Measuring the Effect of Fish Diversion Screens On Turbine Efficiency with the Acoustic Scintillation Flow Meter At Unit 5, McNary Dam

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Abstract

Turbine efficiency measurements were carried out at Unit 5, McNary Dam on the Columbia River in January, 1998. Measurements were made for three different cam curves and one off-cam setting, both with and without ESBS fish screens in place. The cam curves were derived from a previous set of index tests carried out in 1993, and from two different hydraulic modelling techniques of the unit. In each case, power, head and discharge were measured at a series of wicket gate settings. Relative discharge measurement data were collected using Winter-Kennedy taps; absolute discharges were measured with the ASFM. Turbine performance curves were then computed for each case, and the measured performance was compared to that predicted by the modelling techniques and the 1993 index test. The effect of the ESBS screens on the turbine efficiency was calculated; an efficiency loss of 2 to 3% was found over the operating range when the screens were in place. The ASFM is a new instrument, which offers some unique advantages for measuring discharge in low head plants. The principles of each discharge measurement method are briefly reviewed. Factors affecting the accuracy and precision of the ASFM discharge measurement are discussed, and an assessment of the advantages obtainable by using the absolute discharge measured by the ASFM over the relative value provided by the Winter-Kennedy method under these conditions is made.

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Introduction

The Corps of Engineers is currently engaged in a program of improving fish passage through Kaplan turbines, as part of an ongoing upgrading of its facilities on the Columbia and Snake Rivers. The Corps turbine development program is aimed at developing an understanding of areas within an operating turbine environment which may contribute to physical injury of fish, developing design changes to those areas to minimize physical injury and improving turbine performance which has been degraded by the presence of fish screens or other diversion devices. Collecting efficiency information for existing turbines is an important part of the program. A series of measurements were made in Unit 5 at McNary Dam, Umatilla Co., Oregon in January, 1998 for that purpose. The measurements were made to evaluate a series of turbine operating curves and to assess the effect of fish diversion screens on turbine operation, using field-measured data. The predicted operating curves were obtained from previous index testing and from two different turbine modelling techniques. At the plant, power output, head and discharge were measured over a range of operating conditions. Relative discharge through the turbine was obtained from Winter-Kennedy taps and absolute discharge was measured using the Acoustic Scintillation Flow Meter (ASFM).

Plant Configuration

McNary Dam is located at river mile 292 on the Columbia River. The primary purposes of the project are inland navigation and hydroelectric power generation. The powerhouse contains 14 Kaplan turbine/generator sets. Generator nameplate ratings are 70 MW each and can be operated continuously at 115 percent of rated capacity with a maximum power output of 80.5 MW. Each of the Kaplan turbines (5 blade, 280-inch diameter runner, 85.7 RPM) develops 111,300 hp at a design head of 80-feet. The turbines were manufactured by S. Morgan Smith company in the 1950's and have operated satisfactorily since installation.

An individual turbine intake consists of three 20-feet wide bays. Each bay contains slot openings for an operating head gate (emergency closure) and an upstream slot for bulkheads (see Figure 2). To protect downstream migrating juvenile salmonids, fish diversion screens are installed in the bulkhead slot. The screens divert juvenile fish and water up the bulkhead slot where the juvenile fish can enter a system designed to bypass the fish safely to the tailrace of the dam. The screens are installed in the intakes of the turbine units from March 15 through December 15 each year.

Desirable near uniform flows into a turbine intake are disrupted when fish diversion screens are installed. The diversion screens create large scale eddies within the intake resulting in decreased turbine performance. Decreased turbine performance results in less power production and may also create a more harmful environment to some of the juvenile fish which are not intercepted by diversion screens and pass through the operating units.

Derivation of Operating Cam Curves

The cam curves field-tested were derived from three sources: a 1993 Index Test, a low head performance model test and a high head performance model test (VAMCE, 1997). The development of the "On Cam" wicket gate and blade positions are derived from the "off cam" fixed blade angle performance curves measured in each of the techniques used (USACE, 1998). The performance model is a 1:25 scale model of the same prototype turbine field tested in 1993 and 1998 (USACE, 1993; 1998). The initial technique was performance model tested under 1:25 scale water surface conditions (i.e. 75.0 feet of prototype gross head is equivalent to 3.0 feet of model gross head) which has been termed as a Froude condition (which it really is not). The second model technique is the industry standard according to IEC 193 and its addenda. Both of the model tests were performed at the same wicket gate positions and same runner blade angles. The model tests performed a duplication of the field tests and full operating head range performance tests for three conditions: without Fish Screens, with Submerged Travelling Fish Screens and with Extended Submerged Bar Screens (ESBS). The field and model measurements described herein only address turbine operation without fish screens and with ESBS screens installed. The required brevity of this paper permits only presentation of summary information. The following figure presents a comparison of the derived "on cam" curves with no screens installed for each technique.

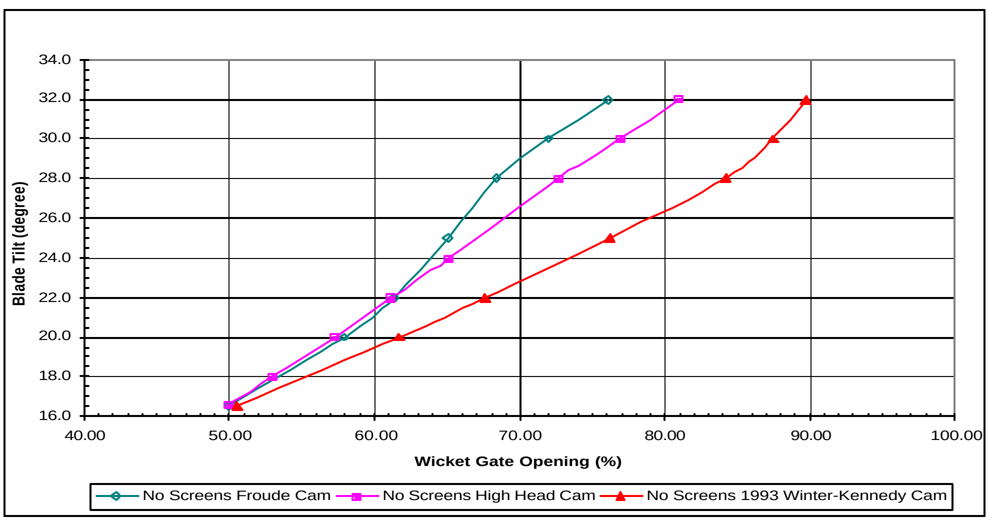

Figure 1: No screens predicted cam curve comparison.

ASFM Installation and Operating Principles

The ASFM's ability to measure absolute discharge under the conditions prevailing in low-head plants was the reason for its use in the Unit 5 tests at McNary Dam. The ASFM uses a technique called acoustic scintillation drift (Farmer & Clifford, 1986) to measure the flow speed of water perpendicular to a number of acoustic paths established across the intake to the turbine. Fluctuations in the acoustic signals transmitted along a path result from turbulence in the water carried along by the current. The ASFM measures those fluctuations (known as scintillations) and from them computes the lateral average (i.e. along the acoustic path) of the flow perpendicular to each path. Both the magnitude and inclination of the flow speed are measured. The ASFM computes the discharge through each bay of the intake by integrating the horizontal component of the flow speed over the height of the intake. The discharges from each bay are then summed for the total discharge. Since 1992, the ASFM has been used in several hydro-electric plants and in some instances compared with other discharge methods such as current meters (Lemon, 1995, Lemon, Caron, Cartier & Proulx, 1998; Lemon et al, 1998).

The ASFM was scheduled for installation in the head gate slots of Unit 5. Unit 5 has three intake bays, each of which was to be equipped with 10 acoustic paths. The transducers were installed on three support frames, one for each bay. The transducer support frames were designed and supplied by the Walla Walla District. Figure 2 shows the location of the measurement plane in the intake and its relationship to the ESBS screen (when installed), and the definition of the quantities measured.

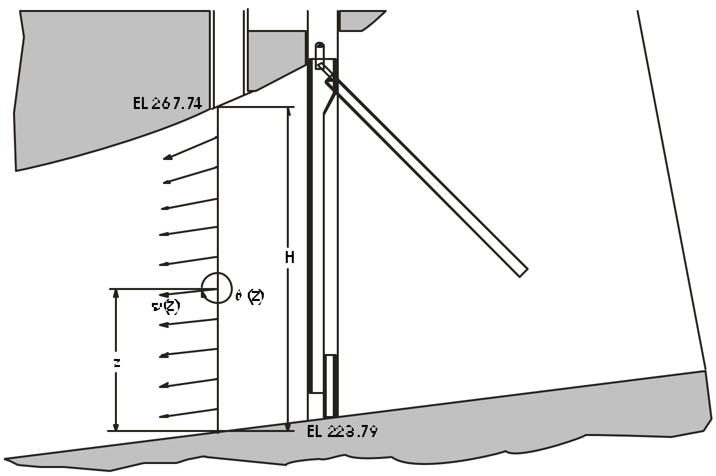

Figure 2: Location of the measurement plane in the intake, and definition of associated parameters.

Data Collection

Two sets of measurements were scheduled to be made, one without the ESBS fish screens and one with the ESBS fish screens. In each case, three cam curves were to be tested and one set of off-cam measurements was to be made. The three cam curves will be referred to as the 1993 Cam, the Froude Cam and the High-head Cam. Two different versions of each exist: one for use without fish screens and one for use with the fish screens in place.

Index Test Measurements Made

The index test procedure generally followed the salient portions of the ASME PCT-18 and IEC 41 test codes. The following measurements were made during the testing: Upper and Lower water surface elevations, Winter-Kennedy differential pressure and independent leg Winter-Kennedy tap pressures, scintillation flows, generator output, wicket gate angle and servomotor stroke, and runner blade angle. Repeatable wicket gate positions were obtained by use of servomotor blocks. The existing electronic control unit (ECU) adjusted the runner blade angle to the stored "on cam" data table for the selected test condition. Test data was also collected from the electronic control unit (ECU), control room, regular manual check measurements made and zero checks made at the beginning and end of each days testing. Electronically measured data was available in real time with corresponding graphical information instantly available for examination during the testing. The preliminary scintillation flow measurements were manually input into the data set prior to changing to another wicket gate setting, a procedure which could easily be automated in future.

Velocity and Discharge Results: ASFM

Typical intake velocity distributions as measured by the ASFM are shown in Figure 3, without ESBS screens and with the screens in place.

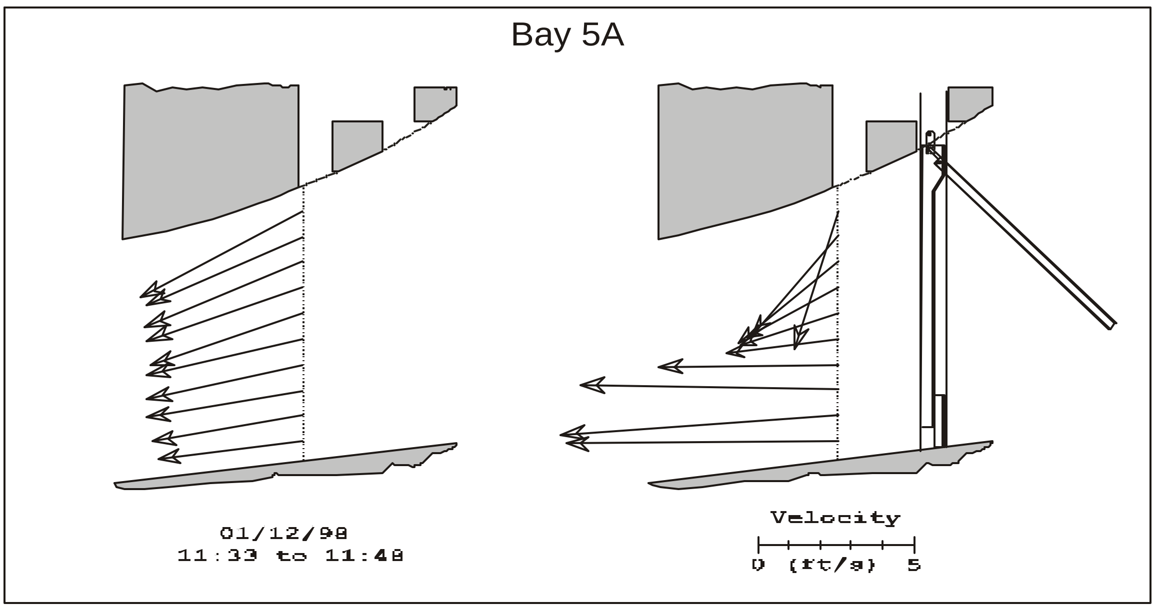

Figure 3: Flow vectors measured in the intake, without ESBS screens (left) and with screens (right).

The screens cause an increase in the current speed in the lower part of the intake, and a strong descending component in the upper part of the intake, which includes a significant flow down the gate slot. The roof and floor of the intake tunnel, and the path followed by the sides of the frame holding the ASFM transducers define a plane surface through which the flow into the intake bay must pass.

The discharge, Q, in terms of the laterally averaged velocity $\boldsymbol{v}$ is:

$$Q = \int_0^H v(z)\cos[q\,(z)]\,L\,dz \qquad (1)$$

where $v(z)$ is the magnitude of the laterally averaged flow at elevation z, $q(z)$ is the corresponding inclination angle, L is the width between the transducer faces and H is the height of the tunnel roof above the floor. The lateral averaging performed by the ASFM is continuous, while the sampling in the vertical was at ten discrete points. Calculating Q then requires estimation of the integral in equation 1 when the integrand is known at a finite number of points. The integral was evaluated numerically using an adaptive Romberg integration, with a cubic spline interpolation in the integrand between the measured points. The measured points do not extend all the way to the tunnel roof and floor; as a result, complete evaluation of the integral requires an evaluation of the flow in the zones next to those boundaries.

The boundary flow at the floor is affected by the presence of the support frame's lower cross-bar, a pipe 0.32 m in diameter, centred 0.37 m above the tunnel floor and 0.49 m upstream of the measurement plane. The lowest ASFM measurement level was 0.93 m above the tunnel floor, so the effect of the cross-pipe had to be taken into consideration in evaluating the flow in the lower boundary. Measurements were made in the existing 1/25 scale physical model of Unit 5 at the USACE Waterways Experiment Station both for the lower boundary zone and for the upper boundary zone at the top of the tunnel. A numerical simulation of the flow around the lower cross-pipe was also performed, using the computational fluid dynamics code CFX TASCflow. The simulation was done because it became apparent that the Reynolds number of the flow around the pipe in the intake (between 250,000 and 900,000) was sufficiently high that the 1/25 scale physical model would not properly represent the wake separation behind the pipe. The results of the numerical simulation showed much better agreement with the data from Unit 5 in the region above the cross-pipe and therefore were used in determining the form of the lower boundary layer approximation. The computations done using different inlet velocities showed that the form of the profile of the horizontal velocity between the floor and the top of the zone influenced by the cross-pipe is invariant over the range of speeds normally found in the intake. A simplified profile of the form $[z/z_0]^{1/7}$ having the same discharge when integrated between the floor and the top of the boundary zone was therefore used.

The treatment at the open upper boundary depends on the presence or absence of the ESBS screens. As may be seen from Figure 3, the presence of the screens causes a strong vertical flow down the gate slot. Figure 2 shows the position of the measurement plane in the intake, in which it can be seen that the measurement plane is slightly upstream of the downstream edge of the gate slot, a distance of 24 cm. The surface of integration cannot be closed without the addition of this area through which water descending the gate slot can travel to the turbine without passing through the primary measurement plane. Since the ASFM measures both components of the laterally averaged velocity, the magnitude of the descending flow can be estimated from the measurement at the uppermost level. Examination of the model measurements in the gate slot showed that even with no screens in place, some descending flow was still present in the gate slot and bypassing the main measurement plane. Computation of the discharge through the gap, Q_G, is therefore required in both cases. The model data were used to evaluate Q_G and then in each case to derive a formula for it in terms of the measurements made at the uppermost measurement level:

Screens in: $Q_G = 1.06 \cdot L \cdot v_{10} \cdot sin(q_{10}) \cdot w_B$

Screens out: $Q_G = 0.4 \cdot L \cdot v_{10} \cdot sin(q_{10}) \cdot w_B$

where L is the width of the intake and w_B is the width of the gap.

The strong descending flow from the gate slot when the ESBS screens are in place also causes mixing and alters the shape of the upper boundary layer. Using the model results as a guide, with no screens in place, V_h was forced to zero at the roof elevation, z_R, along a curve of the form $[(z_R-z)/0.70]^{1/4}$ from an elevation 0.70 meters below the roof, after an extrapolation from the uppermost measured point. With the screens in place, V_h was forced to zero at the roof elevation, z_R, along the curve $[(z_R-z)/1.20]^{2/3}$ from 1.20 meters below the roof, again after an extrapolation from the uppermost measured point.

The total discharge through Unit 5 was then computed for flow condition using the boundary layer forms described above. A measure of the random error present in the resulting discharges may be computed from nine repeat measurements made during the tests. After correction for head changes, the average difference in total discharge between repeat runs was 0.38%. The maximum observed difference was 1.07% and three of the differences were less than 0.1%.

Power and Relative Discharge (Winter-Kennedy) and ASFM Discharge Results

Winter-Kennedy differential pressure measurements were made simultaneously with the scintillation measurements. A standard method for establishing a scalar multiplier to be applied to the square root of the differential pressure measurement was used, Q = K * (D)^1/2. However, for a particular condition the optimum efficiency point was determined using the head adjusted Winter-Kennedy and scintillation flow measurements. The scintillation flow for that optimum point was then used in the above equation along with the appropriate Winter-Kennedy differential pressure to compute the scalar multiplier K. The following Figure 6 shows the comparison of the head-adjusted flows from the scintillation measurements and those computed from the Winter-Kennedy differential pressure measurements. It shows a comparison of the without screen condition and ESBS condition measurements for the Froude model test predicted cam curves.

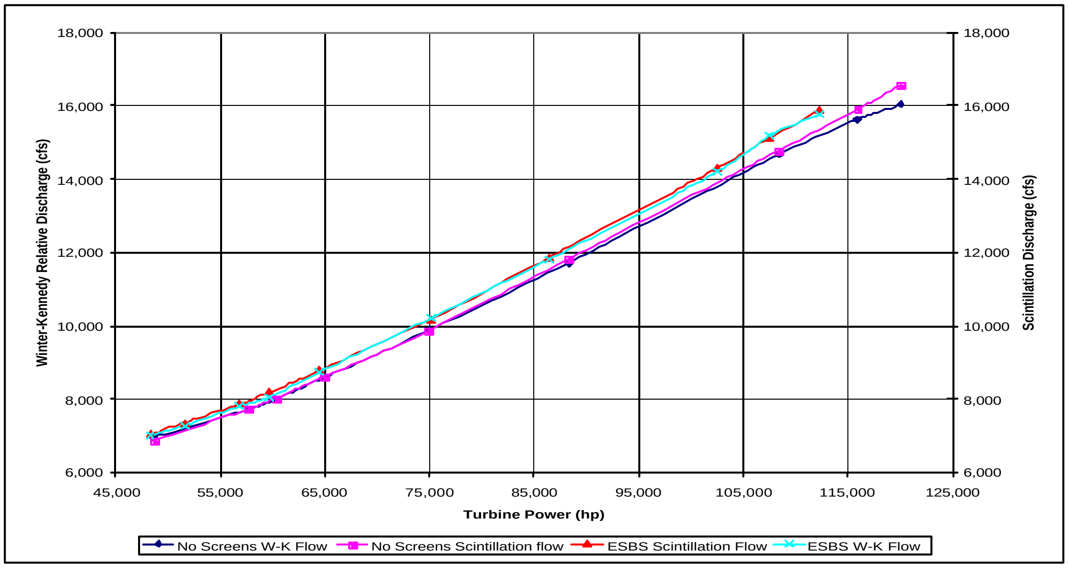

Figure 5: Comparison of ASFM flow measurements to Winter-Kennedy Differential Pressure Relative Flow Measurements Without Fish Screens and with ESBS Screens Installed.

Performance Comparison

The Froude model performance predicted at the common gross head of 75.0 feet and the field measured performance using the scintillation flows are compared for the with and without screen conditions. Figure 6 shows the no screens case.

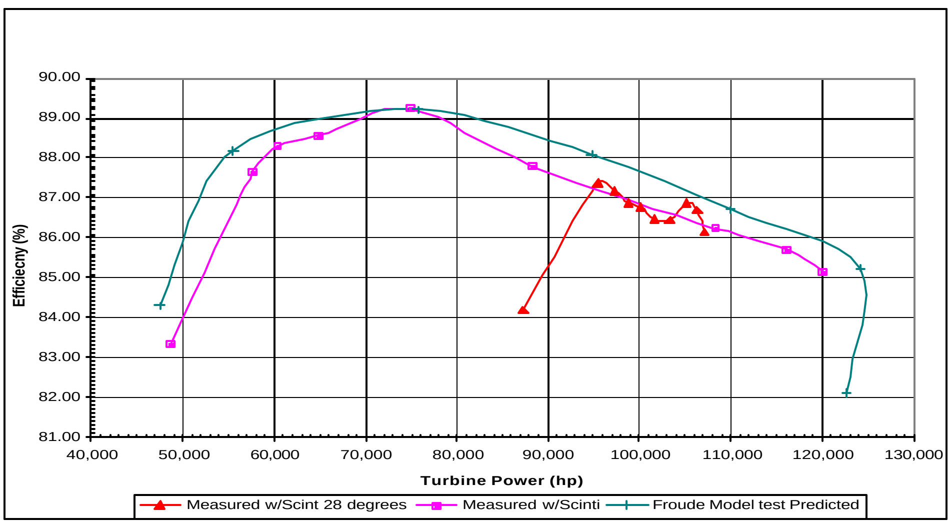

Figure 6: Froude Model Predicted Prototype Performance With No Screens Installed Compared to Field Measured Performance Using Scintillation Flow Measurements.

It should be noted that all model test predictions use model test measured efficiency with no efficiency step-up. Also shown for comparison are the field measurements for a fixed runner blade angle of 28 degrees to identify an "on cam" point from an "off cam" curve. Figure 7 shows the ESBS screens comparison of model predicted to field measured. Again shown for comparison are the field measurements for a fixed runner blade angle of 28 degrees to identify an "on cam" point from an "off cam" curve.

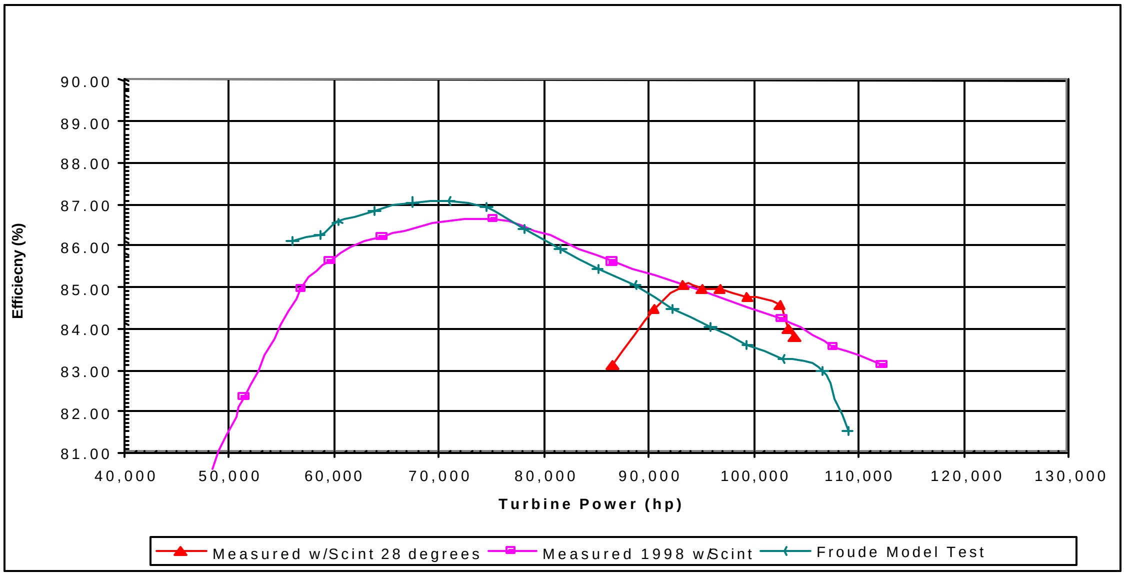

Figure 7: Froude Model Predicted Prototype Performance With ESBS Screens Compared to Field Measured Performance Using Scintillation Flow Measurements.

Conclusions

The presence of the ESBS diversion screens in the intake cause a loss of 2% to 3% in turbine operating efficiency in the normal operating range. Their presence also decreased full load power production by 6%. The field measurements indicate that using a model efficiency step-up over-predicts prototype efficiency, and that field testing provides better accuracy than model testing in the development of blade-gate relationships for Kaplan turbines. The ASFM appears to provide a reasonable measurement of the actual flow quantity and hence of absolute efficiency, and is an effective method for determining the effects of intake modifications on turbine performance. Comparison tests with current meters (Lemon, Caron, Cartier & Proulx, 1998; Lemon et al, 1998) have shown agreement in measured discharge to within 1.5% or better. However additional work is necessary to identify and fully quantify boundary layer effects and the overall accuracy of the method.

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