University of Minnesota
St. Anthony Falls Hydraulic Laboratory

Project Report No. 267

INDEX TEST OF UNIT #1 PROSPECT POWERHOUSE #2

by

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Prepared for

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York, Pennsylvania

and

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INTRODUCTION

An index test was performed September 30 and October 1, 1987, on Unit #1 of Prospect Powerhouse #2, located near the town of Prospect, Oregon. The testing was requested by the American Hydro Corporation and was scheduled to be in conjunction with a possible runner upgrade of the facility. The facility owner is Pacific Power of Portland, Oregon. The primary personnel involved were: Mr. W. Colwill, of American Hydro Corporation; Messr's T. O'Conner and R. Landolt of Pacific Power; Mr. R. Voigt, Jr., of St. Anthony Falls Hydraulic Laboratory, University of Minnesota. Numerous Pacific Power maintenance and operational personnel were also involved.

The purpose of an index test is to determine the relative unit efficiency at various wicket gate positions. Through this type of testing the most efficient wicket gate position can be verified. This is typically determined by varying the wicket gate position from either full gate to closed gate or vice versa, in a series of small, usually 5 to 10%, increments. At each position, approximately 15 to 20 parameters are measured. Some of these parameters such as generator output and relative flow measurement are used in the computation of the relative efficiency values, while others may affect turbine efficiency either directly or indirectly.

The following information was measured and recorded on October 1, 1987:

1. Time at which gate opening was changed.
2. Time at which velocity was measured.
3. Indicator reading on servomotor.
4. Relative displacment of gate ring in inches.
5. Headwater in feet measured via Plant-2 station meter.
6. TWE tailwater elevation measured at staff gauge (ft).
7. ΔP measured in volts.
8. Unit 1 - Penstock pressure measured in feet from gauge on turbine.
9. Unit 1 - Draft tube vacuum measured in feet from gauge on turbine.
10. Unit 1 - Megawatts measured from station meter.

11,12,13. Bearing temperature °C measured at gauges on turbine.

14,15,16. Same as 8, 9, and 10 above, except for Unit #2.

17. Total Plant 1 station megawatts.
18. Water temperature °C measured in tailrace.
19. Gaging station readout in feet--can be converted to cfs.
20. Plant 4 - station megawatts.
21. Plant 4 - penstock pressure.

See Appendix C for tabular format.

Of the twenty-one parameters measured, those of principal importance in determining unit efficiency were relative flow, net head, and generator output. Relative flow was measured using two different methods, in effect providing two different index tests of the unit. The first method of relative flow measurement was the use of a pitot cylinder (velocity head) probe. A 3/8 in. diameter cylinder into which two pressure sensing holes had been drilled 39.25° apart was inserted into the steel penstock just upstream of the powerhouse. The probe was inserted radially so that the holes were approximately 3 inches from the inner pipe wall. Inserting the pipe this distance should effectively avoid any wall effects while at the same time minimize vibrations of the probe. A pitot cylinder probe works on the principle that water flowing at a given velocity creates a dynamic pressure equal to $V^2/2g$. One hole of the probe faces directly upstream measuring the total (static and dynamic) head, while the second is aligned to measure just the static head. This is done by first aligning the probe such that the taps are sensing equal pressure, which indicates the correct direction of flow. The probe is then turned so that one tap faces upstream. Scribe marks on the probe provide an accurate indication of the tap position. The two sensing holes were then connected to a differential pressure transducer which provided a digital readout proportional to the pressure differential sensed by the probe. With each change of servo gate opening, changes in flow were sensed and a corresponding ΔP was recorded.

The second method of relative flow measurement involved the use of a set of static pressure taps. One tap was located on the inside of the scroll case and the second was located where the pitot cylinder had been inserted. Both taps were 1/2" in diameter. As with the first method, these taps were connected to a differential pressure transducer by copper tubing. Location of these taps was such that a convergence occurred between these locations. This factor in conjunction with the second tap being located on the inside of the scroll case provided for different velocities adjacent to each tap and corresponding different static pressures. These different static pressures then provide a ΔP which is sensed by the transducer and is proportional to the square of the flow. The two pressure transducers used in the testing program were Validyne model DP 275-38 and model DP 15-32. Both were calibrated prior to and just after testing.

Both methods used are based on Bernoulli's principle, in general for any location

$$\text{Total head} = z + \frac{P}{\gamma} + \frac{V^2}{2g} \qquad (1)$$

or

$$z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} = z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + h_{L12} \qquad (2)$$

Since, in the case of the differential pressure tap method, the distance between probes is quite short and because headloss (h_L) is proportional to

V^2 and hence ΔP, omitting of the headloss term will have no noticeable effect on the data analysis.

or $$z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} = z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} \qquad (3)$$

The use of a differential pressure transducer eliminates any effects of elevation.

hence $$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} \qquad (4)$$

From the continuity equation (5), the change in cross section between pressure taps 1 and 2 results in a corresponding change in velocity

$$Q = V \cdot A \qquad (5)$$

This change in velocity is further enhanced due to pressure tap #2 being located on the inside of the scroll case, since conservation of radial momentum gives, for any two points on a given radial,

$$V_1 r_1 = V_2 r_2 \qquad (6)$$

With the radius of the inside of the scroll case being less than that of the scroll case centerline the velocity near the inner wall is increased from the mean pipe velocity. The final result is

$$\Delta P = P_1 - P_2 = \gamma \left(\frac{V_2^2}{2g} - \frac{V_1^2}{2g} \right) \qquad (7)$$

Equation 7 is the basic principle behind the Winter-Kennedy method often used for index testing.

The pitot cylinder method relies on the fact that one tap of the probe measures total head while the other measures static head only. Hence,

$$z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} = z_2 + \frac{P_2}{\gamma} \qquad (8)$$

As stated earlier the use of a differential pressure transducer eliminates any effect of elevation.

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} = \frac{P_2}{\gamma} \tag{9}$$

Solving for the Pitot cylinder,

$$\Delta P = P_2 - P_1 = \gamma \frac{V_1^2}{2g} \tag{10}$$

Net head measurement was done using the penstock pressure head gage located at the side of the generator. This gage senses static pressure head just upstream of the turbine. The tailwater elevation was determined using a staff gage located in the tailrace on the right (looking downstream) abutment of the powerhouse.

Entrance velocity head was estimated by relating a known flow and ΔP relationship (at full gate) with the measured ΔP for a particular gate opening. Exit velocity was zero at the location of staff gage.

Combination of the penstock pressure head gage, the tailwater staff gage (TWE), and the entrance velocity head allowed computation of net head (H).

$$H = \text{Penstock Pressure Head} + \frac{V_{entrance}^2}{2g} = \text{TWE} \tag{11}$$

Power output was measured using the station watt meter which had been recently calibrated by Pacific Power personnel.

Water temperature was measured by dropping a hand held thermometer into the tailrace and recording its reading in °C.

Data Analysis

Data recorded on site were analyzed to determine relative unit efficiencies and to detect any inconsistencies. The analysis consisted of plotting combinations of parameters such as estimated headloss versus servo gate opening (Fig. 1). The reason for plotting such a graph was to determine the potential for error in using the penstock pressure gage in the computation of net head. This graph shows that for the no-flow condition the penstock pressure gage gives a reading approximately 26 ft high. Typically with the type of gage in question, this is basically a linear offset increasing with pressure. Since the range of head being measured during testing varied only approximately 18 ft from full scale, any error due to linear offset is quite small, approximately 0.07%.

$$\text{Approximate error} = \frac{\text{gage offset}}{\text{full scale}} \cdot \frac{\text{maximum variance from mean penstock pressure}}{\text{computed mean penstock pressure}} \qquad (12)$$

$$\frac{26}{600} \cdot \frac{9.4}{595.6} \cdot 100 = 0.07$$

Hence, use of the penstock pressure head gage should have very little detrimental effect in the analysis.

The other parameters used in the calculation of net head, the entrance velocity and the tailwater elevation, are small compared to penstock pressure. The entrance velocity head, being related to the ΔP measurement has the greatest likelihood of error. In the worst case event that a given ΔP be in error by 3.1%, please see section on error analysis; the effect of this error would at most be:

$$\text{Percent error} = 1 - \left(\frac{H - .031}{H} \right) \left(\frac{V_{ent}^2}{2g} \right) \qquad (13)$$

for the minimum H and maximum ΔP. Any error due to measurement error in tailwater elevation would be very small, on the order of 0.05 ft or a percent error of

$$\text{Percent error} = \frac{0.05 \text{ ft}}{624.51 \text{ ft}} \cdot 100 \cong .008\%$$

A graph was plotted of ΔP, which is a direct indication of the square of the relative flow, normalized to ΔP_{max} the ΔP recorded at full gate for each flow measurement method, as a function of servo gate opening. One item to be noted on this graph is that the curve for the differential pressure tap method passes through zero near 25% servo gate opening. A zero pressure differential should indicate no flow; however, this is obviously not the case. What apparently causes this phenomenon is a change in the flow regime in the turbine and scroll case. This was noticed during the testing at approximately 60% gate at which point the unit began sounding different and significant power swings where noted. This is concurred by Fig. 2 which shows that for both methods of flow measurement, the parameter $\Delta P/\Delta P_{max}$ shows good similarity from full gate down to approximately 70% gate. A shifting is apparent in the differential pressure tap method curve between 65% and 55% gate below which point the curves again show good similarity with a constant offset being observed. This apparent change in flow regimes causes the localized velocity in the vicinity of the pressure tap to be lowered relative to the average free-stream velocity, hence the corresponding drop in ΔP and reaching of a negative ΔP at 20% gate. A negative ΔP indicates that the velocity was lower at the inner scroll case tap than at the penstock tap.

This phenomenon required that at and below 60% servo gate opening the ΔP for the differential pressure tap method needed to be modified by a correction factor $K_{\Delta P}$ (Figure 2) in order to equilibrate the two methods of index testing.

As stated earlier, the power output of the unit was measured using the station watt meters which had been recently calibrated. In general, this parameter shows good repeatability for a given gate setting, estimated error 0.5%.

Relative efficiency was calculated as the actual unit output in kW divided by head in feet and the square root of ΔP in PSI.

$$E_{rel} = \frac{kW}{H\sqrt{\Delta P/K_1}}$$

This parameter was plotted against unit output in megawatts, Fig. 3. As seen in the figure both curves exhibit similar although unusual characteristics. Peak efficiency occurs at approximately 14 MW for both curves corresponding to about 75% gate opening. As expected, efficiency falls off at very large gate openings, above 15.5 MW (greater than 85% gate). Relative efficiency also falls quite rapidly from 13 MW to 10.5 MW corresponding to gate openings of about 67% to 55%. Below this the rate of change of efficiency slows dramatically until the machine reaches approximately 5 MW or 30% gate opening.

It should be noted that the range from 55% to 70% gate opening corresponds to the apparent change in flow regimes mentioned earlier. During the testing program powerswings up to 0.5 MW were noted at 60% and 65% gate. Similar swings were noted with the pressure transducers used to sense flow. Data analysis shows other inconsistencies in this region with output values of 13.36 MW, 13.10 MW, 12.65 MW, and 13.40 MW, all occurring at 70% gate opening during the testing. In comparison at 95% gate recorded output was 16.85 MW, 16.82 MW, and 16.80 MW, while it was 2.85 MW at 19.8% and 2.95 MW at 20.4% gate. This gives further credence to the apparent flow instabilities from approximately 55% to 70% gate. Comparison of the overall curves show that they are consistent within ± 4.8%. Elimination of the two worst points of comparison 12 and 15 MW reduces the variation to ± 3.1%. The standard deviation of the comparisons is 0.0165 and 0.0128, respectively.

The actual efficiency was computed for 70% and 75% gate opening using the differential pressure tap method. This was done by using a USGS staff gage located just downstream of the plant. An estimated base flow of 430 cfs was measured prior to testing and new readings were taken at 70% and 75% gate. The difference was assumed to be the flow through the unit. Computed efficiencies were 84.6% and 83.1%, respectively. Care should be taken when utilizing these values, however, as any debris lodging near the staff could have a significant effect as a sensitivity analysis shows that an error in ± 0.01 ft reading the staff gage could have an effect of ± 2% in the overall efficiency computed. Also the method of obtaining the rating curve is not known and may in some part have been created synthetically.

Error Analysis

Summation and root mean square evaluation of the various measurement and analysis errors will be presented in this section.

Measurement reading related errors for penstock pressure head are relatively small due to the large head. Estimated reading accuracies ± 0.5 ft

$$\text{Penstock Pressure Head Measurement reading error} = \frac{0.5}{600} = 0.083\%$$

As shown earlier any error due to any potential nonlinearity of the penstock pressure head gage was estimated at 0.07%. Measurement reading error in the tailwater elevation determination would be very small, the reading accuracy being approximately ± 0.05 ft or a resulting maximum percentage error based on net head of (0.05/624.51) x 100 = 0.008%. Measurement reading error of the pressure transducer output is the largest likely error with the apparent fluctuations occurring; the reading may have inaccuracies of approximately 2.0 and 1.0 counts on the voltmeter output for the pitot cylinder and differential pressure methods, respectively.

These correspond to percentage full-scale errors of

$$\text{Pitot cylinder } \frac{2.0}{79.8} \cdot 100 = 2.5\%$$

$$\text{Differential Pressure } \frac{1.0}{32.0} \cdot 100 = 3.1\%$$

The manufacturer stated transducer accuracies of 0.25% full scale. Due to use of less than full scale, full scale reading would have been 120 counts; this relates to sensing accuracies of

$$\text{Pitot cylinder} = (.25)\left(\frac{120}{79.8}\right) = .38\%$$

$$\text{Differential Pressure Tap Method} = (.25)\left(\frac{120}{32.0}\right) = 0.94\%$$

Total flow measurement error involves transducer error as well as a reading or value estimation error. However, these values must be modified by taking their square root as the values recorded were for ΔP which directly relates to velocity squared or flow squared.

Pitot Cylinder

$$\text{Flow Error Summation} = \sqrt{2.5} + \sqrt{0.38} = 1.58 + .62$$

$$= 2.2\%$$

$$\text{Flow RMS Error} = \sqrt{(1.58)^2 + (.62)^2}$$

$$= 1.7\%$$

Differential Pressure Tap Method

$$\text{Flow Error Summation} = \sqrt{3.1} + \sqrt{.94} = 1.76 + .97$$

$$= 2.7\%$$

$$\text{Flow RMS Error} = \sqrt{(1.76)^2 + (.97)^2}$$

$$= 2.0\%$$

Wattmeter Reading

Error in the reading of power output as recorded by the station watt meter was estimated at 0.05 MW, or a resulting % full scale error of

$$\text{Error } \frac{0.05 \text{ MW}}{17.10 \text{ MW}} \cdot 100 = 0.29\%$$

and a % mean scale error of

$$\text{\% mean scale wattmeter reading of } \frac{0.05 \text{ MW}}{12.35 \text{ MW}} \cdot 100 = 0.40\%$$

The station wattmeter used had been just previously calibrated and has an estimated probable inaccuracy of

Station wattmeter probable inaccuracy = 0.5%

Power output error based on the mean scale wattmeter reading is as follows:

Power ERROR summation = 0.40 + 0.50

= 0.90%

Flow RMS ERROR = $\sqrt{(0.4)^2 + (0.5)^2}$ = 0.64%

As given earlier, computation of net head, H, requires the penstock pressure gage reading, the TWE reading, and the estimated entrance velocity head.

Combination of all errors involved in the computation of net head gives the following results.

Net Head Error Summation = 0.083 + 0.07 + .008 + 0.05

= 0.21%

Net Head RMS Error = $\sqrt{(0.083)^2 + (0.07)^2 + (0.008)^2 + (0.05)^2}$

= 0.12%

The total combined error in the values of $KW/H\sqrt{\Delta P/K_1}$ = computed are summarized as follows:

Pitot Cylinder

Estimated Total Summed Error Summation = 0.21 + 2.2 + 0.9 = 3.31%

Estimated Total RMS Error Summation = 0.12 + 1.7 + 0.64 = 2.46%

Estimate Total Summed Error RMS = $\sqrt{(0.21)^2 + (2.2)^2 + (0.9)^2}$ = 2.39%

Estimated Total RMS Error RMS = $\sqrt{(0.12)^2 + (1.7)^2 + (0.64)^2}$ = 1.82%

Differential Pressure Tap Method

Estimated Total Summed Error Summation = 0.21 + 2.7 + 0.90 = 3.81%

Estimated Total RMS Error Summation = 0.12 + 2.0 + 0.64 = 2.76%

Estimated Total Summed Error RMS = $\sqrt{(0.21)^2 + (2.7)^2 + (0.90)^2}$ = 2.85%

$$\text{Estimated Total RMS Error Summation} = \sqrt{(0.12)^2 + (2.0)^2 + (0.64)^2} = 2.10\%$$

The estimated total combined error, summation-RMS or RMS-summation, is approximately 2.4% and 2.8% for the two methods of index testing.

CONCLUSIONS

The two curves shown in Figure 3 exhibit an unusual performance curve for a high head Francis turbine. In general the two curves are similar, agreeing within 3.1% over most of the operating range. This variation is similar to the estimated total accuracy of the tests which was ± 2.4% and 2.8% for the pitot cylinder and the differential pressure tap methods, respectively. In spite of its apparent potential for greater inaccuracy and the fact that the low range ΔP's needed adjustment, the differential pressure tap method seemed more reliable during the testing and seems to have provided more generally consistent data.

The actual unit efficiency as computed using the staff gage located just downstream of the facility was found to be 84.6% and 83.1% for 70% and 75% servo gate opening, respectively. Caution should be used with these values, however, as potential inaccuracies are quite large.

APPENDIX A

SAMPLE CALCULATIONS

$$\text{Net head, } H = \text{Penstock Pressure Head} + \frac{V^2_{entrance}}{2g} - \text{TWE}$$

where $$\frac{V^2}{2g} = \frac{V^2}{V^2_{max}} \frac{V^2_{max}}{2g}$$

$$\frac{V^2_{max}}{2g} = \frac{Q^2_{max}}{2g\ A^2_{entrance}}$$

$$A_{entrance} = \frac{\pi d^2}{4}$$

$$d = 56 \text{ inches}$$

$$A_{entrance} = 17.10 \text{ ft}^2$$

$$Q_{max} = Q_{100\%\ SGO} - Q_{base}$$

where $Q_{100\%SGO}$ (100% servo gate opening) and Q_{base} were determined using the USGS staff gage located just downstream of the plant. The staff reading was recorded and a corresponding flow was obtained from the gage rating tables.

$$Q_{max} = 862.5 - 430 = 432.5 \text{ cfs}$$

$$V_{max} = \frac{432.5}{17.10} = 25.29 \text{ ft/s}$$

$$\frac{V^2_{max}}{2g} = \frac{(25.29)^2}{2(32.2)} = 9.93 \text{ ft}$$

To convert to other flows this value was multiplied by the ratio $\Delta P/\Delta P_{max}$. The 85% servo gate opening of the pitot cylinder method will be used in a sample calculation.

$$\frac{V^2}{2g} = 9.93 \left(\frac{50.2}{79.8} \right) = 6.25 \text{ ft}$$

Penstock Pressure Head = Penstock Pressure Head Gage Reading + elevation of gage

for the same point

Penstock Pressure Head = 591 + 2009.28 = 2600.28 ft

TWE = Tailrace Staff Reading + Base Elevation of Staff

= 1.59 + 1980.0 = 1981.59 ft

H = 2600.28 + 6.25 - 1981.59 = 624.94 ft

The general efficiency index

$$\frac{kW}{H\sqrt{\Delta P/K_1}}$$

where K_1 is the transducer constant of conversion between 0.1 volts and PSI.

K_1 = 61.83 Pitot cylinder method

K_1 = 10.22 Differential pressure tap method.

$$\frac{kW}{H\sqrt{\Delta P/K_1}} = \frac{15.66(1000)}{624.94\sqrt{50.2/61.83}} = 27.81 \frac{kW}{ft\sqrt{PSI}}$$

APPENDIX B

COMPUTED RESULTS

APPENDIX C

DATA RECORDED

Method #1 - Pitot Cylinder

Servo G.O.	Penstock Pressure Head -2009.28 (ft)	Estimated Entrance Velocity Head (ft)	TWE -1980.0 (ft)	H (ft)	ΔP (0.1 volts)	MW	kW / $H\sqrt{\Delta P/K_1}$
10.10	587	9.93	1.7	624.51	79.8	17.15	24.17
9.50	588	9.82	1.65	625.45	78.9	16.85	23.85
9.00	589	8.96	1.68	625.56	72.0	16.30	24.15
10.10	589	9.90	1.65	626.53	79.6	17.10	24.05
10.10	589	9.53	1.67	626.14	76.6	17.10	24.53
9.50	589	9.27	1.67	625.88	74.5	16.82	24.49
9.00	590	8.31	1.63	625.96	66.8	16.33	25.10
8.50	591	6.25	1.59	624.94	50.2	15.66	27.81
8.00	593	5.61	1.64	626.25	45.1	15.05	28.13
7.50	595	5.23	1.64	627.87	42.0	14.22	27.48
7.00	597	4.49	1.52	629.25	36.1	13.36	27.79
6.46	599	1.93	1.48	628.73	15.5	12.17	38.66
7.50	598	5.21	1.46	631.03	41.9	13.33	25.66
7.00	599	4.54	1.44	631.38	36.5	13.10	27.00
6.46	599.5	4.38	1.42	631.74	35.2	12.20	25.59
5.96	600.0	4.48	1.39	632.37	36.0	11.20	23.21
5.00	600.5	3.36	1.26	631.88	27.0	9.26	22.17
3.95	602.0	2.03	1.47	631.84	16.3	6.85	21.11
3.02	602.5	1.12	1.49	631.41	9.0	4.95	20.55
1.98	604.0	0.65	1.37	632.56	5.2	2.85	15.54
0.96	605.0	0.35	1.34	633.29	2.8	1.00	7.423
4.00	602.0	1.97	1.60	631.65	15.8	6.50	20.36
7.05	599.0	5.64	1.63	632.29	45.3	12.65	23.37
9.03	592.0	7.34	1.65	626.97	59.0	15.90	25.96
10.05	590.0	8.77	1.72	626.33	70.5	17.05	25.49

Method #2 - Differential Pressure Tap

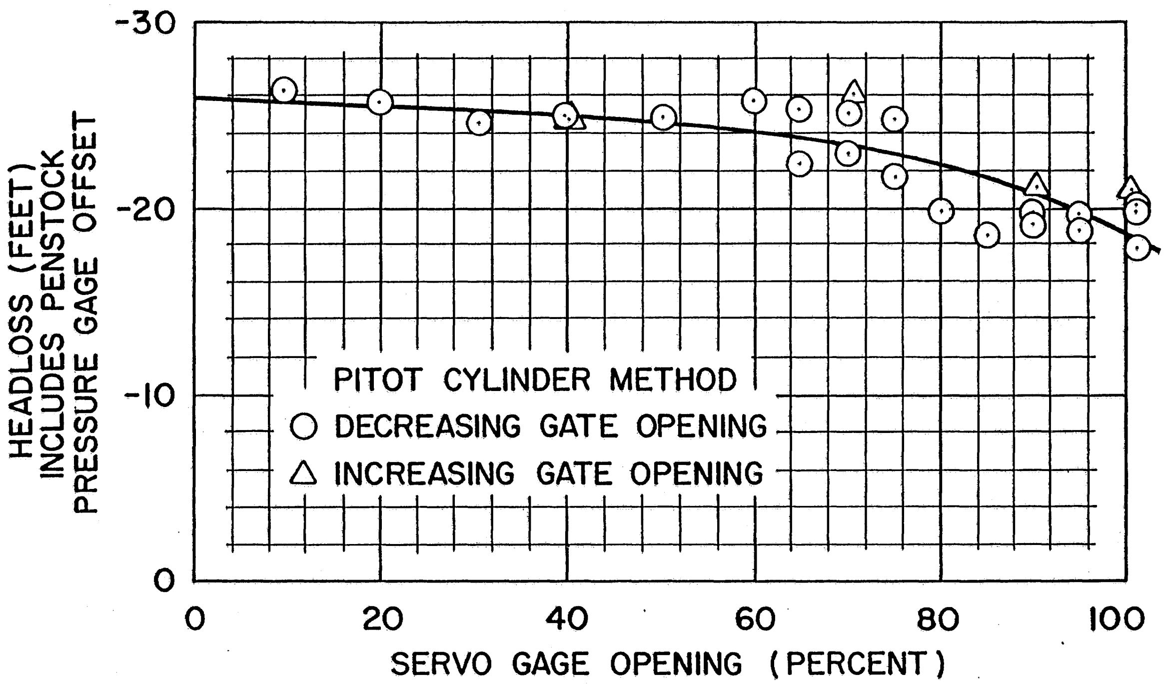
Servo G.O.	Penstock Pressure Head -2009.28 (ft)	Estimated Entrance Velocity Head (ft)	TWE -1980.0 (ft)	H (ft)	ΔP (0.1 volts)	MW	$\frac{kW}{H\sqrt{\Delta P/K_1}}$
10.05	590	9.93	1.68	627.53	32.0	17.10	15.40
9.50	590	9.43	1.68	627.03	30.4	16.8	15.53
9.01	591	8.53	1.67	627.14	27.5	16.25	15.80
8.50	593	6.67	1.66	627.29	21.5	15.55	17.09
8.00	597	5.49	1.60	630.17	17.7	14.45	17.42
7.51	597	5.27	1.52	630.03	17.0	14.15	17.41
7.00	598	4.53	1.48	630.33	14.6	13.40	17.79
6.50	599.5	4.06	1.40	631.44	13.1	12.3	17.20
6.00	600	4.28	1.35	632.21	13.8	11.25	15.31
5.00	600	2.98	1.25	631.01	9.6	4.0	14.72
4.03	601	2.08	1.25	631.11	6.7	6.95	13.60
3.09	603	1.24	1.20	632.32	4.0	5.0	12.64
2.04	606	0.62	1.15	634.75	2.0	2.95	10.50
4.04	601	1.99	1.35	630.92	6.4	6.65	13.32
6.02	600	4.00	1.40	631.88	12.9	10.55	14.86
8.02	596	5.96	1.20	630.04	19.2	14.45	16.73
10.05	589	9.31	1.65	625.94	30.0	17.10	15.95

Variation Between Methods

MW	METHOD #1	METHOD #2	METHOD #1 / METHOD #2
3	2.0	3.27	.612
4	2.36	3.68	.641
5	2.56	3.92	.653
6	2.61	4.07	.641
7	2.67	4.26	.627
8	2.72	4.47	.608
9	2.80	4.56	.614

APPENDIX D

RATING TABLE: ROUGE RIVER, PROSPECT, OREGON



-30
-20
-10
0
HEADLOSS (FEET) INCLUDES PENSTOCK PRESSURE GAGE OFFSET
PITOT CYLINDER METHOD
DECREASING GATE OPENING
INCREASING GATE OPENING
0
20
40
60
80
100
SERVO GAGE OPENING (PERCENT)

Figure 1

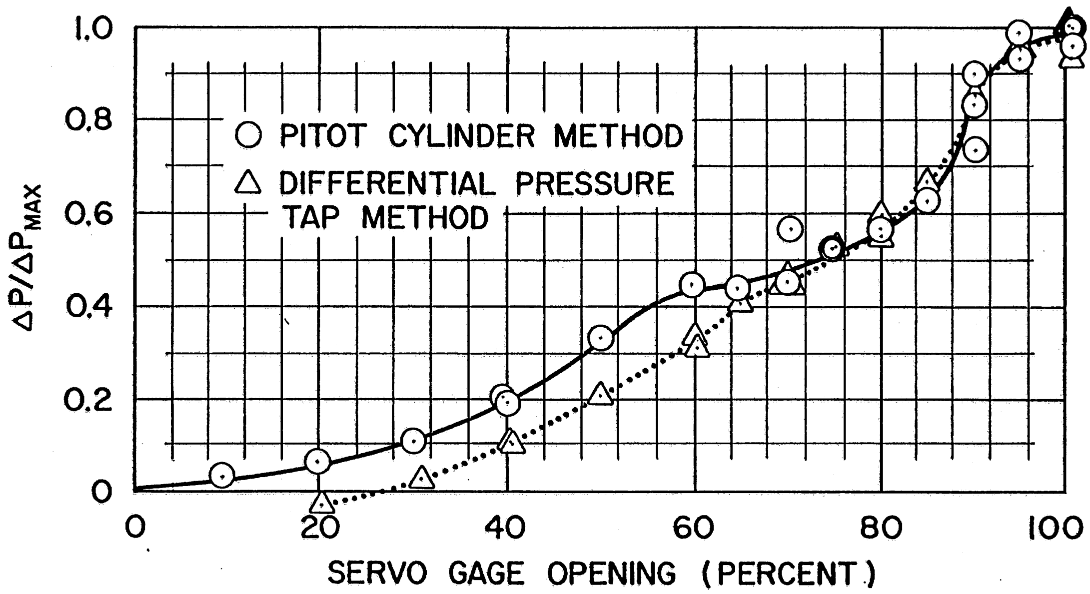

1.0
0.8
0.6
0.4
0.2
0
$\Delta P/\Delta P_{MAX}$
○ PITOT CYLINDER METHOD
△ DIFFERENTIAL PRESSURE TAP METHOD
0
20
40
60
80
100
SERVO GAGE OPENING (PERCENT)

Figure 2

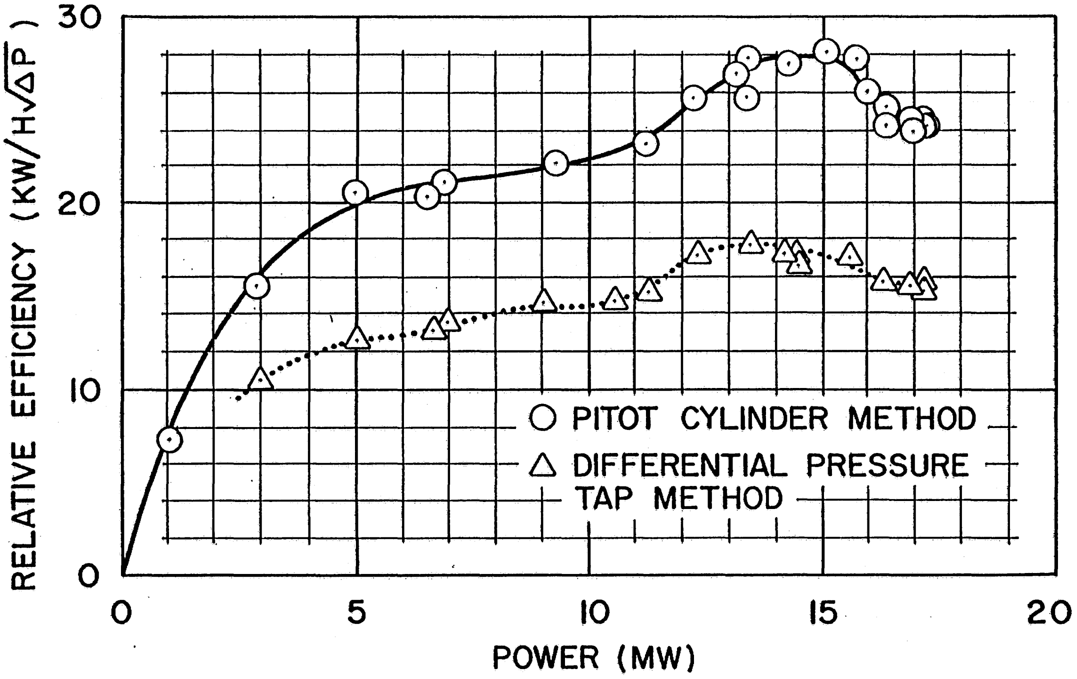

RELATIVE EFFICIENCY (KW/H√ΔP)
30
20
10
0
0
5
10
15
20
POWER (MW)
○ PITOT CYLINDER METHOD
△ DIFFERENTIAL PRESSURE TAP METHOD

Figure 3

ACKNOWLEDGEMENTS

I would like to thank all those involved with the project for their assistance. In particular, I want to thank Messr's. W. Colwill, T. O'Conner, and R. Landolt, as well as the many Pacific Power Operation and Maintenance personnel who assisted with equipment installation and the testing program.