0.9	1.2	2.5	2.8	4.3	4.4	5.7	5.8	11.8	12
13	Penstock Velocity Head, ft (D = 20.5 ft)	0.0	0.0	0.2	0.2	0.3	0.3	1.3	1.3	3.2	3.2	5.5	5.5	7.3	7.5	7.3	13
14	Net Piezometer Head, ft (L9 - L10)	136.5	136.1	136.4	136.2	136.7	136.5	136.3	136.1	133.2	133.1	128.9	129.4	121.6	125.4	118.2	14
15	Residual Velocity Head in Tailrace, ft	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.4	0.4	0.3	0.5	0.4	15
16	Net Total Head, ft (L14 + L13 - L15)	136.5	136.1	136.6	136.4	137.0	136.8	137.5	137.3	136.2	136.1	134.0	134.5	128.6	132.4	125.1	16
17	Servomotor Piston Stroke, in.	3-5/64	3-4/64	6-9/64	6-5/64	6-41/64	6-41/64	10-15/64	10-15/64	13-57/64	13-56/64	17-30/64	17-31/64	21-3/64	21-7/64	21-23/64	17
18	Relative Servopiston Stroke, %	0	0	16.8	16.4	19.5	19.5	39.1	39.1	59.2	59.1	78.7	78.8	98.3	98.6	100.0	18
19	Computed Actual Wicket Gate Opening, %	0	0	14.8	14.4	17.5	17.5	37.7	37.7	58.2	58.0	78.2	78.3	98.5	98.8	100.0	19
20	Unit 1 Power Output, mw	0	0	0	0	3	3	26	26	46	46	63	63	67	70	69	20
	Acoustic Flowmeter Measurements																
21	Velocity in Path D1-U5, fps	+0.07	-0.04	2.90*	2.64	3.19	3.18	6.95	7.09	--	10.85	14.22	14.42**	16.57	16.90	16.73	21
22	Velocity in Path D2-U6, fps	+0.04	+0.02	3.03*	2.60	3.26	3.22	7.12	7.10	10.88	10.97	14.31	14.30**	16.53	16.74	16.75	22
23	Velocity in Path D3-U7, fps	-0.04	-0.05	2.49*	2.52	3.16	3.16	7.11	6.96	10.90	10.97	14.40	14.35**	16.46	15.79†	16.47	23
24	Velocity in Path D4-U8, fps	0	+0.03	2.32*	2.55	3.14	3.10	6.85	6.99	10.96	10.78	14.37	14.47**	16.39	16.63	16.21	24
25	Average Path Velocity, fps	+0.02	-0.01	--*	2.58	3.19	3.16	7.01	7.04	10.91	10.89	14.32	14.38	16.49	16.76	16.54	25
26	Average Conduit Velocity (L25 × 0.96), fps	+0.02	-0.01	--*	2.48	3.06	3.03	6.73	6.76	10.47	10.45	13.75	13.80	15.83	16.09	15.88	26
27	Penstock Discharge, cfs	0	0	--*	1120	1380	1370	3050	3060	4740	4740	6220	6240	7160	7280	7190	27
28	Pressure-Momentum Discharge, cfs	--	--	--	--	1390	1340	3080	3080	4570	4720	6160	6290	7360	--	7300	28
29	Model Discharge (with 1963 adjustment), cfs	0	0	810††	780††	1080††	1080††	2960††	2960††	4740	4720	6250	6270	7170	7290	7110	29
	Scroll-Case Flowmeter																
30	Manometer Differential, ft H_2O	0	0	0.304	0.282	0.428	0.429	2.216	2.142	5.282	5.244	9.110	8.878	11.861	12.161	--	30
31	Model Data and Vortex Theory, cfs	0	0	1060	1020	1260	1270	2940	2880	4580	4560	6050	5970	6930	7020	--	31
32	Calibration from 1963 Tests, cfs	0	0	1070	1030	1280	1280	2980	2930	4660	4640	6170	6090	7070	7160	--	32
33	Plant Recording System, cfs	0	0	1090	1000	1300	1290	2940	2950	4560	4560	6000	5940	6920	6940	--	33
	Surge Tank Volume Change Measurements																
34	Acoustic Flowmeter Record, 1000's of ft^3	--	--	--	--	-- 62.8	42.3	-- 99.7	68.0	-- 128.4	91.4	-- 143.5	99.5	--	--	--	34
35	Water-Surface Elevations, 1000's of ft^3	--	--	--	--	-- 62.2	43.6	-- 105.4	68.5	-- 133.9	92.2	-- 155.6	107.4	--	--	--	35
36	Reynolds Number (from L5 and L26), $\times 10^6$	--	--	--	4.4	5.6	5.5	12.3	12.4	19.3	19.2	25.2	25.4	29.0	29.6	29.4	36

* Affected considerably by surge tank oscillation. ** Data from sequential 10-sec samples. † Isolated occurrence; not used in average. †† Extrapolated below 50% gate opening.

Table 3

Comparison of Discharge Measurements at Common Net Heads

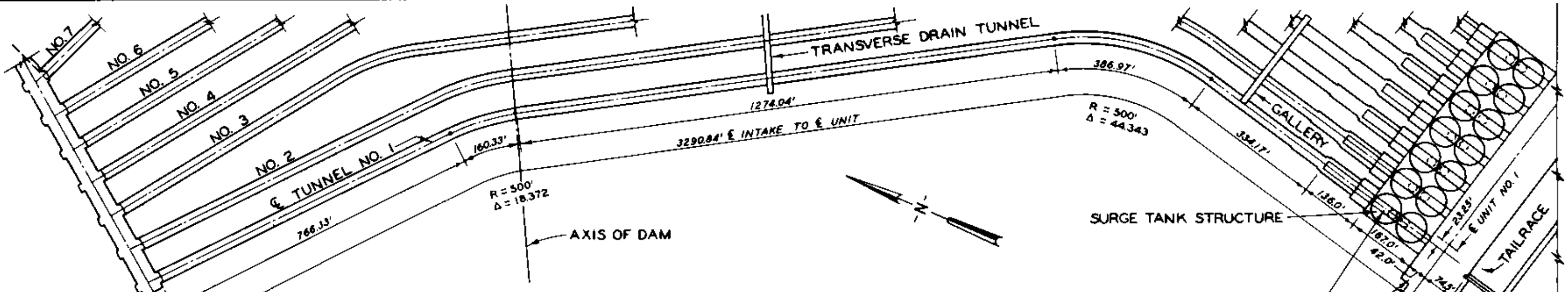
A. Acoustic Flowmeter

Test	Gate Opening %	Net Head ft	Measured Discharge cfs	Adjusted* Discharge cfs	Variation %	Adjusted to 134-ft Net Head cfs
2b	14.4	136.4	1120	--	--	--
1c	17.5	137.0	1380	1380	--	1365
2c	17.5	136.8	1370	1371	-0.65	1356
1d	37.7	137.5	3050	3050	--	3011
2d	37.7	137.3	3060	3062	+0.39	3023
1e	58.2	136.2	4740	4740	--	4701
2e	58.0	136.1	4740	4741	+0.02	4703
1f	78.2	134.0	6220	6220	--	6220
2f	78.3	134.5	6240	6228	+0.13	6228
1g	98.5	128.6	7160	7160	--	7309
2g	98.8	132.4	7280	7174	+0.20	7324
"0"	100.0	125.1	7190	--	--	7441

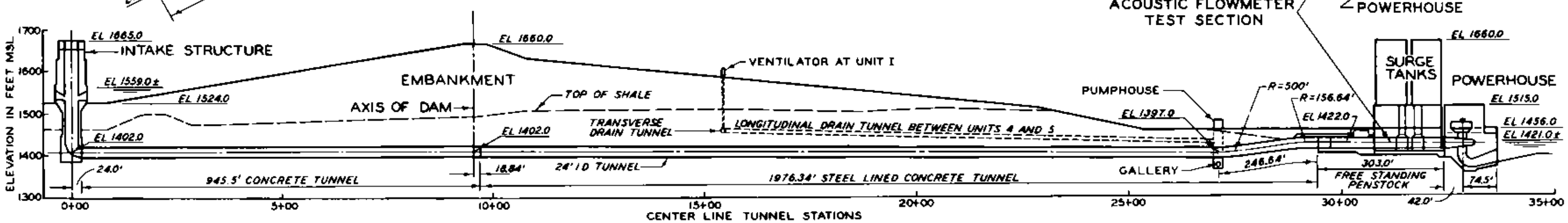
B. Variation for All Methods

Tests Compared	Variation, %, for Given Methods					
	Acoustic Flowmeter	Pressure Momentum	Model (1963 Adj)	Scroll-Case Flowmeter: Model	Scroll-Case Flowmeter: 1963 Calib	Scroll-Case Flowmeter: Recorder
1c-2c	0.65	3.53	--	0.87	0.08	0.70
1d-2d	0.39	0.06	--	1.97	0.61	0.41
1e-2e	0.02	3.31	0.40	0.41	0.41	0.02
1f-2f	0.13	1.90	0.11	1.15	1.49	1.20
1g-2g	0.20	--	0.20	0.17	0.21	1.17
Avg	0.28	2.15	0.24	0.91	0.76	0.70

* Discharges (Q) of 2c, 2d, etc., adjusted to respective net heads (H) of tests 1c, 1d, etc., by $Q_{adj} = Q_{meas} \sqrt{H_1/H_2}$. Differences in paired gate openings assumed negligible.



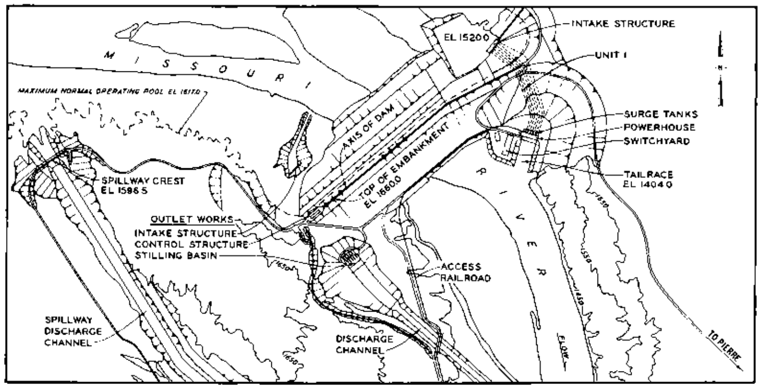
POWER PLANT PLAN



UNIT I PROFILE

SCALE IN FEET

200 0 200 400



PROJECT LAYOUT

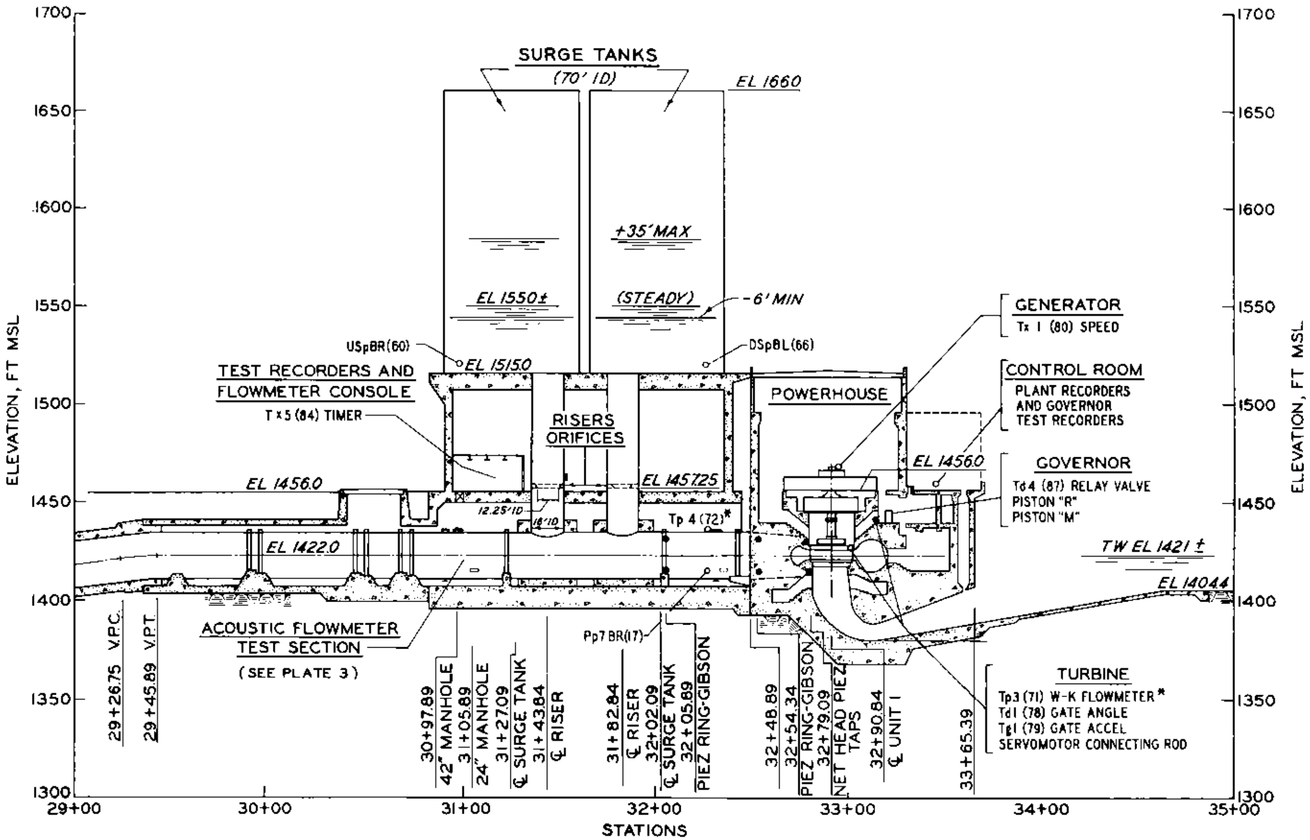
SCALE IN FEET

1000 0 1000 2000

OAHE DAM

POWER PLANT PLAN AND PROFILE
AND PROJECT LAYOUT

PLATE I



INSTRUMENTATION SYMBOLS

LOCATION

- P = PENSTOCK
- S = SURGE TANKS
- T = TURBINE AND TAILWATER
- (84) = LINE NUMBER CORRESPONDING TO TRANSIENTS TESTS SCHEDULE

POSITION

- L = LEFT } (LOOKING DNSTR)
- R = RIGHT } (LOOKING DNSTR)
- B = BOTTOM
- U = UPSTREAM
- D = DOWNSTREAM

INSTRUMENT

- p = PRESSURE TRANSDUCER
- g = ACCELEROMETER
- d = DISPLACEMENT
- x = OTHER
- • = PIEZOMETER

NOTE: HORIZONTAL ALIGNMENT OF TUNNEL IS SHOWN IN PLATE 1

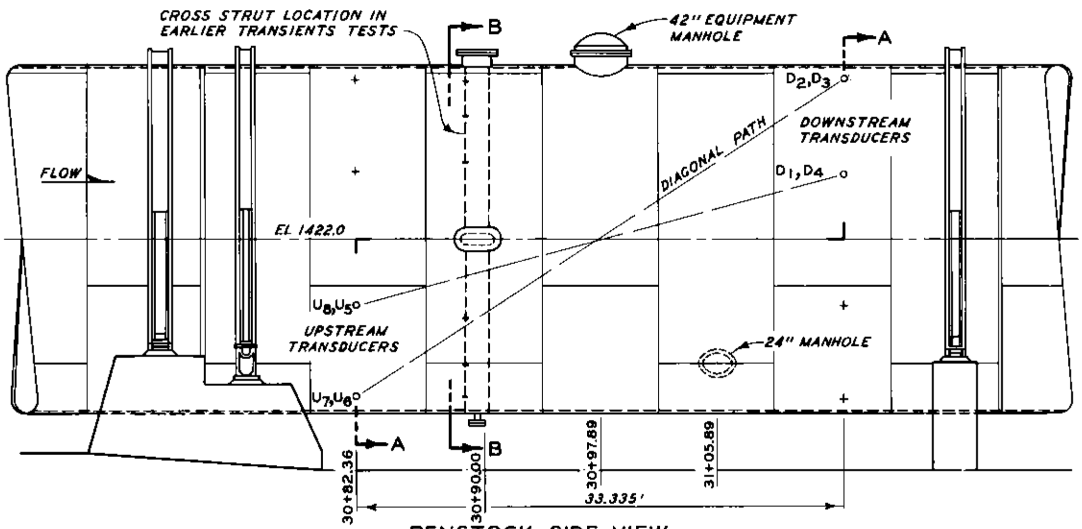
* DIFFERENTIAL PRESSURE TRANSDUCER:
Tp3 (71) - BETWEEN W-K FLOWMETER PIEZOMETERS
Tp4 (72) - BETWEEN GIBSON PIEZOMETER RINGS

OAHE POWER PLANT UNIT 1

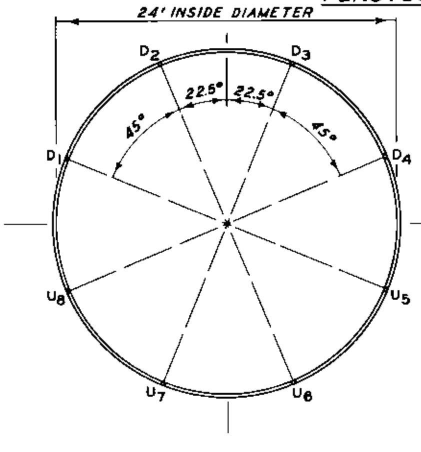
SURGE TANKS AND POWERHOUSE

SCALE IN FEET

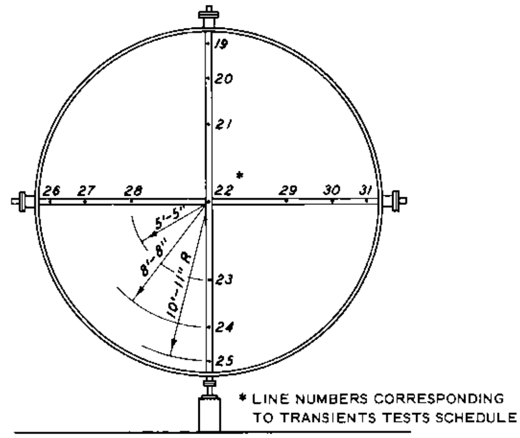
50 0 50 100 150 200



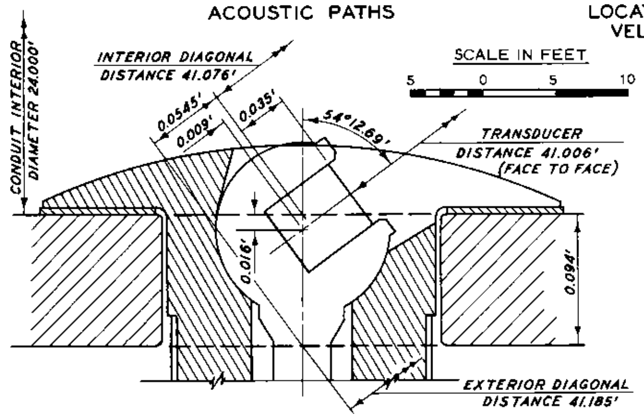
PENSTOCK SIDE VIEW



SECTION A-A
ACOUSTIC PATHS



SECTION B-B
LOCATIONS OF CROSS STRUT
VELOCITY MEASUREMENTS



DETAIL AT TRANSDUCER

SCALE IN FEET
0.1 0 0.1

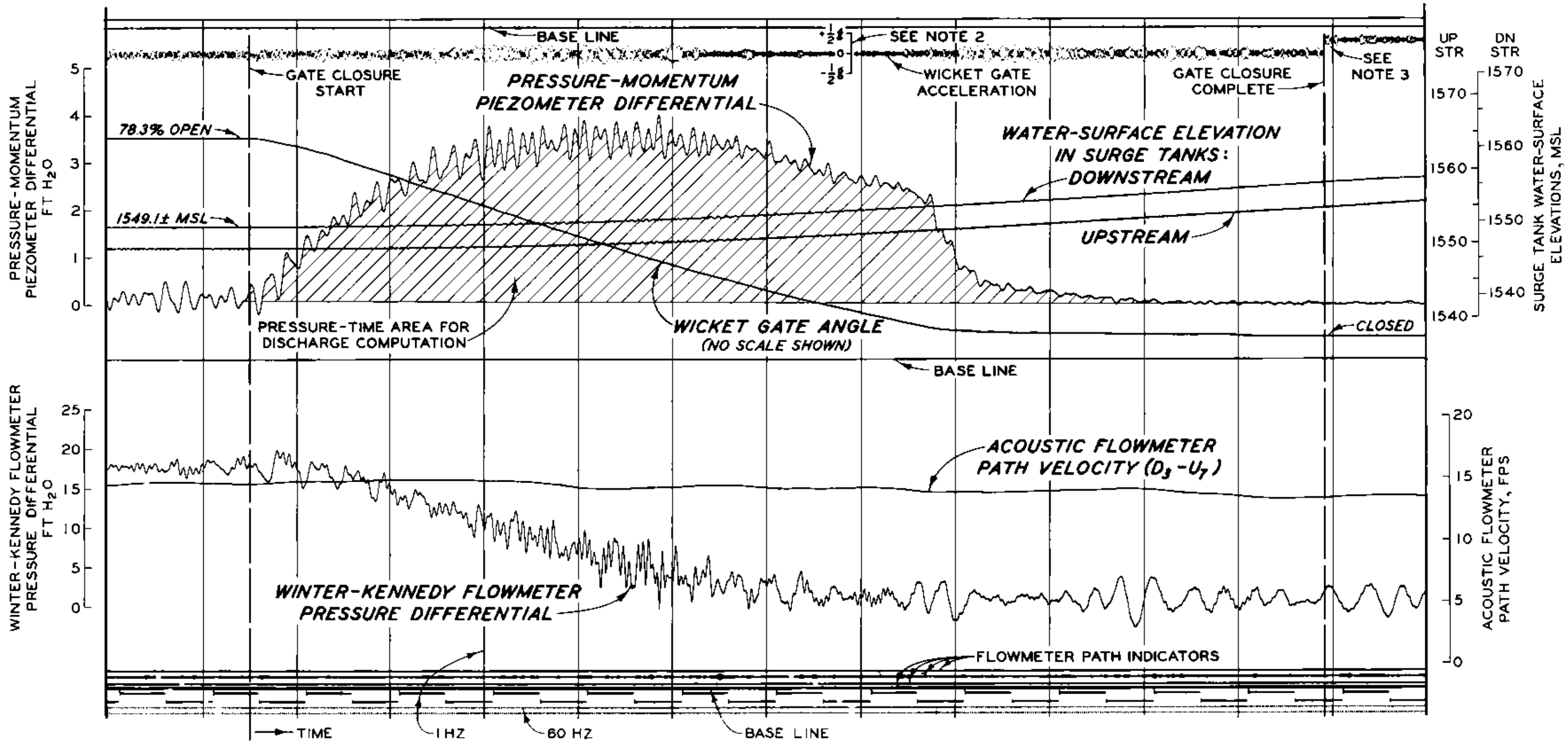
ACTUAL DIMENSIONS COMPUTED FROM POSTTEST MEASUREMENTS OF HOLE COORDINATES WITH PENSTOCK UNDER PRESSURE:

PATH	INTERIOR DIAMETER FT	SECTION LENGTH FT	TRANSDUCER DISTANCE FT
D_1-U_5	23.982	33.332	40.994
D_2-U_6	23.984	33.346	41.007
D_3-U_7	24.048	33.324	41.019
D_4-U_8	23.996	33.330	41.001
AVERAGE	24.002	33.333	41.005

NOTE: MANHOLES CONTAIN PLUGS WITH CURVED INSIDE FACE MATCHING INSIDE SURFACE OF PENSTOCK.

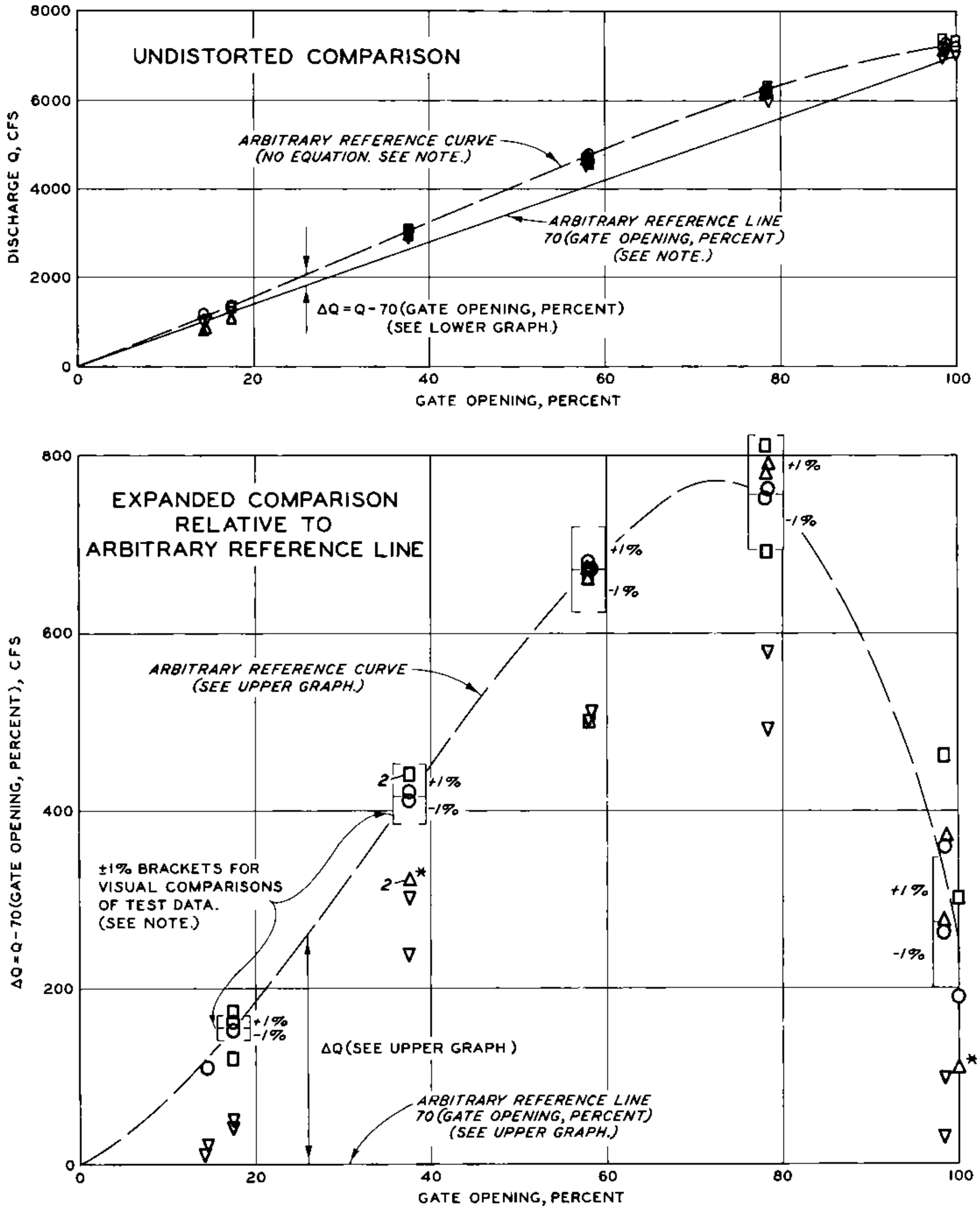
TRANSDUCER DIMENSIONS SHOWN ON SKETCH ARE THEORETICAL FOR DESIGN. ACTUAL DIMENSIONS ARE GIVEN IN TABLE.

ACOUSTIC FLOWMETER TEST SECTION



NOTES:
1. ORIGINAL RECORD 12 IN. WIDE WITH 1.6 IN./SEC CHART SPEED
2. ACCELEROMETER RECORD SCALE IS APPROXIMATE. RECORD USED TO INDICATE START AND COMPLETION OF GATE OPERATION
3. ABRUPT SHIFT IN ACCELEROMETER TRACE POSSIBLY DUE TO SLIGHT TILTING OF PICKUP AT END OF GATE CLOSURE CYCLE

TYPICAL OSCILLOGRAM
LOAD REJECTION-TEST 2F
80%± TO CLOSED GATE



LEGEND

- O ACOUSTIC FLOWMETER
- □ PRESSURE-MOMENTUM
- Δ MODEL-GIBSON
- ∇ SCROLL-CASE METER

NOTE: THE ARBITRARY REFERENCE CURVE, LINE 70(GATE OPENING, PERCENT), AND BRACKETS ARE FOR CONVENIENCE IN VISUAL COMPARISONS OF THE TEST DATA AND HAVE NO PHYSICAL SIGNIFICANCE.

* EXTRAPOLATED; NOT CONSIDERED RELIABLE.

COMPARISONS OF MEASUREMENTS

UNDISTORTED AND EXPANDED

APPENDIX A: SUMMERSVILLE DAM ACOUSTIC FLOWMETER INSTALLATION AND TESTS, MARCH 1966

Introduction

Pertinent features of the prototype

1. Summersville Dam (fig. A1) is located in Nicholas County, W. Va., 34.5 miles above the mouth of Gauley River and about 5 miles southwest from

Fig. A1. Summersville Dam, Gauley River, W. Va. Outlet works at lower left with conduit 3 discharging

the town of Summersville (fig. A2). The dam is a rock-fill structure, 375 ft high and 2280 ft long. Total storage capacity of the reservoir is 413,425 acre-ft of which 390,611 acre-ft is reserved for flood-control storage above minimum pool (elevation 1520). Water is normally released through the flood-control conduits. A 1250-ft uncontrolled saddle spillway with a crest elevation of 1710 is provided for emergency releases.

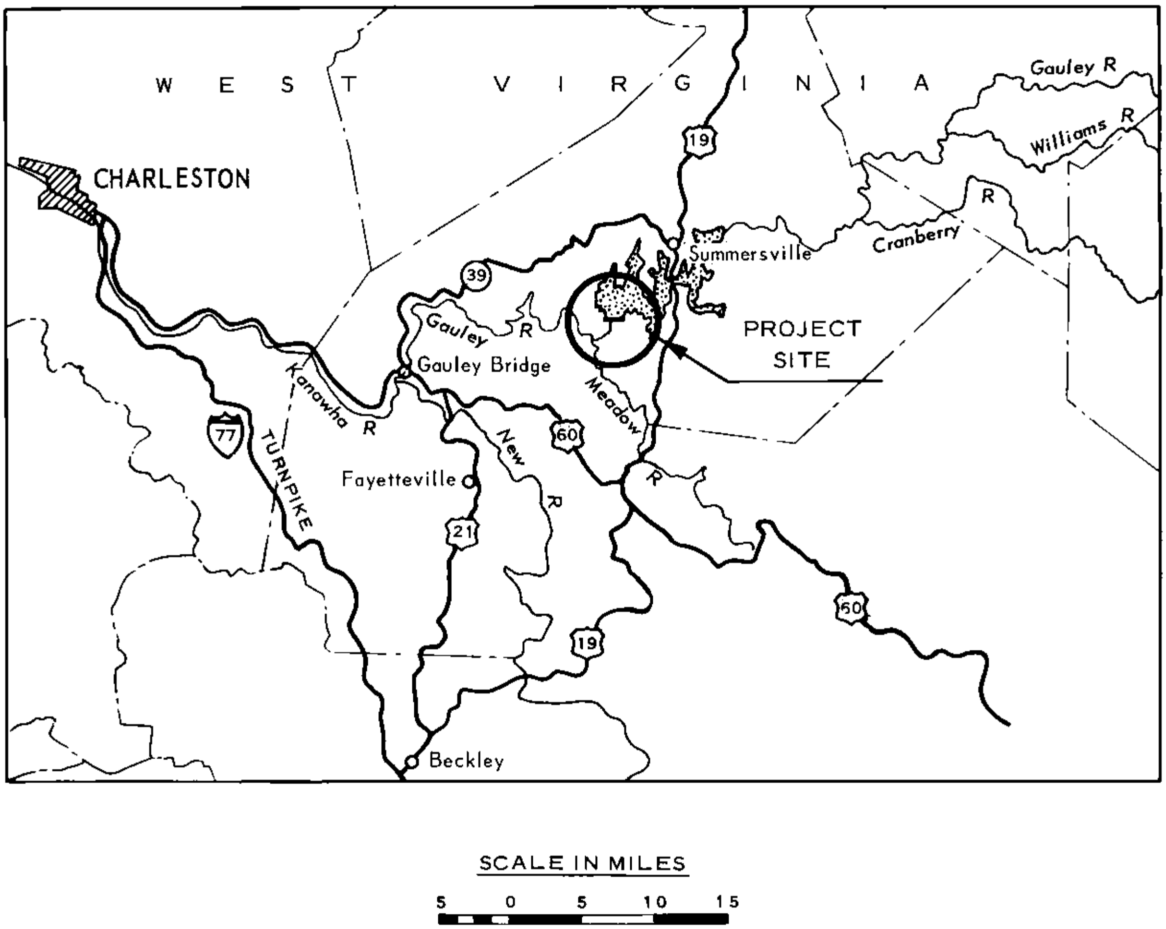


Fig. A2. Vicinity map

Outlet works

2. The Summersville Dam outlet works consists of a 29-ft-diam tunnel about 1700 ft long discharging through a manifold system of three 11-ft-diam conduits averaging about 210 ft long. The outflow is controlled by a 9-ft Howell-Bunger valve at the downstream end of each 11-ft conduit. A 3-ft-diam bypass pipe with a 2-1/2-ft Howell-Bunger valve branches from the upstream 11-ft conduit to discharge low flows. A butterfly emergency valve is located about two diameters upstream from each Howell-Bunger valve. Details of outlet works and valves are shown in plates A1 and A2.

Acoustic flowmeter

3. An acoustic flowmeter system has been installed in the outlet

works for operational gaging of discharges through the tunnel, conduits, and bypass pipe. This system was manufactured by Westinghouse Electric Corporation and previously tested in a 24-ft penstock at Oahe Dam. The locations of the acoustic flowmeter transducer pairs are indicated in plates A1 and A2.

Piezometer system

4. The hydraulic grade lines in the outlet works can be measured with six pairs of piezometers along the concrete- and steel-lined 29-ft tunnel and three pairs along each of the 11-ft steel-lined conduits. The data can be used to determine surface resistance losses, manifold trifurcation losses, and discharge coefficients for the tandem butterfly and Howell-Bunger valves.

Flow conditions

5. Upon completion of the outlet works and the initiation of operation (March 1966), the reservoir was at about crest elevation (1710 msl) of the uncontrolled spillway. This gave a head of about 316 ft above the center line of the 11-ft conduits. The maximum outlet works capacity at this elevation is about 20,000 cfs.

Purpose and scope of tests

6. The hydraulic prototype tests were made to confirm operational readiness and obtain discharge constants for the acoustic flowmeter system. Measurements of piezometric pressures along the tunnel conduits were obtained for definition of the hydraulic grade line.

7. The acoustic flowmeter tests consisted of readings of the flowmeter output for each of the five units (tunnel, 3 conduits, and pipe) at each of several combinations of valve openings, as given in table A1. Stream-gaging measurements were made for a few of the flows as a gross check of the flowmeter performance. The piezometric pressures were measured and recorded for some of the combinations of valve openings used for the acoustic flowmeter tests and are the subject of a separate report in preparation. The acoustic flowmeter measurements of discharge are an integral part of the data obtained in those tests.

Acoustic Flowmeter Installation

8. As can be seen in plates A1 and A2, 10 acoustic flowmeter boxes had been provided in the 29-ft tunnel, the three 11-ft conduits, and the 3-ft low-flow bypass pipe. An extra set of transducer box cover plates had been furnished the flowmeter manufacturer for mounting the transducer adapter assemblies (see fig. A3). It had been originally planned that

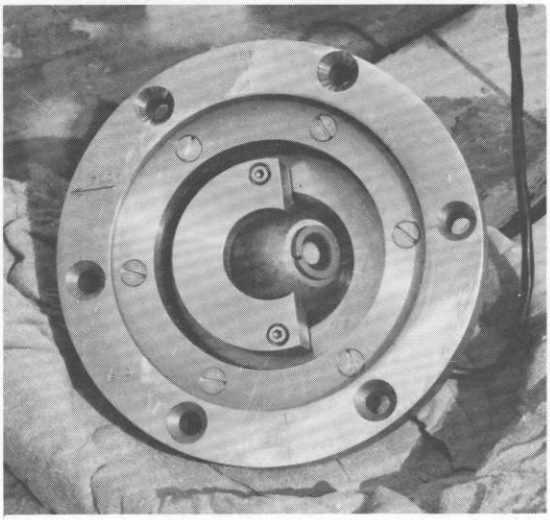


Fig. A3. Transducer adapter assembly. (See fig. 6 of main text for additional detail; outside plate 7-3/4 in. in diameter)

the flowmeter installation would be done "in the dry" while another contractor was completing trifurcation construction. Unforeseen construction difficulties caused delays in trifurcation construction which delayed flowmeter installation beyond the fall of 1965 into the spring flood season. Installation, therefore, had to be done under a very high head and consequent large leakage in the tunnel and conduits.

9. Water levels in the three 11-ft conduits during installation were about 2 ft above the invert and 10 ft in the 29-ft tunnel. Water temperature was 40 F. Scaffolding placed across the 11-ft conduits was used to install the three transducer assembly pairs in the conduits. A temporary sandbagged cofferdam was used to stop about 6 in. of flow at the intake into the 3-ft bypass pipe. Access to the 29-ft tunnel installation was more complicated because of the greater water depth and

inability to carry a boat through the Howell-Bunger valves. A contractor completing grouting work required access to the trifurcation area and his raft of four 55-gal drums could be used during night hours but was not very maneuverable against the leakage current in the tunnel.

10. A number of other difficulties were encountered and worked out during the installation. All pull-box cover plates and transducer assembly covers were bolted on as tight as possible using gaskets and sealing compound. Rubberlike potting compound was molded around the transducers to streamline them and to minimize possible damage from debris. The transducers were aligned with an optical sighting device. The instrument console was installed near the valve control panel (see fig. A4).

11. In a static pressure test heavy leakage began through all electrical conduits and increased in severity as the static pressure increased. Leakage through the two electrical conduits from the 3-ft bypass flowmeter boxes was especially critical because it flowed into the lower part of the valve control panel. Additional leakage problems developed in other parts of the structure, and it was decided to curtail the operation.

12. Temporary seals for the electrical conduits were improvised from pipe fittings and paraffin. When the outlet works was repressurized, the electrical conduit leakage had been reduced to the approximate equivalent of a 1/8-in. stream falling by gravity from the outlet of each conduit. All circuits appeared to function properly. When the tunnel and conduits were unwatered a year later, standard compression-grommet fittings were installed to replace the improvised seals.

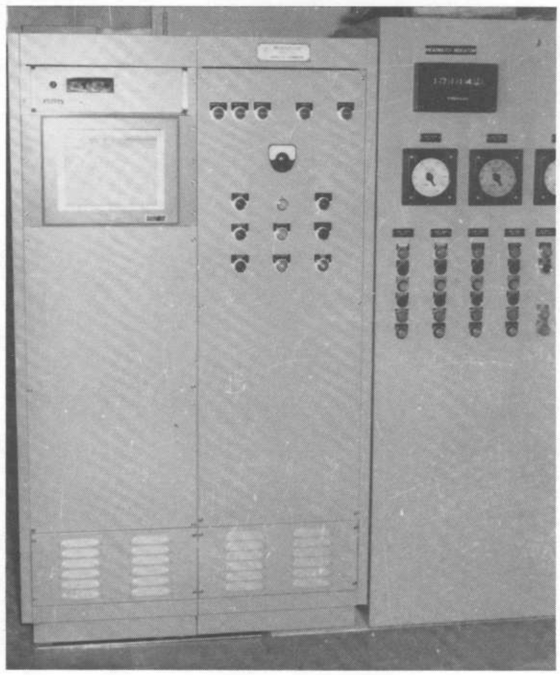


Fig. A4. Flowmeter circuitry console (center) with recorder (left). Valve controls at right

Test Results

13. Discharges as indicated by the acoustic flowmeter and measured by a U. S. Geological Survey stream-gaging party are given in table A1. The sums of the discharges from the individual 11-ft conduits agree with the totals in the 29-ft tunnel within 1.0% for seven, 2.5% for three, and 6.2% for one of the eleven operations. The conditions of less agreement generally occurred when the middle (No. 2) conduit was in operation. Flow in the No. 2 conduit seemed more turbulent than in Nos. 1 and 3, as evidenced by the piezometer measurements, fluctuations in the indicated discharge (up to ±5%), and vibration and drift of the butterfly valve. This turbulence may have been initiated by flow conditions at the conduit entrance in the trifurcation.

14. The USGS measurements agreed with the totals in the 29-ft tunnel within 5.0% for four, 7.5% for three, and 15% for two of the nine measurements. All the USGS measurements were higher than those indicated by the flowmeter. These were the first stream-gaging measurements made at the new gaging station downstream from the project and the flow may have been affected by a number of large boulders in the channel. Maximum velocities were from 5 to 11 fps in the channel.

15. The acoustic flowmeter had been set to give the average velocity across the whole cross section as 96.5% of the average velocity measured across the acoustic path. This corresponds closely to the theoretical value of 96% for a smooth pipe and 97% derived from measured velocities at Fort Randall Dam for flows at similar Reynolds numbers. Although additional check measurements may indicate a need for slight modification of this factor (96.5%), a change at this time is not recommended. Project operation by the District possibly could include additional stream-gaging measurements and various combinations of valve openings to provide more data for verifying or adjusting this factor for each path.

16. A few oscillograph records were obtained of the analog signal input to the digital voltmeter of the flowmeter. Some of the fluctuations recorded at the higher valve openings were attributed to momentary signal dropouts followed by recovery. This behavior appeared to be corrected by

subsequent replacement of one of the components in the circuitry. Turbulence in the flow also caused small fluctuations in the measured velocity. Averages of simultaneous series of readings from both the digital voltmeter and the oscillograph were in very good agreement for some comparisons made only at lower valve openings. A test problem from a built-in test component can be activated at any time to check proper functioning of most of the flowmeter circuits.

17. Path 4 of the flowmeter failed to function at valve openings above about 40%. This was believed due to a high noise level in the 3-ft pipe which triggered the receiving circuit continuously. Subsequent installation of more attenuation in the circuit permitted operation up to valve openings of 95%. It also was found that the 11-ft-conduit paths behaved in a similar manner at valve openings of about 70%. The manufacturer has corrected this condition.

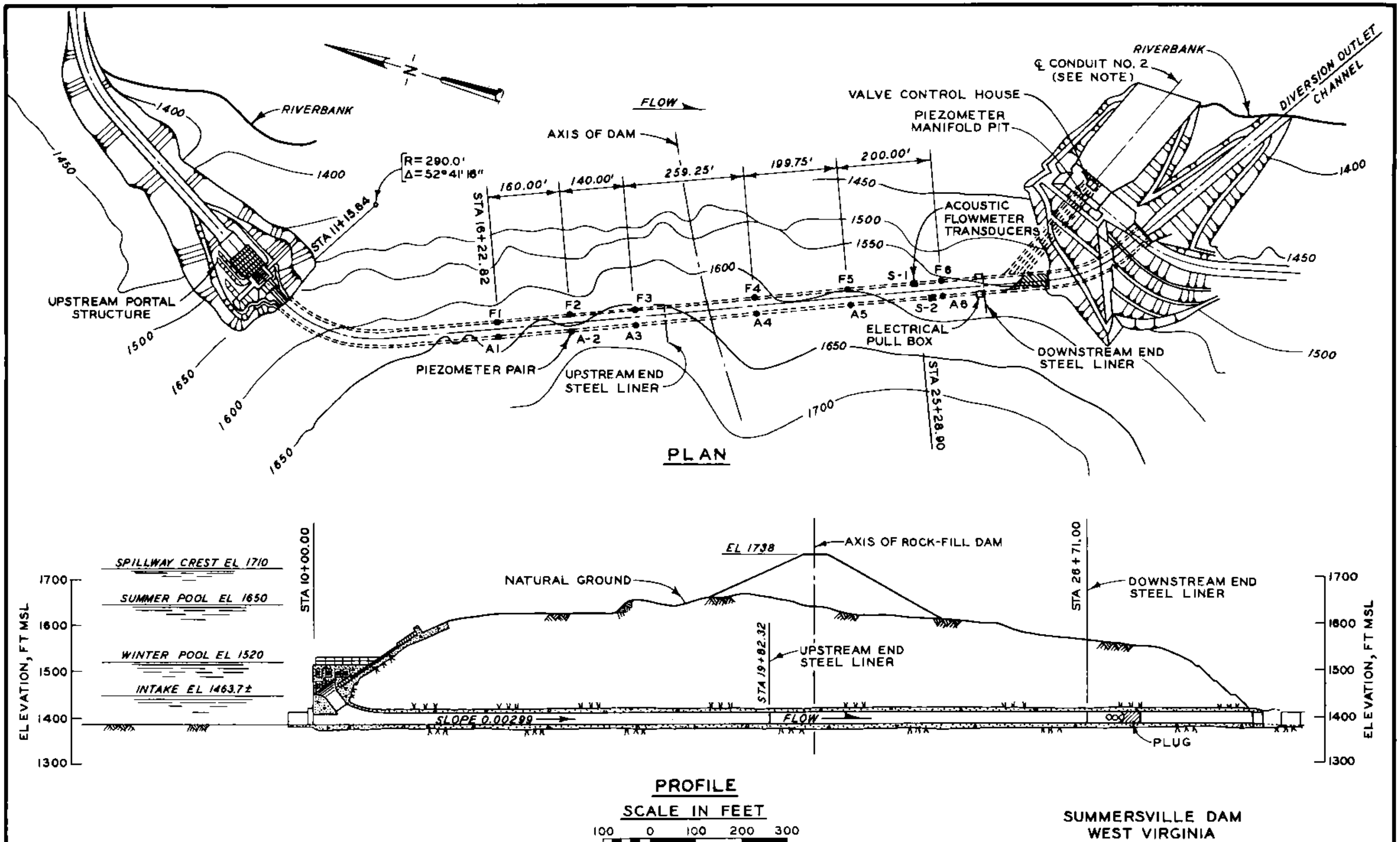
Table A1

Summary of Test Conditions and Discharge Measurements, Summersville Dam

Test No.	Approximate Time EST	Pool El, msl	Tailwater El, msl	11-ft Conduit Valve Openings,* % No. 1	No. 2	No. 3	Acoustic Flowmeter Discharges, cfs** 11-ft Conduits No. 1	No. 2	No. 3	Total	Tunnel	USGS Measurement cfs	Comparison with Tunnel, % Total	USGS
							25 March 1966							
1	1300	1708.92	1362.04	20.0	20.0	20.0	1820	1960	1770	5,550	5,500	6,320	+1.0	+15.0
2	1600	1708.90	1361.94	0	20.0	20.0	0	1960	1820	3,780	3,760	3,980	+0.6	+6.0
							26 March 1966							
3	0825	1707.14	1364.53	24.5	25.0	24.7	2230	2420	2250	6,900	6,800	7,130	+1.5	+5.0
4	1430	1706.43	1367.17	70.5	0	69.8	5560	0	5600	11,160	11,200	11,890	-0.4	+6.0
5	1745	1705.66	1369.39	70.3	70.0	69.8	5600	5260	5520	16,380	16,800	17,660	-2.5	+5.0
							27 March 1966							
6	0930	1704.55	1362.68	25.5	0	24.5	2270	0	2220	4,490	4,500	5,040	-0.3	+12.0
7	1120	1704.44	1363.60	0	70.0	0	0	5330	0	5,330	5,680	6,110	-6.2	+7.5
8	1415	1704.21	1360.55	0	25.5	0	0	2420	0	2,420	2,430	2,530	-0.4	+4.0
9	1630	1703.95	1366.84	40.5	40.5	40.5	3560	3680	3550	10,790	10,600	10,830	+2.0	+2.3
10	1800	1703.72	1363.67	69.0	0	0	5670	0	0	5,670	5,700	--	-0.6	--
11	1840	1703.67	1363.60	0	0	69.0	0	0	5580	5,580	5,550	--	+0.6	--

* Valve opening as indicated at operating mechanism.

** Average value from recorder chart.

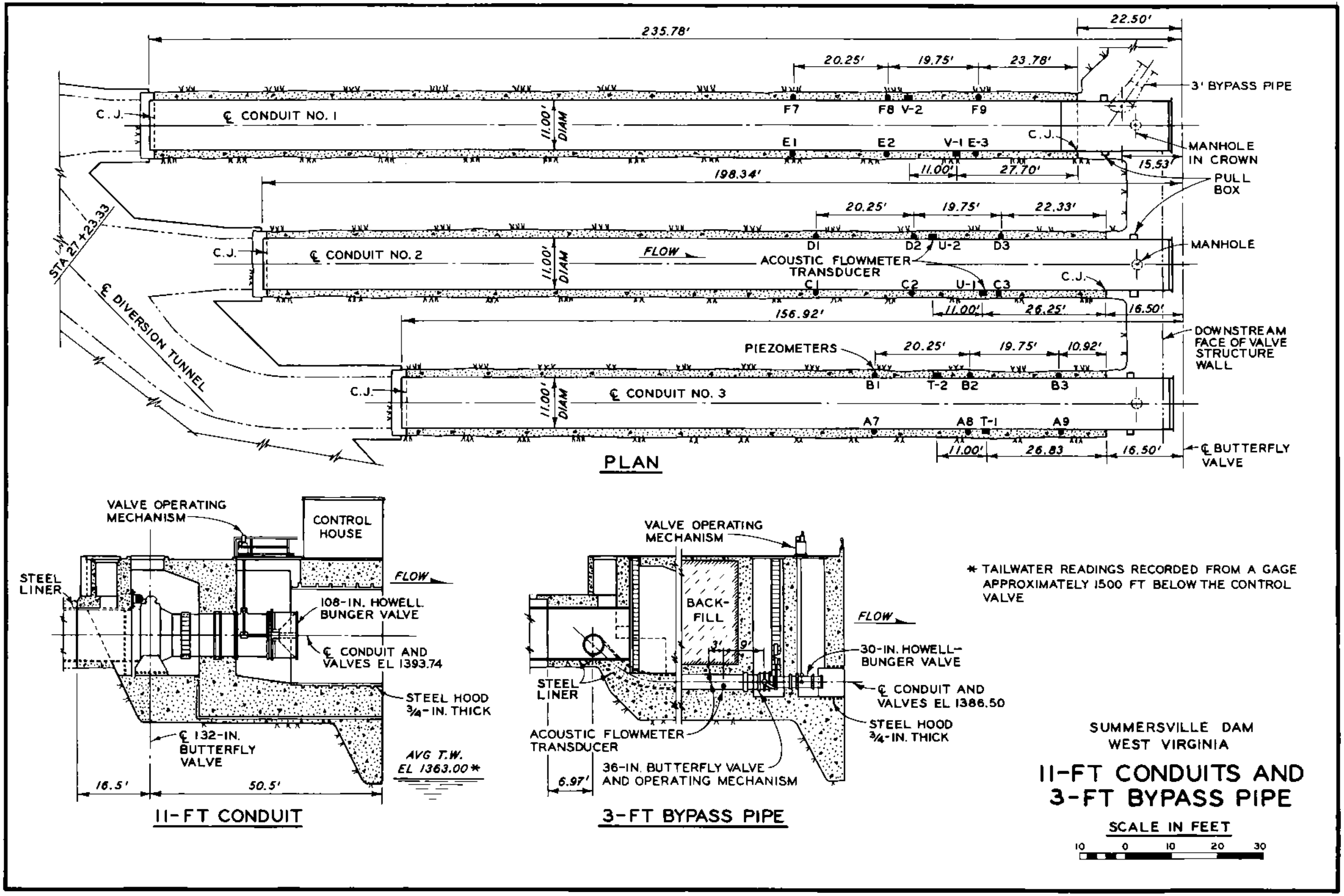


NOTE: SEE PLATE A2 FOR DETAILS OF TRIFURCATION AND OUTLETS CONSTRUCTED AT END OF DIVERSION OPERATION.

SUMMERSVILLE DAM
WEST VIRGINIA

OUTLET WORKS
GENERAL PLAN AND PROFILE

PLATE A2


PLAN
C. J.
℄ CONDUIT NO. 1
℄ CONDUIT NO. 2
℄ CONDUIT NO. 3
11.00' DIAM
235.78'
198.34'
156.92'
22.50'
20.25'
19.75'
23.78'
22.33'
10.92'
11.00'
27.70'
26.25'
26.83
15.53'
16.50'
F7
F8 V-2
F9
E1
E2
V-1 E-3
D1
D2
U-2
D3
C1
C2
U-1
C3
B1
T-2
B2
B3
A7
A8 T-1
A9
FLOW
ACOUSTIC FLOWMETER TRANSDUCER
PIEZOMETERS
3' BYPASS PIPE
MANHOLE IN CROWN
PULL BOX
MANHOLE
DOWNSTREAM FACE OF VALVE STRUCTURE WALL
℄ BUTTERFLY VALVE
STA 27+23.33
℄ DIVERSION TUNNEL
11-FT CONDUIT
VALVE OPERATING MECHANISM
CONTROL HOUSE
STEEL LINER
108-IN. HOWELL BUNGER VALVE
℄ CONDUIT AND VALVES EL 1393.74
STEEL HOOD 3/4-IN. THICK
℄ 132-IN. BUTTERFLY VALVE
AVG T.W. EL 1363.00 *
16.5'
50.5'
3-FT BYPASS PIPE
BACK-FILL
30-IN. HOWELL-BUNGER VALVE
℄ CONDUIT AND VALVES EL 1386.50
STEEL HOOD 3/4-IN. THICK
ACOUSTIC FLOWMETER TRANSDUCER
36-IN. BUTTERFLY VALVE AND OPERATING MECHANISM
6.97'
* TAILWATER READINGS RECORDED FROM A GAGE APPROXIMATELY 1500 FT BELOW THE CONTROL VALVE
SUMMERSVILLE DAM
WEST VIRGINIA
11-FT CONDUITS AND
3-FT BYPASS PIPE
SCALE IN FEET
10 0 10 20 30

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1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Engineer Waterways Experiment Station Vicksburg, Mississippi		2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP
3. REPORT TITLE ACOUSTIC FLOWMETER PROTOTYPE EVALUATION TESTS		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final report		
5. AUTHOR(S) (First name, middle initial, last name) Ellis B. Pickett		
6. REPORT DATE January 1968	7a. TOTAL NO. OF PAGES 58	7b. NO. OF REFS 27
8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 2-810 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
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13. ABSTRACT

Prototype tests of an acoustic flowmeter system were made in a 24-ft-diam power penstock at Oahe Dam to evaluate the system prior to permanent installation in the outlet works at Summersville Dam. Comparative discharge measurements included acoustic, penstock pressure-momentum (Gibson), turbine model test ratings, scroll-case pressure differential (Winter-Kennedy flowmeter), and surge tank volume changes. The acoustic flowmeter measurements were very consistent and many of the comparisons were within 1%. The location of the measuring section for a single-path acoustic flowmeter must be selected to give a known or measurable relation between the flow pattern of the whole section and that along the acoustic path.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Acoustic flowmeters						
Discharge measurement						
Flowmeters						
Oahe Dam						
Summersville Dam						