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Index Testing of Hydraulic Turbines

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The object of this paper is (*a*) to bring to the attention of operating companies the benefits derived from index tests of hydraulic turbines, and especially those of the adjustable-blade propeller or Kaplan type; (*b*) to enumerate and discuss the presently known methods of determining relative discharge and hence relative efficiency; (c) to present an example of an index test of an adjustable-blade propeller turbine in sufficient detail to provide a guide for the conduct of such a test.

An index test of a hydroelectric unit is a means of determining the efficiency of the unit over its full range of gate opening or output, this efficiency being relative to an assumed or estimated peak efficiency. This relative efficiency may be that of the turbine alone or of the complete unit, whichever is desired. A comparison of the nature of each of the measured and derived quantities for index testing and also for an acceptance test in accordance with the ASME Power Test Code is given in Table 1.

TABLE 1 COMPARISON OF INDEX TEST WITH ACCEPTANCE TEST

	Index test turbine	Index test unit	ASME test code
Head..........	Net or gross	Gross	Net
Output.........	Turbine hp	Generator kw	Turbine hp
Discharge......	Relative cfs	Relative cfs	Absolute cfs
Efficiency......	Relative	Relative	Absolute

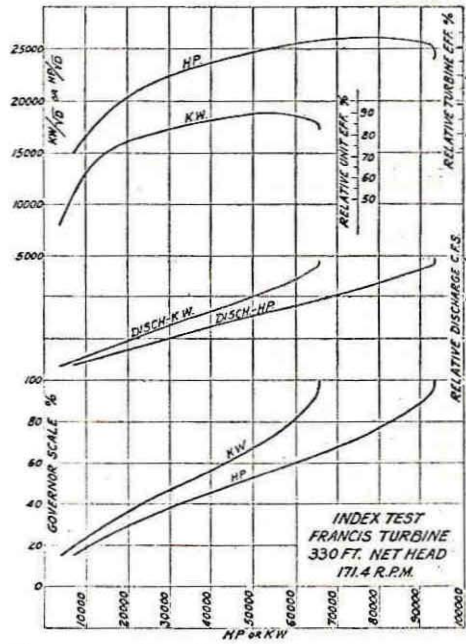

FIG. 1 EXAMPLE OF DATA OBTAINED FROM INDEX TEST OF FRANCIS TURBINE

BENEFITS DERIVED FROM INDEX TESTING

The principal specific benefits derived from the results of an index test are as follows:

1 The gate opening and load at which peak efficiency is obtained are determined, and also the relative efficiencies at other gate openings and loads, thereby permitting the most economical use of water and distribution of load among the units on a system (within the limits that such use and distribution are restricted by other factors).

For practical reasons, it is seldom that a turbine is installed in a setting fully homologous with that of the laboratory model upon which its expected performance is based. This is particularly true where new turbines are installed in existing structures or extensions of powerhouses already constructed, since the shape and size of the water passages, such as intake, case, and draft tube are usually restricted. The output and efficiency of the prototype will, in nearly all such cases, vary from that stepped up for size and head from the model in the conventional setting.

An example of the type of data obtained on a Francis turbine by index testing is shown in Fig. 1.

In distribution of a given load between two or more units the most economical operation is obtained when the units are operated at loads such that the slopes of the output versus Q curves are equal.[2] This information may be provided by index testing. If a powerhouse contains units which are not duplicates, it is important that one of each size or type be tested.

Generally, the higher the specific speed of the turbine the greater is the slope of the efficiency versus gate-opening curve over the usual operating load range, and the narrower is the range of gate opening at which best efficiency is obtained. It follows that the higher the specific speed of a turbine, the more valuable the information obtainable by index testing becomes from the standpoint of economical load distribution.

Index tests have been made on 34 units of types other than Kaplan manufactured by the company which the author represents.

2 In the case of Kaplan turbines, in addition to (1), an index test is a means of determining whether the blade-gate relationship is such as to produce the best efficiency obtainable through the full range of load. If it is not, the index test provides the information necessary to make the proper changes on that particular unit to obtain the best blade-gate relationship. In practically all cases where index tests have been run on this type of turbine, it has been found that by changing the gate-blade relationship as indicated by the test data, the output per unit of discharge has been increased—in some cases appreciably.

A typical example of the improved performance resulting from an index test of a Kaplan turbine is shown in Fig. 2.

The turbine manufacturer which the author represents, has, as as of June 1, 1950, 162 turbines of the Kaplan type in operation. Of these, 43 units have been tested by the index method and 8 more are scheduled to be tested within the next few months.

3 Data are provided for the relative rating of a permanently

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NOTE: Statements and opinions advanced in papers are to be understood as individual expressions of their authors and not those of the Society. Manuscript received at ASME Headquarters, August 18, 1950. Paper No. 50—A-52.

[2] "Inter-Relation of Operation and Design of Hydraulic Turbines," by F. H. Rogers and L. F. Moody, *Engineers and Engineering*, vol. 42, July, 1925, pp. 169–187.

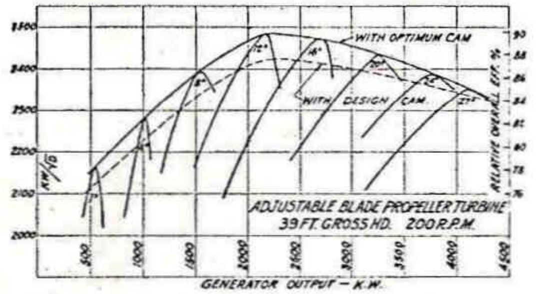


FIG. 2 EXAMPLE OF DATA OBTAINED FROM INDEX TEST OF ADJUSTABLE-BLADE PROPELLER TURBINE

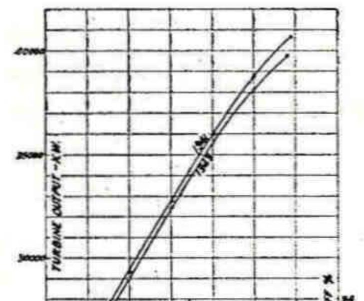


FIG. 3 EFFECTS OF 8 YEARS OF TURBINE OPERATION AS DETERMINED BY INDEX TESTS

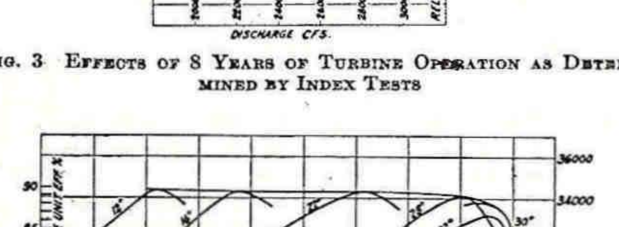


FIG. 4 INDEX TEST OF ADJUSTABLE-BLADE PROPELLER TURBINE ILLUSTRATING LOSS OF EFFICIENCY BEYOND CAVITATION LIMIT

installed flowmeter. Thus the flowmeter may thereafter be used either continually or periodically to measure the total effects on efficiency of various changes in the unit, such as increase of runner or gate clearances, pitting, erosion, and the like. The effects of these may then be evaluated and the advantages, and proper timing and extent of repairs weighed on a sound economic basis.

An example of this application of index testing is shown in Fig. 3.

4 When the unit is so set with respect to tail water as to be influenced by cavitation, the effects upon power and efficiency may be shown, and safe operating limits determined. An example of this application is shown in Figs. 4 and 5.

INTERPRETATION OF TEST DATA

The series of individual curves in Fig. 4 show the data obtained at each of several fixed blade angles of an adjustable-blade propeller turbine, the output varying with gate opening. The envelope curve is the performance obtained with the proper blade

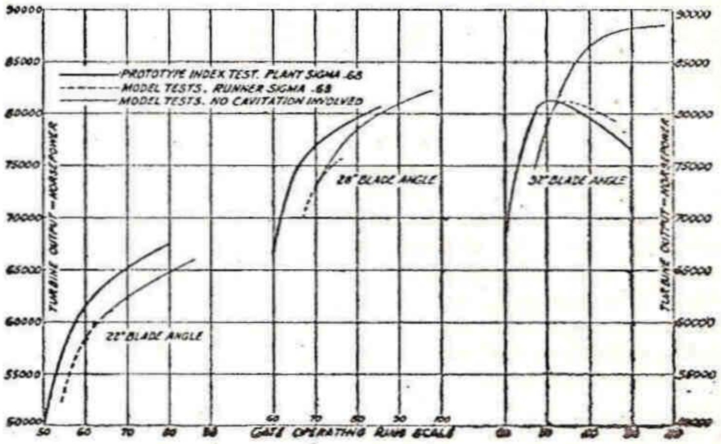


FIG. 5 COMPARISON OF MODEL AND PROTOTYPE TESTS SHOWING EFFECT OF CAVITATION ON TURBINE OUTPUT

angle center-gate opening relationship. It will be noted that the performance suffers appreciably in both output and efficiency when the blade angle is increased from 28 to 32 deg. This is the effect of cavitation as will be seen from the following.

The full heavy lines in Fig. 5 show the performance obtained during an index test of the prototype unit (derived from the same information as shown in Fig. 4, during which tests the plant sigma was 0.68). The light full lines are the outputs which would be obtained if the turbine setting were such that no cavitation were involved (i.e., at a much higher value of sigma), as determined from a laboratory test of a homologous model. The dashed lines are the outputs of the same model with an elevational setting corresponding with that of the prototype, that is, at sigma 0.68.

It will be noted that at 22 deg blade angle, no loss was caused on the prototype by cavitation; in fact, there was an increase of about 6 per cent in output over that of the model runner. With 28 deg blade angle, at the lower gate openings, the same increase is noted, but at larger gate openings the prototype performance approaches the model performance more closely. At 32 deg blade angle, there was still an increase in output over the model at the lower gate openings, but, above 67 per cent gate-operating-ring stroke, both the model and the prototype drop off in power from the unrestricted performance curve very materially because of cavitation. Correspondingly, there is also a very large drop in efficiency under this condition for the same reason.

Thus, referring to Fig. 4, the index test showed up the effect of cavitation. Where the efficiency and power drop off in a manner not indicated in tests on a cavitation-free model, it shows that the unit is operating beyond the cavitation limit and by comparison with the model tests, a safe operating limit may be set.

METHODS OF DETERMINING RELATIVE DISCHARGE

The several methods of determining relative discharge of a hydraulic turbine are with one exception modifications of well-known methods of measuring absolute values as covered by the ASME Power Test Code for Hydraulic Prime Movers. They are based upon sound basic hydraulic principles but are subject to the same limitations and requirements in their respective fields of use as the absolute methods. There is one very important additional requirement of the relative method, namely, that the flow pattern remain practically constant throughout the full range of flow to be measured.

Briefly, the several methods are as follows:

By Pitot Tube. In the ASME Power Test Code, the conditions for use of Pitot tubes in acceptance tests are, in part, as follows

"The measuring section shall be located in a straight run of closed penstock at a distance equal to at least ten pipe diameters from any upstream and at least five pipe diameters from any downstream bend, elbow, Y-branch pipe, valve, intake, or any obstruction to smooth flow."

For an absolute flow measurement at least two complete traverses are made at right angles to one another, whereas for index testing a measurement at one point only is made for each test run. Therefore, for index testing it is even more important that the flow be consistent in direction at the one point of measurement.

By Current Meter. Relative discharge of a turbine may be determined by a single current meter of any type in either an open or closed conduit, provided the flow pattern is consistent at the point of measurement over the full range of discharge to be metered. This condition is rarely encountered in an open channel, and it is very difficult to be certain whether it is or not. Furthermore, this method requires more time for the runs than the others. There may be a few instances, however, where this method may be used to advantage.

Friction Loss and Velocity-Head Method. This method is dependent for accuracy upon there being considerable head loss in the closed conduit to the turbine. The difference in pressure at the inlet to the turbine and that at some point in the penstock upstream, or at the forebay, should be at least 3 ft at the rated output of the turbine. This difference represents the sum of the losses between the two points and the difference in velocity head, if any. Both the velocity head and the losses are directly proportional[3] to V^2 and hence to Q^2. Therefore, $Q = K\sqrt{h_1 - h_2}$, where h_1 and h_2 are the pressures in feet of water at the upper and lower measuring points, respectively. If the friction losses in a conduit vary with time, as is usually the case, this method may not be used to indicate periodically the effects of wear, pitting, and the like, on the efficiency of the turbine. This is the method which is not a modification of an accepted method for measuring absolute discharge.

Venturi-Section Method. If the turbine has a closed conduit with a straight run containing a standard Venturi tube, or any converging section having a similar effect, this may be used to indicate relative discharge. The difference in pressure between a point in a straight section of uniform-diameter conduit immediately upstream of the convergence and a point at the throat should be at least 3 ft at rated output of the turbine for dependable results.

Methods Depending Upon Venturi Principle. The difference in pressure between any two points of the turbine itself or of its case, one at high pressure and low velocity, the other at low pressure and high velocity, may be used to indicate relative discharge, provided the flow is consistent in direction and the difference in pressure is adequate. There are today, two well-known methods of applying this principle, namely, the Winter-Kennedy and that of Joseph A. Peck. Each of these methods has been proved to give consistent relative discharge values by comparison with absolute discharge measurements run concurrently.

The originators of these two methods have by theoretical computations, aided by laboratory tests and field experience, been able to predict with remarkable accuracy in recent years the value of K in the formula $Q = K\sqrt{h_1 - h_2}$ for their respective methods.

The Winter-Kennedy Method.[4] Pressure differences existing in the conventional turbine spiral or semispiral case set up by acceleration of the water from the outer to the inner water surface are utilized in this method. The means of measuring these differences are flush piezometers located as indicated in Fig. 6. Laboratory tests on a 16-in. turbine model have shown this method to give consistent results with a pressure difference of only 9 in. of water at full gate of the turbine and that this consistency is independent of gate opening and head. The same has been proved for large turbines many times as, for example, on the Bonneville Station Service unit which is rated at 5000 hp, 50 ft head, 257 rpm, and has an 81-in. adjustable-blade propeller-type runner. Acceptance tests were run on this unit at heads of 29, 40, 50, and 56 ft, with the flow measured by the Allen salt-velocity method. Concurrently, permanently installed piezometers located according to the Winter-Kennedy principle were calibrated so that they could be used at later dates for absolute measurement of flow. Fig. 7 shows log D versus log Q to be a straight line with slope such that $Q = D^{.49}$ where Q = absolute quantities measured by Allen salt-velocity method, and D = differential pressure as indicated by the Winter-Kennedy piezometers.

J. A. Peck Method. Two piezometer orifices are located on one

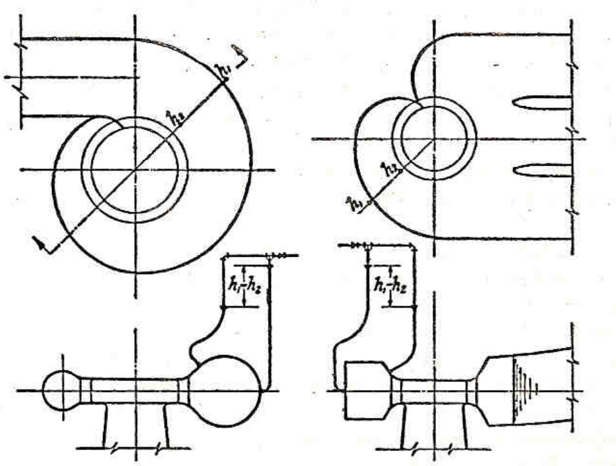


FIG. 6 ILLUSTRATING APPROXIMATE LOCATIONS OF WINTER-KENNEDY PIEZOMETERS FOR INDEX TESTING

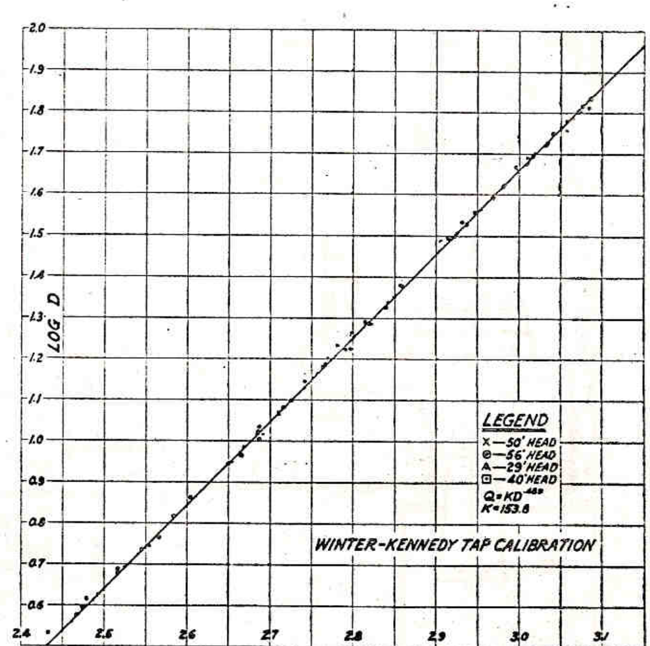


FIG. 7 COMPARISON OF ABSOLUTE DISCHARGE WITH DEFLECTIONS OF WINTER-KENNEDY DIFFERENTIAL PIEZOMETERS

[3] "An Engineering Concept of Flow in Pipes," by C. W. Harris, Proceedings of the ASCE, vol. 75, May, 1949, pp. 555–577.

[4] "Improved Type of Flow Meter for Hydraulic Turbines," by I. A. Winter, Proceedings of the ASCE, vol. 59, April, 1933, pp. 565–584.

of the stay vanes between which the water passes on its way from the case to the wicket gates and thence to the turbine runner (see Fig. 8). The pressure at the leading edge of the vane is less than static by only the small percentage of velocity head not recovered by impact, while the pressure on the side of the vane is less than static by the full velocity head. The pressure difference obtained is directly proportional to V^2 and hence to Q^2. This method was first tried out by Mr. Peck at the laboratory of the author's company in connection with model tests for what was then the Fifteen Mile Falls Development of the New England Power Company on the Connecticut River. The results checked with the absolute measurements made by the laboratory weir. The pressure differential at full gate and 10 ft head was 18 in. of water.

At Swinging Bridge No. 1 plant of the Rockland Light and Power Company, near Port Jervis, N. Y., the absolute discharge of a Francis turbine rated at 7200 hp, 118 ft head, 300 rpm was measured concurrently by the Allen salt-velocity method and the Pitot tube method; also, the differential deflection of the Peck piezometers. Fig. 9 shows log D versus log Q to be a straight line with slope such that $Q = 141.3\, D^{.50}$ where Q = absolute quantities in cfs, and D = differential pressure as indicated by the Peck piezometers. It will be noted that all the points are very close to the line.

Other Methods. In this category are many possible variations in location of the piezometer taps. In most turbines built during the last 10 years, provisions have been made by the manufacturer and/or the purchaser for piezometers and piping to an accessible location for index testing. This is particularly true in the case of adjustable-blade propeller turbines where the index tests may be used to adjust or check the cam controlling the blade-gate relation to assure that the maximum possible efficiency is being obtained from the unit. However, when these provisions have not been made, it has always been found possible, in the author's experience, to install some temporary piezometers for this purpose. Examples of the many possible locations are shown in Fig. 10 (*a*, *b*, and *c*).

In some instances two or three different locations of the low-pressure piezometer were used simultaneously on the same turbine. Whenever the values $\sqrt{D}$ did not fall in a smooth curve when plotted against gate opening, this indicated that one of

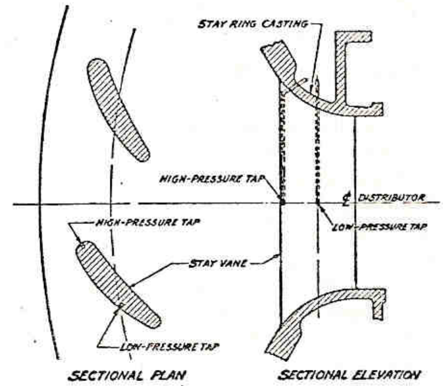


FIG. 8 LOCATION OF PIEZOMETERS FOR PECK METHOD

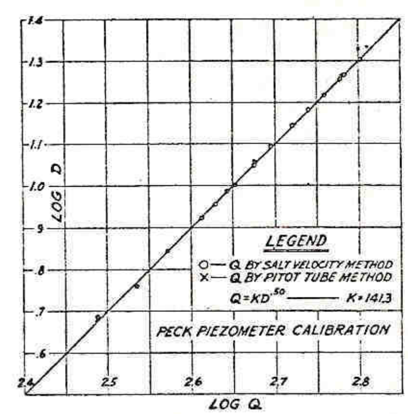
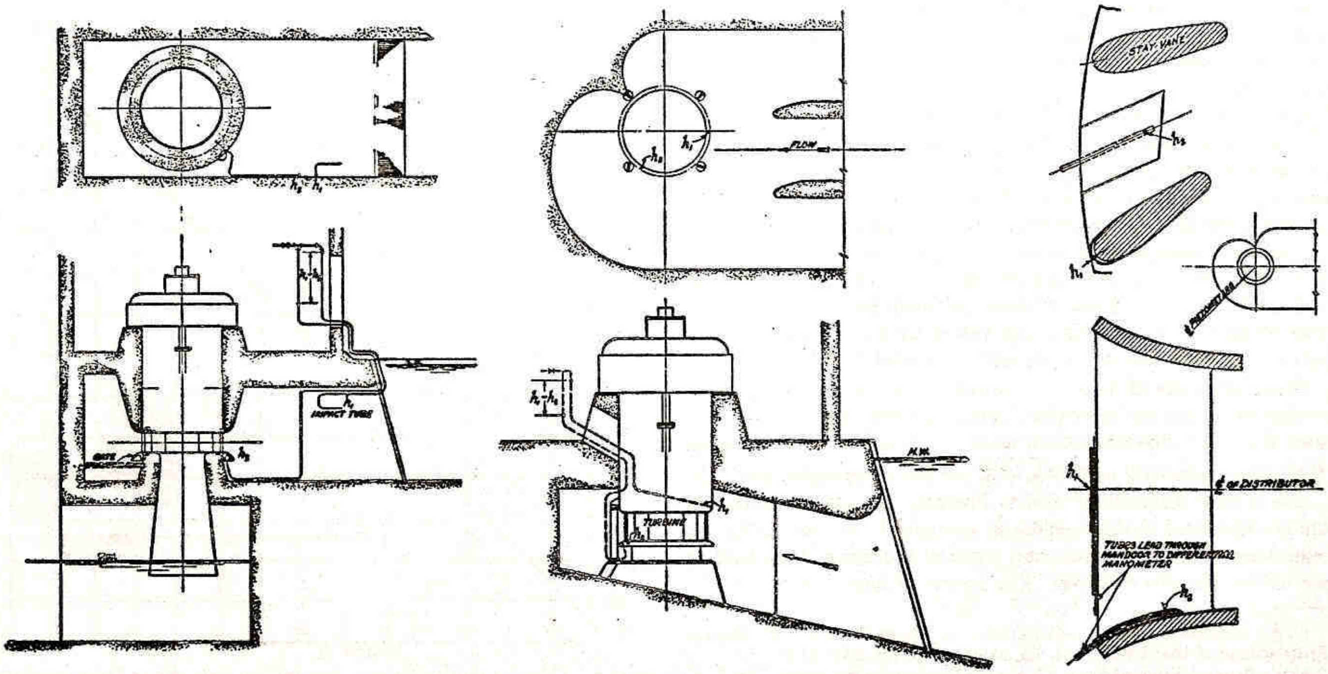


FIG. 9 COMPARISON OF ABSOLUTE DISCHARGE WITH DEFLECTIONS OF PECK DIFFERENTIAL PIEZOMETERS



(a) (b) (c)

FIG. 10 ILLUSTRATING LOCATIONS OF TEMPORARY PIEZOMETERS FOR INDEX TESTING these piezometers was being affected by change in flow direction or turbulence and that set of readings was discarded in favor of a more consistent set. All of the locations shown in Fig. 10 have been used by the author and found to give consistent values. They were not used simultaneously with any absolute method of water measurement. However, after the blade-gate cam was changed in accordance with the results of the tests, an increase in power output per unit of piezometer deflection was observed showing that some increase in efficiency had been obtained.

Example of an Index Test on an Adjustable-Blade Propeller Turbine

Description of Unit. The turbine, which has a 127-in-diam, five-blade runner, operates at gross heads from 38 to 52 ft, is rated at 9000 hp at 44 ft head, 163.6 rpm, and is direct-connected to a 9500 kva, 0.7 pf, 3-phase, 60-cycle generator. Under normal flow conditions, head-water level is quite constant, and tail-water level varies several feet due to tide. The elevation of the center line of the distributor is +2.5 ft, and the center line of the runner is —1.4 ft. The turbine is set in a concrete semispiral case and discharges through an elbow draft tube. The general arrangement is shown in Fig. 11.

Under the conditions at this station, the accuracy of absolute discharge measurements by any of the presently known methods would be open to question.

Piezometers and Manometer. Provision for two piezometers was made at the time the semispiral case was constructed, orifice plates having been set flush in the concrete, and 1/4-in. piping having been laid to an accessible location. The orifices were plugged to prevent damage and stoppage. The location of the piezometers is as shown in Fig. 11.

Immediately prior to the test, the orifices were inspected, the plates ground smooth, and the plugs removed. Also at that time the piezometer piping was extended by plastic tubing to a differential manometer, in the form of an inverted U-tube, so arranged that the water level could be depressed an equal distance for both legs of the manometer by means of compressed air, to a level convenient for reading. This is permissible because the absolute pressures in the individual legs of the manometer are not important, only the differential pressure is necessary for index testing. (In some plants the pressures are too low to be read on a manometer accessibly located, in which case the air in the top of the manometer may be rarified by means of a bicycle pump with plunger reversed until the level in the manometers is visible.) The importance of getting all the air out of the tubing by bleeding of the manometers prior to the tests cannot be emphasized too greatly.

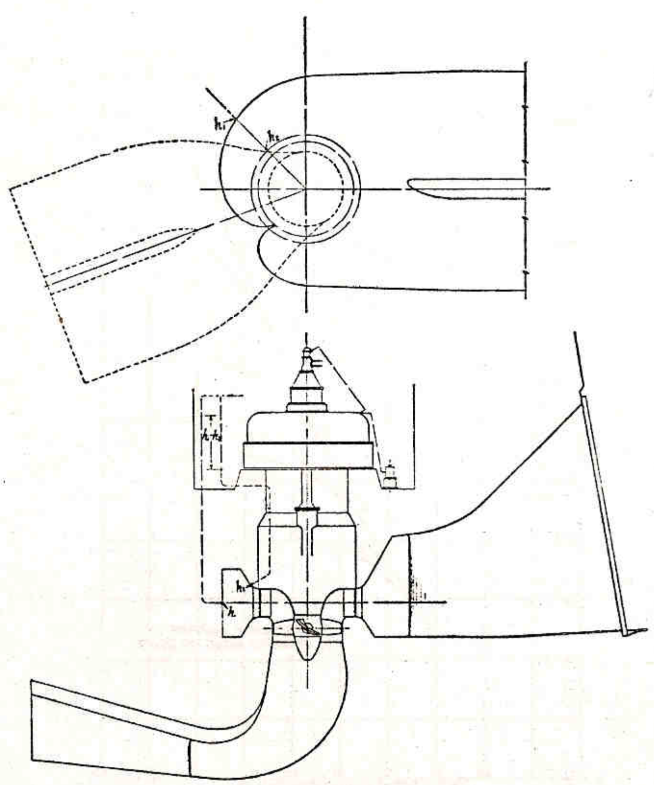


Fig. 11 General Arrangement of Adjustable-Blade Propeller Turbine Showing Location of Winter-Kennedy Piezometers

Inspection of Turbine and Calibrations:

1 The water passages of the turbine were examined for any signs of pitting, corrosion, erosion, or defects.

2 All debris was removed from the turbine, intake passages, and trash racks.

3 Clearances top and bottom of wicket gates were measured and recorded.

4 With gates closed, the gates were checked for tightness; any that were open were adjusted by means of eccentric gate pins.

5 The openings between each pair of gates were measured at about 75 per cent of full opening, averaged, and one pair selected between which the opening was nearest the average. The opening between this pair was calibrated against governor servomotor stroke from 0 to 100 per cent stroke at each 10 per cent stroke.

6 The blade-angle indicator on the generator floor was calibrated against blade-angle indications on the runner hub. Also, at each blade position, the travel of the upper end of the inner oil pipe relative to a fixed point on the oil head was measured. (In the case of blade operation other than hydraulic, obtain some other external, mechanical, and definite indication of blade angle.) This provision is necessary in case it is desired to duplicate the blade-angle positions for further tests at a later date.

7 Clearances at the periphery of each blade at the center line of blade rotation were measured.

Conduct of Test. During the index tests, the cam controlling the blade angle was removed from the control valve and the blade positions were set manually at five, successive, fixed blade angles, 8, 12, 16, 22, and 28 deg. Test runs were made at six different positions of the wicket gates for each of these blade angles, the positions being selected at and on each side of what was expected to be the most efficient position for the particular blade angle. These positions were determined from the manufacturer's cam-curve (see Fig. 15). Each run required about 5 min.

The observations during the tests were as follows:

Blade Angle and Gate Opening. Care was taken in setting the runner blades and wicket gates to always come up to the desired settings so that all lost motion due to clearances was taken up in the same direction. This insured consistency in these settings and provided for accurate reproduction at a later date. Since the blade-angle scale had parts which were removable and might be replaced improperly, the distance between the end of the inner oil pipe and the underside of the oil-head cover was measured at each blade angle as an additional precaution.

Head. Throughout the test, readings of headwater and tailwater elevations were taken on staff gages at 5-min intervals. The differences of these elevations, the gross head, varied from 39.0 to 43.4 ft during the test owing to the effect of tide upon the tail water (Table 2, columns 4, 5, and 6). The gross head of 41 ft was selected as a common basis for the test because it was one of the heads at which turbine guarantees had been made and also because it was close to the average head during the test. For the purpose intended, it was considered unnecessary to determine the net head since the head losses would be very low.

Relative Discharge. Ten pairs of readings of the differential manometer were taken during each run at 15-sec intervals. Since the levels in the two legs of the manometer usually fluctuate slightly, it is important that an observer be assigned to each leg and that they read simultaneously. The average differential D for each run, Table 2, column 7, was computed and $\sqrt{D}$, column 8, uncorrected for head, was plotted against governor scale as the test proceeded, Fig. 12. Thus any irregular points, as would be caused by air in the manometer tubing or by erroneous readings, would have been immediately evident and the condition producing them remedied.

After the test was run and head readings became available $\sqrt{D}$ values were corrected to the common gross head of 41 ft. Since $\sqrt{D}$ is a measure of discharge, it is directly proportional to $\sqrt{H}$. These corrected values of $\sqrt{D}$, column 9, Table 2, are also shown in curve form in Fig. 12.

Power. During each run, three readings of about 1 min each were taken of the revolutions of the integrating watthour meter. An even number of revolutions of the meter disk were timed with a stop watch. These individual readings were averaged and the output in kilowatts computed from the formula

$$Kw = K \times \text{revolutions per sec}$$

$$K = \frac{3600}{1000} \times \text{PT ratio} \times \text{CT ratio} \times \text{meter constant}$$

$$= 28{,}800 \text{ for this particular meter}$$

To the generator output, column 10, Table 2, for each run was added the sum of the generator losses and the exciter input, column 11, obtaining the turbine output in kilowatts, column 12, and in horsepower, column 13. The values of turbine horsepower were then corrected by the ratio of $H^{3/2}$ to a common head of 41 ft and plotted against governor scale, Fig. 13. The generator manufacturer's guarantees of efficiency were used in determining the generator losses. The direct-connected exciter input was taken as its measured output, from readings taken during the test, divided by its efficiency, also as given by the manufacturer.

Applying the Test Data. The values of horsepower, column 14, divided by $\sqrt{D}$, column 9, are a measure of the relative efficiency of the turbine. These values, column 15, plotted on turbine output are shown in Fig. 14.

It will be seen that the maximum value of Hp/$\sqrt{D}$, namely, 1974, and, therefore, maximum efficiency, occurred at an output of 6660 hp. It was assumed that the maximum turbine efficiency for this head was 91 per cent as per the manufacturer's "experience curve." The relative efficiency at other points was then proportioned directly, column 16, Table 2, and an efficiency scale added to Fig. 14. Also, on the basis of this assumption, the relative discharge (at Hp/$\sqrt{D}$ = 1974) is

$$Q = \frac{550 \times \text{hp}}{62.4 \times H \times E} = \frac{8.815 \times 6660}{41 \times .910} = 1574 \text{ cfs}$$

Also, since $Q = K\sqrt{D}$

$$K = \frac{1574}{3.360} = 467$$

Relative discharge at the other runs was then figured from $Q = K\sqrt{D}$, using $\sqrt{D}$ in column 9, Table 2, and noted in column

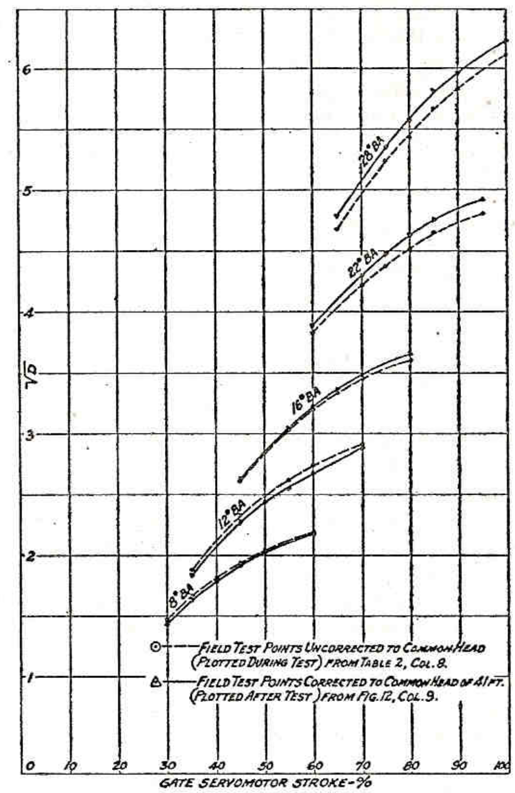


Fig. 12 Relative Discharge D, Uncorrected and Correcte to 41 Ft Common Gross Head

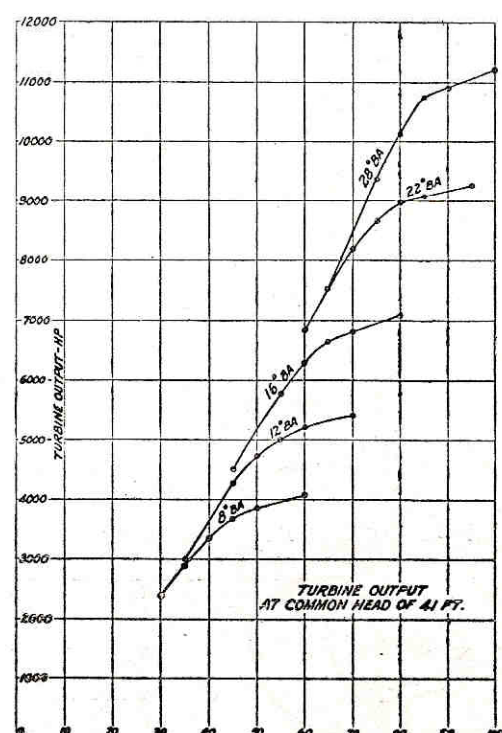


Fig. 13 Turbine Output, Corrected to 41 Ft Common Gross Head

TABLE 2 SUMMARY SHEET OF INDEX TEST DATA

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
RUN No.	TIME	GOV. SCALE	BLADE ANGLE	HW.	TW.	GROSS HD. FT.	D INCHES	$\sqrt{D}$	$\sqrt{D}$ 41 FT. HD.	GENERATOR OUTPUT-KW	LOSSES KW	TURBINE OUTPUT KW	TURBINE OUTPUT HP.	HP. 41 FT. HD.	FROM SMOOTH CURVES $HP/\sqrt{D}$	RELATIVE EFF.	RELATIVE Q
1	8:15	70	12°	43.8	0.4	43.4	8.434	2.902	2.822	4175	218	4393	5880	5405	1915	88.3	1317
2	20	60		.8	0.6	.2	7.503	2.740	2.668	4000	215	4215	5645	5205	1950	89.9	1245
3	28	55		.9	0.8	.1	6.855	2.618	2.552	3802	212	4014	5380	4990	1952	90.0	1195
4	34	50		.8	0.9	42.9	6.227	2.493	2.439	3567	208	3775	5055	4722	1937	89.3	1138
5	40	45		.9	1.1	.8	5.415	2.328	2.278	3203	204	3407	4560	4275	1877	86.6	1063
6	45	35		.9	1.1	.8	3.517	1.880	1.840	2198	191	2389	3200	3000	1630	75.2	859
7	52	30	8°	43.8	1.2	42.6	2.139	1.462	1.434	1687	186	1873	2510	2369	1652	76.2	670
8	56	35		.6	1.3	.3	2.767	1.662	1.636	2088	190	2278	3050	2910	1779	82.0	764
9	9:00	40		.5	1.5	.0	3.302	1.816	1.795	2405	194	2599	3480	3353	1868	86.2	838
10	06	45		.4	1.8	41.6	3.750	1.935	1.920	2618	196	2814	3770	3685	1918	88.5	896
11	10	50		.5	2.0	.5	4.083	2.040	2.028	2722	197	2919	3910	3840	1900	87.6	947
12	15	60		.5	2.2	.3	4.779	2.185	2.177	2865	199	3064	4105	4068	1868	86.2	1016
13	20	45	16°	43.3	2.6	40.7	6.830	2.612	2.621	3125	202	3327	4450	4495	1715	79.1	1225
14	25	55		.5	2.8	.7	9.212	3.035	3.045	4045	216	4261	5705	5765	1893	87.3	1421
15	31	60		.6	3.0	.6	10.213	3.197	3.222	4400	222	4622	6190	6285	1950	90.0	1505
16	36	65		.5	3.2	.3	11.115	3.333	3.360	4620	226	4846	6485	6660	1974	91.0	1569
17	40	70		.5	3.4	.1	11.923	3.451	3.490	4695	227	4922	6590	6810	1965	90.6	1625
18	44	80		.5	3.6	39.9	13.005	3.603	3.653	4850	230	5080	6800	7085	1932	89.1	1705
19	52	60	22°	43.5	3.8	39.7	14.626	3.822	3.886	4630	226	4856	6500	6820	1755	86.0	1813
20	57	70		.4	3.8	.6	17.851	4.222	4.300	5550	244	5794	7760	8190	1905	87.8	2007
21	10:01	75		.3	4.0	.3	19.119	4.372	4.466	5810	250	6060	8120	8640	1933	89.2	2087
22	06	80		.3	4.2	.1	20.423	4.519	4.630	5970	254	6224	8340	8970	1930	89.0	2160
23	10	85		.4	4.2	.2	21.621	4.651	4.755	6060	256	6316	8455	9060	1918	88.4	2220
24	14	95		.3	4.2	.1	23.031	4.800	4.918	6170	258	6428	8610	9260	1880	86.7	2295
25	12:25	65	28°	43.5	4.2	.3	21.913	4.678	4.780	5060	234	5294	7095	7550	1580	72.9	2230
26	29	75		.4	4.2	.2	27.351	5.230	5.350	6250	260	6510	8720	9350	1756	81.1	2482
27	33	80		.3	4.2	.1	29.461	5.430	5.565	6770	272	7042	9430	10130	1820	84.0	2597
28	38	85		.2	4.2	.0	32.174	5.665	5.810	7160	282	7442	9970	10750	1855	85.6	2698
29	43	90		.4	4.1	.3	33.851	5.820	5.950	7360	286	7646	10250	10910	1835	84.6	2777
30	46	100		.4	4.0	.4	37.160	6.095	6.220	7580	292	7872	10550	11200	1802	83.1	2903

17 and plotted in Fig. 14. Thus Fig. 14 was developed from the test results into a form directly comparable with the "experience curve" originally furnished by the turbine manufacturer as part of his proposal specification.

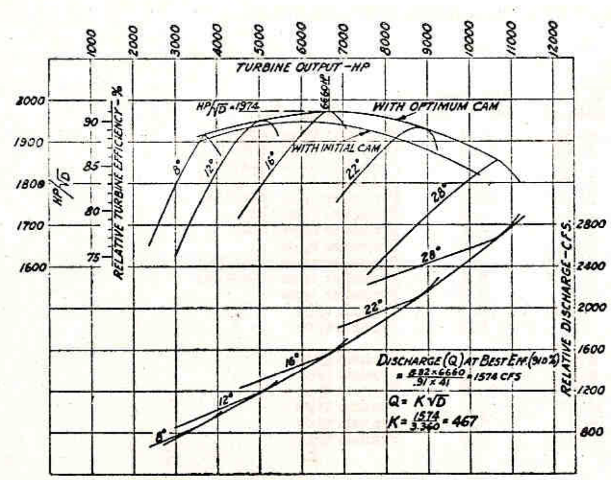


FIG. 14 HP$\sqrt{D}$, RELATIVE EFFICIENCY AND DISCHARGE CURVES

Correcting Blade-Gate Cam. It will be remembered that the blade-gate cam was removed at the beginning of the test. The efficiency envelope curve, therefore, represents the optimum performance obtainable, not necessarily that with the cam in place. In Fig. 15 is indicated the blade-gate relationship produced by the "initial cam."

Transferring this relationship to the individual blade-angle curves in Fig. 14, the relative performance envelope with the initial cam was obtained. The difference between the two envelope curves in Fig. 14 marked "with initial cam" and "with optimum cam" represents the improvement possible by altering the shape of the cam surface.

During the actual running of the test, the original steel cam was duplicated in hardwood by a mechanic. Now the hardwood cam was altered by saw and rasp to produce the optimum relationship indicated in Fig. 14. It was then installed in the control valve, and the mechanism actuated through a full stroke to check whether it produced the desired blade-gate relationship. Minor changes were then made to the wooden cam as found necessary and, when it was finally correct, the metal cam was machined to duplicate it.

The comparison of the initial and optimum cams for the particular unit tested is shown in Fig. 15.

Conclusion

Much useful information can be obtained economically from an index test of a reaction turbine. Such a test may be conducted in all respects, except for the measurement of discharge, in accordance with the ASME Power Test Code. There is no definite assurance that the best possible efficiency is being obtained from an adjustable-blade propeller turbine unless a field check of the blade-gate relationship is made. An index test is a relatively inexpensive means of determining the optimum blade-gate relationship. It is recommended that all reaction turbines, and especially adjustable-blade propeller turbines be tested by the index method where absolute methods are considered inadvisable because of some unusual condition or because of the expense involved.

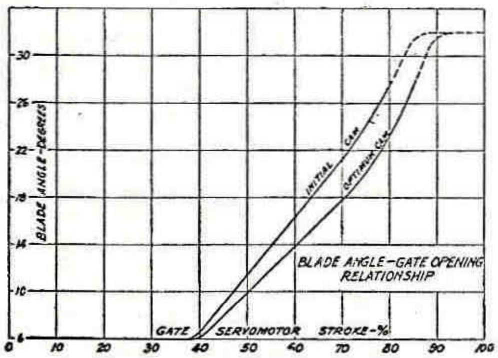


Fig. 15 Comparison of "Design" and "Optimum" Cam Shapes

Discussion

Hugh J. Davis.[6] The author has made a very worth-while contribution to this hitherto neglected topic, and is to be commended for the scope of presentation as well as thoroughness of detail embodied in his paper.

It is the intent of this discussion to offer additional remarks and supporting data, based mostly upon the writer's own experience, which, in effect, supplement the analysis presented by the author. It is believed that this additional information will be of assistance primarily to those who desire to become versed in the technique of turbine index testing.

Since the principles underlying index testing are well established, successful execution necessarily hinges upon the manner in which the detailed conduct of the test is carried out. For this reason the writer would like to discuss in some detail the four main types of measurements required, which may be listed as follows:

1 Relative discharge measurements.

2 Head determination: (*a*) Tail-water elevation measurements; (*b*) headwater elevation measurements; (*c*) casing intake pressure measurements.

3 Power measurements.

4 Other measurements.

Relative Discharge Measurements. These measurements consist of obtaining the average of fluctuating manometer readings, the manometers being connected to carefully installed piezometer taps which measure an arbitrary differential head theoretically proportional to the square of the discharge.

The author has indicated the various locations where these piezometer taps may be placed to advantage. The writer has had experience with only one of these, the Winter-Kennedy type, and Table 3 of this discussion is offered as an aid in predicting the maximum deflection to be expected for a proposed installation utilizing this method of measuring relative discharge.

The installations referred to in Table 3 are sites which are personally familiar either to the writer or to the author (as indicated by footnote), and have been selected because of the clear-cut application of the Winter-Kennedy principle. The variation between values presented in the percentage column are felt to be significantly small when the following factors are contemplated:

(*a*) The range of head and type of plant considered.

(*b*) In the Winter-Kennedy system there are usually one high-pressure and three low-pressure taps. The optional low-pressure (higher velocity) piezometers are located relatively close to one another but at variable radii, all four openings normally being located in the same radial plane. (Reference is made to the author's Fig. 6 which shows the general location of the high-and low-pressure stations.) The final decision as to which one of the three low-pressure piezometers is to be paired with the high-pressure tap to obtain the desired deflection is often governed by consistency of results, but sometimes by the requirement of maximum permissible deflection.

(*c*) The maximum gate (and blade) opening for a given in-

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TABLE 3 MAXIMUM DEFLECTION EXPECTED FOR PROPOSED INSTALLATION

Item	(1) Project	(2) Rated head, ft.	(3) Test head, (net) ft	(4) Max W-K deflection at full gate, ft	(5) Per cent (4) ÷ (3)	Remarks
1	Wheeler No. 3	48	50	4.67	9.3	Propeller type (FB)
2	Wheeler No. 4	48	50	5.20	10.4	Propeller type (FB)
3	Ft. Loudoun No. 1	65	65	4.22	6.5	Propeller type (Kaplan)
4	Ft. Loudoun No. 2	65	65	4.27	6.6	Propeller type (Kaplan)
5	Chickamauga No. 3	36	50	5.15[c]	10.3	Propeller type (Kaplan)
6	Holcombe No. 1	42	41	3.45	8.4	Propeller type (FB)
7	Holcombe No. 2	42	41	4.08	10.0	Propeller type (FB)
8[a]	Bonneville service unit	50	56	5.61	10.0	Propeller type ..
9[a]	Bonneville Nos. 1 & 2	60	53	4.83[c]	9.1	Propeller type (Kaplan)
10[a]	Bonneville Nos. 3–6	60	60	5.11[c]	8.5	Propeller type (Kaplan)
11[a]	Rio Negro Nos. 1 & 2	...	70.5	6.5	9.2	Propeller type
12[a]	Douglas No. 1	...	81[b]	4.85	6.0	Francis type
13[a]	Jordan Dam Nos. 1–4 (Uruguay)	...	90	5.6	6.2	Francis type
14[a]	Douglas No. 3	...	102	6.0	5.9	Francis type
15[a]	Cherokee No. 1	100	113[b]	6.71	6.0	Francis type
16[a]	Douglas No. 3	...	113[b]	11.3[c]	10.0	Francis type
17	Narrows No. 1	132	144	14.1	9.8	Francis type
18[a]	Ocoee No. 3	280	280	18.5	6.6	Francis type
19[a]	Tokette, Ore.	...	406	18.7	4.6	Francis type

[a] Data obtained from author before adjustment.
[b] Adjusted to net head from gross head.
[c] Adjusted to 100 per cent gate from part gate.

stallation is a matter of judgment based on the rationalization of several design factors.

Therefore it may be concluded that for turbines whose intakes are designed along orthodox lines and whose relative-discharge taps are located according to the Winter-Kennedy system, the maximum manometer deflection in feet of water to be expected at full gate will probably not be over about 10 per cent of the actual head during the test. A margin of at least 2 ft (of water) over the maximum computed deflection is recommended in determining the size of the manometer board, in order to allow for fluctuations, displacement resulting from air leakage, and safety margin.

Since the head on the majority of propeller-type turbines is under 60 or 70 ft, a water manometer of the inverted multiple U-tube type is usually the most convenient for these installations. When four piezometer openings are provided, the manometer board should be furnished with 4 glass tubes (preferably backed with cross-section paper, 10 divisions to the inch), with the lower ends connected to the individual taps, and the upper ends to a horizontal manifold which constitutes the top side of the inverted U. One end of this manifold should be connected to a drain for thorough and periodic flushing out of all air pockets, and the other end to an air-pressure supply for depressing the water-column levels to the desired elevation. In the event the manometer station has been located too near headwater level, other less reliable means may be utilized for flushing, such as circulating water through the tubing and out by way of the orifice opening. As the author indicated, in cases such as these a vacuum line rather than an air-pressure line is needed for connection to the manifold. It is strongly recommended, however, that whenever feasible the manometer station be located at an elevation low enough to insure maximum ease of manipulation and reliability of measured data.

Rapid fluctuation of the manometer column is a frequent characteristic of this type of measurement. In order to reduce this motion and to facilitate making the required observations, valves in the individual piezometer lines are sometimes utilized to throttle the free surging of the measuring fluid. It is felt by some authorities that undue throttling of a manometer line is at times responsible for the average of a set of readings to reflect incorrectly the true average of the quantity being measured. This might be true if the coefficient of discharge of the throttled valve were not identical in both directions, and also if the cycle of change taking place was a relatively gradual one. A method recommended by the writer which eliminates possible introduction of error, and at the same time increases greatly the ease of making observations is to make use of a simple, foot-operated clamping device. The rubber hoses connecting the manometers to the piezometer-tubing outlets may be threaded through the clamp in such a manner that at any desired instant circulation, and therefore fluctuations, can be totally eliminated instantaneously in each line. The only precaution is to so design the clamp that the same volumetric change takes place in each tube when pinched. This is easily checked, when the turbine gates are closed, by making certain that the slight meniscus rise resulting from the operation of the clamp is equal in each tube.

When the head on the plant is such as to make the value of the water deflection larger than it is practical to measure, such as is often the case with Francis-type turbines, recourse is made to the use of mercury as a measuring fluid. The manometer in this case takes the form of a simple U-tube. A refinement is sometimes made by using a pot-type single-leg manometer which eliminates one of the readings, and possibly also reduces the magnitude of column fluctuations. This type, however, requires careful calibration and handling. For installations where deflections are large enough to require the use of mercury, the need of installing 3 low-pressure taps is reduced, as the effect of erratic piezometer action on the end result should be lessened. Provisions for periodic flushing out of all trapped air as well as air separating out from solution are, of course, as imperative as before.

Figs. 7 and 9 of the paper indicate graphically that the exponent n in the equation $Q = KD^n$(D being the manometer deflection, Q the discharge, and K a coefficient) results in values of 0.489 for the Winter-Kennedy system and 0.50 for the Peck method, when evaluated experimentally. The writer would like to offer an additional empirical check on this exponent by presenting Fig. 16.

The data shown in Fig. 16 were obtained recently for a Francis installation tested under a head of about 144 ft, the absolute discharge values being obtained by one of the generally accepted methods. In this case the calibration curve, shown as a continuous straight line in Fig. 16, may be given as $Q = KD^{0.53}$.

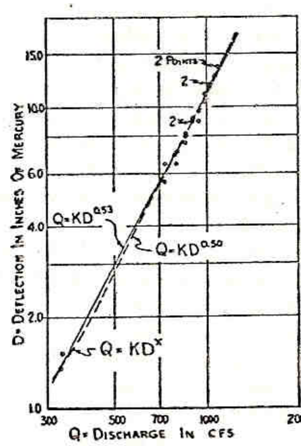

Fig. 16 Calibration Curve of Winter-Kennedy Piezometers

However, another curve may also be drawn which would satisfy the experimental points equally well, and whose equation could be written as $Q = KD^{0.50}$ for the major upper portion, and $Q = KD^x$ for the lower curved portion, x being a variable, gradually increasing from its minimum value of $^1/_2$. The justification for the foregoing analysis is that in this particular case the lower two points can be shown to lie just inside the "transition zone" where complete turbulence is not a characteristic of the flow, and where energy conversions should not be expected to be exactly proportional to the square of the discharge. This particular example has been cited merely to focus attention on the possibility that in any given instance the foregoing concepts may be applicable.

Another factor which should be considered in this connection is the experimental errors which of course are ever present in any type of measurement, including absolute-discharge determinations, especially in the lower ranges. This may have a bearing on the apparent discrepancies attributed to the piezometer results.

The writer's conclusion, therefore, based on the analysis of the field data which have come to his attention, is that the assumption, making $n = 0.50$ in the relative-discharge equation (for turbulent flow), has been empirically confirmed well within the limits of experimental error.

Head Determination. On some plants, such as on most Francis-turbine installations, the gross head may be considerably higher than the net turbine head, mostly as a result of penstock losses. On other plants, such as on many propeller-type turbines, the gross head may be nearly equal to the turbine net head, trash-rack losses possibly being the only measurable difference between the two.

In the former case it is desirable to obtain measurements of the gross head as well as the net head since the operators are interested in the performance of the over-all plant as well as the turbine proper. In the latter case it is good practice to inspect the trash racks to insure that the head loss at this point is not excessive as a result of collection of debris, ice, or other obstruction.

For each type of plant, therefore, it is usually necessary to measure both tail-water and headwater elevations during an index test. In the plant with penstock losses it is necessary, in addition, to obtain a pressure measurement at a point near the casing intake, at which location it will usually be found that the turbine manufacturer has provided piezometer taps for this purpose.

(*a*) *Tail-water elevation measurements:* Since in the usual case the turbine manufacturer has power guarantees to meet, it is desirable that tailwater elevations be measured in a manner which fulfills the requirements of the ASME "Power Test Codes—Hydraulic Prime Movers," revised and adopted May 6, 1949. As these conditions are somewhat rigid, it may be stated that measuring the tailrace elevation at a single location for a plant housing several units is usually not satisfactory. A carefully located staff gage, or stilling-box piezometer, may be required for each unit tested. If a temporary board staff is used, the divisions should be in feet and tenths of a foot, and large enough to be read easily from the nearest vantage point. The importance of giving tailwater measurements careful consideration cannot be overemphasized, especially for the lower head plants where the percentage error becomes rather critical.

The occurrence of cavitation in the turbine is closely related to tailwater elevation. Since the incidence of the cavitation phenomena is often accompanied by a measurable change in the turbine performance, it is essential that the tail-water elevation during the test should not attain a value smaller than the guaranteed minimum. In this connection it is also well to insure that the plant sigma under the actual test conditions falls within design limits.

(*b*) *Headwater elevation measurements:* These measurements offer a minimum of difficulty as the average water surface elevation is usually considerably more uniform than in the tailrace. A single location for the entire plant is usually satisfactory, the gage often consisting of either a board or tile staff.

(*c*) *Casing-intake pressure measurements:* As mentioned, these measurements are sometimes needed to obtain the net turbine head. In this type of plant the headwater pressure is usually high enough to preclude the use of a water manometer. Gages commonly utilized for this purpose are mercury U-tube manometers, deadweight gage testers, or calibrated Bourdon gages.

Power Measurements. It is the writer's experience that in measuring output better results are obtained by making use of the generating unit integrating watthour meter than by attempting to average fluctuating values read from an indicating wattmeter. The advantage of the first method, even under the questionable assumption that both instruments are equally reliable, is that it automatically produces a correctly averaged power output during a specific time interval. The chances for undetected reading errors are also considerably greater in the second method.

The watthour-meter method consists of timing accurately by means of a stop watch an arbitrary number of whole revolutions of the revolving meter disk, which are tallied and later counted. The number of disk turns may vary from 10 to 50, depending upon the output and also upon the meter. In the event readings on an indicating meter are not recorded simultaneously, it is advisable to obtain a rough output check by making a second determination for a much shorter time interval, say, 3 to 10 revolutions. The intent should be to record the output over a time interval approximately concurrent with the observations being made at the various other stations. Under normal conditions a time interval of 3 to 4 mins for each run should provide ample time to obtain reliable averages of the various quantities being measured.

Additional comparative readings on an indicating wattmeter are desirable for the following reasons:

(*a*) As a rough check on the kilowatthour-meter results.

(*b*) To obtain data on possible power "swings," i.e., by recording maximum and minimum values during each run.

(*c*) To furnish the operator a relative calibration of the two meters.

Power-factor observations should also be made at periodic intervals since generator efficiencies, which are usually furnished in terms of electric output and power factor, are needed to compute turbine output.

Other Measurements. In order to ascertain the detailed performance of a turbine in connection with an index test, additional measurements are made, some of these being essential and others optional. In the author's presentation of the actual example of an index test on a Kaplan turbine, the following essential measurements or observations were described:

(*a*) Correlation between servomotor stroke and guide-vane opening (prior to test).

(*b*) Correlation between stroke of the Kaplan-head inner oil pipe and blade-angle indicator (prior to test).

(*c*) Measurement of guide-vane and runner clearances and inspection of all piezometer openings (prior to test).

(*d*) Governor gate-dial indicator and Kaplan-head blade-angle indicator (during test).

Other desirable measurements, intimated but not specifically mentioned in the author's paper, are as follows:

(*e*) *Servomotor-stroke measurements:* Accurate servomotor-stroke positions should be measured at intervals during each test run. Readings taken on a machinist's scale between machined surfaces is usually the most expedient. The immediate importance of these measurements is that it provides an accurate parameter against which may be plotted other variables while the test is in progress, thus providing information as to which of the measured data is possibly erratic.

(*f*) *Pilot-valve lift measurements:* Micrometer measurements of the "lift" on the pilot valve controlling the blade-gate relationship on a Kaplan turbine should be taken. As was pointed out by the author, the cam normally governing the lift on this valve is removed during the major portion of the index test. In order to determine readily the desired shape of the revised cam, accurate determinations of the pilot-valve lift must be made for each arbitrary setting of the runner blade angle.

There are other considerations which should be mentioned in connection with reference to the blade-gate cam. Many of these cams are furnished by the manufacturer with graduations in the form of a head scale, and provisions for rotating the cam so as to obtain a reading on the cam corresponding to the head on the plant. Before starting the index test, it is imperative that the cam be set for the estimated average head on the turbine during the period of the test. When this cam is replaced, after removal and reshaping, care must be used that it is oriented with respect to the gate-restoring mechanism exactly in its initial position, as well as in resetting it correctly with respect to head. If these precautions are not taken, a check test of the new cam profile may yield disappointing results.

The following additional measurements are optional, although often quite desirable, and are included for the sake of completeness:

(*g*) *Air-admission measurements:* It is at times desirable to obtain information regarding the relative quantity of air being admitted to the turbine over the range of gate openings. The effect of air admission at various locations of the flow passage on the discharge, power, and efficiency characteristics of the turbine is beyond reliable prediction. It is well to determine this effect as part of the index test, particularly in the event that air is being admitted for gate openings which correspond to the normal operating range of the turbine. A simple U-tube water manometer may be used for this purpose.

(*h*) *Servomotor-pressure measurements:* Even though these measurements are not actually an integral part of the index test, they are usually considered supplementary to such a test as they furnish valuable data as to whether or not the gate or blade mechanism is functioning as intended. Calibrated Bourdon-gage readings are taken over the full stroke in both the opening and closing direction with the piston moving slowly but uniformly throughout each stroke. Because of the nature of this test it is usually made independently of other measurements, and in the case where the unit generating capacity is not a relatively minor portion of the system load, it is essential that the power dispatcher is fully informed of the proposed test, particularly as to time of execution. It is sometimes possible to avoid system disturbance either by employing a water rheostat to dissipate the energy generated, or by utilizing a sister unit in the same plant to reject or accept load in the converse manner from the unit being tested.

In order to present the necessary perspective regarding the numerous measurements discussed, the writer would like to close this discussion by making a few remarks pertaining to the actual procedure which may be followed in performing this type of test. The author has made a valuable presentation of many details of such a procedure in connection with a specific Kaplan installation. The following remarks are intended to supplement and also parallel in a more general manner this phase of the paper.

General Index Test Procedure. A test of this type which involves unusually costly equipment should be under the direct supervision of a qualified engineer who necessarily must assume full responsibility as to methods and results. As is often the case, the operating company may request the turbine manufacturer to execute such a test. In that event the manufacturer's representative should have recognized authority to make the measurements which are deemed desirable, and to operate the unit at his best discretion so as to provide the required information. In order to facilitate delegating this authority in the field, it is advisable that there be present at the site an operating company official who has jurisdiction over the plant personnel, and whose authority will also be recognized by the power dispatcher when requests are made regarding the operation of the unit to be tested.

Since field conditions often do not lend themselves readily to the somewhat unusual requirements of an index test, it is usually desirable for the test engineer to arrive on the site a day or so prior to the date scheduled for the test. This will allow time for observation of the plant in operation as well as for inspection of gages, tubing, and instruments, and to recommend any possible alterations or additions.

The personnel required consists of a number of observers stationed at the various measuring points, an operator at the governor panel, and a calculator who makes various plots from the measured data while the test is in progress. The total number of participants may be as high as ten or twelve, and it is good practice to brief this personnel prior to the test on the general procedure and to issue individual instructions. It is particularly essential to be entirely specific as to the manner of taking and recording the various observations.

As many test runs should be taken as are needed to define satisfactorily the performance characteristics of the unit. This number will vary depending upon the judgment of the calculator (who may at times be the engineer in charge of the test), the consistency of the plotted points, and the type of turbine under test. Typical intervals between gate openings may be given as either 10 per cent or 5 per cent, depending on the portion of the efficiency curve being defined. The over-all time required for the test may vary from 3 to 4 hr for a Francis turbine to 8 to 10 hr for a Kaplan wheel. In the latter case another 2 or 3 hr of testing time may be needed to obtain a confirming check on the final cam profile. Longer over-all times will of course be needed if it is not possible to obtain clearance from the power dispatcher for a period sufficient to complete the entire test in one attempt.

Each test run should last long enough to allow the observers to obtain as many readings as will result in a reliable average. An average is reliable, of course, only when it contains a reasonably probable error and the value of this error may be unfavorably affected by many uncontrollable factors. For example, such factors as severe wave action, or air entrainment accompanying turbulent flow, in the tailrace, will require a relatively long period of observation—or at least a larger number of observations than would be needed if conditions were more favorable. The same type of consideration should be given particularly to the manometer deflections which measure relative discharge, since the nature of these readings makes them susceptible to relatively large percentage errors.

Without attempting to set a definite rule, a typical run may last 3 to 5 min, during which time 10 periodically spaced readings of all fluctuating values may be taken. Twenty readings, however, are sometimes preferable on some measurements, such as the Winter-Kennedy deflections, if erratic results indicate such a need.

The writer feels that it is important to make an attempt to obtain all the observations relating to a specific test run approximately concurrently with respect to time. In the author's illustration of a specific test on a Kaplan installation, mention was made of tailwater elevations being taken on a staff gage at 5-min intervals. In this instance apparently the primary factor affecting the tailrace elevation was the gradual tidal effect. In order to provide the actual example of a markedly different situation the curves shown in Fig. 17, herewith, are presented.

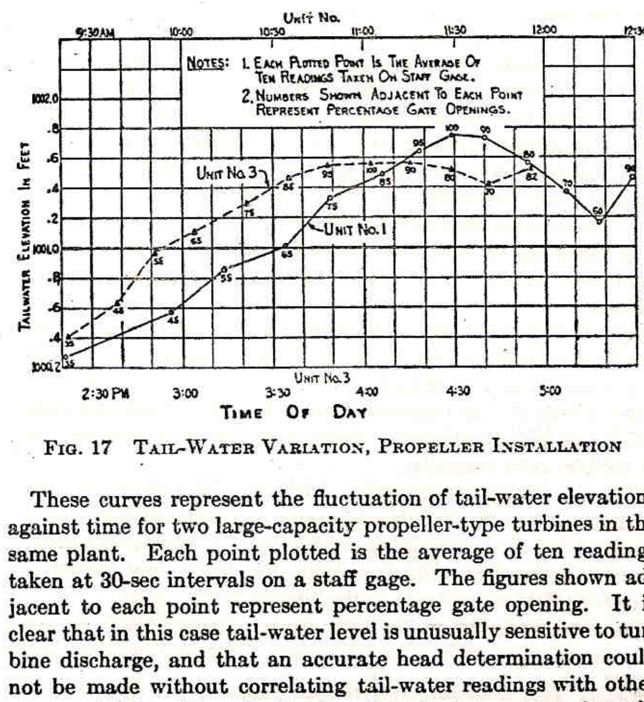

FIG. 17 TAIL-WATER VARIATION, PROPELLER INSTALLATION

These curves represent the fluctuation of tail-water elevations against time for two large-capacity propeller-type turbines in the same plant. Each point plotted is the average of ten readings taken at 30-sec intervals on a staff gage. The figures shown adjacent to each point represent percentage gate opening. It is clear that in this case tail-water level is unusually sensitive to turbine discharge, and that an accurate head determination could not be made without correlating tail-water readings with other measured data. Since the head on this plant was approximately

41 ft during the test, an error in tail-water elevation of 0.2 ft would result in an error of about 1/2 per cent in efficiency and about 3/4 per cent in output.

The problem of correlating the measurements of the participating personnel, located as they usually are at remote stations throughout the plant, may be solved in various ways. In the foregoing example an outdoor siren was sounded for the beginning of each run, this signal being clearly audible throughout the powerhouse proper, as well as at the outdoor stations. Telephone communication was available between the calculator's table, the turbine pit, and the governor floor. When all of the data from the previous run had been supplied to the calculator for plotting, phone instructions were given to the operator at the governor panel for the next gate setting, and for sounding the siren signaling the subsequent test run.

In conclusion it should be emphasized that the foregoing remarks are intended as a supplement to the author's fine paper, with the intent of disseminating whatever additional information the writer may have acquired from field experience. It is hoped that other authors will add to what has already been written.

W. B. Hess.[6] Although considerable economies have been achieved in the operation of hydroplants, as related to their load characteristics, the system requirements, available river flows, and the optimum utilization of storage, there is generally inadequate knowledge of the actual operating efficiency of individual hydro units and too little appreciation of the potential gains that can be achieved from such information. In many cases the entire knowledge of unit efficiencies may be based on data obtained from stepped-up model tests or field acceptance tests made at or near rated head. The model efficiency data may be reasonably indicative of prototype efficiency near the peak efficiency range; but experience has shown it to be very inaccurate at the high load ranges, particularly when the unit is operating in or near the critical cavitation zone.

Field acceptance tests are usually conducted at only one value of head and are made shortly after initial installation. For such tests the water passages are smooth, the shaft alignment good, and all operating conditions are held as constant as possible. These conditions are not representative of those encountered in subsequent operation. Only continuous metering of turbine discharge or periodic checks of operating efficiency by a suitable index method will detect inefficiencies caused by trash on the intake screens, rust, and foreign-matter accumulations on the turbine and intake passages, pitting from cavitation, shaft eccentricity, or other change in physical condition. The varying load conditions resulting from frequency and load regulation may be further factors in reducing unit efficiencies, because when a unit is regulating frequency or load, the blades lag the motion of the gates so that best efficiency relationship of blades and gates is seldom obtained.

Even though the losses from these several sources may sometimes appear small percentagewise, the accumulated energy loss can attain a considerable magnitude. A loss of only 0.1 per cent in the efficiency and maximum output of the combined Safe Harbor and Holtwood hydrostations would cause an average loss of 1,500,000 kwhr annually.

Although the author is familiar with the initial index and turbine field tests on the Safe Harbor units, it is believed that a brief discussion on the subsequent installation of turbine-discharge meters and the derivation therefrom of a continuous record of operating efficiency will add to the interest of the paper.

There are installed in the Safe Harbor hydroelectric station seven main units with adjustable-blade (Kaplan) turbines and two small service units with Francis-type turbines. The adjustable-blade machines are rated 42,500 hp at 55 ft head; the Francis types are rated 3100 hp at the same head. All units have Winter-Kennedy scroll-case piezometer taps which have been calibrated on five main and one service unit by actual field tests using the two-type current-meter method and checked in two cases against Gibson tests.

The scroll-case piezometers of each unit are connected to a Leads and Northrup Centrimax flowmeter to provide a continuous measure of individual unit discharge. Totalizing relays provide for indicating, integrating, and recording the discharge of the entire station. The hourly integration of the actual station draft, integrated generator output, and recorded average head provides all the data necessary for calculating station efficiency. These data are recorded every hour on a station log sheet; and comparison is made of the actual efficiency of station operation with the expected maximum for the prevailing conditions of operation.

Daily checks of individual unit over-all efficiency are also made. On a number of occasions maladjustments of the blade-gate relationship have been detected. These instances usually occur after a maintenance outage and sometimes following an adjustment for some abnormal operating condition, after which, due to changing shift personnel, return to the proper setting is overlooked. On several occasions a drop in efficiency of as much as 4 per cent has been detected on the service (Francis) units. This loss is caused by the failure of a water seal around the turbine shaft; mud and dirt clog the water-supply lines making the seal ineffective.

At Safe Harbor it is conservatively estimated that an average annual gain of 5,000,000 kwhr (a little more than 0.5 per cent of the average annual output) is effected by the system of continuous-discharge metering and efficiency checks.

The turbine-discharge metering provides, in addition, a method for conducting "one-man" efficiency tests on any unit. The turbine discharge is integrated by means of totalizing relays which indicate the amount of water on a five-digit counter. The revolutions of the integrating watthour meter are transferred to a similar counter by means of a phototube and electronic relay. The two counters are started and stopped simultaneously; therefore, at constant head the ratio of the number of counts accumulated in the test period is a direct measure of relative efficiency. During the test period, while the counts are accumulating, the test man records the head from accurately calibrated water-stage recorders, as well as other data necessary for a complete efficiency test run.

The importance of testing in the maximum output range cannot be overemphasized. The effects of cavitation on the performance of the turbine in this range are very critical, and to obtain the maximum power with a minimum of pitting damage some measure of the severity of the action is advantageous. Since vibration is a measure of relative severity of cavitation, vibration-sensitive elements have been installed on the draft-tube manhole doors of the main units. The degree of vibration is indicated on meters located in the station control room and, during periods of wide-open operation, the unit outputs are limited to predetermined values of vibration.

Index tests made at small increments of blade angle within the maximum output range have shown that optimum load, efficiency, and vibration are quite sensitive to the blade-angle setting. The results of a test are shown in Fig. 18, herewith. It will be noted that an increase of 125 kw is obtained for this particular unit by decreasing the blade angle manually approximately 1 deg. In this range of loading, the blades are normally wide open, or nearly so, while the load is varied entirely by gate opening, there being no corresponding movement of the blades.

[6] Senior Test Engineer, Safe Harbor Water Power Corporation, Conestoga, Pa. Mem. ASME.

Since maximum loads are usually carried during periods when the river flow equals or exceeds maximum station draft, efficiency is not given too much consideration; however, the gain of 2.1 per cent in this case reduces the discharge 220 cfs per unit and, on the basis of the entire station, results in an additional gain of 30 kw from an increase in head due to less water entering the tailrace. These gains for the entire station amount to approximately 1000 kw or about 1,300,000 kwhr annually during the high flow periods of an average year.

The characteristics of the unit illustrated in Fig. 18 are typical of, and the gain shown is the average for, all units. Actually, even though the main units are of the same design, there are differences between individual units of such magnitude as to warrant detailed

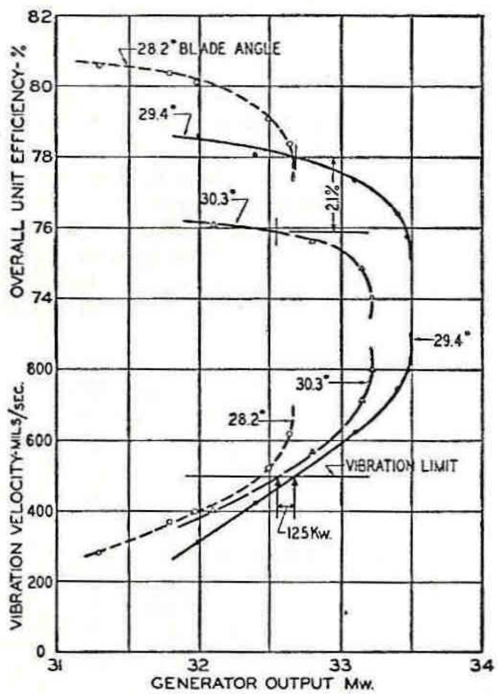

FIG. 18 MAXIMUM OUTPUT TESTS ON ADJUSTABLE-BLADE PROPELLER TURBINE STATION OPERATING (GROSS) HEAD 53.3 FT

testing on each machine. The optimum blade-gate relationship also varies at different operating heads.

Installation or selection of a proper index should be given careful study. Combinations of scroll-case piezometers usually provide consistent results; however, single-point current-meter or Pitot-tube indexes, due to changes in flow pattern, can produce erroneous and inconsistent results. During the initial turbine field tests at Safe Harbor, units adjacent to the one under test were held at constant load to minimize change in flow pattern, but even in this case the entire area of flow was traversed.

The writer's experience in making field acceptance tests on automatically adjustable-blade turbines indicates that maximum-efficiency capabilities can be obtained only by tests at fixed blade angles with test runs being taken at several gate openings through the peak range. Testing on the cam, due to play in the mechanism, lap in the valves, and so forth, usually does not produce the optimum blade-gate relation or conditions conducive to the absolute maximum efficiency.

H. E. HOUSE.[7] Since 1945 over twenty different tests have been run on the Santeetlah, Cheoah, and Calderwood power plants owned by subsidiaries of The Aluminum Company of America. All of the units tested are of the Francis type.

A question concerning the cost of running an index test has been raised. The time required to obtain the test data is generally 4 to 5 hr. It has been found convenient to establish servomotor-piston settings using a 50 divisions per inch metal engineer's scale. The man reading the scale has telephone communication with the man at the governor. The governor is blocked using the load limit. Plant load is held constant by the switchboard operator using a unit not under test. Five readings at 30-sec intervals have given good results. As soon as the five readings are taken, the man at the servomotor piston calls for the next point. Power output versus gate setting, and Venturi deflection versus gate setting are plotted as the test proceeds. Total engineering personnel man-hours will generally run 280 to obtain the data and prepare the test report. Twenty-four man-hours, mechanic's time, are required to set up the test equipment and remove it upon completion of the test.

A four-stage mercury column for measurement of head has given consistent and accurate results. Each of the four U-tubes is 6 ft high and made of $^3/_8$-in. Tenite tubing with steel compression-type fittings.

In addition to turbine-performance data, considerable worthwhile information concerning tunnel and penstock losses has been obtained.

C. L. NORRIS.[8] The basic method of index testing given in the paper has been used by the Authority on some 60 units of the Francis, Kaplan, and fixed-blade propeller types. Of all the methods mentioned by the author for testing turbines, the index-testing method is the only one which can be made and repeated as often as necessary at very small cost. As stated, although the values are relative, the results leave no doubt in the operator's mind as to how the unit should be operated to obtain the maximum power from the available water supply.

The author has stated that for each blade-angle setting accurate measurements should be made so that the blade setting could be reproduced for check readings, if later found necessary. In the making of a great many tests the Authority has found that to reproduce a blade-angle setting is practically impossible. The better method is to plot all quantities as they are taken and, if necessary, take as many check readings as desired before moving to the next blade angle. In many cases, after the entire test has been completed, it will be found that additional readings are desired, in which case an entirely new set of readings should be taken for the blade-angle position in question.

The author has covered the entire testing procedure in sufficient detail to enable engineers familiar with hydraulic turbines to conduct an index test, with one exception; this is reproducing on the new cam the path of the cam follower when passing through the peak of the individual blade-angle curves as represented by the envelope curve when drawn through these peaks. This is shown by optimum cam in Fig. 14 of the paper. Before the cam is removed the unit should be operated through the entire range of blade movement. At each desired blade angle the position of the cam follower should be marked on the face of the cam, and for each blade position the vertical location of the follower should be established with reference to a fixed point. With the cam removed and the test made for any given blade angle, obtain the vertical location of the follower. This dimension, as compared with the previous dimension for this particular blade angle, will determine how much the cam is to be altered at that particular point. All of these measurements should be made and recorded carefully. Without these measurements,

[7] Aluminum Company of America, Alcoa, Tenn. Mem. ASME.

[8] Assistant to Head Mechanical Engineer, Tennessee Valley Authority, Knoxville, Tenn. Mem. ASME.

which are required to be able to shape the new cam, the entire test would be valueless.

One of the basic reasons for installing Kaplan turbines is the fact that the head variations are usually a large percentage of the rated head. In view of this it is necessary to have operating curves which show the characteristic of the turbine over the entire range of head. These curves should show efficiency, discharge, power, and gate-blade relation for all heads. These curves should, of course, be as accurate as possible. The index test is ideally suited to obtaining relative values for these quantities for the test head. In order to obtain the required values for other heads, it is necessary to run test at other heads since the relationship between power and heads does not vary as the 3/2 power, owing to the characteristics of the runners. However, it is not always convenient or possible to obtain tests at the desired heads, in which case the test data should be reduced for other heads in accordance with the relation of the test data at the test head to the model test curves.

In order to obtain the greatest possible power with installed equipment, every unit in every plant should have at least one index test performed. It is desirable to have tests at as many heads as possible, and, as stated by the author, for continuous efficient operation these tests should be repeated periodically.

W. J. Rheingans.[9] This paper is quite timely, because ASME Committee No. 18 on Power Test Codes for Hydraulic Prime Movers has been working for the past 3 or 4 years on a supplement on index testing to be added to the Hydraulic Prime Movers Test Code. The committee has recognized the importance of index tests and the object of the supplement is to set standards for this type of test, similar to the way the main test code sets standards for acceptance tests. However, the object of the supplement will be to set forth the general limiting conditions for making index tests, and it will not be a textbook or manual on the subject. Therefore, a paper of the type presented by the author, which goes into the details of how to make such tests and gives actual examples of index tests is quite valuable.

Unfortunately, the author does not go into much detail regarding the measurement of head and power output for index tests. It should be emphasized that when making index tests it is not necessary to measure the head on the turbine or the generator output with the degree of accuracy required by the Test Code for acceptance tests. Many short cuts can be taken to reduce the cost of making the tests and to speed up the actual testing. For example, the pressure head, on a closed conduit to the turbine, can be measured with a pressure gage connected to a single piezometer, and the tailrace elevation can be measured on a staff gage located at some convenient point in the tailrace.

The generator output can be obtained from the switchboard indicating meters, although the kilowatthour meter, such as used by the author in the example of the test cited, is usually preferable. The greatest saving in time and expense in measuring generator output during an index test is that the requirement for calibrated instruments and instrument transformers is eliminated.

The author did not mention the fact that the true net head on the turbine cannot be determined with an index test, because the absolute discharge is not measured and therefore the true velocity-head corrections cannot be made to the head measurements. However, the error is usually so small that it has very little influence on the results.

The statement by the author that index tests will show the most economical use of units on a system is open to argument. It is true that an index test will show the most economical use of a single unit or of a group of identical units, but, since it does not measure the true discharge of any of the units, the most economical use of a combination of various types of units on a system cannot be determined accurately by means of such index tests.

The author does not explain his statement that the most economical operation is obtained when units are operated at loads such that the slopes of the output versus Q curves are equal. Although he makes a reference to a previous article on this subject, it would seem that this is important enough to warrant a few words of explanation.

Fig. 3 of the paper shows results of index tests made in 1941 as compared to tests made in 1949. The author calls attention to the fact that some flowmeters using friction loss in the penstock are subject to change with time. The same is true of most flowmeters, including Venturi-tube types, and Winter-Kennedy taps. These methods are all subject to variation with time as has been demonstrated by accurate calibration. Therefore, too much reliance cannot be placed upon comparative index tests made over a long period of time.

The author does not explain the $Kw/\sqrt{D}$ value used in Figs. 1, 2, and 4, at the time he discusses these figures.

The various methods of determining relative discharge mentioned by the author correspond to the methods being proposed by Committee No. 18 for its supplement on index testing. However, under Pitot tube, the supplement will also include the "Pitometer."

The supplement proposes to set a minimum limit of 1.5 ft of water differential at full turbine discharge at rated head for the Venturi section, the friction-head loss and velocity-head method, the Winter-Kennedy method, and the Peck method. The author has suggested 3 ft of water differential for these methods which would have a tendency to increase the accuracy of the tests.

J. F. Roberts.[10] This paper on the subject of index testing is very timely because it comes at the same time that the ASME Test Code Committee is reviewing this subject and is also in the process of drafting instructions so that index tests can be conducted properly and the greatest benefits obtained from the results. Index testing, while it does not measure the quantity of water accurately, does measure the relative discharge at different outputs of the turbine. Most engineers agree that the efficiency at best point can be estimated within 2 to 5 per cent, so that the values of discharge can be computed at all other horsepower outputs within this same degree of accuracy. On the modern vertical-shaft units with a reasonably good setting, the estimate of best efficiency should be near the lower limit of 2 per cent, although on the older multiple-runner units, it might be difficult to agree on the estimates within the 5 per cent figure. Even with this variable, it is possible to keep records of discharge throughout the year, and such records are extremely valuable in future forecasting of power output properly.

Attention should be called to a publication printed by the National Electric Light Association,[11] which gives a great deal of useful information on the subject and is recommended as a reference for anyone interested in the subject.

Forrest Nagler was a strong advocate of index testing during all his years of activity in the hydroelectric field, and he has written several papers on this subject. During recent years our company has made index tests on a large number of plants, especially Kaplan-turbine plants, and particularly almost every plant installed on the system of the Tennessee Valley Authority.

[9] Allis-Chalmers Manufacturing Company, Milwaukee, Wis. Men. ASME.

[10] Manager, Hydraulic Department, Allis-Chalmers Manufacturing Company, Milwaukee, Wis. Mem. ASME.

[11] "Water Wheel Tests and Operating Records of Plant Discharge," National Electric Light Association, Publication No. 278-34, March, 1928.

Table 4, herewith, lists some of the large plants that have been index-tested

TABLE 4 WRITER'S COMPANY PLANTS WHERE INDEX TESTS HAVE BEEN CONDUCTED

Name of plant	No. of units	Horse-power each	Head ft	Rpm	Type
Kentucky, TVA.....	5	44000	48	78.3	Kaplan, concrete casing
Pickwick, TVA.....	4	48000	43	81.8	Kaplan, concrete casing
Cheoah—Aluminum	4	24000	180	171 1/2	Francis—plate case
Co..............	1	45000	188	164	Francis—plate case
So. Cal. Edison—					
Kern..........	3	10750	865	250	Horizontal double-overhung impeller
Big Creek 1.......	1	22500	1900	375	
Big Creek 2A.....	1	56000	2200	250	
Wilson Dam, TVA..	10	35000	92	100	Francis—concrete casings
Hoover—B of R.....	7	115000	480	180	Francis—steel casings
Canadian Aluminum, Saguenay.........	8	100000	208	128 1/2	Francis—steel casings
Calderwood—Aluminum Company....	3	56000	213	150	Francis—steel casings

R. A. Sutherland.[12] The author has given a clear description of the steps in index testing and makes out a good case for its use in all installations, particularly with adjustable-blade propeller turbines. It is well known that a complete efficiency test is in many cases very expensive, especially with low-head turbines, which is perhaps the main reason that such a test is not generally made. The index test gives information of great value to the operators, at much less expense than an absolute efficiency test, and, if this fact were more generally realized, the index test might become more general. In this connection, it would be useful if the author could give some indication of the cost of conducting such a test and reducing the test data to a usable form, and an indication of the approximate time that a machine must be taken out of regular service for the test. In many cases the loss of production would be a charge against the cost of the test.

Referring to the author's Fig. 14, it is noted that at 8000 hp (to take an example), a gain of approximately 2 per cent in efficiency of a certain Kaplan wheel could be realized by a change of cam shape consequent on an index test. For a run of river unit, the increased output might be worth, roughly, \$3000 per year or represent a capital gain, of, say, \$30,000.

I. A. Winter.[13] The data presented are related primarily to the performance of adjustable-blade propeller-type turbines. The application of index testing to this type of installation is much broader than has been experienced with the fixed-blade propeller and Francis-type units. Considerable advantage can be had, however, through the use of index testing for improving the performance of the latter types.

The practical use of the index method of testing hydraulic turbines includes optimum performance of units under variable-head conditions, which is an important phase of the Bureau of Reclamation's operation, because of the requirement for the generation of electrical energy from large quantities of stored water used primarily for irrigation purposes, thus producing wide fluctuations in reservoir levels. Advantages of index testing to be had under these conditions are comparable to those obtained with the adjustable-blade propeller turbines as discussed by the author. Another important use of the method is to determine the effect on performance of units under varying tail-water conditions, where the sigma setting is considered to be critical. Also, there are numerous examples of the application of this technique to evaluating the results of alterations to turbine runners, guide vanes, draft tubes, intakes, and other water passages which influence the hydraulic performance of the unit.

The author has pointed out the difficulty of obtaining accurate pressure readings at the manometers because of the entrainment of air and other types of interference. To these cautions should be added the importance of avoiding low points in the pressure lines where mercury, inadvertently injected into the lines by faulty manipulation of the manometers, could accumulate and interfere with the proper deflections in the manometers. Adequate drain connections should be provided at low points if sufficient slope to assure freedom from this trouble cannot be provided. The effect of temperature on the surface elevation or pressures of water in piezometer lines having considerable vertical height should be appreciated fully; and, if the piezometer lines are to be exposed, means should be provided for continuous circulation of water through the lines except while measurements are actually being obtained. This will assure minimum error, due to a difference in specific gravity of the water in the penstocks and in the pressure lines.

It is not necessary that the differential-pressure means be installed initially in the turbine casing to be able to conduct a satisfactory index test involving the measurement of flow of water through the turbine. Many satisfactory installations of scroll-case differential-pressure taps have been made by inserting the high-pressure piezometer line through the casing from within the turbine pit and tack-welding or clipping the pipe line around the casing to the outside horizontal center line where the high-pressure orifice is located. The inner or low-pressure connection can be installed from within the turbine pit by drilling and tapping the pressure orifice in the exposed portion of the speed ring. A recent installation of this type has been used successfully in Unit 1 of the Parker Power Plant of the Bureau of Reclamation for the purpose of investigating the effect of trimming the turbine-runner blades.

Control of the wicket-gate position by means of the governor gate-limit device during the test is inadequate, as field experience has demonstrated that the most consistent electrical and hydraulic measurements are obtained when the turbine gates are blocked in a fixed position, using metal inserts between the collar on the servomotor piston and the servomotor cylinder head. These blocks are usually machined to represent increments of $2^1/_2$ per cent of the total servomotor stroke, and, by means of a suitable combination of stops of various thicknesses, it is possible to obtain a complete traverse of the turbine performance with relatively few blocks.

Control of flow through the water passages of a hydraulic-turbine installation with the unit operating at constant head and speed is effected (*a*) by the position of the turbine wicket gates and (*b*) by the area of the runner vent. The relation between the total orifice area of the wicket-gate opening is established readily by calibration with the casing empty and the machined servomotor blocks in position. This makes it possible to translate servomotor-piston travel in inches accurately into orifice area in square feet during the test. The total orifice area of the runner vent can be determined by calibration in the shop, or after installation if necessary, to a very high degree of accuracy. Thus the two controlling orifices of the water passage can be established. An example of the application of this technique is shown in Table 5 on the following page.

The purpose of the calibration is to permit the interpretation or extrapolation of a measured performance of one unit to several units of like design in a given plant. Interpretation of the effects of the difference in areas of runner vents for similar turbines involves indeterminate factors and for this reason it is desirable to specify turbines of like design to have vent areas within 1 per

[12] Hydraulic Engineer, Ebasco Services, Inc., New York, N. Y. Mem. ASME.

[13] Head, Hydraulic Machinery Division, Bureau of Reclamation, Denver, Col.

TABLE 5 EXAMPLE OF RUNNER VENT AND WICKET GATE CALIBRATION

Unit	Area runner vent, sq ft	Area wicket gates at 70 per cent open, sq ft
1........	106.4	115.9
2........	106.4	Not available
3........	106.5	116.9
4........	106.0	Not available

cent in a group of identical units. This degree of accuracy may be questioned, however, but it is not necessary to obtain final dimensions in the original castings, as minor chipping of high places and building up of low spots by welding makes it feasible to obtain values within these limits. With like runner-vent areas, it may be concluded that the discharge values between identical units when stated in terms of the coefficient of discharge of the wicket gates will give results within 1 per cent of comparable values. An example of results obtained by this procedure is shown in Fig. 19 of this discussion.

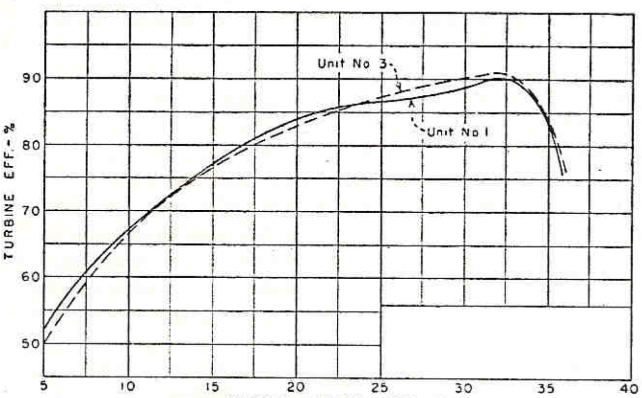

FIG. 19 COMPARISON OF EFFICIENCY OF LIKE UNITS USING COEFFICIENT OF DISCHARGE OF TURBINE-GATE OPENINGS AS BASIS

Another important item in investigating the relative performance of several units of similar design in a given power plant is the measurement of the electrical output. It is believed that best results are obtained by calibrating the individual watthour meters of the several units with a given standard and counting the revolutions of the meter disks throughout the test periods, utilizing a high-grade accurate timer. The advantage of the watthour meter over portable meters is the absence of errors inherent in temporary hook-ups, meter calibrations, change of constants, transformers, and the like. The meters can be sealed to insure comparable results for subsequent tests in a continuous program of investigation. The use of electrical measurements as the prime mover for determining relative hydraulic performance between like units is not recommended as it is believed the gate-area orifice-discharge coefficient is a more suitable parameter.

AUTHOR'S CLOSURE

The suggestions, both general and detailed, offered by Mr. Davis regarding the conduct of an index test are interesting and are certainly a valuable addition to the paper.

Mr. Davis, in calling attention to Figs. 7 and 9 of the paper, states that they indicate that the exponent n in the equation $Q = K\ D^n$ is 0.489 for the Winter-Kennedy system and 0.50 for the Peck method. This, as Mr. Davis realizes, as indicated by his comments thereafter, was not the author's intention. The exponent n theoretically should be 0.50 for piezometers correctly located by either of the systems mentioned, or by any others, and, where field tests have not or do not confirm this, something must be wrong with the piezometer locations or with the absolute-discharge measurement.

The author in his presentation of the paper submitted additional evidence that with the piezometers properly located, the exponent $n = 0.50$. For the record, this additional evidence is presented in Figs. 20 and 21, herewith. Fig. 20 shows log D versus log Q where Q was measured by the Gibson method on one of the main Kaplan turbines at the Safe Harbor Plant of Safe Harbor Water Power Corporation. A line with slope such that the exponent $n = 0.50$ certainly fits all the points. Fig. 21 shows the same data for one of the Francis Station service units in the same plant. In this case the absolute discharge was measured

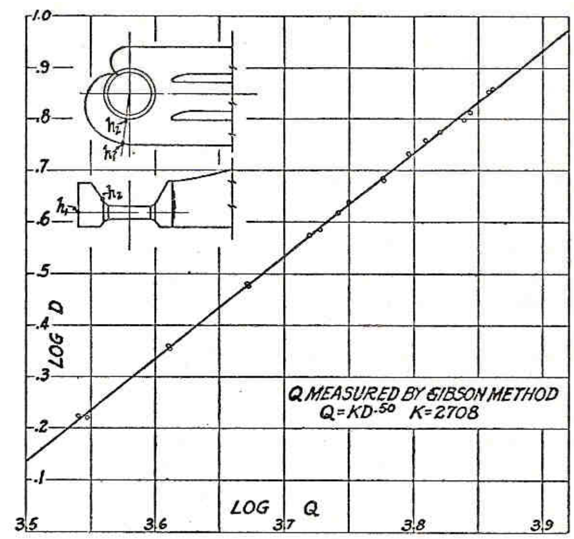

FIG. 20

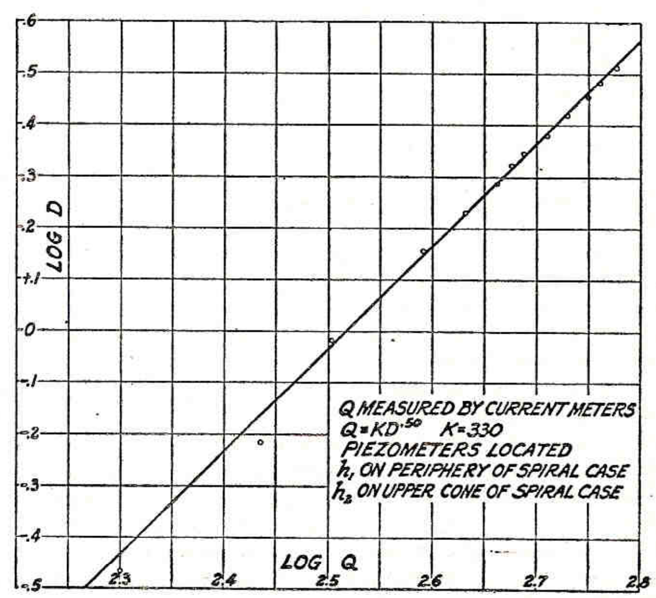

FIG. 21

by current meters. Here again a line with slope $n = 0.50$ fits the points, with the exception of the two at the lowest discharge values. It was the opinion of the engineers concerned that the piezometers were located properly and that, at these very low velocities, it was the absolute measurements of discharge which were in error and not the relative discharge indicated by the piezometer differentials.

Where index tests are to be run, it is essential that the piezometers be located correctly, and this should be done by one both technically and practically qualified. When this is done, the exponent n definitely will be 0.50.

Mr. House has given some data indicative of the man-hours required to conduct an index test. This partially answers the question brought up in Mr. Sutherland's discussion regarding cost. The loss of production from the turbine is chiefly a matter of the outage for inspection, a check on the wicket-gate adjustment and calibration, and, in the case of a Kaplan turbine, on the blade-angle calibration. All of these normally can be performed in about 4 hr; however, if piezometer taps have not been installed previously, this usually means an additional 4-hr outage. The operation during the test being nearly all at less than full load means an additional output loss, the amount of which depends upon the size of the unit. In nearly all instances, the total loss can be kept to a minimum by so timing the test dates. One of the important advantages of an index test over an acceptance test is that it can be run on short notice whereas the acceptance test requires lengthy preparation, and the availability of special instruments, especially for the discharge measurements, does not always coincide with the most economically advantageous date for the test from the outage standpoint.

Mr. Hess' discussion has provided an outstanding example of the application of index-test data in securing continual efficiency indication and maximum efficiency of operation from a given unit under varying conditions of both hydraulic input and electrical output. In practically all operating companies there are engineers qualified to make similar applications to meet specific conditions. The expense necessary to plan and carry out such applications in most cases would be negligible, compared with the gain in yearly output resulting therefrom—as indicated by Mr. Hess' discussion.

Both Mr. Norris and Mr. Davis point out, in the case of a Kaplan turbine, the advisability of locating by measurement the position of the cam follower for each of several blade angles to facilitate alteration of the cam surface. This point was overlooked by the author because, although he actually has never made such measurements, he has never failed to get the cam right on the second try. Either Mr. Norris or Mr. Davis could probably do the same. The aim is to correct the cam properly in the minimum possible time, and the great majority of test personnel could accomplish this end by making the measurements suggested.

Mr. Rheingans has called attention to the fact that the author did not amplify his statement regarding the most economical distribution of load between units. A ready reference to this subject is available.[14] The author trusts that Mr. Rheingans' remarks regarding the accuracy of index tests will not be misconstrued. They can be as accurate relatively as the acceptance tests are absolutely. However, frequently gross head can be used in place of net head and guaranteed generator and exciter efficiencies may be used where actual test results are not available.

It is particularly interesting to note from Mr. Roberts' discussion the number of large turbines, manufactured by his company, tested by the index method as listed in Table 4. The benefits derived from index-testing small units are, of course, equally important to the owner. Once, the author, in testing a 50-in-diam Kaplan turbine in a vacuum setting under 8-ft head, was able to increase the output from 50 to 55 kw as a result of an index test. Three men did the whole job in 64 man-hours, including the report. The owner of that small turbine was certainly pleased; a gain of 5 kw represented quite a saving in purchased power in a year's operation of his small business.

As Mr. Winter was one of the pioneers of the index-testing method and is a foremost authority on the subject today, his comments are particularly valuable—as much for his general agreement with the author's views as for his suggestions. It is most regrettable that one of the other great pioneers and proponents of index testing—Mr. Joseph A. Peck—is no longer among us to participate in the discussion.

[14] "Handbook of Applied Hydraulics," by C. V. Davis, McGraw-Hill Book Company, Inc., New York N. Y., 1942, pp. 656–657; section 14 by L. F. Moody.