FINAL REPORT – PILOT SCALE TESTS
ALDEN/CONCEPTS NREC TURBINE

U.S. DEPARTMENT OF ENERGY
ADVANCED HYDROPOWER TURBINE SYSTEMS PROGRAM

Contract No. DE-AC07-99ID13733

by

Thomas C. Cook, P.E.
George E. Hecker, P.E.
Stephen V. Amaral
Philip S. Stacy
Fangbiao Lin
Edward P. Taft

Sponsored by
U.S. DEPARTMENT OF ENERGY

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ALDEN RESEARCH LABORATORY, INC.
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EXECUTIVE SUMMARY

Alden Research Laboratory, Inc. (Alden) has completed pilot scale testing of the new Alden/Concepts NREC turbine that was designed to minimize fish injury at hydropower projects. The test program was part of the U.S. Department of Energy's (DOE) Advanced Hydropower Turbine Systems Program. The prototype turbine operating point was 1,000 cfs at 80 ft head and 100 rpm. The turbine was designed to: 1) limit peripheral runner speed; 2) have a high minimum pressure; 3) limit pressure change rates; 4) limit the maximum flow shear; 5) minimize the number and total length of leading blade edges; 6) maximize the distance between the runner inlet and the wicket gates and minimize clearances (i.e., gaps) between other components; and, 7) maximize the size of flow passages.

Based on two dimensional and three dimensional computational fluid dynamics (CFD) analyses, a new runner geometry was developed with three helical blades attached to a central hub and a shroud attached to the outside edges of the blades, thereby eliminating all gaps. Flow approaches the runner from a conventional scroll case, passes through a "radial" (horizontal) space containing few but relatively long wicket gates, and then into a gradual downturn that leads to the runner entrance.

A pilot scale facility was designed and constructed to test a 1:3.25 reduced scale turbine with and without wicket gates. The test loop was operated at flows ranging between 50-95 cfs and 35-85 ft heads and the pilot scale turbine was operated at speeds ranging between 200-375 rpm to determine the Best Efficiency Point (BEP) over the range of wicket gate positions. Engineering tests were conducted to define the turbine BEP speed and head/flow combinations without and with wicket gates. Biological testing was conducted to evaluate turbine passage survival relative to: 1) fish injection location at the turbine inlet, 2) size of fish, 3) species, 4) high and low turbine speed/head/flow conditions, 5) BEP with and without wicket gates, and 6) off-BEP wicket gate positions. A final CFD analysis was completed as part of the pilot scale study to investigate the turbine flow patterns at off-BEP wicket gate positions for comparison to the flow patterns at the BEP gate position and observed fish injury at the different gate settings. Final engineering tests to define the turbine operating characteristics completed the pilot scale test program.

BEP Testing Without Wicket Gates

Preliminary engineering tests indicated that the original CFD analysis predicted the turbine BEP reasonably well. The measured BEP without wicket gates was about 86% with about 93 cfs at 80 ft turbine head and 345 rpm for the high head condition, and about 85.4% with about 64 cfs at

38 ft turbine head and 240 rpm for the low head condition. The original CFD design predicted the full-scale prototype turbine BEP to be 89% at 325 rpm with 95 cfs at 80 ft turbine head.

Preliminary tests with rainbow trout (75-150 mm long) verified the acceptability of the test methods and procedures selected for the estimation and evaluation of turbine survival. Control survival during these preliminary tests was 100%, indicating that handling and holding procedures were optimum for minimizing fish injury and stress associated with testing. Testing with rainbow trout (92-131 mm long) demonstrated that treatment fish release depth in the test loop pipe upstream of the turbine inlet did not affect fish survival rates. There was no statistical difference among the survival rates for the three release locations, which ranged from 92.1% to 92.9% for immediate survival (one hour survival) and 90.3% to 91.0% for total survival (immediate survival plus 96 hour delayed survival). Therefore, fish injection for all subsequent tests was at one (mid-depth) position.

Tests with two sizes of rainbow trout indicated that survival rates through the turbine without wicket gates were related to fish size and operating conditions, as shown in the table below. Smaller fish had significantly higher survival rates than larger fish at both head conditions. Both size fish had higher survival rates at the lower rotation speed/head condition than at the higher rotation speed/head condition, but these differences were not statistically significant.

RAINBOW TROUT TESTS AT BEP WITHOUT WICKET GATES

Operating Condition (Speed/Head)	Average Fish Length	Immediate Survival (1 hr)	Total Survival (1 hr plus 96 hr)
240 rpm/38 ft	94 mm	94.8%	92.7%
240 rpm/38 ft	174 mm	89.1%	88.4%
345 rpm/80 ft	93 mm	92.5%	91.0%
345 rpm/80 ft	173 mm	84.2%	83.3%

BEP Testing With Wicket Gates Installed

Preliminary engineering tests with the wicket gates installed indicated that the BEP was at a wicket gate setting that was 18.2° from fully closed, about 4° more closed than the original CFD-predicted BEP gate position of 22°. Test loop pump operation and turbine vibrations limited testing to gate positions ranging between 16° and 26° from fully closed. At the 18.2° gate position, a low and high head condition was selected for biological testing. The low head condition was 240 rpm with 60.6 cfs at 40 ft turbine head and the high head condition was 345 rpm with 84.1 cfs at 80 ft turbine head. The measured efficiency for the pilot scale turbine was about 85.5% at the 240 rpm/40 ft head BEP condition and 86.5% at the 345 rpm/80 ft head BEP condition.

Results of rainbow trout tests with the 18.2° BEP gate position showed statistically similar survival rates to the tests without wicket gates. These results indicate that the wicket gates do not contribute to turbine passage mortality. Tests with three sizes of rainbow trout confirmed that survival rates were related to fish size and the turbine rotation speed/head condition. A summary of the rainbow trout test results with wicket gates is presented in the following table.

RAINBOW TROUT TESTS AT BEP WITH WICKET GATES

Operating Condition (Speed/Head)	Average Fish Length	Immediate Survival (1 hr)	Total Survival (1 hr plus 96 hr)
240 rpm/40 ft	38 mm	97.6%	96.2%
240 rpm/40 ft	85 mm	96.5%	95.5%
240 rpm/40 ft	170 mm	90.4%	90.4%
345 rpm/80 ft	38 mm	96.0%	96.0%
345 rpm/80 ft	85 mm	93.3%	92.2%
345 rpm/80 ft	175 mm	82.0%	80.7%

BEP Testing With Other Species

Tests with two sizes of smallmouth bass also documented that smaller smallmouth bass had significantly greater survival rates than larger smallmouth bass at the lower rotational speed/head BEP test condition (240 rpm/40 ft). Smallmouth bass survival rates were consistent with the rainbow trout survival rates for the similar size groups of each species.

American eel of two size groups had immediate survival rates of 100% and total survival rates greater than 98% with the turbine operating at the BEP wicket gate position and 240 rpm/40 ft head. The high survival for both size groups demonstrates that eel survival was not a function of size within the range of lengths tested.

Tests with the pilot scale turbine operation at the 240 rpm/40 ft head BEP condition with alewife and coho salmon resulted in survival rates for these species that generally were similar to rainbow trout of comparable size. However, white sturgeon survival rates were significantly higher than coho salmon and alewife survival rates. A summary of the test results for species other than rainbow trout is presented in the following table.

SMALLMOUTH BASS, AMERICAN EEL, WHITE STURGEON, ALEWIFE, AND COHO SALMON TESTS AT BEP WICKET GATE AND 240 RPM/40 FT HEAD

Species	Average Fish Length	Immediate Survival (1 hr)	Total Survival (1 hr plus 96 hr)
Smallmouth bass	69 mm	98.2%	97.4%
Smallmouth bass	155 mm	92.6%	89.5%
American eel	249 mm	100.0%	99.6%
American eel	431 mm	100.0%	98.3%
White sturgeon	103 mm	98.3%	97.0%
Alewife	87 mm	95.4%	93.7%
Coho salmon	102 mm	95.4%	93.1%

Significantly higher survival rates for white sturgeon and American eel compared to the other species that were tested demonstrate that species may be an important factor affecting passage survival rates, depending on species-specific physical characteristics and behaviors.

Off-BEP Testing

Testing of rainbow trout with the turbine operating at five off-BEP gate positions resulted in fish survival rates at all gate positions similar to survival rates at the BEP gate position. There was no statistical difference among the survival rates estimated for the five off-BEP wicket gate positions and the BEP gate position. A summary of the off-BEP biological test results is presented in the following table.

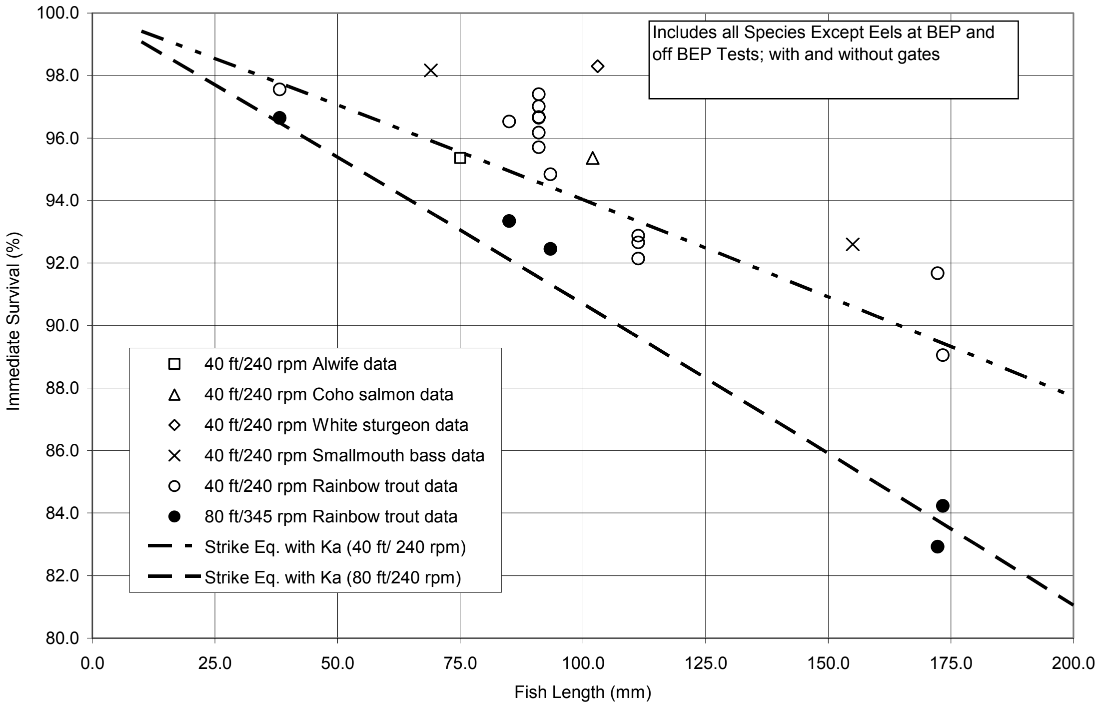
OFF-BEP TESTS WITH RAINBOW TROUT

Wicket Gate Angle from Fully Closed	Operating Condition (Speed/Head)	Average Fish Length	Immediate Survival (1 hr)	Total Survival (1 hr plus 96 hrs)
18.2° (BEP)	240 rpm/40 ft	91 mm	96.4%	94.0%
16°	240 rpm/38 ft	91 mm	95.8%	94.9%
20°	240 rpm/38 ft	90 mm	97.0%	94.7%
22°	240 rpm/40 ft	92 mm	97.4%	95.5%
24°	240 rpm/38 ft	91 mm	96.8%	95.6%
26°	240 rpm/40 ft	91 mm	96.3%	95.4%

Injury Types

The most prevalent injury observed among immediate treatment mortalities for all tests was bruising, which typically occurred between the gill arch and the posterior margin of the dorsal fin. The relatively high rates of bruising observed on immediate mortalities, combined with the occurrence of lacerations and a small number of severed bodies, suggest that the primary mechanism of immediate fish mortality was physical strike with the leading edge of the runner blades. Descaling and eye injuries, which are indicative of other types of injury mechanisms (shear, pressure, gaps), were minimal, and injuries related to these types of mechanism are believed to be minor with the Alden/Concepts NREC turbine. Increasing the thickness of the leading edge was identified as a possible improvement in the runner design. The runner leading edge in the pilot scale turbine was thinner than the prototype turbine due to geometric scaling. Literature indicates that a thicker leading edge would lower strike-induced mortality.

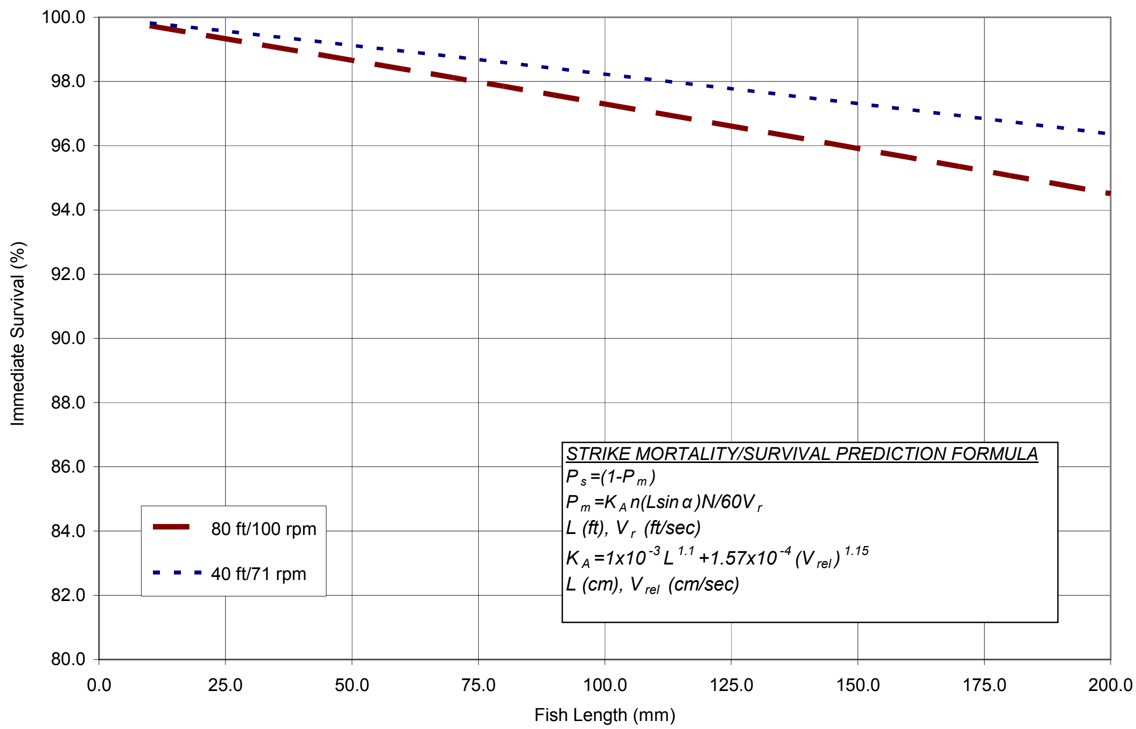
Test results for all species except American eel are shown on the following figure. Also shown, as dashed lines, are the immediate survival rates in relation to fish lengths for the 40 ft/240 rpm and 80 ft/345 rpm operating points based on a strike equation (Bell 1991) used in the hydroelectric industry and a strike mortality coefficient (K_A) derived from Alden's test data.



PILOT SCALE TURBINE FISH SURVIVAL VERSUS FISH LENGTH

Predicted Full Size Turbine Fish Survival

Fish lengths tested in the pilot scale turbine were taken to represent the same fish lengths as in the field (i.e., the fish length was not scaled). Heads and, therefore, flow velocities and blade tip speeds tested in the pilot scale turbine (4 ft diameter) were the same as they would be in the full size prototype turbine (13 ft diameter). Survival in the prototype turbine is expected to be greater than the survival measured in the pilot scale turbine because of the greater spacing of the blade leading edges in the full size turbine. The use of the same strike probability equation illustrated above for the pilot scale turbine indicates that the full scale turbine should have a total survival of about 98% or higher for fish lengths equal to or less than 75 mm at both the 80 ft/100 rpm and 38 ft/71 rpm turbine heads, as shown on the following figure. For fish lengths between 75 mm and 150 mm, the survival in the prototype turbine is expected to be about 96% or higher at 80 ft/100 rpm and about 97.5% or more at 38 ft/71 rpm.

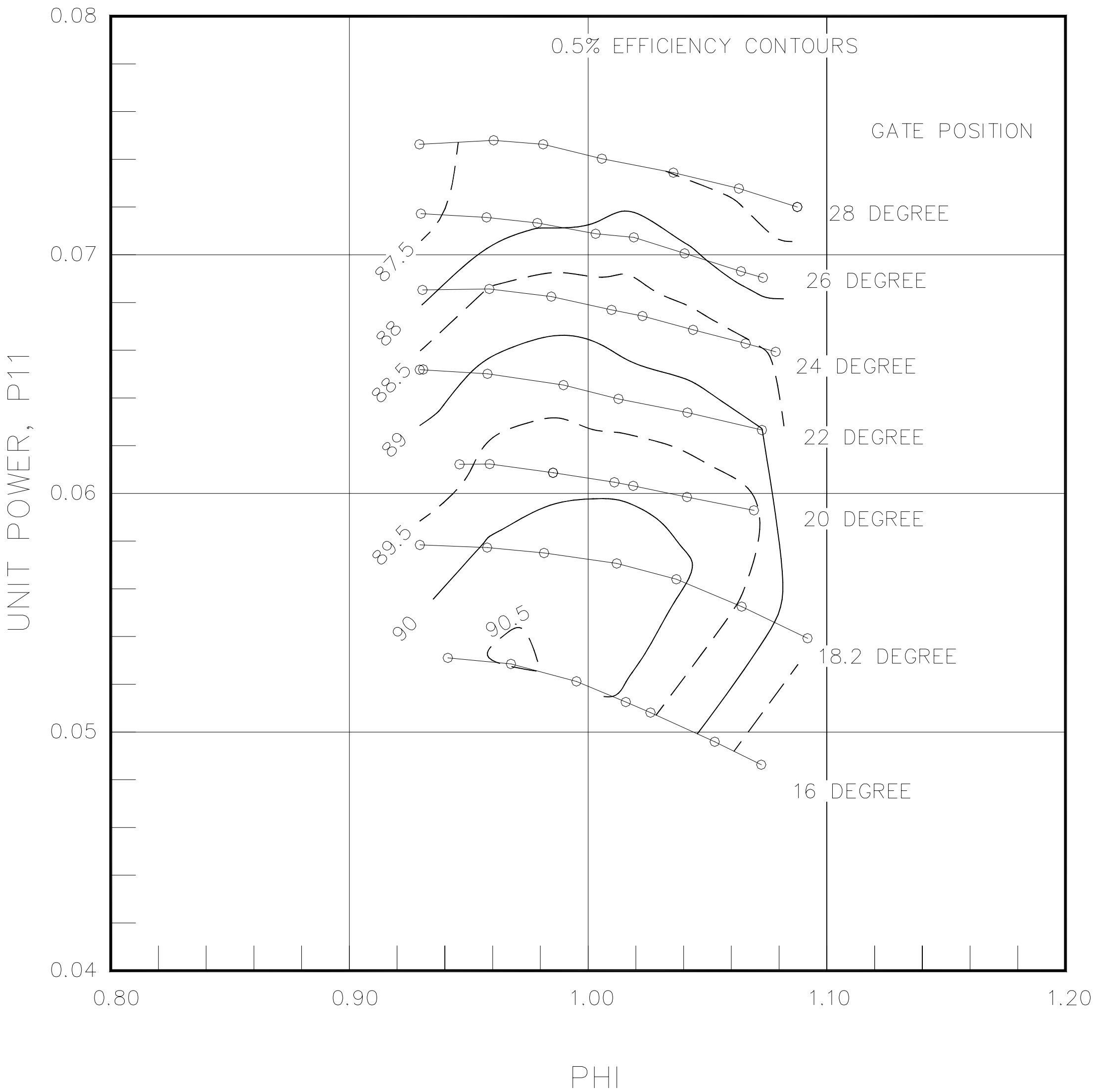


PREDICTED FULL SIZE TURBINE FISH SURVIVAL VERSUS FISH LENGTH

Prototype Turbine Power

Final engineering tests indicate that the predicted maximum efficiency of full sized turbine would be about 90.5%, as shown on the following hill chart figure. The prototype efficiency includes the normal step-up in efficiency from pilot scale to full size turbine (scale effects) and a correction for the measured excess leakage (3% of turbine flow) in the pilot scale turbine due to a worn bottom seal. A detailed analysis indicated that the uncertainty of the efficiency measurements was about 0.5% at the 95% confidence interval. Tests with and without wicket gates did not show any measurable differences in turbine efficiency. No changes in efficiency resulted from varying the pressure under the head cover, indicating the turbine bearing losses were not sensitive to down-thrust.

Measurements of the velocity distribution (axial and tangential) at the exit of the draft tube documented considerable swirl in the flow leaving the runner at the BEP. This swirl indicates that the turbine efficiency may be improved by reshaping the blades.



PROTOTYPE TURBINE HILL CHART

Final CFD analysis showed that the best predicted turbine efficiency was at the gate angle and runner rotational speed (rpm) actually measured for the BEP. The analysis also showed that a pressure reversal from the high to low pressure side occurred over a small section of the trailing blade length, indicating that improvements to the turbine efficiency may be realized by some reshaping of the blades.

The turbine unit power (p_{11}) is lower than for conventional Francis and Kaplan units at the design head due to the flow restriction resulting from the selected wicket gate height relative to the turbine diameter. A greater power density may be achieved by increasing the height of the radial space (wicket gates) and redesigning the turbine blades accordingly.

Final CFD Analysis

The CFD results for off-BEP wicket gate positions indicated that flow characteristics in the runner were similar at all of the gate settings tested with fish. The local minimum pressure in the runner over the range of tested wicket gate positions (16°-26° from full closed) was consistent with Alden's original design value (about 10 psia) and was more than the 7.4 psia recommended in the literature (Abernethy 2002). Available literature (Abernethy 2002) indicates fish survived pressure change rates of -500 psi/sec, which is a higher rate than the original Alden/Concepts NREC turbine design criteria (80 psi/sec). Areas of negative pressure change rates in excess of -500 psi/sec occurred near the leading edge of the runner blades with smaller areas near the runner blade trailing edges at all wicket gate positions analyzed (16°-26°) and tested with fish. Areas exceeding -500 psi/sec were larger at the high head/speed (80 ft/345 rpm) than the low head/speed (40 ft/240 rpm). The literature (Nietzel 2000) indicates that salmon and American shad survive strain rates greater than 500/sec, which is significantly greater than the original Alden/Concepts NREC strain zone criteria of 180/sec. High flow strain areas (strain rates greater than 500/sec) were relatively small and were limited to spots near the leading and trailing edges and the blade surfaces at all wicket gate positions analyzed and tested with fish (16°-26°).

Conclusions

The pilot scale test results indicate that the Alden/Concepts NREC turbine has the potential to pass fish at hydroelectric projects with minimal injury and mortality. The next step in the development of the Alden/Concepts NREC turbine is to redesign the turbine runner using the verified CFD model. The pilot scale measurements have documented that this model can be used to predict turbine performance and assess flow characteristics in the runner. Refinements to the design should improve the high survival rates measured in the pilot scale turbine. Increasing the thickness of the leading edge on the runner blade would further minimize fish mortality due to strike. Reshaping the leading and trailing edges of the runner blade geometry would eliminate pressure reversal and excess residual swirl and, thus, improve power efficiency. Increasing the radial height at the runner inlet would increase the power density for a given runner diameter.

Any design refinements resulting from the CFD analysis would be tested in a prototype full scale turbine test program. The prototype testing would provide data to verify fish survival and turbine efficiency predicted from the pilot scale study results. If necessary, design changes could be tested in the pilot scale test loop prior to the prototype test program.

1.0 INTRODUCTION

Alden Research Laboratory, Inc. (Alden) and Concepts NREC conducted a research program to develop a new turbine runner to reduce fish mortality at hydroelectric projects. The program was part of the Advanced Hydropower Turbine Systems Program sponsored by the U.S. Department of Energy (DOE). The conceptual design phase of the program defined a new hydro-turbine runner with a unique geometry that meets criteria that should allow safe passage of fish through the runner while achieving hydraulic power efficiency comparable to other turbines. The conceptual design phase of the new Alden/Concepts NREC turbine was presented in Alden's report entitled "Development of a More Fish Tolerant Turbine Runner, Advanced Hydropower Turbine System", dated January 1997 (Cook et al. 1997).

The second phase of Alden/Concepts NREC's research program was the detailed design of a pilot scale test facility that could be used to quantify the effect on fish passing through the runner and verify the basic hydraulic characteristics of the new turbine. The goal of this phase was to prove that the turbine could be designed and built. The detailed design of the test facility and the pilot scale turbine was presented in Alden's report entitled "Final Report, Alden/NREC Fish Friendly Turbine, DOE Advanced Hydropower Turbine System" dated August 2000 (Cook et al. 2000).

The construction phase for development of the Alden/Concepts NREC turbine was described in the Pilot Scale Test Facility Construction Report dated December 2001 (Cook 2001). The pilot scale turbine test loop was located within an existing building at Alden in Holden, Massachusetts. The test facility was a closed flow loop with a pump, fish injection system, pilot scale turbine, and fish collection system. The pilot scale turbine included a scroll case, removable wicket gates, runner, shaft dynamometer, and draft tube. The facility had auxiliary systems for holding and examining fish, controlling water quality, and for monitoring turbine performance.

The fourth phase of the turbine development program involved biological and engineering testing of the pilot scale turbine. Installation and testing of a prototype turbine at a hydroelectric site will complete the development program. This report summarizes the results of the pilot scale testing of the Alden/Concepts NREC turbine without and with wicket gates. The testing without wicket gates was conducted in the fall of 2001 and included evaluation of the turbine operating characteristics and the effectiveness of the turbine in passing rainbow trout. Testing with wicket gates was conducted in the spring and fall of 2002 and included final evaluation of turbine performance and biological evaluation of rainbow trout, smallmouth bass, coho salmon, alewife, white sturgeon, and American eels passing through the turbine.

2.0 OVERVIEW OF TEST PROGRAM

The pilot scale test facility was constructed to evaluate the effects of the Alden/Concepts NREC turbine on fish passing through the runner and to measure the hydraulic characteristics of the new turbine. To fully understand the pilot scale testing phase of the project, a summary of the program objectives and the experimental scope of work are provided in the following sub-sections.

2.1 Objectives

The main objective of the pilot scale turbine tests was to quantify the effects on fish that pass through the Alden/Concepts NREC runner. This objective was accomplished by comparing the injury and survival rates of fish released upstream of the turbine (treatment groups) with those of control fish introduced in the same way downstream of the turbine. The turbine was designed using Computational Fluid Dynamic (CFD) analysis to pass fish with minimal injury. The pilot scale turbine was fabricated and installed in a test loop which was specifically designed and constructed to test the turbine. Fish handling and collection systems were designed and constructed to minimize the potential for stress and/or injury in order to provide the most accurate assessment possible of the effects on fish passage through the turbine. Fish holding tanks and water quality control systems were installed to allow evaluation of observable injuries among treatment and control fish and to document survival over a four-day period following testing. High speed video equipment was installed to visualize and record flow and fish passage. This flow visualization was used to correlate the type of fish injury to turbine/runner features and to identify possible future improvements to the runner, if necessary. Actual runner improvements were, however, not part of the pilot scale test program described herein.

A second objective was to measure the hydraulic characteristics of the Alden/Concepts NREC turbine. Equipment was installed to measure water-to-shaft power efficiency, pressures, and velocities for comparison to Computational Fluid Dynamic (CFD) predictions and for correlation to any observed fish injury. Tests for the onset of cavitation in the runner were not possible due to facility operational constraints and were not necessary because of the high absolute pressures within the runner.

2.2 Turbine Design Criteria

Flow characteristics of the Alden/Concepts NREC turbine were compared to biological criteria which were identified as important parameters relative to safe passage of fish through turbines (Cook et al. 1997). These original criteria used to design the turbine were:

1) 40 ft/sec maximum peripheral runner speed;
2) 10 psia minimum pressure;
3) 80 psi/sec maximum pressure change;
4) 15 ft/sec/inch (180/sec) maximum shear;
5) Minimum number and total length of leading blade edges:
6) Maximum distance between runner and wicket gates, and minimum clearance between other components; and,
7) Maximum size flow passages.

Final design of the turbine resulted in a 13 ft diameter runner with three blades providing the design operating point of 1,000 cfs at 80 ft turbine head (Cook et al. 2000). This design was selected to meet all of the original criteria except for peripheral runner speed. For the 13 ft runner diameter, the peripheral runner speed was 68 ft/sec.

The pilot scale turbine was tested with fish at the prototype turbine design head (80 ft) and the corresponding peripheral runner speed for best efficiency. However, since test fish experienced more rapid changes in velocity and pressure (in space and time) in the pilot scale turbine than they would in a larger prototype installation, tests were also conducted at about 40 ft turbine head with a lower peripheral speed. Biological test results at the two heads and speeds were compared to CFD analysis of the flow characteristics at BEP and off-BEP wicket gate positions to identify potential sources of fish injury and to refine the design criteria for acceptable fish passage.

2.3 Experimental Scope

The basic logic of the test program is shown in Figure 2-1, which is a simplified representation of the complex, interactive series of events, results, and decisions that occurred during testing. The facility design, construction, and operations checkout were completed in September 2001.

Preliminary engineering and fish tests without wicket gates were completed in November 2001. The preliminary engineering and fish tests with wicket gates were completed in November 2002 with final engineering tests with wicket gates completed in January 2003.

Preliminary engineering tests ensured that fish testing was conducted at known and predictable operating points. The points of best efficiency without wicket gates were obtained for the design head and for a lower head by varying the runner rotational speed and recording the flow. The best efficiency point (BEP) was used to evaluate fish passage through the runner alone without the wicket gates, which may influence fish injury.

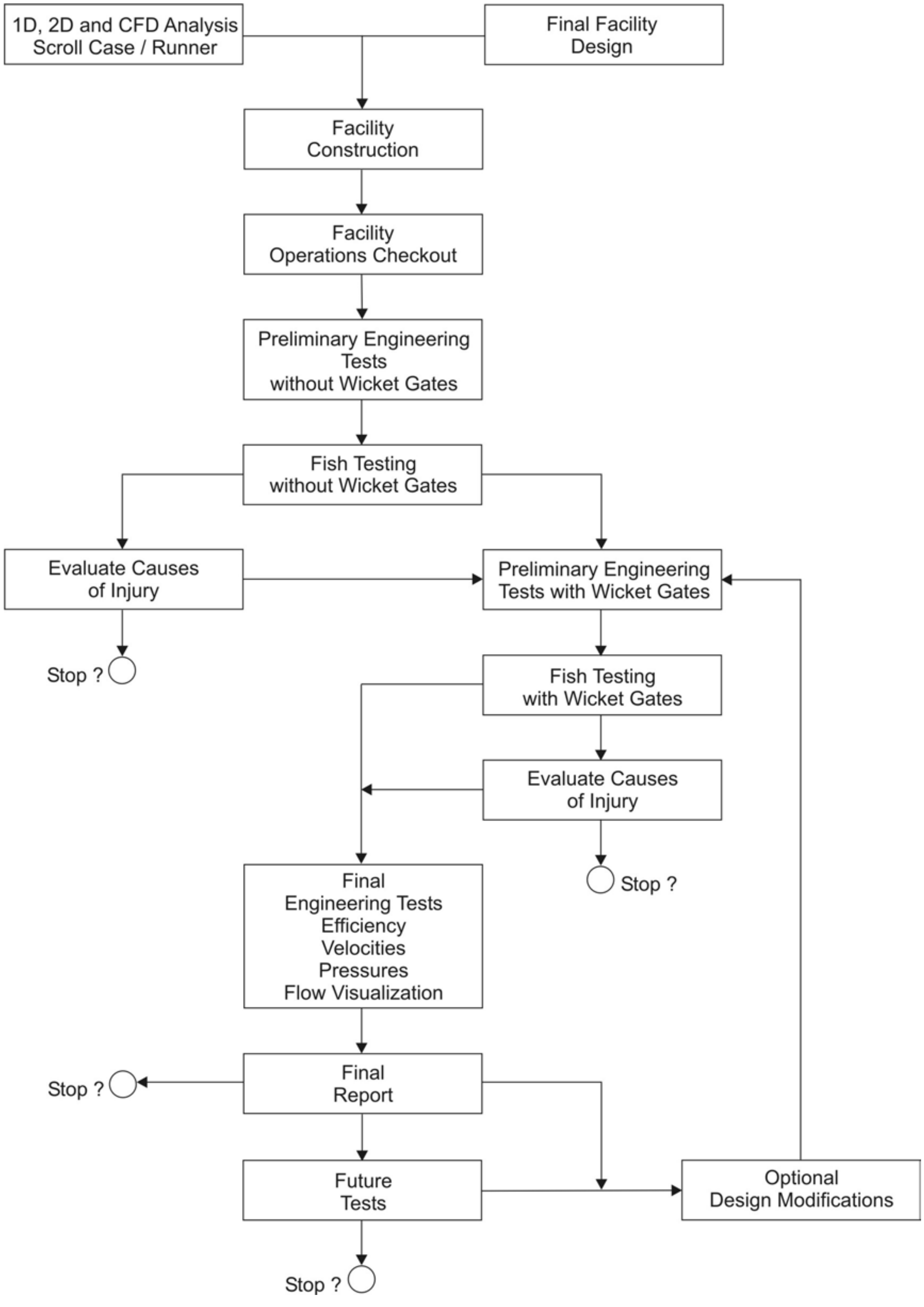


FIGURE 2-1 TEST PROGRAM LOGIC

In December 2001, the wicket gates were added to the turbine. Preliminary engineering tests were then conducted to verify the BEP, so that the subsequent fish tests in the spring and fall of 2002 could be directly compared to tests without the wicket gates. Off-BEP testing was also conducted to evaluate turbine operating characteristics at different wicket gate positions and to determine effects on fish survival due to decreased turbine efficiency. Additional CFD analysis was completed at off-BEP wicket gate positions for comparison to the CFD results at the BEP and observed fish injury at various gate positions.

Final engineering tests were conducted: 1) to determine turbine efficiency in the form of a "hill chart" for various wicket gate openings, 2) to measure local velocities and pressures upstream and downstream from the runner, and 3) to observe flow and fish approaching and exiting the runner. Flow visualization within the runner was not possible in the test facility due to the attached shroud around the perimeter of the turbine runner blades.

2.4 Schedule

In March 2000, the DOE Technical Committee and Alden agreed on the facility design and conditions to be tested. In April 2000, the DOE authorized Alden to proceed with procurement and/or fabrication of the test loop components and construction of the pilot scale test facility. The test facility was completed in August 2001 with installation of the turbine and scroll case without wicket gates. Operational checkout of the test loop components and turbine were conducted in September 2001 to fine-tune the equipment and verify that the anticipated operating points and data could be attained.

Preliminary engineering tests of the Alden/Concepts NREC turbine without wicket gates were conducted in September 2001 followed by biological tests with rainbow trout in October and November 2001. Preliminary engineering tests with wicket gates were conducted in April 2002, followed by testing with rainbow trout and other species during April-May and September-November 2002. Final engineering tests on the pilot scale turbine with wicket gates were conducted in November-December 2002 and completed in January 2003. Off-BEP CFD analysis was performed during January-February 2003.

3.0 TEST FACILITY COMPONENTS, EQUIPMENT, AND INSTRUMENTATION

The pilot scale test loop was designed to evaluate the effects of fish passage through the turbine and to obtain the water-to-shaft power efficiency. A number of design features were included in the test loop to produce predictable and controlled conditions for fish testing, including a gentle fish injection and collection system, a cooling system to control water temperature, and instrumentation to measure flow and pressures. Test loop components had surface finishes and clearances that were necessary to prevent fish injury. A dynamometer allowed operation of the turbine at various speeds, which not only allowed selection of the best head-speed combination at the design point, but also allowed testing at other head-speed combinations. Test loop instrumentation allowed the turbine efficiency to be determined with an uncertainty of about 0.5% at a 95% confidence level.

3.1 Turbine

The initial conceptual design effort for the Alden/Concepts NREC turbine resulted in a relatively large runner for the selected design point of 1,000 cfs and 80 ft head. Head losses in the scroll case and draft tube were estimated to be about 5 ft, resulting in a 75 ft design head for the runner. The pilot study design included further development of the runner to reduce the diameter from about 17 ft to about 13 ft at the selected design point. That runner size was then scaled down to the pilot scale runner diameter of 48 inches resulting in a geometric scale ratio of 3.25. A computer graphic showing a cut-away view of the pilot scale turbine is presented on Figure 3-1.

Turbine components were fabricated in local shops and included the scroll case, wicket gates, runner, runner housing, runner seals, and draft tube, as shown on Figure 3-1. Since the pilot scale turbine was intended for experimental use only, an aluminum casting was used for the runner. Coatings or other surface treatments in the flow passage were not used to strengthen the surface. The turbine thrust bearing and shaft were purchased new from a pump supplier.

The scroll case was designed and constructed to facilitate installation/removal of the wicket gates for testing with and without the gates. The pilot scale turbine scroll case did not have any stay vanes, which guide the flow and structurally tie the two halves of the scroll case together in a conventional scroll case design. Instead, the pilot scale scroll case had external radial ribs to maintain the integrity of the shell halves and eliminated all obstruction in the flow path. The open flow path allowed an evaluation of fish injury due to the runner only by tests of the turbine without wicket gates.

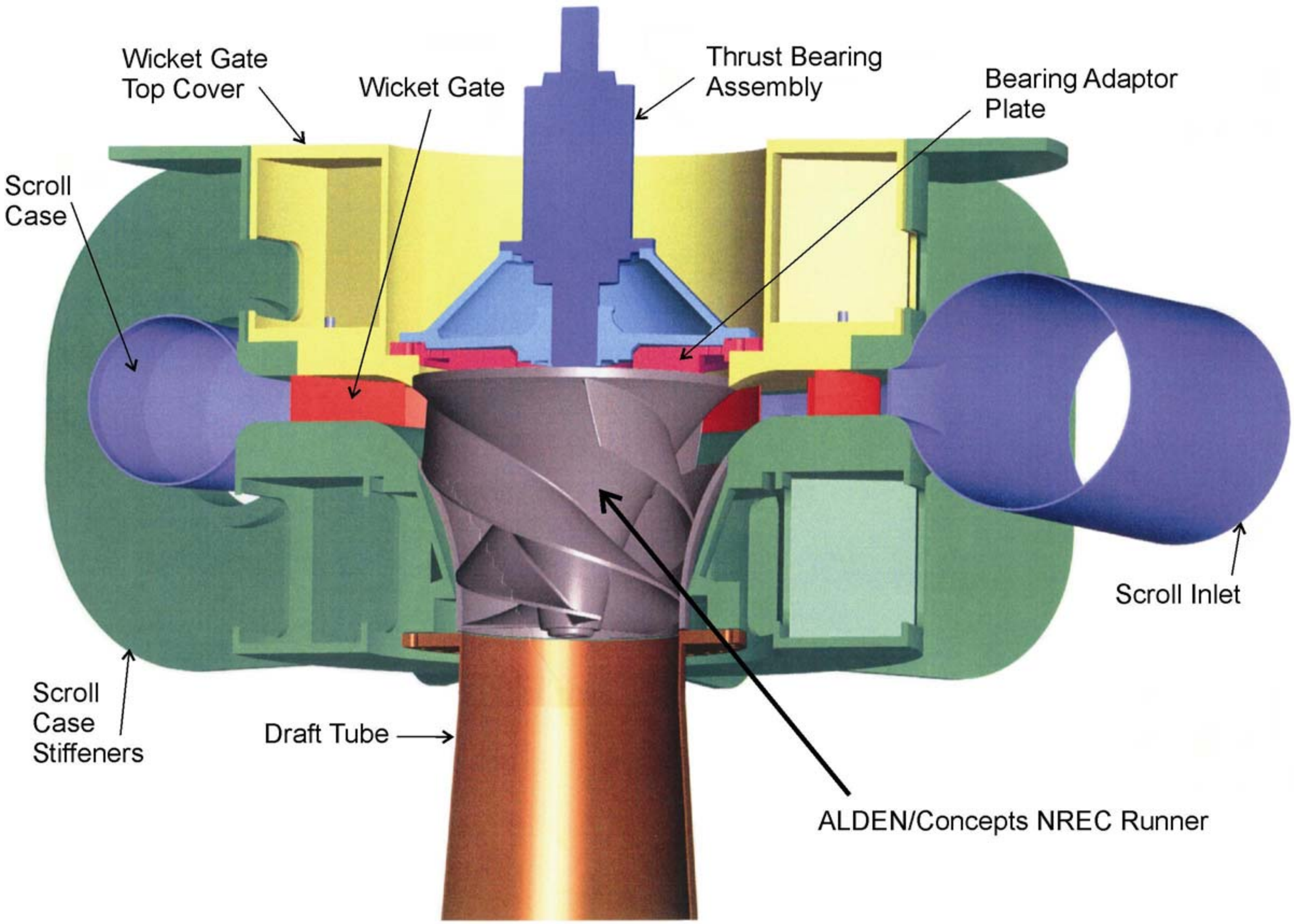


FIGURE 3-1 PILOT SCALE TURBINE CUT-AWAY VIEW

A dynamometer was used to absorb the turbine power and to control the runner speed. The dynamometer allowed the turbine speed to be adjusted to change the flow angles at the runner blade leading edges for a given head and wicket gate setting, if installed. The speed was varied to achieve the best efficiency at the design head, thus defining the BEP. The dynamometer also allowed the pilot scale turbine to be tested as a hydraulic model at different heads.

3.2 Test Loop

The turbine test facility was designed and constructed to test the pilot scale size turbine at the actual turbine design head of 80 ft (runner head of about 75 ft). The fundamental features of the facility include the penstock, scroll case, turbine runner, and draft tube. A plan and elevation of the flow test loop are shown in Figure 3-2 and Figure 3-3, respectively. The facility was a closed pipe loop with a free surface fish collection system. A 2,000 horsepower pump, shown on Figure 3-4, provided the design point flow condition of 95 cfs at 80 ft head for the 4.0 ft diameter pilot scale runner.

The test loop was constructed of standard steel pipe that was sized and configured to minimize head losses. The pipe sizes ranged from a 35 in diameter at the scroll inlet up to a 66 in diameter downstream of the draft tube.

The turbine scroll case was oriented horizontally, similar to typical Francis and Kaplan unit installations, so that the turbine shaft and draft tube entrance were vertical, as shown on Figure 3-5. The draft tube expanded from the turbine discharge diameter of about 2.8 ft to the diameter of a standard 4 ft long radius 90° elbow. The draft tube was designed with a gentle expansion and long radius elbow to minimize fish injury that could be caused by turbulence resulting from a sudden expansion and to allow an assessment of fish injury due to other parts of the turbine. Following the discharge elbow, the test loop transitioned to a 5.5 ft diameter cross section pipe leading to the fish collection screen and collection tank.

3.3 Fish Injection and Collection

The treatment fish injection system, which was located upstream of the turbine inlet, recreated the increasing pressure versus time history experienced by fish entering an intake from near the water surface and traveling through a short penstock to the turbine (typically about one minute). The test program was selected to simulate the pressure history of a surface-acclimated fish because: 1) most migratory species, including salmon smolts, are surface-oriented during their downstream migration; and 2) acclimating fish to high pressures for extended periods prior to introduction would have required a complex oxygenation system to maintain acceptable water quality.

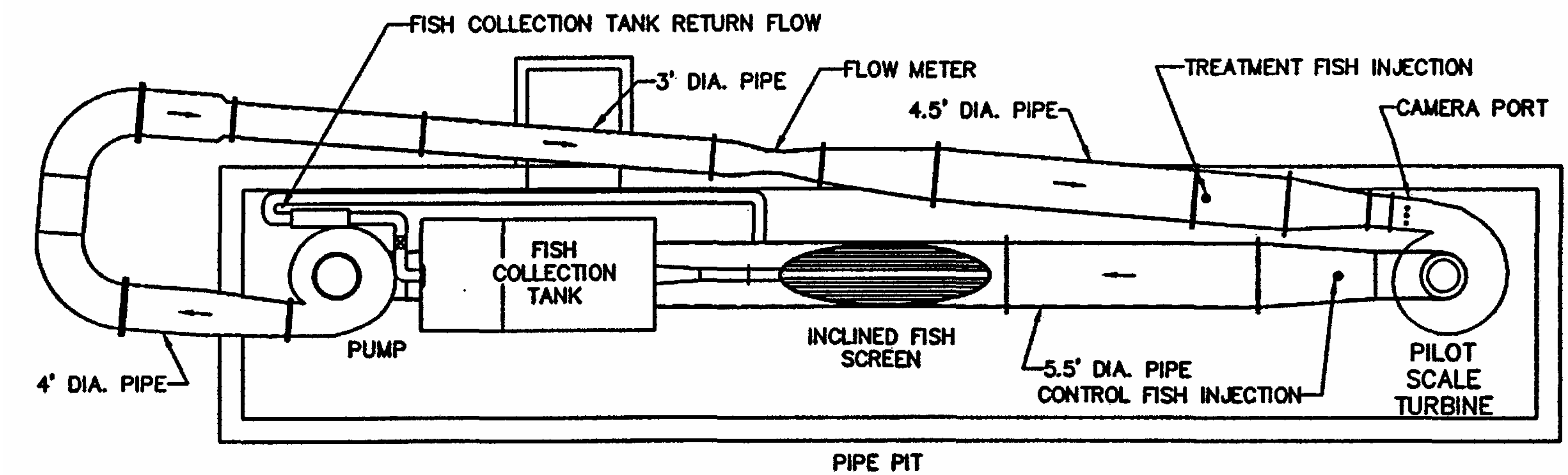


FIGURE 3-2 TEST FACILITY GENERAL ARRANGEMENT - PLAN

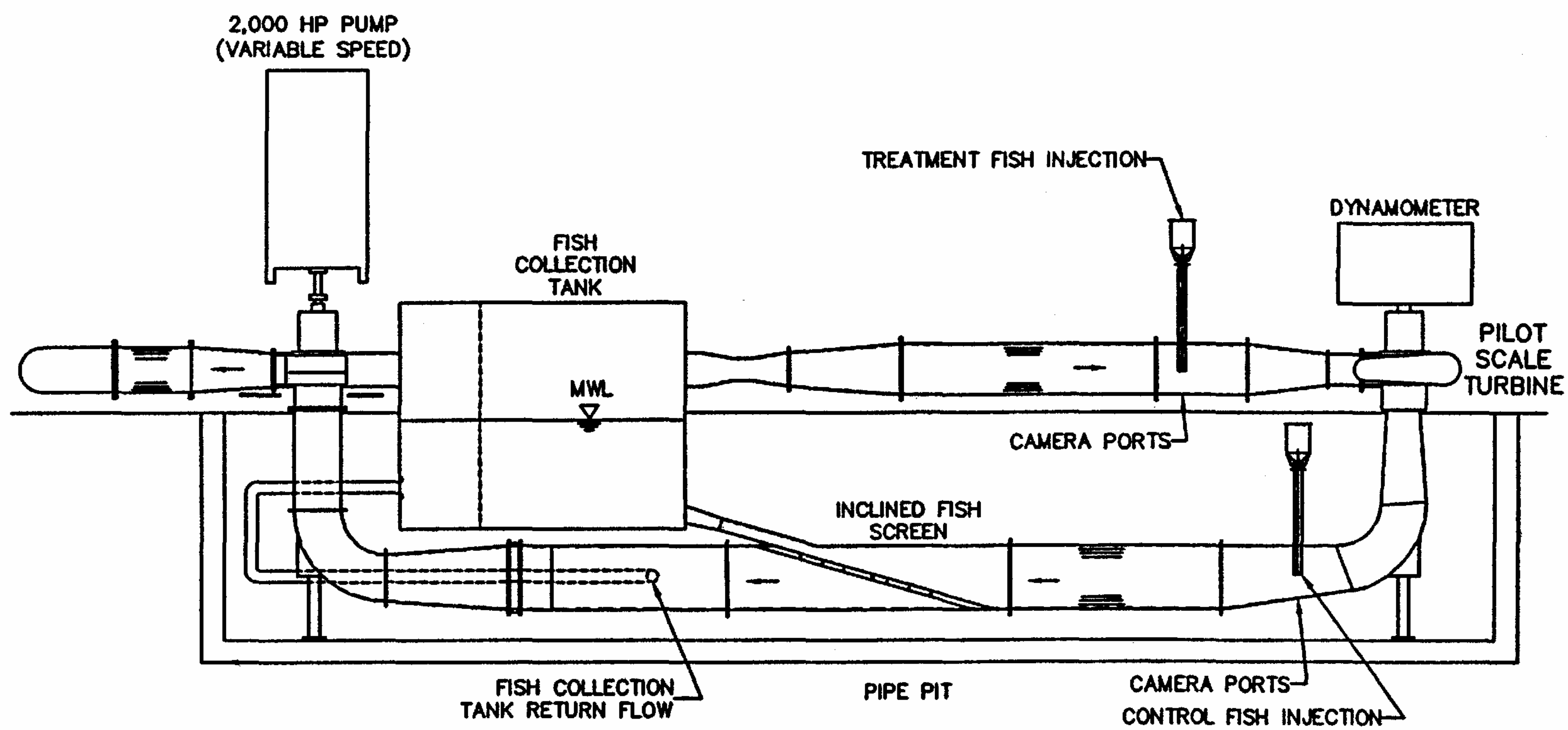


FIGURE 3-3 TEST FACILITY GENERAL ARRANGEMENT – ELEVATION

FIGURE 3-4   TEST LOOP PUMP

FIGURE 3-5   TURBINE SCROLL CASE

Test (treatment) and control fish were injected into the test loop using identical systems. The fish were placed in a water filled tank which was connected to the test loop with a vertical pipe at the bottom of the tank. A ball valve in the pipe isolated the tank from the loop flow. An air tight cover was then closed on the tank and compressed air was introduced into the top of the tank to equalize the pressure in the tank (with fish) to that of the flow loop. Once equalized, the isolating ball valve was opened and additional air was used to push the water and fish in the tank down into the test loop.

The treatment fish injection system was designed for injection at three levels within the conduit (top, middle, and bottom). Using the same method, control fish were injected downstream of the operating turbine to allow a comparison of the injury rate of two groups of fish; i.e., both groups experienced the injection and collection process, but only one group passed through the turbine. The time frame for injection of both sets of fish (treatment and control) was considered "simultaneous" since the control fish were released within about 15 minutes of the treatment fish. The control injection pipe was also designed to allow fish injection at the top, middle, and bottom of the conduit and to be fully removed from the flow path during injection of treatment fish.

Treatment and control fish were recovered from the flow with an inclined collection screen similar to the Eicher screen evaluated in previous studies at Alden and at the Elwha Project for the Electric Power Research Institute. The collection screen was about 20 ft long and had an elliptical shape, as shown on Figure 3-6. The water velocity approaching the screen was 3-7 ft/sec, depending on the test condition, to ensure that the fish moved with the flow but were not subject to impingement on the screen. The wedge wire screen had 2 mm slot openings and 2 mm bar widths and was fixed at an angle of 16° from the axis of the test loop pipe. Most of the test loop water passed through the screen, with about 3-5 cfs diverted to a bypass at the top of the inclined screen, depending on the screen approach velocity, where fish were guided into an open fish collection tank. The bypass flow exited the collection tank through a screen at a very low velocity (0.1 ft/sec) and was pumped back into the main test loop downstream of the collection screen. Bypass flows were controlled by operation of a bypass pump.

At the completion of a test run, flow into the collection tank was shut off and the tank was drained. As the tank water level dropped, fish were guided to one side via a sloped floor. They were then removed from the collection tank by opening a knife gate valve, which gradually lowered the water level until all fish were guided through the gate valve and into a secondary dewatering tank. To avoid injuries to fish that could have resulted from opening the gate valve under high pressure, the water level in the secondary water tank was controlled at a slightly lower water level than the collection tank. The secondary dewatering tank had a sloping floor that guided fish into a smaller volume of water from which the fish were netted and transferred to buckets.

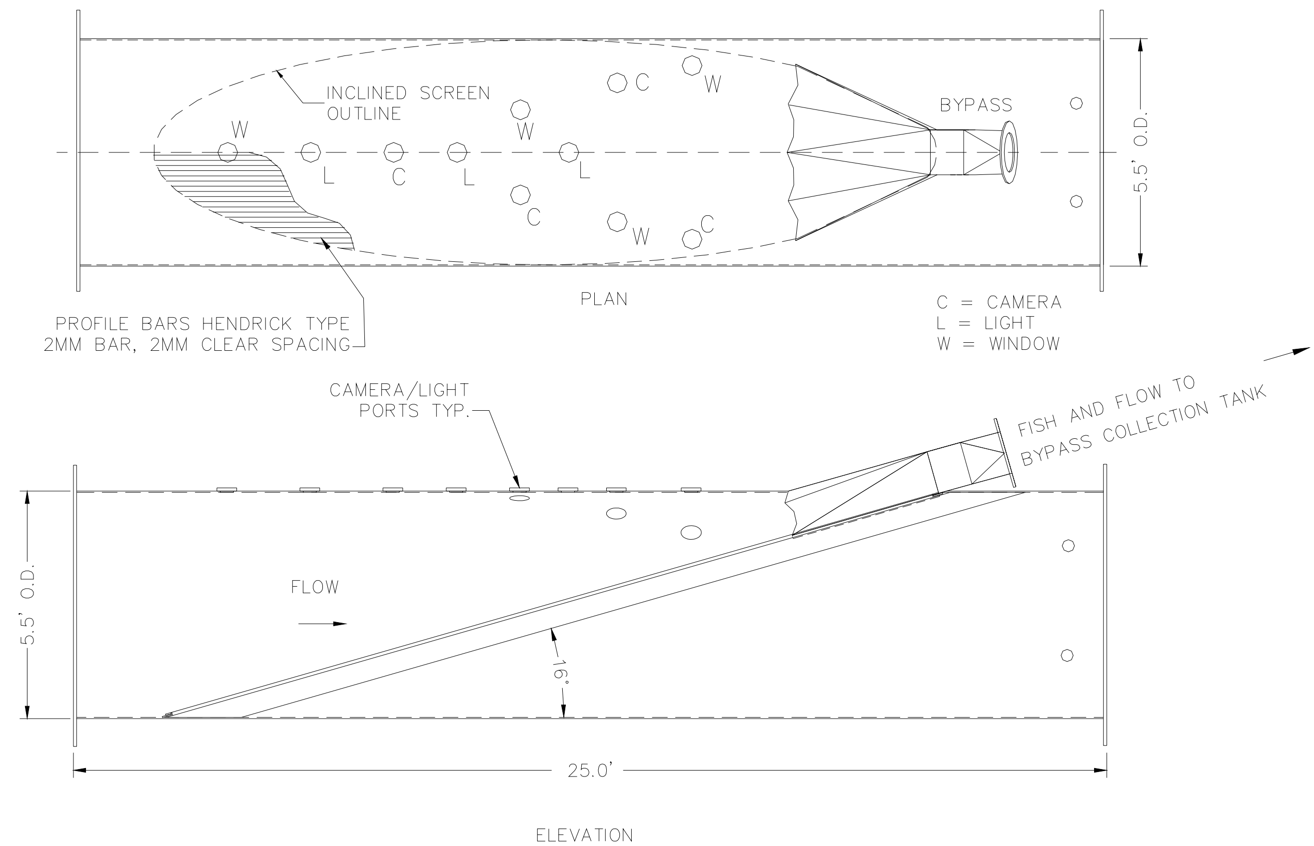


FIGURE 3-6 EICHER FISH COLLECTION SCREEN

3.4 Instrumentation

Test loop flow was measured using a calibrated Venturi meter in the pipe leading to the turbine. A differential pressure (DP) transducer cell measured the head difference across the flow meter pressure taps. The DP cell signal was monitored and recorded using a standard PC equipped with an analog to digital (A/D) board and Test Point software used by Alden's Instrumentation Department. Turbine net inlet and outlet pressures were also measured with transducers and monitored and recorded using a PC data acquisition system. Piezometric taps were installed at various locations along the scroll case and the draft tube, as shown on Figure 3-7. A differential pressure cell was installed between scroll inlet taps and the draft tube exit taps to measure the turbine static head. Data from this pressure cell was used to time average changes in pressure between these locations. Turbine total dynamic head (TDH) was calculated using the measured static head and calculated velocity head at each tap location using flow and pipe areas.

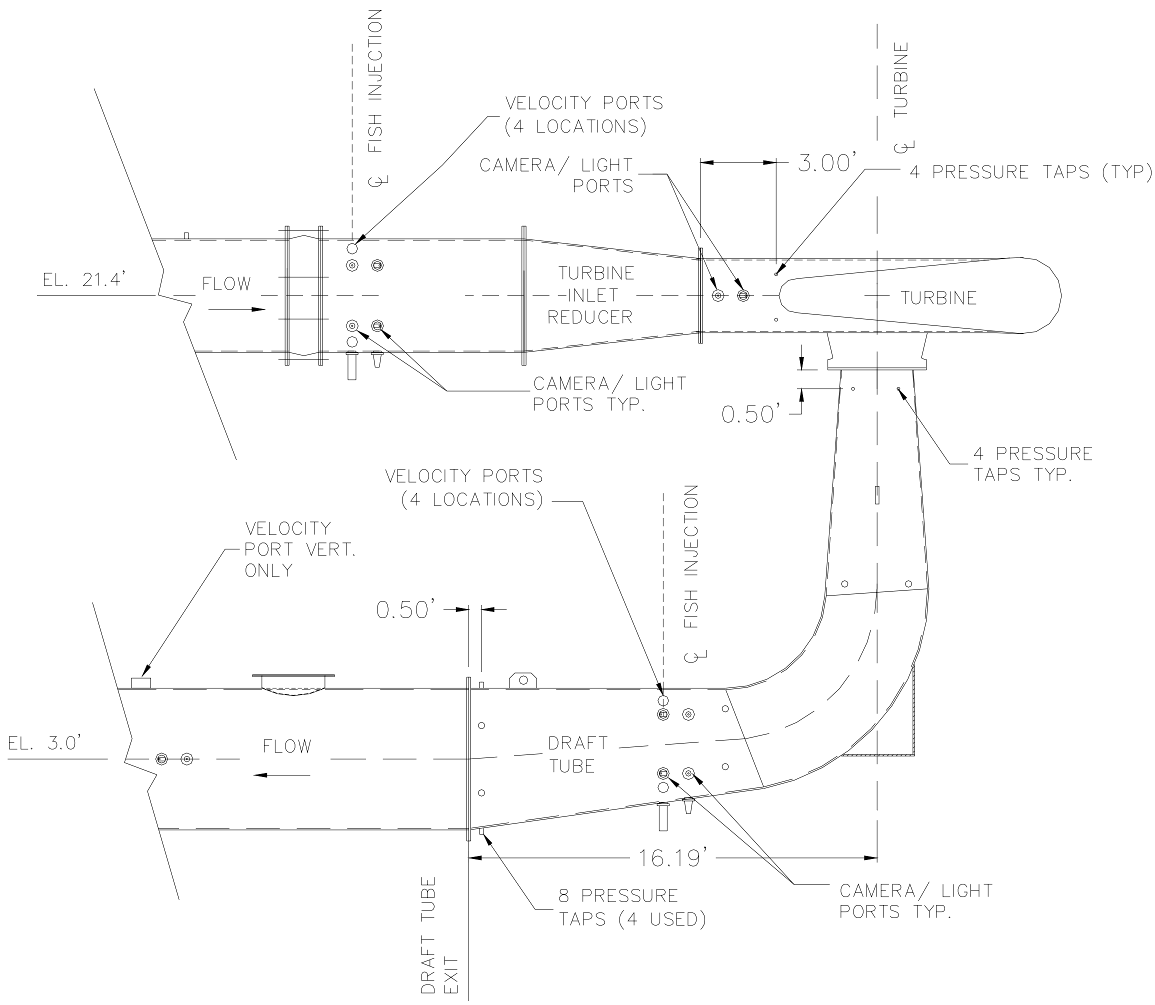


FIGURE 3-7 PRESSURE MEASUREMENT LOCATIONS

Three inch round acrylic windows were strategically installed at the scroll case inlet, in the scroll case about one-third of the distance around from the inlet, and in the draft tube to allow lighting and observation of the flow and fish entering and exiting the turbine. A high-speed video camera and lights were mounted in the windows to record flow and fish passage. View ports and cameras were also installed near the fish injection systems and above the inclined fish collection screen to observe fish along the screen.

To operate the pilot turbine, the energy produced at the shaft was absorbed by an oil shear brake dynamometer coupled to the turbine shaft. A separate oil cooling system removed the heat absorbed by the brake. Turbine speed (rpm) was automatically controlled using an electronic feed-back system which adjusted the braking torque applied by the dynamometer. The dynamometer was cradled so that a measurement of the restraining torque produced by the dynamometer could be measured using a load cell on an arm at a precisely measured distance from the center of shaft rotation. This system was calibrated *in situ* using dead weights traceable to National Institute of Standards and Technology (NIST). Turbine shaft speed and the torque instrumentation were part of the dynamometer system. Measurements of turbine speed (rpm) and torque yielded shaft power directly, and turbine efficiency was calculated based on the input flow and head.

3.5 Mechanical Equipment

Ancillary pump systems were installed to fill, drain, filter, and cool the water in the test loop. The cooling system was sized based on an estimate that 20 percent of the test loop pump power and 10 percent of the turbine power would be transferred as heat to the test loop water. For testing with fish, the system water temperature was maintained between 50 and 70° F, depending on the season. The chiller automatically monitored inlet temperature and regulated the cold outlet water temperature to maintain the desired mixed test loop water temperature.

3.6 Fish Holding

Fish holding facilities were installed for rearing and/or acclimation of test fish, for holding marked groups two days prior to testing, and for holding recovered test fish for a 96-hour observation period after testing. Six large (440 gallon) circular tanks were available for rearing and/or acclimation. A total of 18 smaller (210 gallon) circular tanks were installed for holding marked fish groups (treatment and controls) prior to and following testing. The smaller tanks were fitted with weighted net liners to facilitate removal of fish without injury and net tops that prevent fish from jumping out of the tanks.

All of the fish holding facilities were connected to a common water supply to ensure that optimum and uniform water quality conditions were maintained in each holding tank. An existing concrete sump with about 300,000 gallons storage capacity served as the water supply reservoir. Town of Holden water was used to fill the supply reservoir. A large steel tank, located within the supply reservoir, with a storage capacity of about 4,000 gallons, was used for treatment of water entering the fish holding facilities.

A combination of mechanical, biological and chemical filtration was provided for the fish holding facilities, and a chiller was used to control water temperatures during the summer months. Carbon, diamataceous earth (DE) and zeolite filters, and an Ultra Violet (UV) sterilization system were installed to treat the holding water. An aeration system was installed to ensure that dissolved oxygen in each tank was maintained at levels near saturation. Inflow to each circular rearing tank was directed at an angle to establish a circular flow pattern with an average velocity of 0.2 to 0.7 ft/sec. Each tank was fitted with a center drain to promote automatic removal of fish feces and uneaten food, and the water level in each tank was regulated using an external standpipe.

4.0 ENGINEERING TESTING

Preliminary testing of the turbine was conducted in the fall of 2001 to determine the Best Efficiency Point (BEP) of the turbine operating without wicket gates, and in the spring of 2002 to determine the turbine BEP with wicket gates for subsequent fish testing and quantification of the turbine efficiency. To accomplish this, the turbine speed was set using the dynamometer control system and the test loop pump speed was adjusted to achieve the desired turbine head. This produced a measured flow and turbine shaft output power, yielding the remaining parameters needed to determine the turbine performance. Results are provided in Section 4.7 for the tests without wicket gates and in Sections 4.8 through 4.11 for tests with wicket gates.

The minimum local pressure within the runner was about 10 psia (at the blade trailing edges), based on CFD analysis with a cross-sectional mean static pressure of about 13.5 psia at the turbine outlet. Therefore, cavitation was not an issue and cavitation inception tests were not conducted. Measurements of the cross-sectional mean, time average static pressures at the runner exit were made, but local pressure measurements within the runner exit cross-section were not practicable.

4.1 Test Loop Flow Meter Calibration

To provide an accurate measurement of flow through the turbine, the test loop Venturi meter was calibrated in Alden's main gravimetric facility where primary flow measurement is traceable to NIST standards. The certified flow measurement uncertainty of this facility is better than 0.25% at the 95% confidence level. Since the amount of residual swirl from the test loop pump was not known at the time of the meter calibration, and since such swirl or velocity asymmetry may affect the flow meter performance, the flow meter calibration was performed using two different upstream piping arrangements. One upstream pipe configuration was a straight line, as shown on Figure 4-1, which yielded minimal swirl and velocity asymmetry. The other configuration had a tee and a short radius bend, as shown on Figure 4-2, followed by 36 ft (12 diameters) of straight pipe to generate swirl in the pipe approaching the flow meter. Both upstream pipe configurations included the test loop pipe section located immediately upstream of the meter, which had ports for a velocity probe. Velocity measurements upstream from the meter were obtained for both calibration piping configurations.

A detailed discussion of the flow meter calibration results are presented in Appendix A. Calibration data for the velocity probe are presented in Appendix B, and calibration data for the velocity measurement differential pressure cells are presented in Appendix C. A summary of the flow meter calibration is provided in the following sections.

FIGURE 4-1   FLOW METER STRAIGHT PIPE CALIBRATION LOOP

FIGURE 4-2   FLOW METER TEE AND SHORT RADIUS ELBOW CALIBRATION LOOP

4.1.1 Velocity Measurements

In conjunction with the flow meter calibration with both piping configurations, velocity measurements were made along three of the four available traverses about 13 ft (4.3 pipe diameters) upstream from the meter entrance. These velocity measurements were later repeated when the turbine test facility was operational in order to select which of the flow meter calibrations, with or without swirl, would be most similar to conditions in the turbine test loop. During calibration, the measurements in the fourth traverse could not be obtained because the port was inaccessible in the calibration test loop.

4.1.2 Approach Velocity Distribution with Straight Pipe Configuration

Measurements in the three velocity ports upstream of the flow meter with the calibration piping in a straight configuration are presented in Appendix A, Table A-1. The data are plotted on Figure 4-3, with Port 3R being repeat measurements of Port 3. The non-dimensional velocity (v/Vc) is defined as the measured velocity (v) divided by the average of the centerline velocity measurements (Vc). The non-dimensional radius (r/R) is defined as the radial distance (r) from the wall to the velocity measurement location divided by the pipe radius (R).

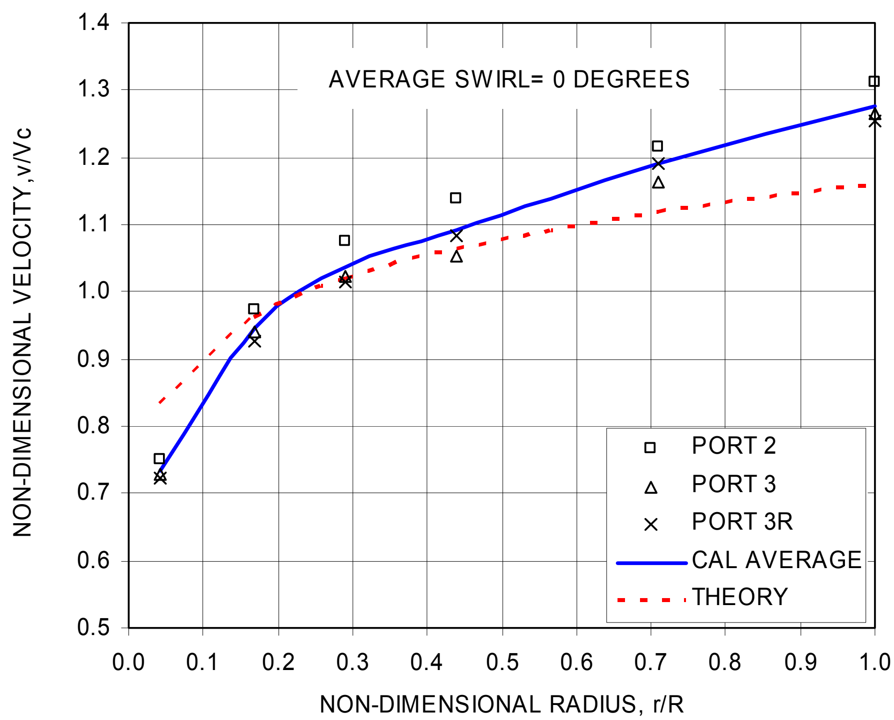


FIGURE 4-3 FLOW METER CALIBRATION VELOCITY TRAVERSE – STRAIGHT PIPE, 42 CFS

A review of the data indicated that there was a discrepancy with the Port 1 data set. Due to time constraints, velocities at this port could not be re-measured and were not included in the analysis.

The dotted line in Figure 4-3 represents the theoretical distribution profile if the flow were fully developed, as discussed in Appendix A. The theoretical distribution was based on the pipe Reynolds Number (Re) during the traverse measurements of about 2.5×10^6. The theoretical velocity profile indicates that the actual flow profile (shown by the solid line) with the straight pipe was not fully developed, since actual velocities decrease quicker towards the wall. A likely cause for this difference was the upstream flow straightener in the calibration test loop, which did not provide enough flow near the pipe wall.

To obtain the angle of any tangential velocity components, the probe was manually aligned to the flow by equalizing pressures on the two side ports. The probe angle with respect to the pipe axis was then measured externally using a taut line and protractor. The entire angle data set was corrected by 1.3°, which was the average measured angle of the approach flow at the centerline of the pipe (where there should not be any flow angle). Corrected, the average approach flow angle was zero degrees, indicating that the approach flow had negligible swirl. Similarly, no radial velocity components of interest were measured.

4.1.3 Approach Velocity Distribution with Tee Piping Configuration

Similar velocity measurements were conducted with a pipe Tee, which was installed just after the calibration test loop main header manifold, followed by a short radius bend to introduce swirl in the flow approaching the Venturi meter. These measurements were necessary to determine the effects of swirl on the flow meter discharge coefficient. The velocity data with swirl are presented in Appendix A, Table A-2 with the velocity traverse distribution shown on Figure 4-4 for this configuration. The average (tangential) swirl angle in the approach flow was about 3.7 °. The swirl forced more flow towards the pipe wall as shown in the velocity data at about r/R = 0.3. Therefore, the measured velocities (shown by the solid line) are closer to the theoretical predicted values (shown by the dashed line). Measured pitch angles (radial) were negligible, with the average being less than 0.5°.

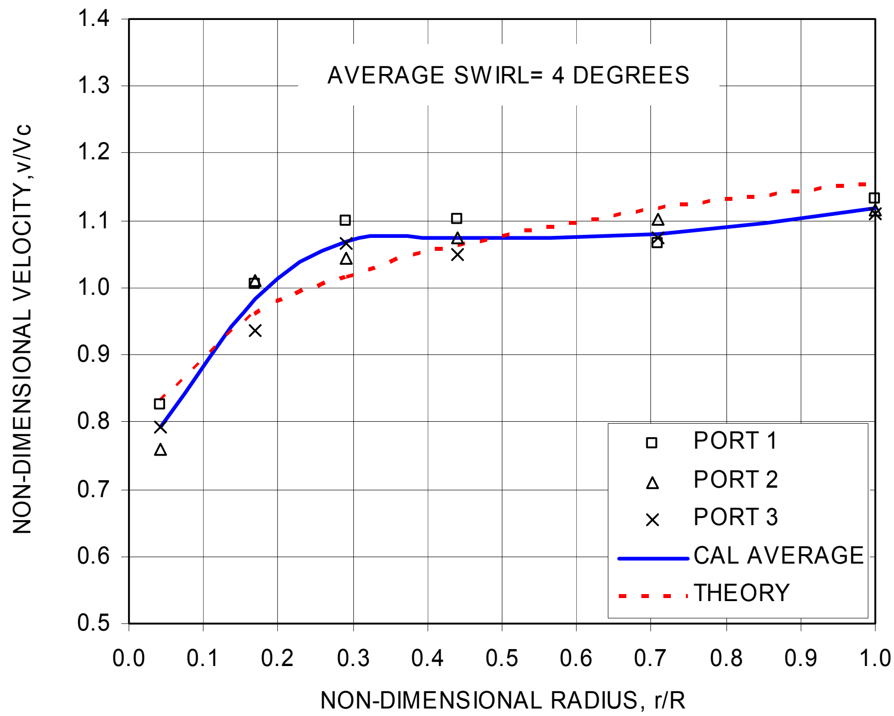


FIGURE 4-4 FLOW METER CALIBRATION VELOCITY TRAVERSE – TEE CONFIGURATION, 42 CFS

4.1.4 Meter Coefficients

The flow meter calibration data for both straight pipe and Tee configurations are provided in Appendix A, Attachment 1. Figure 4-5 shows the discharge coefficient versus Re for both upstream pipe configurations. Although there was a consistent shift in the coefficients with the straight pipe versus the upstream Tee, the overall change was within 0.2%.

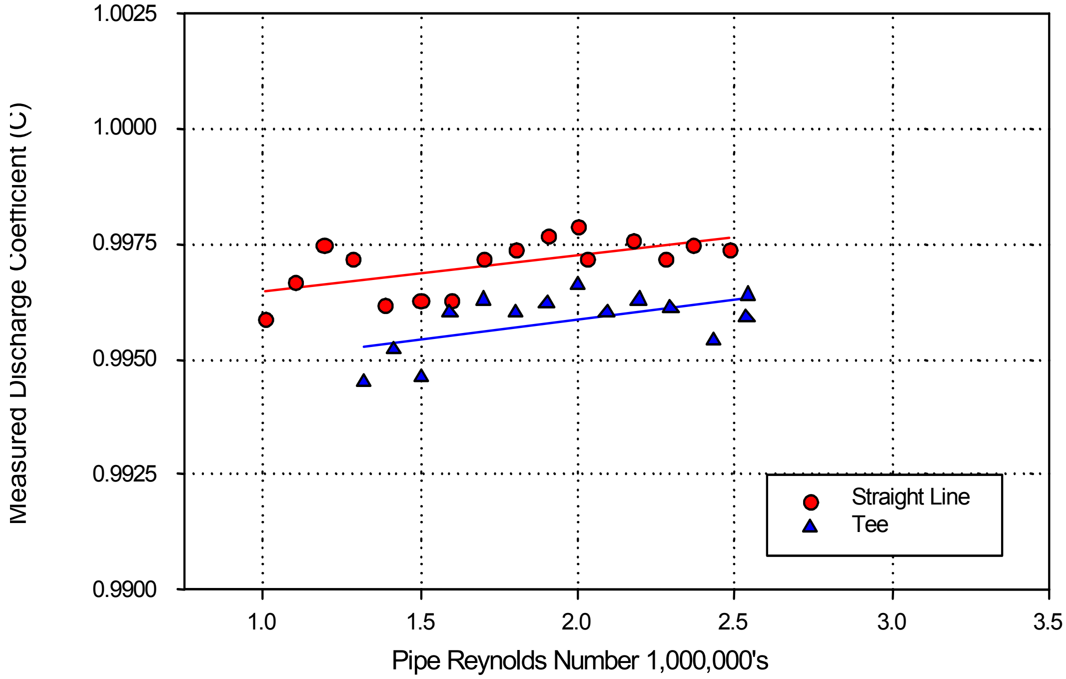


FIGURE 4-5 36 INCH VENTURI METER MEASURED DISCHARGE COEFFICIENT (C_D)

As discussed in Appendix A, the flow meter discharge coefficient was calculated from the calibration data in accordance with ASME PTC 19.5, Draft VII -May 2000, Section 5.4. The resulting meter coefficient (C) versus the throat Reynolds number curve over the range of expected meter use in the turbine test flow loop is shown on Figures 4-6 and 4-7 for the two calibration piping configurations. Flow conditions approaching the meter in the two calibration configurations and in the test loop were compared to select one of these calibration curves for turbine testing, as discussed in Section 4.6.1.

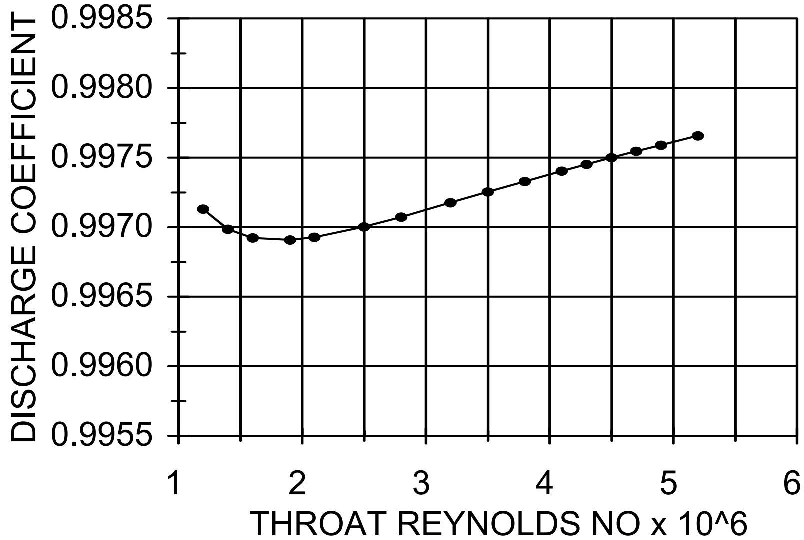


FIGURE 4-6 CALCULATED FLOW METER COEFFICIENT (C_D) – UPSTREAM STRAIGHT PIPE

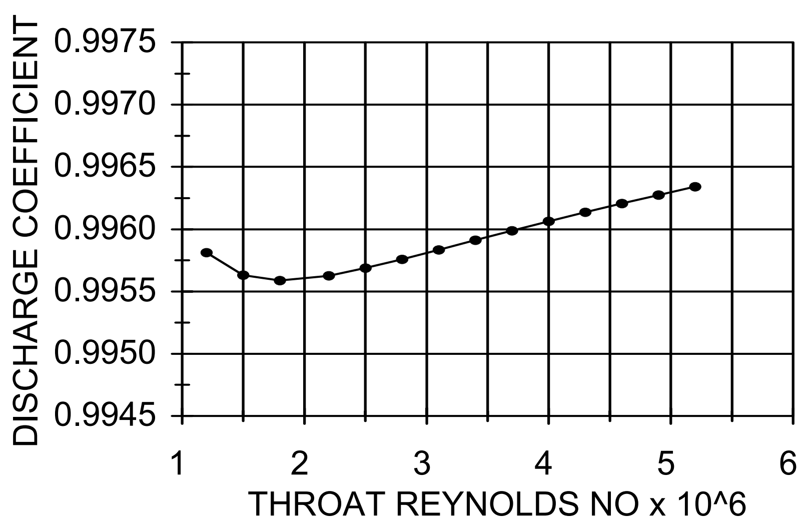


FIGURE 4-7 CALCULATED FLOW METER COEFFICIENT (C_D) – UPSTREAM TEE CONFIGURATION

4.2 Fish Bypass Flow Measurements

Bypass flow into the fish collection tank was measured using one of Alden's 12 x 8 in Venturi meters which was installed downstream of the fish bypass pump. Eighteen and five diameters of straight pipe were installed upstream and downstream of the meter, respectively. The accuracy of the meter was ± 2.5% over the bypass flow range for the test conditions. A differential pressure cell was installed to measure the Venturi meter pressure signal (H_b), and this signal was used to indicate bypass flow on the data acquisition computer.

Since the fish bypass flow was set to provide a fish bypass velocity equal to the velocity approaching the inclined fish collection screen and does not affect turbine performance, accurate measurement of the fish bypass flow was not necessary. Preliminary biological tests indicated most fish entered the fish collection tank with bypass flow rates set using the existing meter calibration over the range of test conditions (2.6 cfs at 63.7 cfs turbine flow up to 3.8 cfs at 92.7 cfs turbine flow). Therefore, additional calibration of the 12 in Venturi meter was not needed.

4.3 Pressure Measurements

Six differential pressure cells were used to measure and monitor test loop flow conditions. Each pressure cell had a transmitter that sent a voltage signal to the data acquisition computer which converted the signal to the appropriate ft and cfs. The data acquisition computer displayed the raw and converted data and periodically stored the data in a file. Engineering and biological test conditions were documented using a two-minute simultaneous record of each pressure cell. Approximately 1,200 samples were averaged over the two-minute record period. Flow conditions that were monitored included: the test loop flow, turbine head, tailwater level, fish bypass flow, and test loop pump head. The sixth cell was installed to measure either the scroll case or the draft tube pressure drop, but only one pressure drop at a time.

A dead weight pressure Transfer Standard was used to calibrate each of the differential pressure cells, with the data acquisition computer as an integral unit. Table 4-1 summarizes the initial calibration data for each of the pressure cells. All of the pressure cells have a straight line calibration curve and measurement values (y) were calculated using the equation $y = m\,x + b$, where m is the slope of the line, x is the voltage reading from the transducer, and b is the line intercept on the ordinate axis. The accuracy of all the pressure measurements was expected to be better than 0.1% over the calibration range for each cell.

TABLE 4-1
DIFFERENTIAL PRESSURE CELL CALIBRATION DATA

Pressure Measurement	Calibration Range (psi)	Slope (m)	Intercept (b in psi)
Test Loop Flow Meter	0-8	1.126869	-2.243917
Turbine Head	0-50	6.251296	-12.487650
Tailwater level	0-33	3.751875	-7.769151
Fish Bypass Flow Meter	0-4	0.540570	-1.071800
Test Loop Pump Head	0-50	6.256559	-12.362490
Scroll/Draft Tube Pressure Drop	0-4	0.537360	-1.059560

The pressure cells were also calibrated after the tests without wicket gates, between the spring and fall 2002 wicket gate tests, *in situ* during the fall 2002 testing, and after all testing was completed. All of these calibrations had slopes and intercepts that were within 0.1% of the initial values. All pressure cell calibration data is provided in Appendix D.

During preliminary tests with wicket gates, the gasket at the flange between the Venturi meter and the upstream pipe section was found to be improperly positioned, thus affecting the pressure tap readings, resulting in an understatement of flow by slightly less than 2%. As discussed in Appendix E, the gasket was trimmed and a series of tests conducted to determine a correction factor for the flow measurements that were obtained with the improper gasket. All flow values presented in this report reflect this flow correction factor.

4.4 Dynamometer Load Cell Calibration

As previously mentioned, the dynamometer oil shear brake absorbed all of the energy generated by the turbine while a cooling system removed the heat absorbed by the oil. The dynamometer was cradled so that the restraining torque could be measured using a load cell on an arm at a precisely measured distance from the center of the shaft rotation. Load cell measurements were transmitted to the data acquisition system for display and recording.

Torque measurements were calibrated *in situ* by applying known weights, traceable to NIST, to a calibration arm that was connected to the load cell while the turbine was not operating. Details of the dynamometer calibration arm are shown on Figures 4-8 and 4-9. The *in situ* calibration correlated the load cell output directly to ft-lbs of torque (T) using the linear equation T = $m x + b$, where x is the voltage reading from the transducer. The slope m and the intercept b were derived from the *in situ* calibration. Force on the load cell was computed by multiplying the weight by the mechanical advantage (3.5) provided by the calibration arm.

Turbine torque that was indicated and recorded on the data acquisition computer was based on the dynamometer load cell *in situ* calibration and computed by multiplying the measured force on the load cell by the radial distance between the load cell and the center of the turbine (3 ft).

Preliminary engineering tests in the fall of 2001 without wicket gates and in the spring of 2002 with wicket gates were conducted with the load cell that was supplied with the dynamometer. The manufacturer rated the accuracy of the load cell at 0.2% of full scale (20 lbs). Over the range of operation in the test loop (1,000-1,800 lbs), the manufacturer's accuracy was expected to be 1-2% without any calibration. As discussed in Appendix F, the accuracy of the torque measurements was found to be about 0.6% at the 40 ft head test condition and about 0.4% at 80 ft head, about the accuracy selected for design of the facility (0.5%).

Preliminary engineering tests in June 2002 with the wicket gates indicated that a more stable load cell was needed to better define the turbine performance characteristics. Therefore, the torque measurement load cell and electronic readout were replaced prior to final engineering tests in the fall 2002. The manufacturer's rated accuracy of replacement load cell was 0.02% of full scale (2 lbs), resulting in a 0.3% accuracy in the torque measurements at the 80 ft head test condition.

Calibration data for the two load cells that were used to measure torque are provided in Appendix E.

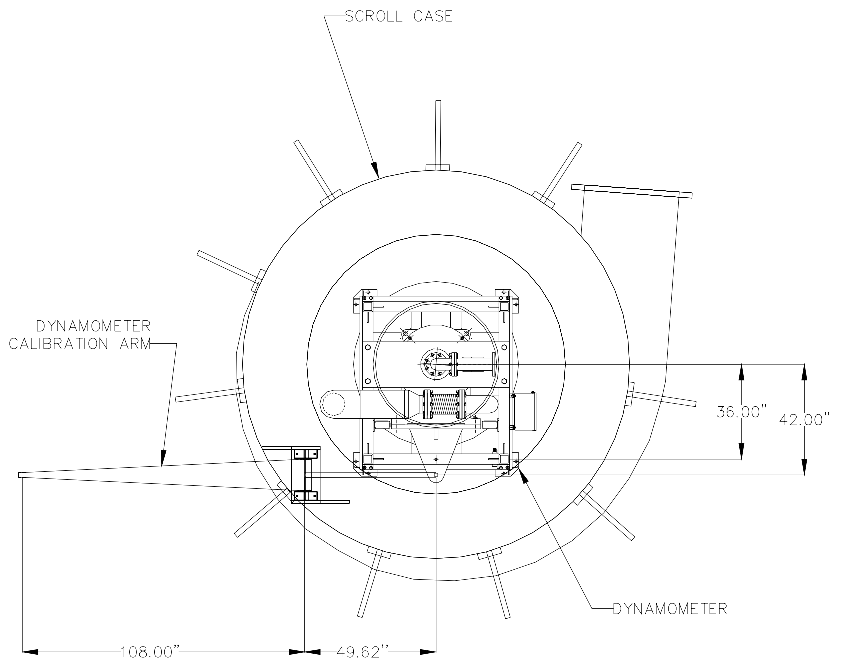


FIGURE 4-8 DYNAMOMETER CALIBRATION ARM - PLAN

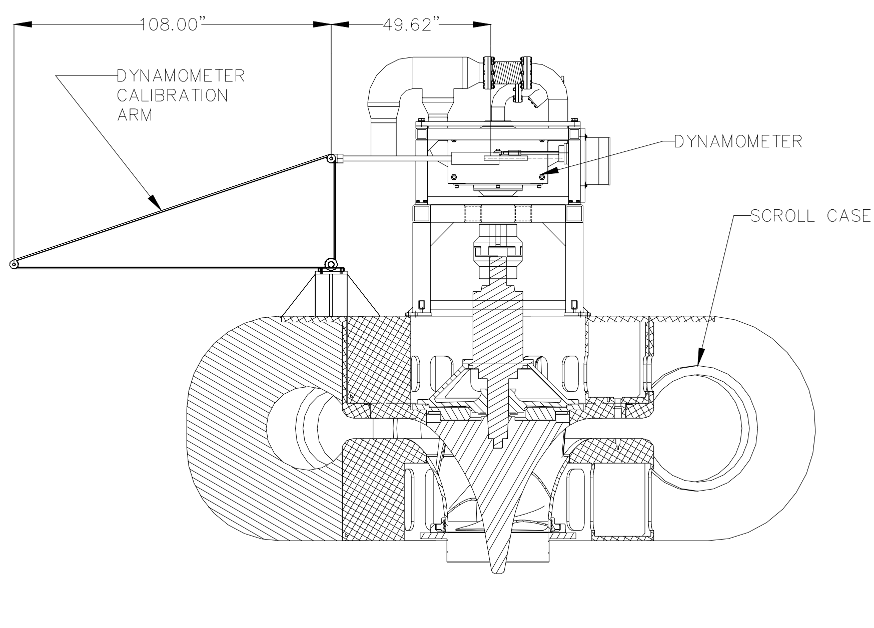


FIGURE 4-9 DYNAMOMETER CALIBRATION ARM – SECTION

4.5 Turbine Shaft Speed

The turbine shaft speed was regulated by a speed (rpm) sensor that was integral to the dynamometer control system. The sensor included a multi-tooth sprocket mounted on the turbine shaft and a magnetic pick-up and counter. The counter sent a digital signal to the dynamometer control system for adjusting the brake friction to maintain a selected speed. The counter signal also provided a speed readout on the control panel. The manufacturer's specified accuracy for the dynamometer speed sensor was ± 0.15 rpm, which was 0.1% over the operating range (200-400 rpm).

To assure that Alden's data acquisition system did not interfere with operation of the dynamometer, a separate magnetic pick-up and counter was installed to measure the runner shaft speed off the same multi-tooth sprocket that was used to measure speed for controlling the brake. This counter sent an analog signal to the data acquisition computer for continuous monitoring of the runner shaft speed during a test. The analog counter also had ± 0.15 rpm accuracy.

4.6 Velocity Measurements

Velocity measurements in the test loop were taken upstream of the Venturi flow meter (Figure 3-3), just upstream of the treatment fish injection location (Figure 3-3), and just downstream from the control fish injection (slightly upstream from the end of the draft tube) (Figure 3-7) during the fall 2001 preliminary engineering tests without wicket gates. The measurements upstream of the flow meter were obtained for comparison to the measurements taken during calibration of the flow meter to determine the appropriate flow meter calibration discharge coefficient. The velocity measurements upstream of the treatment fish injection and downstream of the control fish injection were obtained to define flow conditions at the fish injection points and identify fish injection locations that were similar for both the treatment and control fish. The measurements downstream from the control fish injection were also obtained to better understand the swirl leaving the turbine and to determine a kinetic energy correction factor (for the end of the draft tube) needed to calculate the head on the turbine. In addition, velocity measurements were obtained in the downturn at the runner inlet downstream of the wicket gates during final engineering tests for comparison to the CFD analysis.

The test loop velocity measurements are discussed in detail in Appendix F. The key findings from the velocity measurements are summarized in the following sections.

4.6.1 Upstream of Flow Meter

Velocity measurements in the test loop upstream of the Venturi flow meter were taken at the same traverse locations and with the same 5-hole pitot probe that was used during the flow meter calibration. Complete sets of measurements were made at two operating conditions: 1) a turbine head of about 80 ft and a corresponding flow of 93.7 cfs, and 2) a turbine head of about 38 ft and a corresponding flow of about 65.2 cfs. The measurements for each operating condition are summarized in Appendix F, Tables F-1 and F-2 and are shown on Figures 4-10 and 4-11.

Tangential flow (swirl) angles at each measuring point upstream of the flow meter were small for both operating conditions. The swirl angles were 1.2 and 0.3° for the 80 ft and 38 ft heads, respectively. These low swirl angles indicated that flow swirl approaching the Venturi flow meter was negligible and similar to the swirl measured during the flow meter calibration with the straight pipe. Therefore, the flow meter discharge coefficient for the straight pipe, Figure 4-6, was used to determine test loop flow during the turbine tests.

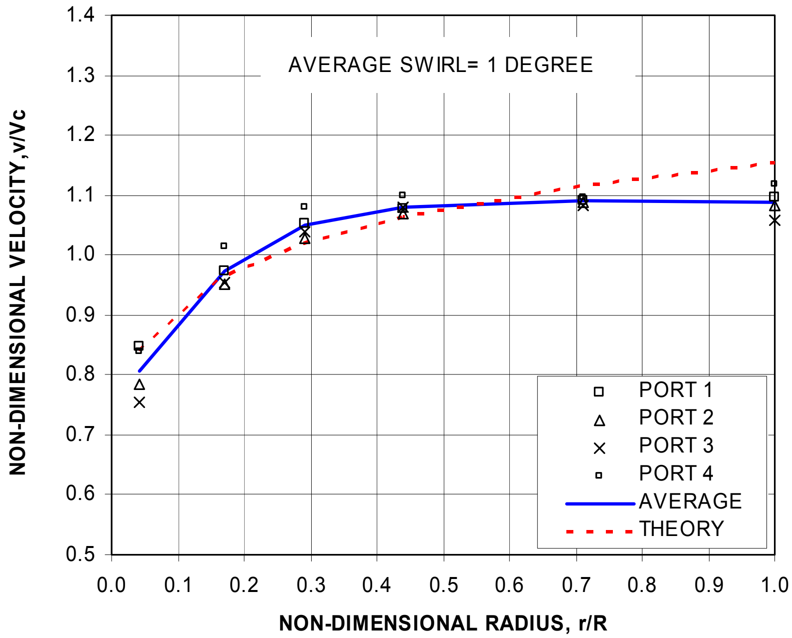


FIGURE 4-10 VELOCITY DISTRIBUTION IN TEST LOOP APPROACHING FLOW METER AT 80 FT HEAD

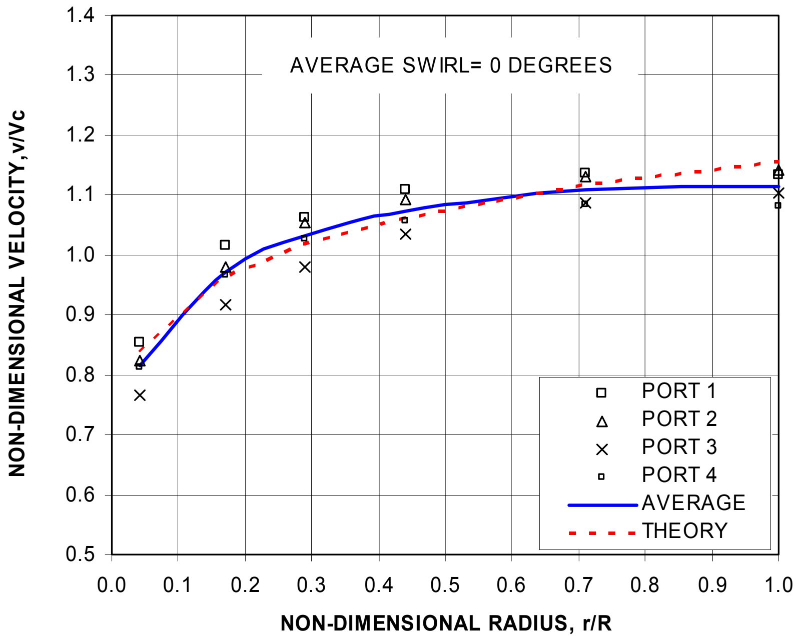


FIGURE 4-11 VELOCITY DISTRIBUTION IN TEST LOOP APPROACHING FLOW METER AT 38 FT HEAD

4.6.2 Treatment Fish Injection

Velocity measurements taken in the test loop just upstream of the treatment fish injection location, which are summarized in Appendix F, Tables F-3 and F-4, were obtained at two operating conditions: 1) a turbine head of about 80 ft and a corresponding flow of 93.7 cfs, and 2) at a turbine head of about 38 ft and a corresponding flow of about 65.2 cfs. The 80 ft measurements with 93.7 cfs showed a uniform distribution with an average velocity of about 5.8 ft/sec and a negligible swirl angle of 1°. With 38 ft of turbine head and 65.2 cfs, the average velocity was 4.0 ft/sec. At these lower velocities, the pressure readings were somewhat low for the DP cell and the data were more scattered, but a generally uniform velocity distribution was evident as shown on Figures 4-12 and 4-13 for the 80 ft and 38 ft turbine head measurements, respectively.

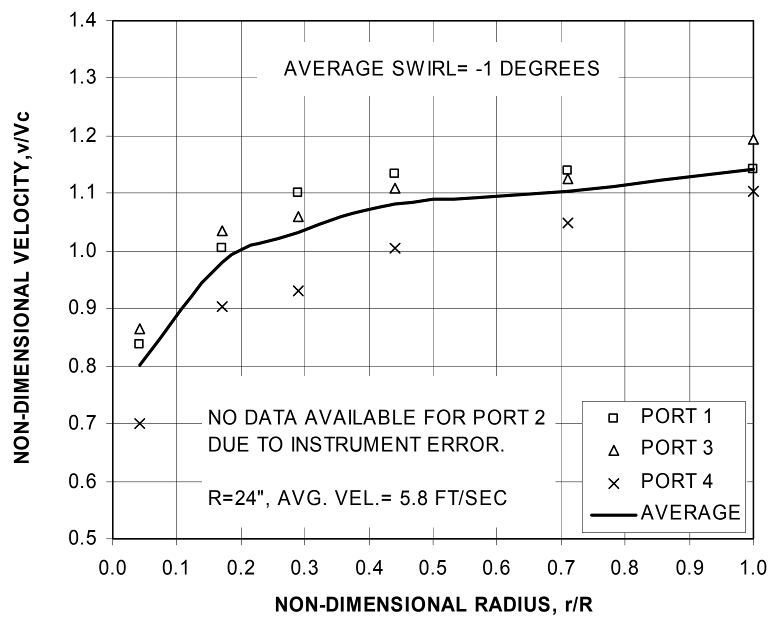


FIGURE 4-12 VELOCITY DISTRIBUTION AT TREATMENT FISH INJECTION LOCATION WITH 80 FT HEAD, 92.7 CFS, 335 RPM

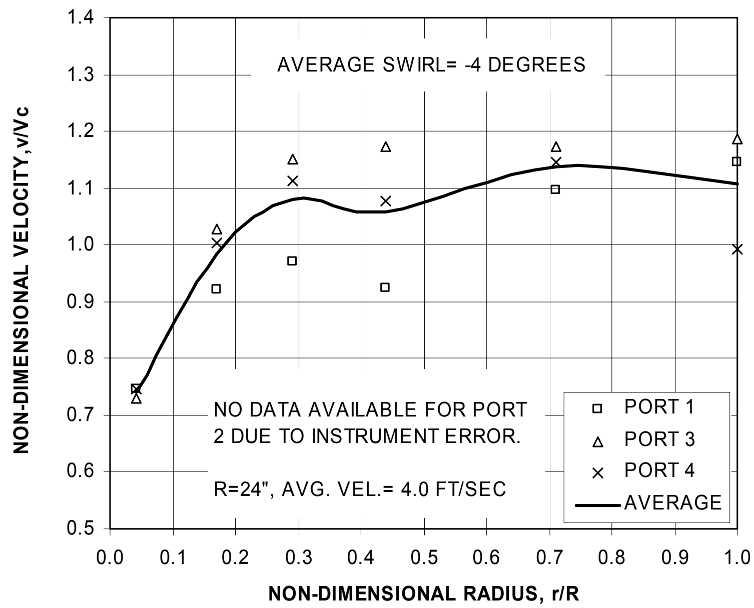


FIGURE 4-13 VELOCITY DISTRIBUTION AT TREATMENT FISH INJECTION LOCATION WITH 38 FT HEAD, 65.7 CFS, 235 RPM

4.6.3 Control Fish Injection

Velocity measurements taken just downstream from the control fish injection (slightly upstream from the end of the draft tube) without wicket gates indicate that at the BEP (335 rpm) and 80 ft head, the axial velocities are somewhat low in the center of the pipe and higher at the outside wall, especially near the bottom of the draft tube, as shown in Figure 4-14. Time averaged swirl angles are shown on Figure 4-15, indicating cells of flow rotating in different directions.

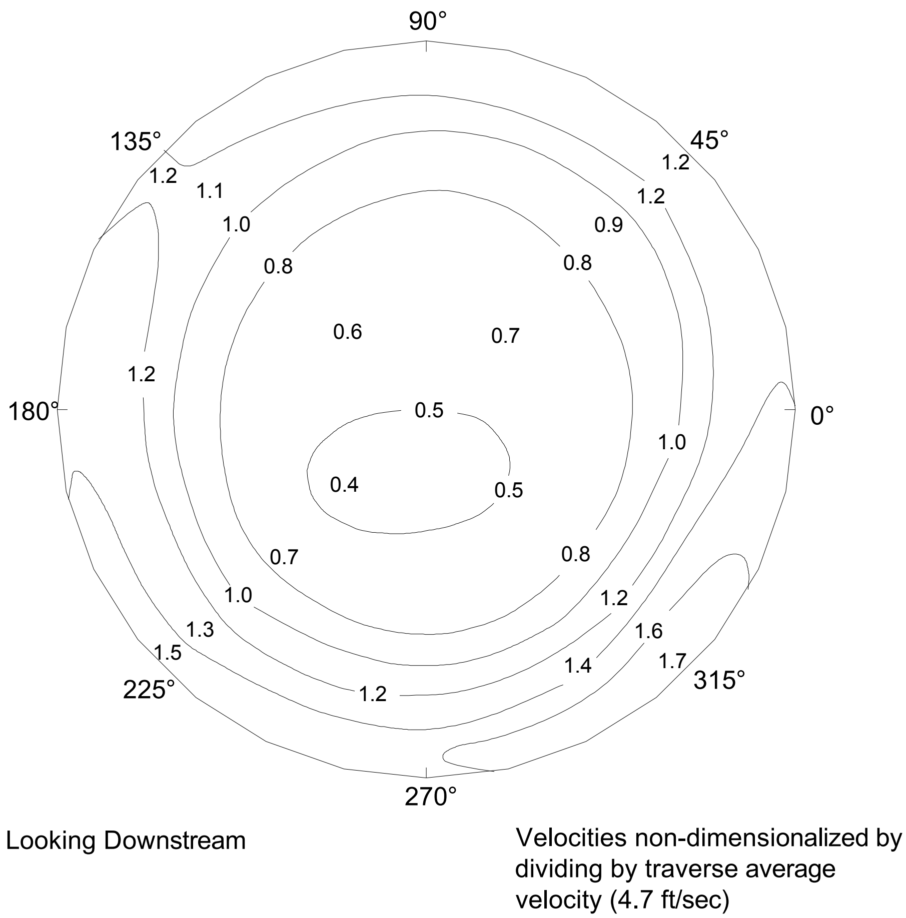


FIGURE 4-14 VELOCITY PROFILE AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 80 FT HEAD, 92.7 CFS, 335 RPM (BEP)

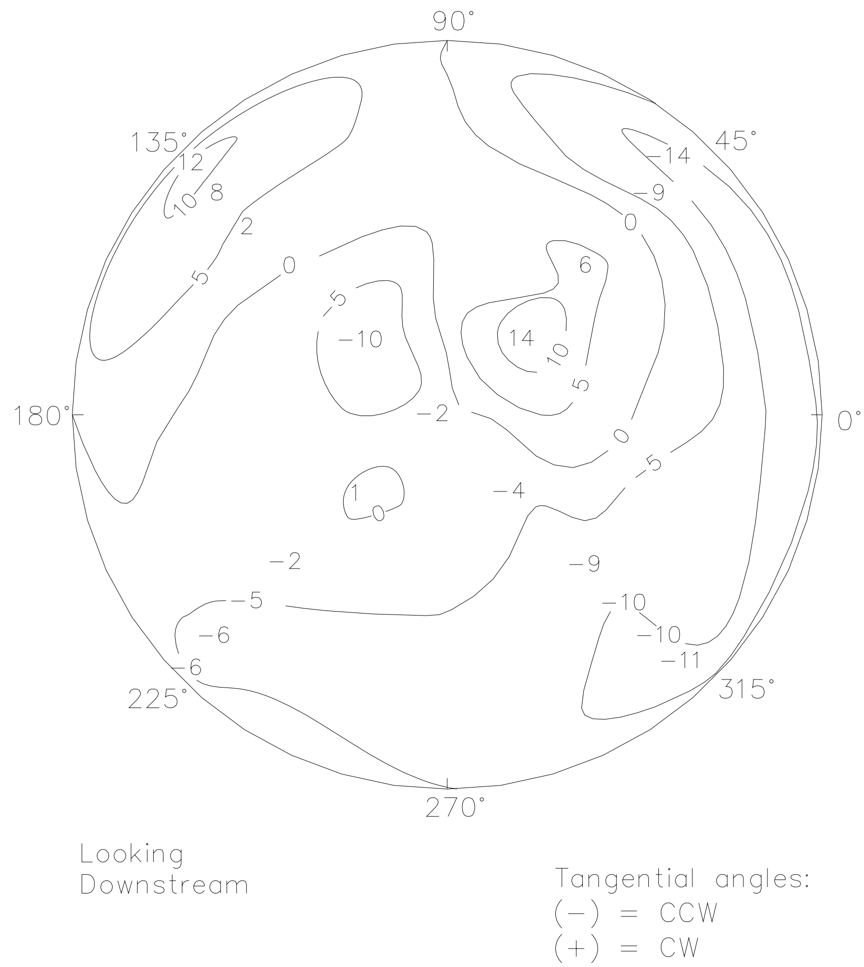


FIGURE 4-15 TANGENTIAL FLOW ANGLES AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 80 FT HEAD, 92.7 CFS, 335 RPM (BEP)

Theoretically, the flow pattern leaving the turbine should be the same at another head if tested at the BEP (i.e., the same φ) at that head. Velocity measurements with wicket gates at a 38 ft turbine head with 235 rpm and at an 80 ft head with 345 rpm confirmed the expected similar flow patterns. The resulting data, shown in Appendix F, Table F-8 and on Figures 4-16 and 4-17, indicate a similar axial velocity and similar tangential swirl angle distributions as the 80 ft BEP data on Figures 4-14 and 4-15.

Velocity data for the actual measured BEP wicket gate angle at the 80 ft condition is presented in Appendix F, Tables F-9 and F-10 and shown on Figures 4-18 and 4-19. Comparison of the axial velocities in Figure 4-18 (the actual measured BEP gate angle) with Figure 4-14 (the actual measured BEP without wicket gates) indicates that the wicket gates produced a more uniform axial velocity distribution at the end of the draft tube than produced without the wicket gates. However, tangential swirl angles were higher with the wicket gates in the actual measured BEP position (Figure 4-19) than for without wicket gates (Figure 4-15). As discussed in Appendix F, velocity measurements at different gate positions indicated that the residual swirl leaving the runner is sensitive to gate position.

Axial velocity data obtained without wicket gates (Figures F-5 and F-11) were used to determine a kinetic energy correction coefficient (α) of 1.5 for the average velocity head ($V^2/2g$) at the end of the draft tube. The kinetic energy correction coefficient at the BEP wicket gate position was determined to be 1.0 based on axial velocity data in Figures F-13 and F-16 in Appendix F. However, in accordance with the American National Standard Code, ASME-PTC 18-1992, a kinetic energy correction coefficient was not used to determine turbine head and efficiency.

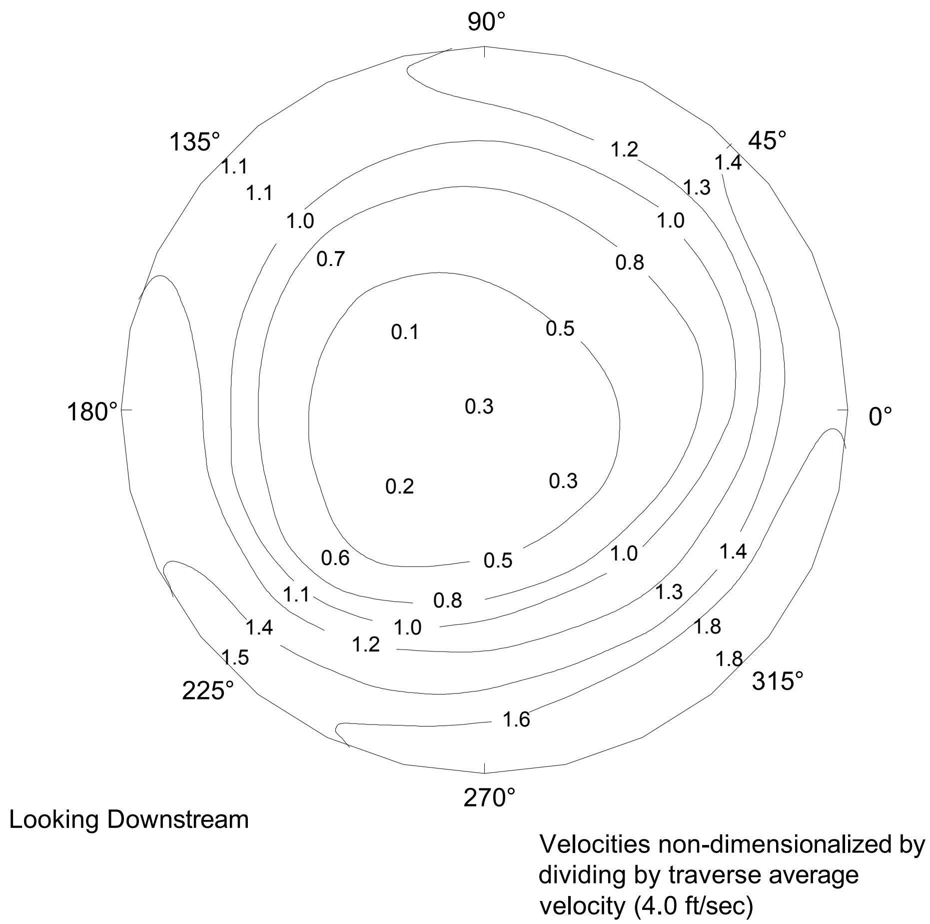


FIGURE 4-16 VELOCITY PROFILE AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 38 FT HEAD, 65.7 CFS, 235 RPM

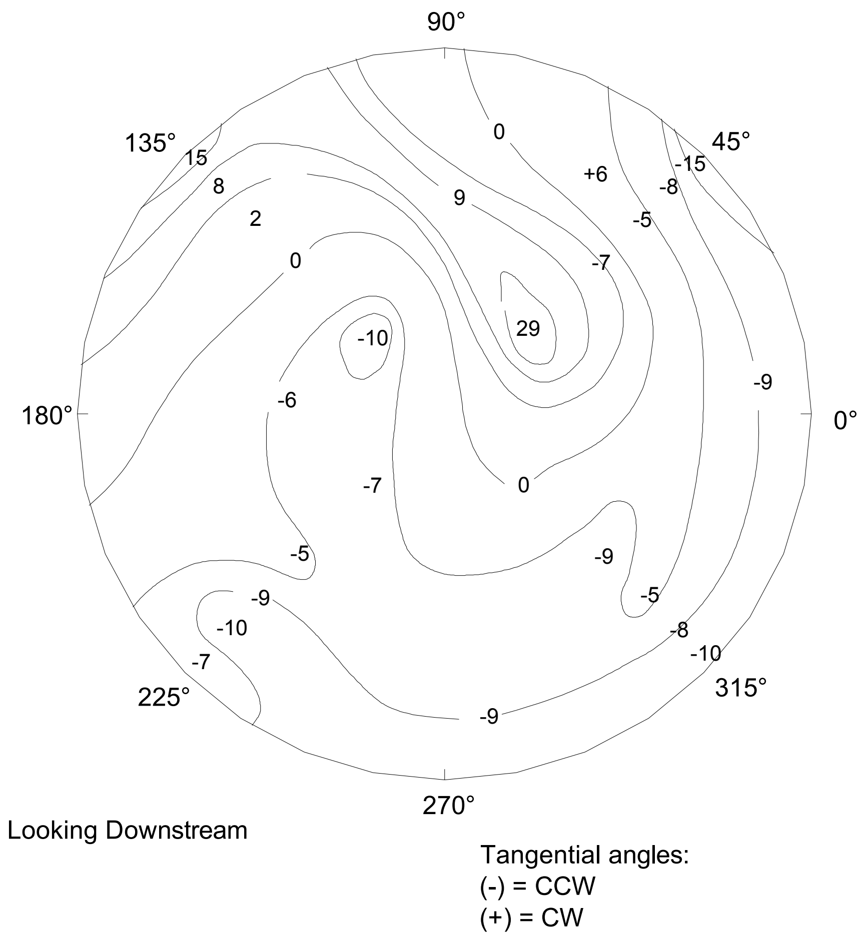


FIGURE 4-17 TANGENTIAL FLOW ANGLES AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 38 FT HEAD, 65.7 CFS, 235 RPM

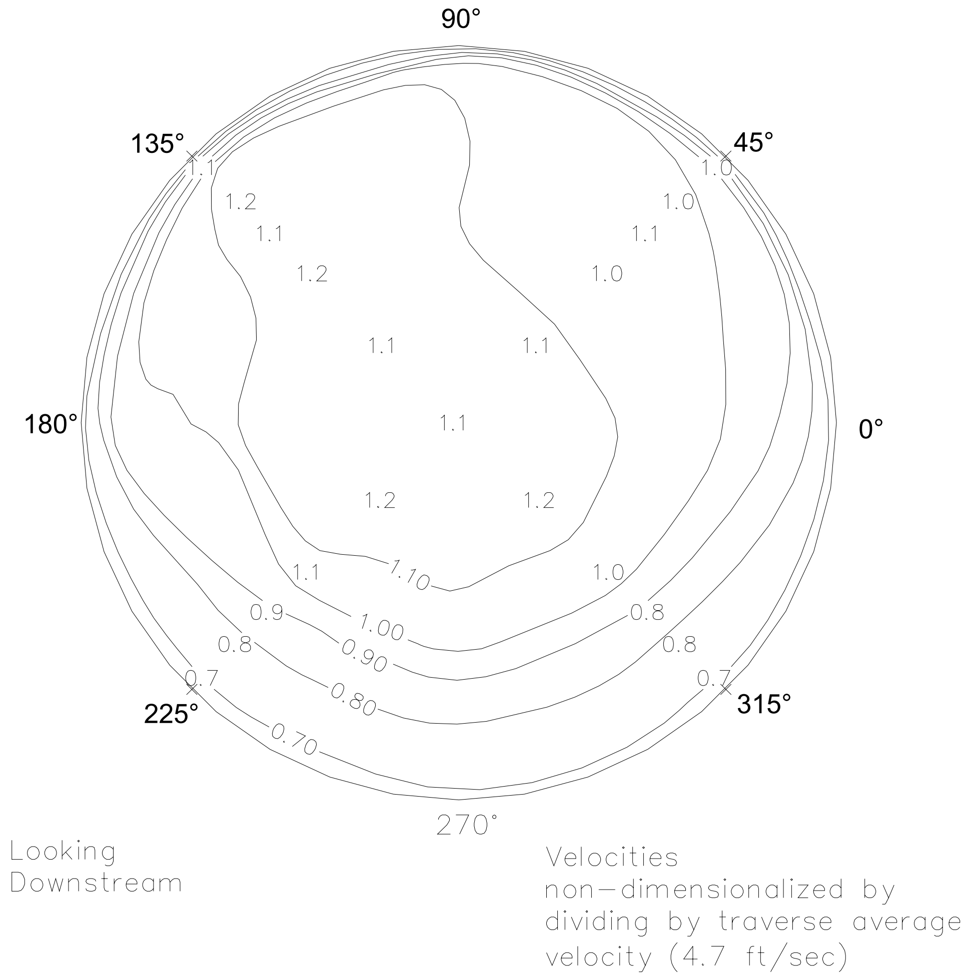


FIGURE 4-18 VELOCITY PROFILE AT CONTROL FISH INJECTION LOCATION WITH 18.2° WICKET GATE ANGLE (ACTUAL BEP), 80 FT HEAD, 92.7 CFS, 345 RPM

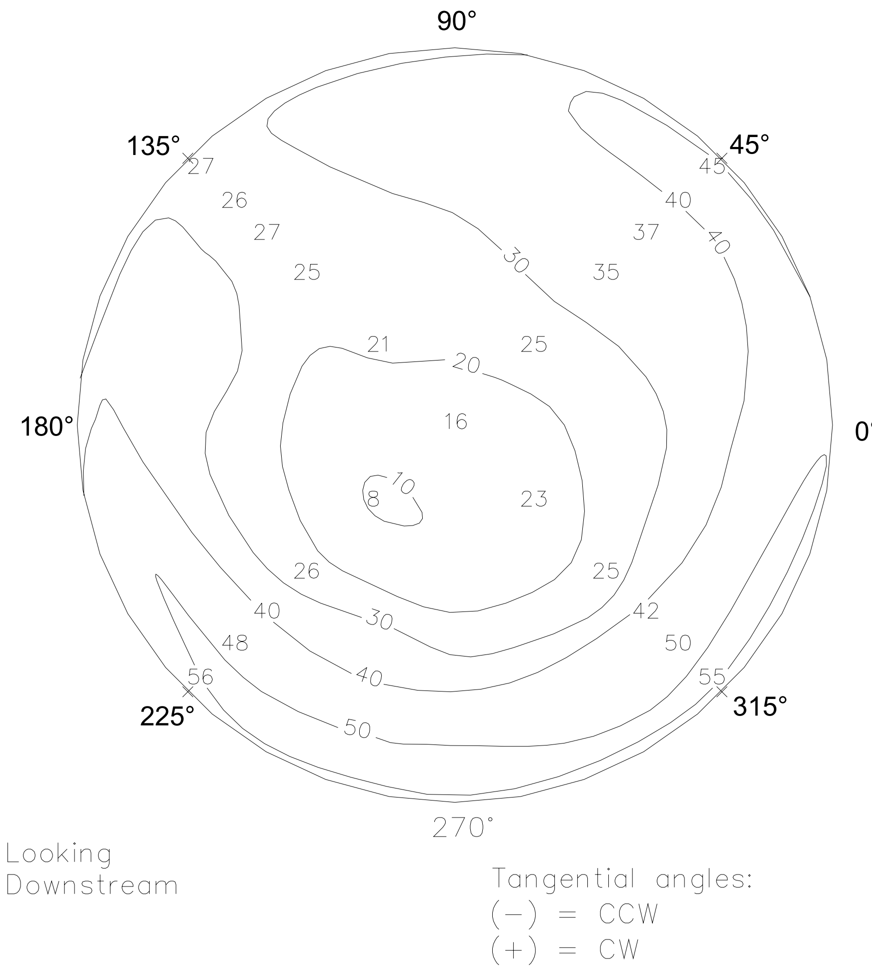


FIGURE 4-19 TANGENTIAL FLOW ANGLES AT CONTROL FISH INJECTION LOCATION WITH 18.2° WICKET GATE ANGLE, 80 FT HEAD, 92.7 CFS, 345 RPM

4.6.4 Turbine Runner Inlet

Runner inlet velocity measurements are presented in Appendix F, Table F-11. Measured radial angles of the absolute velocity ranged between 68.2° and 73.0° with the 18.2° wicket gate position (actual BEP) at the 40 ft and 80 ft head operating conditions. At the actual BEP gate position, the average radial angle was 70.3°, agreeing with the 69° design angle predicted with the original CFD analysis.

Measured absolute velocities in the downturn were 20.7 to 23.4 ft/sec at 40 ft and 29.0 to 32.4 ft/sec at 80 ft heads with the wicket gates at the BEP position (18.2°). These velocities are lower than the leading edge velocities shown on Figure 4-20 because the probe was located some distance away from the leading edge and velocities within the scroll decrease with distance from the center of the runner. The predicted velocity at the location of the measurements is 22.7 ft/sec compared to the 22.6 ft/sec average measured velocity for 40 ft head with the 18.2° gate position. At 80 ft head, the predicted velocity at the measured location is 33.2 ft/sec compared to the 31.1 ft/sec average measured velocity with the wicket gates at 18.2°.

At a 22° wicket gate position, which was the BEP gate angle predicted with the original CFD design, the average measured radial angle was 68.5° for the 40 ft head operating condition, compared to the original 69° design angle. The average measured velocity was 20.8 ft/sec, compared to the 22.7 ft/sec predicted velocity during the original design.

The runner inlet velocity measurements indicate that the original CFD analysis predicted flow angles and velocities at the leading edge of the runner with good accuracy, but overestimated the turbine flow for the design head.

4.7 Turbine Performance without Wicket Gates

Any energy conversion process has less than 100% efficiency due to internal losses. The efficiency of converting the hydraulic power inherent in a given flow and head to shaft power from the turbine runner, although less than 100%, is reasonably high compared to other energy conversions. Modern hydraulic turbines have efficiencies of 90% or higher. Defining efficiency as the shaft power output divided by the hydraulic power input,

$$\eta = \frac{\text{shaft output power}}{\text{hydraulic input power}} = \frac{P_{shaft}}{\gamma\, QH/550} \qquad \text{4-1}$$

where, for U.S. customary units:

η = efficiency (%)
P_{shaft} = turbine shaft output power (hp)
γ = specific weight of water, ($lb_f/ft^{3)}$
Q = flow (ft^3/sec)
H = turbine head (ft)

The shaft power output is calculated from

$$P_{shaft} = \omega T \quad 4\text{-}2$$

where ω is the angular velocity of the shaft and T is torque. In U.S. customary units,

$$P\ shaft = 2\ \pi\ n\ T\ /\ 550 \quad 4\text{-}3$$

where,

n = rotational rate (rev/sec)
T = torque (ft-lb_f)

Therefore, the efficiency of the pilot scale turbine is obtained from

$$\eta = 2\ \pi\ n\ T\ /\ \gamma\ Q\ H \quad 4\text{-}4$$

Variables included in Equation 4-4 were directly measured during the pilot scale testing. The overall efficiency of a turbine designed for a specific head, flow, and speed will diminish when operating at off-design points, i.e., a combination of higher or lower head, flow, or speed that results in a different phi value, as discussed below.

The basic test procedure was to set a turbine speed using the control system of the dynamometer and then vary the test loop pump speed until the head across the turbine was at the desired value. Each such operating point resulted in a measured flow and turbine output.

The turbine head, H, is the total dynamic head (TDH) and is defined as the static head plus the velocity head ($\alpha V^2/2g$) at the runner inlet minus the velocity head at the draft tube exit. Based on the measured velocity distribution at the control fish injection location, a kinetic energy correction factor of 1.5 was calculated for the flow conditions at the draft tube outlet without wicket gates, as discussed in Appendix F.

The full size runner (13 ft diameter) was designed for a head of 75 ft and a speed of 100 rpm. Due to the reduction in the pilot scale runner diameter by a factor of 3.25, the design speed of the pilot scale runner was expected to be 325 rpm to maintain the same blade tip speed and the same velocity triangle when tested at the design head of the full scale runner.

The design velocity triangle in the horizontal plane at a runner head of 75 ft is shown on Figure 4-20. Based on 1-D and 3-D CFD analyses, the absolute inlet velocity, V_1, is 38 ft/sec and is oriented at about 69° forward (downstream) from the radial direction (Cook et al. 2000). At 325 rpm, the blade tip speed, u, is 68 ft/sec. These two vectors result in a relative velocity of 35 ft/sec oriented essentially in line with the blade's leading edge to avoid flow separation.

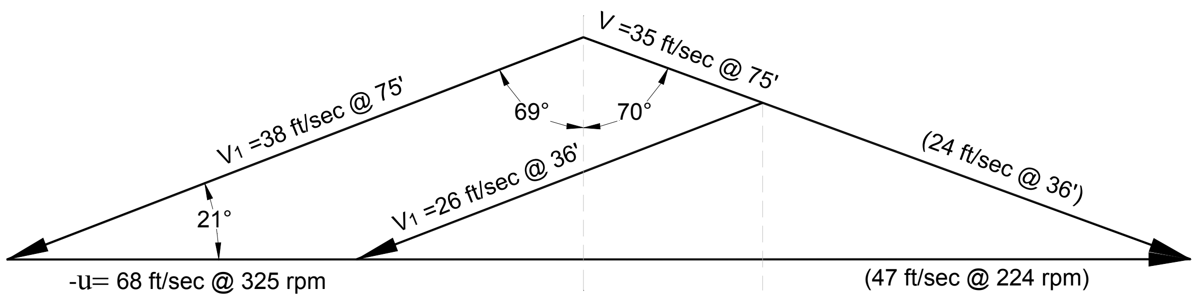


FIGURE 4-20 VECTOR DIAGRAM AT LEADING EDGE BASED ON CFD DESIGN

Figure 4-20 also shows the design velocity triangle at a runner head of 36 ft. Orientation of the absolute inlet velocity does not change since this is governed by the scroll geometry, but the magnitude decreases to about 26 ft/sec by the ratio of the square root of the heads. The blade tip speed at the BEP for 36 ft would decrease by the same ratio to 47 ft/sec to maintain the same relative velocity orientation, yielding a relative velocity magnitude of 24 ft/sec at a 36 ft head.

The runner head is developed by the moment of momentum in the approach flow, minus any residual moment of momentum leaving the runner (Daily 1961). Assuming the residual angular momentum at the runner exit is zero, as predicted by the initial CFD analysis, the theoretical runner head, H_r, is given by

$$H_r = u\, V_t / g \qquad \text{4-5}$$

where, u is the blade leading edge (tip) speed and V_t is the tangential velocity component of the inflow. This theoretical runner head is the maximum possible head assuming no losses. The "ideal" runner head is the head on the turbine minus losses in the scroll case and draft tube. The head on the turbine is the total energy at the scroll case inlet minus the total head at the draft tube outlet. These values were calculated by the data reduction system once the rotational speed, flow, and pressures at the scroll inlet and draft tube outlet were recorded.

Losses in the scroll case without wicket gates were measured for comparison to the CFD results. For this purpose, three static pressure ports were positioned around the circumference of the radial space near the runner inlet in the radial space. By adding the velocity head to these pressures, the total head at the runner inlet was calculated and subtracted from the total head at the scroll inlet to determine the scroll loss without wicket gates.

Due to the complex velocity distribution at the runner outlet, the total energy at the runner outlet could not be determined and, therefore, the loss in the draft tube could not be measured with any meaningful accuracy.

The actual runner head (H_a) is based on the measured output power and flow:

$$H_a = 2 \pi n T / \gamma Q \qquad 4\text{-}6$$

The ratio of the actual to the ideal runner head is the runner efficiency.

By maintaining a theoretical runner head (H_r) of about 75 ft at various rotational rates (rpm), the point of maximum efficiency of the turbine without wicket gates was determined to be just under 86.2% with a turbine head (H) of about 80 ft**,** as shown by the data in Table G-1 in Appendix G. The loss in the scroll case (without wicket gates or stay vanes) was about 1.2 ft at this operating point, which is consistent with the loss predicted during design. However, the rotation rate at this BEP was about 340 rpm, somewhat higher than the design value of 325 rpm. This higher measured speed may be explained by the -2° flow incidence angle (more radial) to the leading edge that was included in the original design. Increasing the rotation rate (rpm) would reduce this incidence angle and minimize flow separation at the leading edge. The flow at the BEP for 80 ft turbine head (75 ft runner head) was 92.7 cfs versus the design value of 94.7 cfs. Therefore, the actual velocity triangle at the leading edge is slightly different than design velocity triangle (Figure 4-20). Assuming the scroll case design controls the absolute inlet velocity angle (69º), the velocity triangle with measured flow and rotational speed for BEP operation without wicket gates is shown on Figure 4-21. This figure indicates relative velocities were slightly higher than originally predicted, and these changes are within the accuracy of CFD and the measurements.

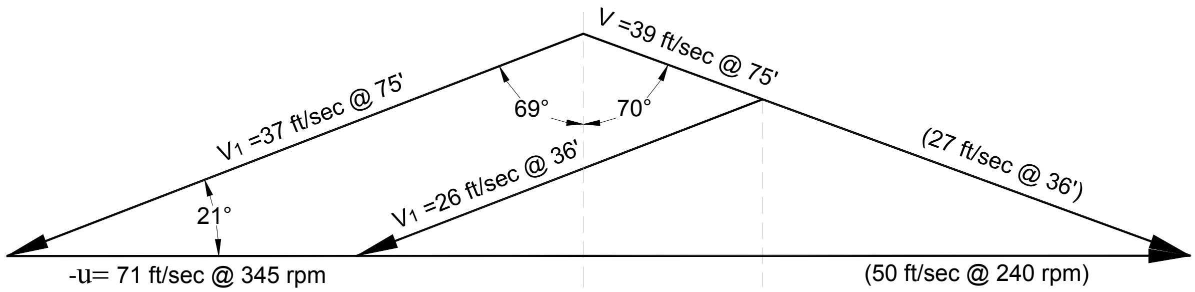


FIGURE 4-21 VECTOR DIAGRAM AT LEADING EDGE BASED ON PILOT SCALE TURBINE MEASUREMENTS WITHOUT WICKET GATES

Tests at other constant turbine heads produced the horsepower versus speed (rpm) data presented in Table G-1 (Appendix G) and shown on Figure 4-22. For each head, there is a speed which produced the maximum power, but the highest turbine efficiency is not at that speed. Turbine rpm versus turbine efficiency for various constant heads is shown in Figure 4-23, which indicates the BEP for each head and that the maximum efficiency generally increases with head. This trend is consistent with scale effects and will be discussed below in Section 4.10.

Turbine power performance is typically plotted against a non-dimensional parameter called phi (φ), which is the ratio of the blade tip speed to the spouting velocity, which is the maximum theoretical velocity for a given potential energy (head). With the turbine diameter in inches, the tip speed (in ft/sec) is

$$u = \pi \, n \, D/(60x12) \qquad 4\text{-}7$$

where D = turbine diameter in inches.

The spouting velocity is

$$(2gH)^{1/2} \qquad 4\text{-}8$$

Therefore, the ratio phi (φ) is

$$\varphi = n\, D/(1839H^{1/2}) \qquad 4\text{-}9$$

In effect, this is one of the homologous equations or dimensionless parameters for turbine performance and combines turbine rotation speed and head, rather than showing output and efficiency versus speed for constant heads separately as on Figures 4-22 and 4-23. By plotting turbine efficiency versus φ, a more general trend is evident, as shown on Figure 4-24, and the best efficiency for the various heads tested, slightly less than 86.5%, is at a φ of about 1.0. There is some difference in maximum efficiency and the best φ between the lowest and the highest head tested. These differences may be related to more scale effect at the lower head, as discussed in Section 4.10.

For the purpose of biological testing without wicket gates, φ values of 1.015 and 0.995 were selected for 80 ft and 38 ft turbine head BEP conditions, respectively. Operational setpoints for the two BEP test conditions without wicket gates were 1) 80 ft turbine head, 345 rpm, and 92.7 cfs; and, 2) 38 ft turbine head, 240 rpm, and 63.7 cfs.

Turbine performance is typically presented in the form of a "hill chart", in which the turbine output is plotted versus φ for various wicket gate openings, and contour lines of constant efficiency are super-imposed to determine the best operating point. Turbine output, P, is non-dimensionalized with the hydraulic input power, QH, in a "hill chart". Since Q is proportional to D^2V, area (D^2) times velocity (V), and V is proportional to $H^{1/2}$, the unit power, p_{11}, is expressed as

$$p_{11} = P/[(D/12)^2H^{3/2}] \qquad 4\text{-}10$$

Since the turbine had no wicket gates for these initial tests, there is only one line of data, as shown on Figure 4-25. Data points near phi (φ) equal to about 1.0 are at the BEP; other data are off the BEP. Subsequent tests with wicket gates allowed additional data to be plotted on the "hill chart", as presented in Section 4.8. Compared to other types of turbines, the unit power at the BEP (about 0.063) is relatively low, which can be attributed to the relatively small height of the radial space (or height of the future wicket gates) for the diameter of the runner. This feature, dictated by the biological criteria for low flow-induced shear in the runner, reduces the inflow for a given head. An increase in height of the radial space and, therefore, in power and unit power may be achievable with a redesign of the runner, assuming the favorable hydraulics needed for safe fish passage can be maintained in the design.

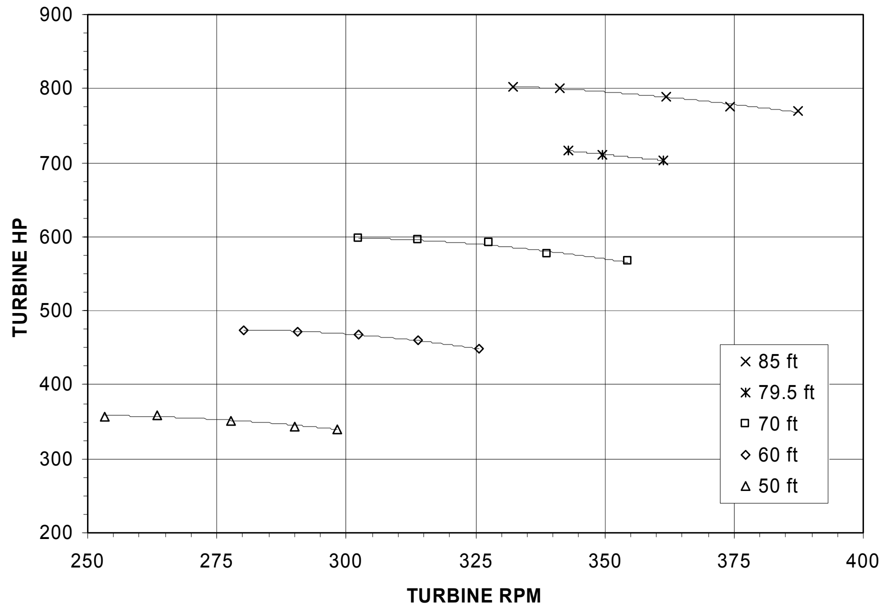


FIGURE 4-22 TURBINE POWER VERSUS SPEED (RPM) WITHOUT WICKET GATES

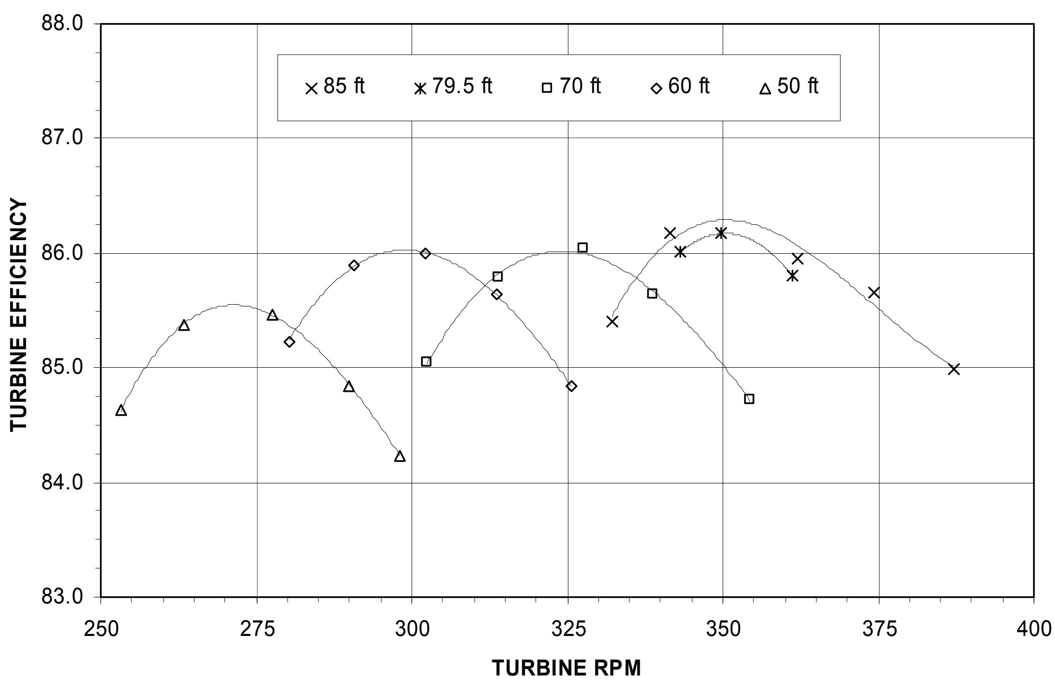


FIGURE 4-23 TURBINE EFFICIENCY VERSUS SPEED (RPM) WITHOUT WICKET GATES

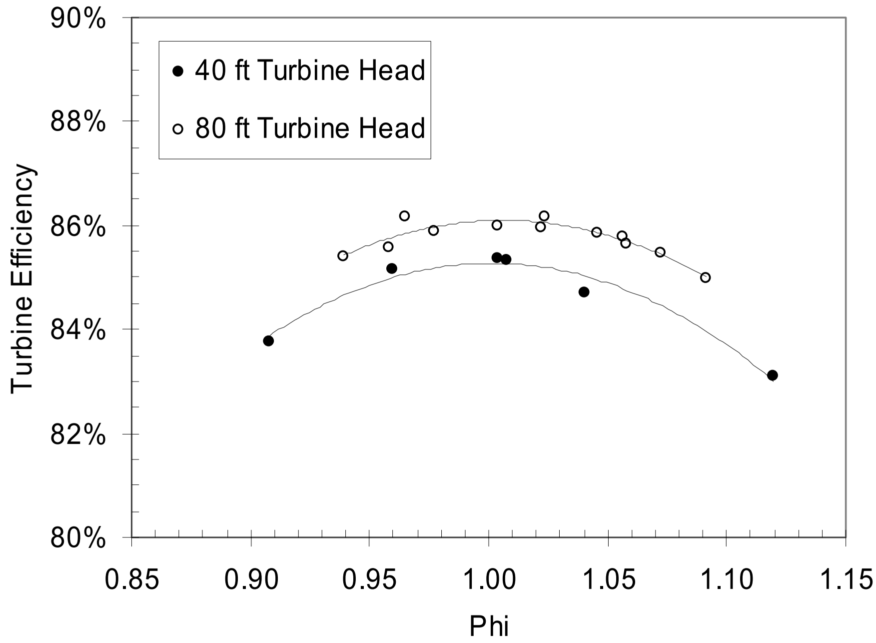


FIGURE 4-24 EFFICIENCY VERSUS PHI (φ) WITHOUT WICKET GATES

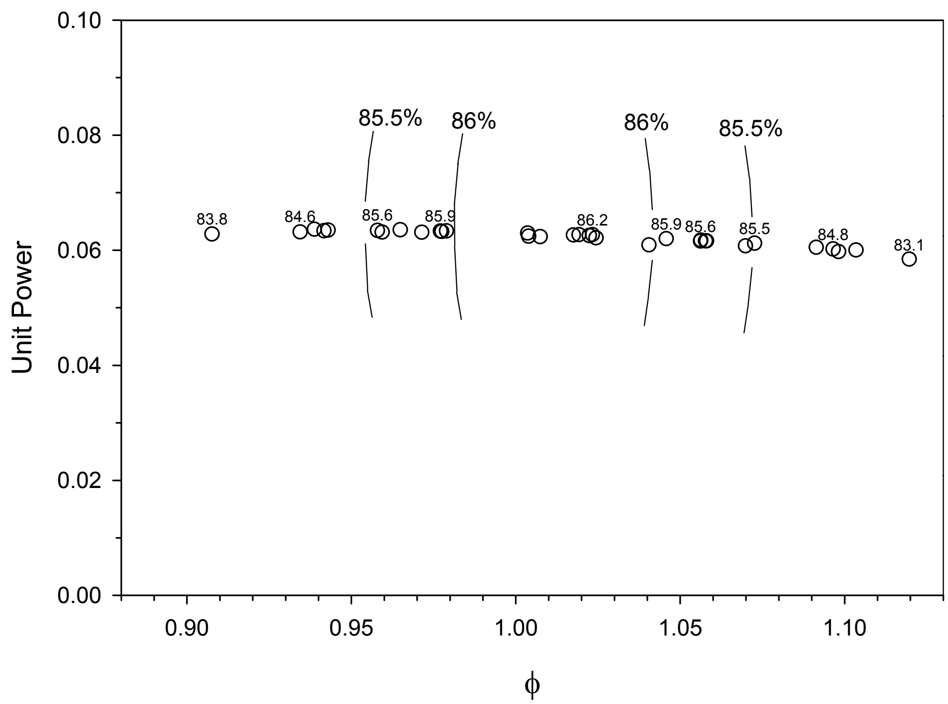


FIGURE 4-25 UNIT POWER VERSUS PHI (φ) WITHOUT WICKET GATES

Power for the pilot scale turbine was about 720 HP at a turbine head of 80 ft, as measured (Figure 4-22) and as calculated using equation 4-10, with the unit power of 0.063. Specific speed (n_s) is calculated from:

$$n_s = n\ P^{1/2} / H^{5/4} \qquad \text{4-11}$$

At a turbine head of 80 ft and a speed of 345 rpm (i.e., the BEP), the specific speed for the turbine without wicket gates was about 39, which is somewhat lower than specific speeds for other types of turbines at that head. This lower specific speed is due to the lower power density of the Alden/Concepts NREC turbine, as discussed above.

4.8 Preliminary Engineering Tests with Wicket Gates

In December 2001, following biological testing of the turbine without wicket gates, the pilot scale test facility was drained and the turbine dismantled for installation of the wicket gates. Preliminary tests were conducted in April 2002 to determine the BEP gate position for the spring biological tests with rainbow trout for comparison to the results from the fall of 2001 biological tests without wicket gates. Additional preliminary engineering tests were conducted in June and September-November 2002 to obtain more data about the test loop operation and to incorporate instrumentation changes that better defined turbine performance. Final engineering tests were conducted in December 2002 and January 2003 to better define the operating characteristics of the turbine.

The full open wicket gate position on the pilot scale turbine was structurally limited by the geometry of the scroll case downturn to 38.5º from fully closed. The BEP wicket gate position predicted by CFD analysis was 22º from the fully closed position. Each gate had an indicator ranging from -22º (fully closed) to +16.5º (fully open), with the 0º angle equal to the predicted BEP angle (22º from fully closed). A negative indicated angle corresponded to a more closed gate position while a positive indicated angle corresponded to a more open gate position. Wicket gate positions presented in this report refer to the gate angle from the fully closed position (0º to 38.5º).

4.8.1 April 2002 Preliminary Engineering Tests with Wicket Gates

Preliminary tests with wicket gates were conducted in April 2002 to identify the BEP wicket gate position and the value of φ to be tested with rainbow trout for comparison to the test results without wicket gates. The preliminary engineering wicket gate tests were conducted at gate angles of 16°, 18°, 20°, 22°, and 24° open from full closed to bracket the expected BEP wicket gate positions. Tests for each gate position were conducted at turbine heads of 38 ft and 80 ft with varying turbine speeds.

Tests at a 14º wicket gate angle were also attempted, but data could not be obtained at the 38 ft turbine head. The dynamometer could not control the turbine at a low enough speed for the flow at the 38 ft head. To limit potential damage to the turbine because of vibrations at the 14º position, no tests at a higher head were conducted.

The preliminary engineering data that was obtained in April for the five gate positions are presented in Table G-2 (Appendix G). Plots of highest measured turbine efficiency for each wicket gate position versus gate angle for the 38 ft and 80 ft turbine head data are presented on Figure 4-26.

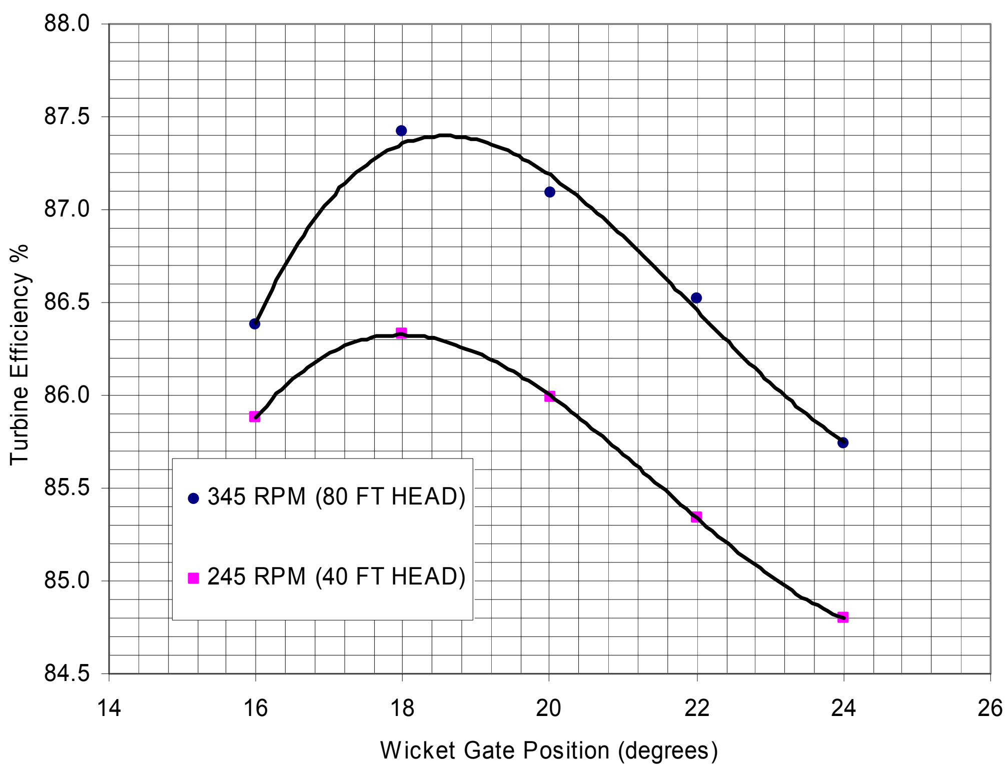


FIGURE 4-26 TURBINE EFFICIENCY VERSUS WICKET GATE POSITION BASED ON APRIL PRELIMINARY TEST DATA

The wicket gate BEP position was selected at 18.2º based on Figure 4-26. Measured turbine efficiency versus Phi (φ) for the 18.2º gate position is shown on Figure 4-27. Phi (φ) values of 1.015 and 0.990 were selected for the high and low BEP test heads. Turbine speeds of 345 rpm and 240 rpm were selected to allow a valid comparison of the biological tests with wicket gates to tests without wicket gates. Turbine heads of 80 ft and 40 ft provided the BEP φ values for the 345 rpm and 240 rpm speed, respectively. The resulting operational setpoints for the two BEP test conditions with wicket gates were 1) 80 ft head, 345 rpm, and 84.1 cfs; and, 2) 40 ft head, 240 rpm, and 60.6 cfs.

Figure 4-28 shows the minimum width between the gates at four gate positions. The relationship between minimum width and percent gate open area versus gate angle is not linear, as shown on Figure 4-29. Analysis of the preliminary engineering test data determined that the BEP occurred at an 18.2° wicket gate angle, about 4° more closed than the BEP gate angle indicated by the CFD analysis. A more detailed discussion of this difference is provided in Section 7.0.

The spring and fall 2002 biological tests were conducted at the two setpoints described above. However, during the spring biological testing, the turbine efficiency varied over a 0.2% range at the 40 ft/240 rpm condition and 0.6% at the 80 ft/345 rpm condition, as shown on Table G-3 (Appendix G) and Table G-4 (Appendix G), respectively. During the fall tests at the 40 ft/240 rpm setpoints, the turbine efficiency varied 1.0%, as shown in Table G-5 (Appendix G). The turbine efficiency during the spring biological tests was lower than the peak efficiency measured during the preliminary engineering tests (Figures 4-25 and 4-26). The BEP efficiency during biological testing was 0.9% lower at the 40 ft/240 rpm set point and 0.7% lower at 80 ft/345 rpm set point. Because of these measured differences in efficiency, additional preliminary engineering tests were conducted to obtain more data about the test loop operation and, if required, to incorporate instrumentation changes that would more accurately define the turbine performance characteristics with the final engineering tests. These additional engineering tests were performed while the biological tests with wicket gates were being completed.

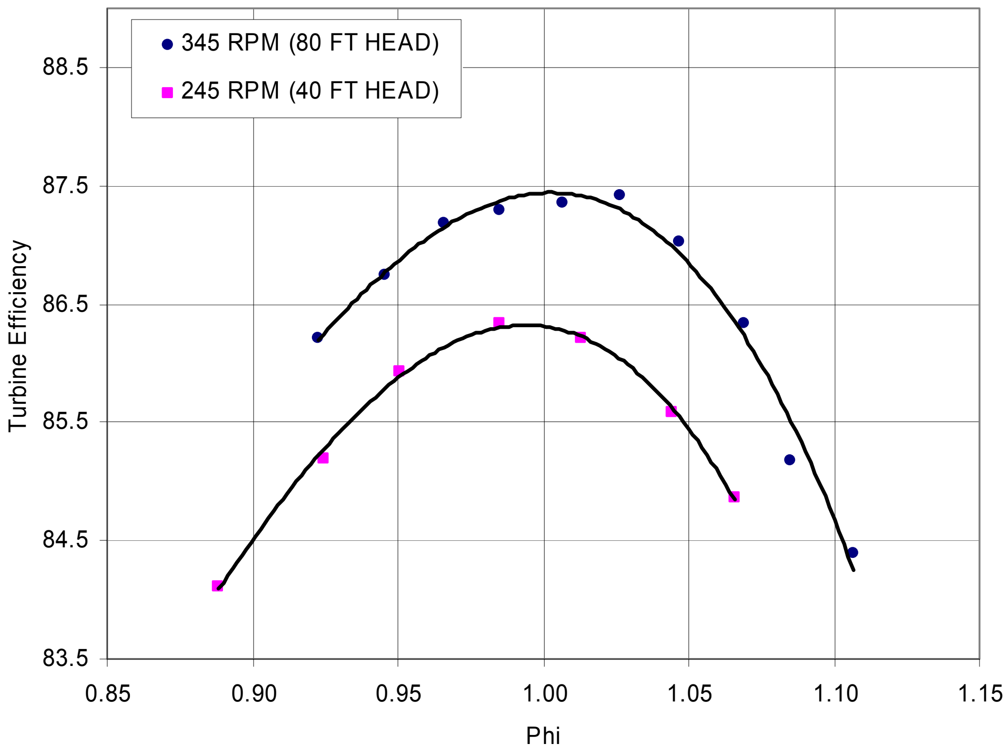


FIGURE 4-27 TURBINE EFFICIENCY VERSUS PHI (φ) FOR 18.2 ° WICKET GATE GATE POSITION BASED ON APRIL PRELIMINARY TEST DATA

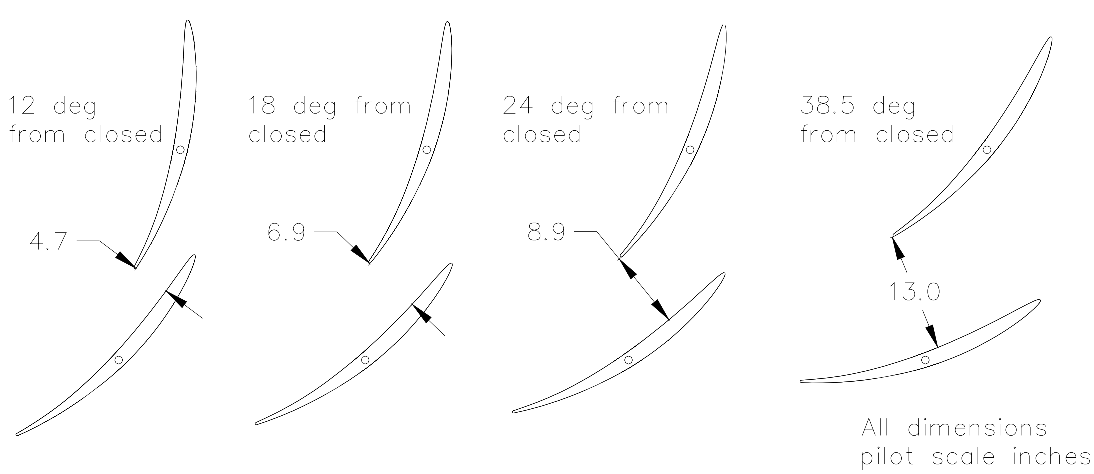


FIGURE 4-28 MINIMUM WIDTH BETWEEN WICKET GATES

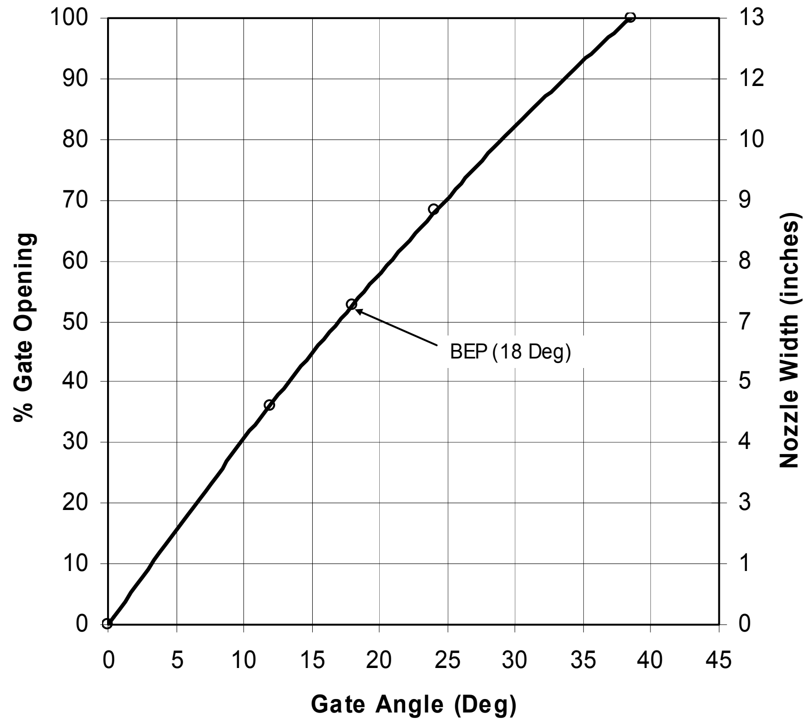


FIGURE 4-29 WICKET GATE OPEN AREA AND NOZZLE WIDTH VERSUS ANGLE FROM CLOSED POSITION

4.8.2 June 2002 Preliminary Engineering Tests with Wicket Gates

Additional engineering tests were conducted at wicket gate angles of 16°, 18°, 24°, 26°, and 28° open from fully closed. The 16°, 18°, and 24° gate tests included repeat tests for the April data and tests at φ values lower and higher than the φ's tested in April to expand the Hill Chart. Tests at the 26° and 28° gate angles were conducted to obtain data at more open gate positions. Tests for each gate position were conducted at varying turbine heads around 38 ft (37.3 ft to 49.2 ft) and 80 ft (67.6 ft to 81.7 ft) with varying turbine speeds.

The preliminary engineering data for the five gate positions tested in June are presented in Table G-6 (Appendix G). Plots of highest measured turbine efficiency versus gate angle for the 38 ft and 80 ft turbine head tests are presented on Figures 4-30 for the June data. Measured turbine efficiency versus Phi (φ) for the 18.2º gate position is shown on Figure 4-31. The June data indicated a BEP similar to the BEP selected from the April data (18.2º gate angle and φ = 1.015 and 0.990 the high and low test heads (nominal 38 ft and 80 ft). However, a comparison of the April (Table G-1) and June (Table G-6) engineering data indicates that the turbine efficiency based on the June data was 0.5 to 1.0% lower than the efficiency based on the April data. The lower efficiency in the June engineering data was similar to the lower BEP efficiencies at both head/speed conditions found during the spring 2002 biological tests (Tables G-3 and G-4).

Turbine seal wear (increased leakage) and extraneous torque (dynamometer oil hose effects) were possible explanations for this lower efficiency, and additional tests were conducted to investigate the variations in measured efficiency, as discussed in the following sections. Oil hose effects could have resulted from changes in the hose characteristics or pressure. Bottom seal wear may have occurred during the April wicket gate tests at off-BEP positions when the turbine was subjected to significant vibrations while operating with large gate openings.

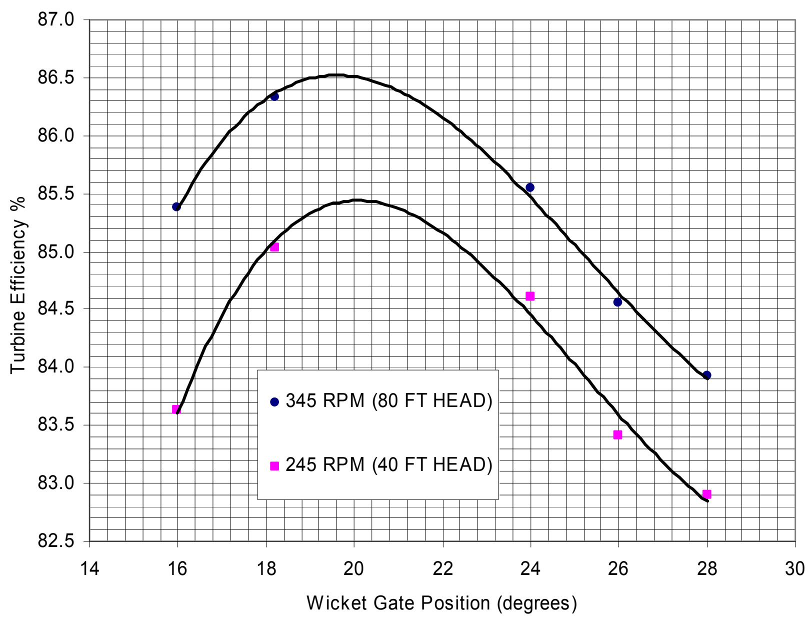


FIGURE 4-30 TURBINE EFFICIENCY VERSUS WICKET GATE POSITION BASED ON JUNE PRELIMINARY TEST DATA

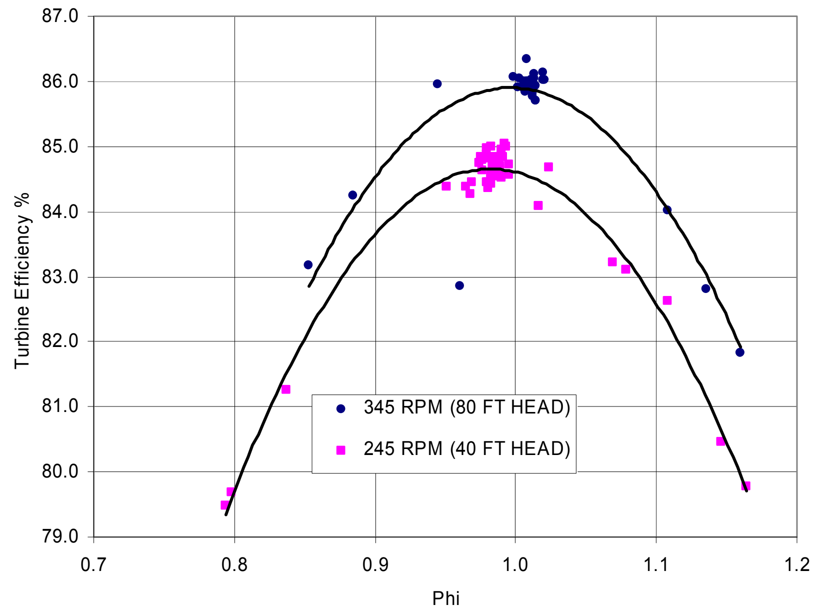


FIGURE 4-31 TURBINE EFFICIENCY VERSUS PHI (φ) FOR 18.2° WICKET GATE POSITION BASED ON JUNE PRELIMINARY TEST DATA

4.8.3 Test Loop Instrumentation Tests

Preliminary engineering tests with and without the wicket gates included a number of tests designed to verify proper operation of the test loop instrumentation and acceptable data collection. Concerns that these tests addressed were:

- dynamometer oil hose characteristics effects on torque measurements
- dynamometer oil hose pressure effects on torque measurements
- temperature effects on torque load cell power supply and raw signal\
- preload effects on torque measurements
- stability of torque zero with no turbine load
- torque load cell stability during operation
- variations in torque load cell calibrations
- test loop head and flow pressure transducer stability
- uniformity of piezometric tap measurement for turbine head
- uniformity of piezometric tap measurement for test loop flow

- *in situ* differential pressure cell calibrations
- scroll expansion effects on turbine inlet flow patterns and velocity head
- bearing friction effects on turbine efficiency
- runner downthrust effects on turbine efficiency
- shaft seal flow effects on turbine efficiency
- runner bottom seal leakage effects on turbine efficiency

Test data and a discussion of each of theses concerns are presented in Appendix H. Key findings of the preliminary instrumentation tests are summarized in the following sections.

Dynamometer Oil Hose Characteristics **-** Turbine efficiency during the biological tests with wicket gates in the spring 2002 for the two head conditions did not show any obvious trends in the torque measurements (efficiency). The data, which is summarized in Appendix H, Table H-1, indicated that characteristics of the three different oil hoses that were used on the dynamometer had negligible effects on the measured torque at the lower head/speed condition (40 ft/240 rpm condition). At the 80 ft/345 rpm condition, the average measured efficiency with the second 150 psi temporary hose was greater than the average efficiency with the original 150 psi and the 200 psi hose. However, the average BEP efficiency for each hose was within 0.3% of the average BEP efficiencies for all of the hoses.

Additional engineering tests were conducted at oil temperatures ranging between 90º F and 150º F to verify that oil temperature did not affect the dynamometer torque measurements. The measured turbine torques and efficiencies for oil temperatures tested, which are summarized in Appendix H, Table H-2, conclusively proved that oil temperature did not affect the dynamometer torque measurements.

Dynamometer Oil Hose Pressure **-** Tests were conducted with no rotation on the turbine and with and without the oil pump operating at various oil temperatures to determine if pressure in the dynamometer oil hose could affect the torque load cell. These test results, which are summarized in Appendix H, Table H-3, indicated that there is less than 1 ft-lb torque difference between the zero load cell reading with and without oil pressure. These test results indicated that the oil pressure had negligible affects on the torque measurement.

Torque Load Cell Power Supply and Raw Signal Temperature Effects - Tests were conducted at various air temperatures to investigate temperature effects on the load cell power supply and raw signal. Test data recorded with the turbine operating at the 40 ft/240 rpm and 80 ft/345 rpm setpoint and with the power supply at various air temperatures, as shown in Appendix H, Table H-4, indicated that the supply voltage was constant at all ambient temperatures. Since the stability of the load cell is directly related to the stability of the power supply, the constant supply voltage at different air temperatures for all of the test conditions indicated that temperature did not affect the power supply and the load cell (torque) measurements.

The raw (un-amplified) signal from the load cell was also recorded for several calibrations and was found to correlate well with the (amplified) voltage used in the loop data acquisition system, as shown in Appendix H, Table H-5. These data indicated that the amplifier system was stable and consistent with the raw voltage produced by the load cell.

Dynamometer Preload Tests - Preload tests were conducted to determine if the operating point on the load cell affected the measured turbine efficiency at the 40 ft and 80 ft test conditions. The calibration arm system was used to apply a preload to the load cell such that the signal magnitude at the lower torque (40 ft head) condition would be similar (or higher) to that normally produced by the 80 ft operation condition. Applying preload also shifted the load cell operating point into a region of lower hysteresis (friction in load cell linkage and calibration arm), which was found to be present in the system at the lower loadings by the calibrations.

The addition of the preload to the 40 ft operating condition shifted the load cell signal to approximately 1 volt above that produced by the 80 ft condition. The measured efficiency at the 40 ft head remained approximately 1% below that of the 80 ft head condition, as shown in Appendix H, Table H-6. This difference was consistent with the efficiency measurements without the preload at the 40 ft operating condition.

All preload data initially collected were lower than typically measured during biological tests. Because of this shift, the tests were repeated and efficiency data were first collected without the preload and then, while the turbine was operating, the calibration arm and preload was installed and measurements were repeated. The arm was removed and installed again that day and was left in place when the system was shut down. When the test loop flow stopped, a tare of the additional load (preload) was taken and the data collected with the preload installed was post-processed to calculate efficiency.

The results (Appendix H, Table H-6) were identical to the earlier preload tests, in that the turbine efficiency was independent of the load cell operating point; with and without the preload. These results indicate that the operating point of the load cell, in terms of voltage, did not produce a shift in the measured turbine efficiency at the 40 ft and 80 ft test conditions.

Stability of Torque Zero with No Turbine Load - Measurements of indicated torque (torque used to calculate turbine power and efficiency) showed a residual drag of -13 ft-lbs to 30 ft-lbs in the morning before starting the test loop with the oil system on and off, as shown in Appendix H,

Table H-7. Daily posttest torque measurements (Appendix H, Table H-7) indicated a residual drag of 40 ft-lbs to 60 ft-lbs. When the dynamometer brake system was manually shaken, or the oil system was turned back on, the residual torque dropped to less than 12 ft-lbs. If the brake was not shaken at the end of a test day, the residual torque was found to diminish somewhat overnight and return to within 12 ft-lbs of zero when the oil system was turned on the next morning. These posttest torque values show that when the test loop was shutdown at the end of the day, there was a substantial residual drag on the load cell. However, these high posttest torques were easily reduced to a negligible value (less than 12 lb-ft) either by shaking the brake system, or turning on the oil pump. This "offset" torque (less than 12 ft-lbs), which amounts to about 0.1% of the torque at the 80 ft turbine head condition, was not considered significant enough to correct measurements, but was included in the uncertainty analysis for the final engineering performance test data.

Load Cell Stability During Operation - The stability of the original torque load cell during operation was evaluated by monitoring turbine performance at various temperatures that were experienced in the test facility. Temperature sensors were installed to document:

- load cell body temperature
- air temperature near the load cell
- temperature of the load cell electronics module
- oil temperature (dynamometer lube flow)
- outside air temperature.

During all of the biological testing in September, these temperature measurements did not indicate any trends associated with oil temperature and load cell body and air temperatures changes. Turbine efficiency increased about 0.5% over the course of a day with load cell electronics temperature increases of 10° F (Appendix H, Figure H-8).

Tests were conducted to isolate the temperature effects of the oil and the load cell electronics. While at the 80 ft operating point and maintaining a constant electronics temperature, the dynamometer oil temperature was allowed to increase from 105° F to 135° F. Standard performance measurements for these operating temperatures, as shown in Appendix H, Table H-8, showed clearly that the oil temperature did not affect the recorded efficiency and that the oil temperature did not affect the characteristics of the oil hose connected to the dynamometer as discussed above.

During tests at the 40 ft operating point while maintaining constant oil temperature, an electric heater was used to raise the temperature of the panel containing the load cell electronics module.

The load cell electronics were heated from 80° F to 95° F over the course of one hour. Performance measurements, which are presented in Appendix H, Table H-8, indicated that efficiency increased steadily by 0.25% with the increasing load cell electronics temperature were recorded periodically throughout the hour. All other temperatures (air, oil, load cell body) remained constant within 2° to 3° F. These results/observations indicated that the load cell system supplied with the dynamometer was not stable at the two operating points. The calibration stability discussed in the following section verified the need to replace the load cell for the final engineering tests.

Variations in Torque Load Cell Calibrations - The first four torque load calibrations, which were conducted during the fall 2002 tests without wicket gates and the spring 2002 tests with wicket gates, produced cell coefficients that were within 0.75% of each other. These initial calibrations indicated that the uncertainty of the torque measurements was about 0.75%. In order to obtain additional data about the stability of torque measurement load cell which was supplied with the dynamometer, additional load cell calibrations were conducted between September 5 and October 10, 2002. Although the load cell calibrations were fairly stable throughout the test period, as shown in Appendix H, Table H-9, the cell had two significant shifts (0.4% and 0.8%) for no apparent reason. In general, over the September 2002 test period, the stability of the load cell was less than desired (i.e., drifted greater than 0.2%). For these reasons, the load cell which was supplied with the dynamometer was replaced with one sized for the actual torques generated by the turbine. The original load cell was sized for testing turbine power on the order of 1,000 hp with capacity for up to 1,800 HP for off-BEP testing, while the replacement load cell was sized for the 400-800 HP measured torques at the 40 ft and 80 ft head conditions.

Loop Head and Flow Pressure Transducers - During the fall 2002 biological testing, "end of the day" recordings of the test loop flow and the turbine head measurement transducers were obtained with flow in the system completely stopped. These measurements were obtained to verify that the difference in measured turbine efficiency at the two test heads was not due to measurement errors, including possible air accumulation in the manometer lines during tests. As shown in Appendix H, Table H-10, the measurements yielded deflections of less than 0.002 ft and 0.083 ft for the flow and turbine head transducers, respectively. The zero offsets for flow and head were deemed to be negligible relative to turbine efficiency and the transducers were considered adequate for the final engineering tests. A 0.002 ft correction in the flow measurement deflection would have amounted to less than 0.01% in overall turbine efficiency. Correction of the data for the 0.08 ft head offset would have produced a 0.1% increase in overall turbine efficiency at the 40ft condition and 0.05% at the 80 ft condition.

Uniformity of Piezometric Tap Measurements for Turbine Head - A survey of the pressure taps at the 40 ft operating point indicated that the maximum deviation within the four inlet pressure taps was 0.066 ft and 0.05 ft within the four draft tube pressure taps, which was well below the 20% velocity head limits at both locations and the 1% net head limit (0.4 ft). This data, which is presented in Appendix H, Table H-11, indicated that there was no significant tap effect influencing the reliability of the turbine head measurement.

Uniformity of Test Loop Flow Measurements - Measured turbine efficiency during the spring 2002 biological tests with wicket gates was lower than the measured efficiency during preliminary testing. Because of these variations in efficiency, surveys of the flow meter pressure taps were conducted in September 2002 during the scheduled biological tests. The piezometer readings in each of the venturi taps (inlet and throat) were individually measured using the same methodology used to survey the turbine head taps, as discussed in Appendix H.

Table H-12 in Appendix H presents the results of these surveys at the 40 ft and 80 ft BEP operating setpoints. The initial surveys on September 20th, 23rd, and 24th identified lower differential pressures using the top inlet and throat taps than differential pressure using the manifolded taps, corresponding to lower indicated flows. Additional surveys were completed on September 26th and October 1st to verify the results of the previous surveys and to fully document the pressure measurements on the flow meter. Although the effect on flow could not be determined from these measurements, the difference in indicated flow between the upper and lower taps was on the order of 1%.

The test loop was opened and the flow meter was inspected on October 3, 2002 prior to final engineering tests. This inspection focused on the flow meter pressure taps and the meter throat for any deposit or organic growth that could have affected the indicated flow. Although nothing was found within the meter itself, the inspection revealed that the rubber gasket used in the pipe flanges immediately upstream of the meter had been installed such that the gasket material projected into the flow a maximum of approximately 1.5 inches at the top of the pipe. The lower pressure readings on the upper taps in the meter inlet and throat which were obtained during the tap surveys conducted on September 26 and October 1 (with the gasket protruding) were consistent with pressures that would be expected with the upper taps being in the wake of the protruding gasket.

Construction records indicated that this flange had been loosened by the general contractor to adjust a minor misalignment of the test loop pipe during installation of the turbine scroll case. This pipe adjustment was made after the test loop had been inspected by Alden personnel, but prior to initial operation in the fall 2001. Therefore, the gasket was protruding in the pipe prior to the initial engineering tests without wicket gates and was in the flow for the engineering and biological testing with the wicket gates up to the October 3 inspection.

The protruding gasket was trimmed and surveys of the flow meter tap pressures were repeated on October 4 at the 40 ft and 80 ft operating setpoints. The survey data without the protruding gasket, which is presented in Table H-12, showed very uniform pressures at both taps sets and at both operating points. These data with the gasket corrected indicated there was no reason to suspect the meter was not performing as it did during its calibration in October 2000.

Tests with the corrected gasket determined that the previous test loop flows, with the protruding gasket, were 1.81% low at the 80 ft operating point and 1.91% low at the 40 ft point. An average correction factor of 1.0186 was applied to all flow measurements obtained before October 3, 2002. The effect of this increase in flow after correcting the gasket was to reduce the calculated turbine efficiencies by 1.86%.

In Situ Differential Pressure Cell Calibrations - *In situ* calibrations of the turbine head and the test loop flow meter differential pressure cells were completed prior to the final engineering tests. The *in situ* calibrations, which are provided in Appendix G, were all essentially the same as the previous calibrations (± 0.1%) that were conducted in Alden's Calibration Department.

As part of this *in situ* calibration, all piezometer lines were reinstalled to slope continuously upward to minimize low points and potential air traps. Comparing turbine operating data before and after the *in situ* calibrations (Appendix D, and Table H-13, Appendix H) indicates that there were no measurable differences in head and flow with the new lines and the original lines. This comparison verifies that the procedures used to bleed the DP cells were adequate.

Scroll Expansion Measurements **-** Laser measurements of the scroll at the 40 ft and 80 ft test operating conditions and without the turbine and test loop on were obtained to investigate the effects of potential geometry, and therefore, velocity changes in the scroll case between the two conditions. As discussed in Appendix H, no vertical downward expansion was measured from 0 to 80 ft head. Vertical upward expansion was 0.0045" at 40 ft and 0.011" at 80 ft heads. Horizontal expansion was 0.008" at 40 ft and 0.014" at 80 ft. These expansions, which are consistent with the values predicted with the computer model used to design the scroll case, verified that there was no significant geometry change which could affect flow patterns or velocity head at the runner inlet.

Turbine Bearing Friction Analysis - Prior to final assembly of the pilot scale turbine, preliminary tests on the turbine bearing indicated that the bearing friction without any downthrust was 1.0-1.5 HP at 240 rpm and 1.7-2.1 HP at 345 rpm, depending on the seal water pressure. These friction losses, which are presented on Figure 4-32, are about 0.5% and 0.2% of the turbine output measured during the preliminary tests with wicket gates at the 240 rpm and 345 rpm speeds, respectively. These preliminary friction tests indicate that some of the difference in turbine efficiency measured at the two heads could be attributed to bearing friction.

Tests with downthrust on the bearing shaft could not be conducted prior to turbine assembly or after the turbine installation in the test loop. However, partial runaway tests were contemplated during the final engineering tests to estimate the total mechanical and viscous friction with downthrust. Knowing the mass of runner and acceleration during first few seconds of load rejection, the total friction under load could have been determined if the residual friction on the dynamometer was known. Because the test loop pump speed could not be reduced low enough to determine the relationship between residual friction in the dynamometer and speed, and operating the turbine at speeds approaching 400 rpm would have damaged the runner, partial load rejection tests were not conducted and bearing/viscous friction with downthrust could not be measured in the pilot scale turbine.

Therefore, power consumption for the rolling elements in the bearing was calculated based on formulas for friction due to the applied load (downthrust) and fluid viscosity, as discussed in Appendix H. The pilot scale turbine bearing friction was calculated to be about 0.75 HP and 1.1 HP at 240 rpm and 345 rpm speeds, respectively, with downthrust. These calculated bearing friction losses were about 50% of the losses measured for the bearing and seal packing without any downthrust on the runner at both test conditions (1.5 HP at 240 rpm and 2.1 HP at 345 rpm). The calculated bearing friction was about 0.3% of the pilot scale turbine power at 240 rpm and 0.1% at 345 rpm. The measured bearing and shaft seal friction was about 0.5% of the pilot turbine power at 240 rpm and 0.2% at 345 rpm.

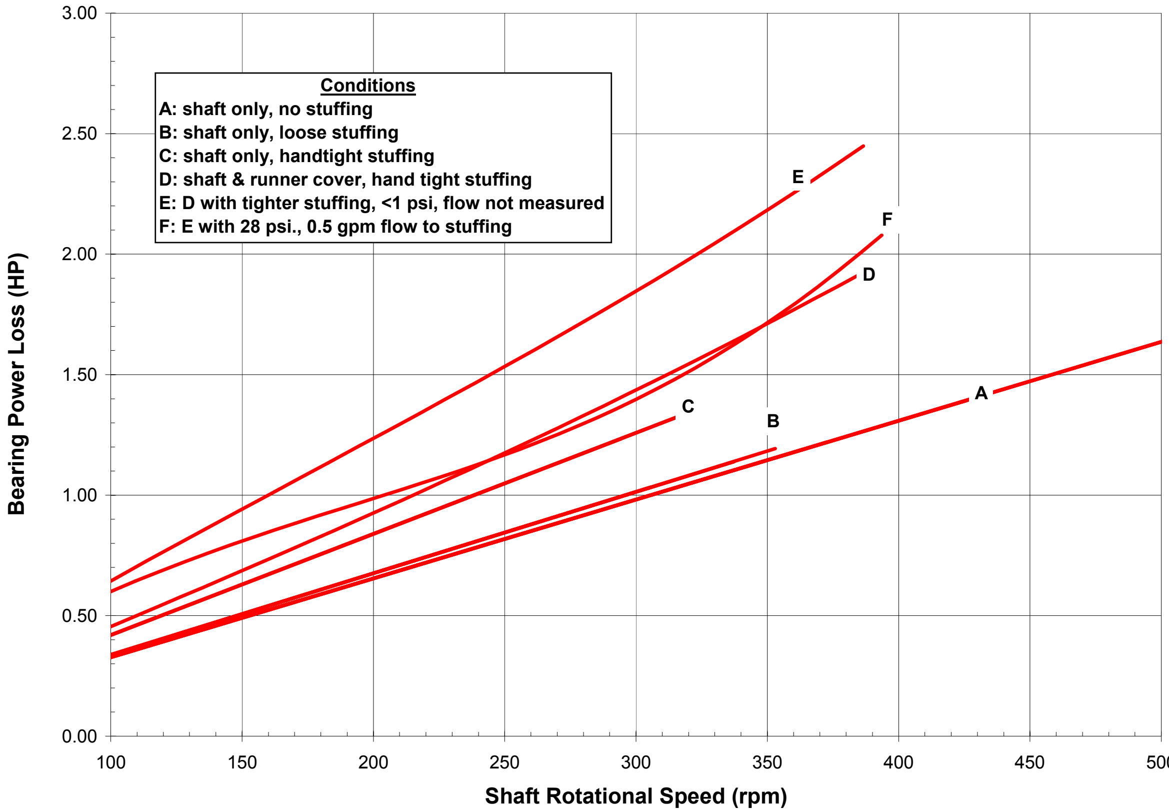


FIGURE 4-32   PRELIMINARY BEARING FRICTION TEST RESULTS

Both the measured bearing and seal packing friction measurements without downthrust and the calculated bearing friction with downthrust for the pilot turbine were consistent with bearing and seal friction expected for similar components. Therefore, bearing and shaft seal friction were considered a scalable loss. Bearing and shaft seal friction accounted for about 0.3% of the difference in measured efficiency between the 240 rpm and 345 rpm conditions

<u>*Turbine Runner Downthrust Effects*</u> - Tests with the runner head cover vent valve throttled indicated that there was no difference in the turbine efficiency with the head cover vent valve completely closed and fully open, as shown in Appendix H, Table H-34. With the vent valve closed, the additional downthrust on the runner bearing was estimated to be 31,000 lbs assuming the full turbine head (40 ft) was acting on the top cover. With the vent valve open, all bearing downthrust was due to water flowing through the runner, approximately 14,000 lbs assuming the top cover seal has minimal leakage. These test results indicated that bearing friction loss was not affected by downthrust on the top cover. If bearing friction was a major contributor to the turbine losses, the measured efficiency should have decreased with the higher downthrust.

Turbine Shaft Seal Flow **-** During operation of the turbine, a small amount of water was delivered to the seal box from the scroll case inlet pipe (high pressure). During initial operational testing without wicket gates, the runner shaft seal was tightened to assure a small drip out of the packing. The packing was never adjusted at any time after this initial tightening, but always had a small drip indicating that the packing was properly adjusted. During normal operation, small air bubbles in the seal water plastic tubing indicated that there was flow into the seal box, but this flow was too small to be accurately measured. Even with a booster pump, which has a design point of 1.5 gpm at 30 ft head and a shutoff head of 48 ft, flow measurements in the line were not possible. This low flow at both heads indicated that shaft seal flow did not affect turbine efficiency measurement at the high and low head test conditions.

Bottom Seal Leakage Measurements **-** In early December 2001, the turbine bearing/runner assembly was pulled out of the scroll case for installation of the wicket gates. During reassembly of the turbine, the runner was manually turned to check for binding. During this check, and for the remainder of the winter, all water was drained from the test loop.

The test loop was prepared for engineering tests with wicket gates in February 2002. During initial operation, the runner would not rotate. Inspection of the runner indicated that the runner had dropped down about ¾ of an inch and was seized in the scroll case. The displacement was the result of water filling and freezing in the hollow portion of the runner hub sometime in the mid-December 2001 to mid-February 2002 period. Apparently, water had leaked into the runner casting during the first operational period and was not detected during the turbine disassembly and reassembly for installation of the wicket gates.

The turbine bearing and adaptor plate and the runner top plate were shipped as a unit to a machine shop for repair. The bottom seal, which remained in place at the top of the draft tube when the runner was removed, was inspected and found damaged. The seal showed considerable wear and measurements of the inside diameter of the seal indicated that the clearance had increased to 0.055 inches from the 0.010 inch design clearance. The bottom seal backing ring was repaired *in situ* in order to limit the repair time to several days.

The runner and bearing assembly was rebalanced and installed back in the test loop for the spring tests. During the preliminary tests in April 2002 to determine the BEP wicket gate position, the turbine operation near BEP for the each gate position indicating that the runner repairs were adequate. In fact, the April preliminary engineering tests indicated that the BEP turbine efficiency with wicket gates was actually higher than the turbine efficiency without wicket gates. However, off-BEP tests produced unacceptable turbine vibrations at φ values less than 0.95 and unacceptable pump vibrations at φ values greater than 1.05. Off-BEP tests at the 16°, 18°, and

24° gate positions produced very rough operating conditions, which may have created additional wear on the bottom seal leading to increased leakage.

Changes in turbine efficiency during biological testing in the spring 2002, as discussed in Appendix H, indicated a mechanical change in the turbine such as increased bottom seal leakage. In order to maintain the schedule for biological testing with wicket gates the turbine was not disassembled to inspect the condition of the bottom seal. Instead, measurements of the bottom seal leakage were obtained at the 40 ft and 80 ft operating conditions, and the final engineering test data was adjusted for what was found to be abnormally high bottom seal leakage that would not exist in a prototype turbine.

Dye dilution measurements with the turbine operating at the 40 ft/240rpm and the 80 ft/345 rpm BEP wicket gate positions determined the bottom seal leakage rates shown on Figure 4-33. A complete description of the flow measurement techniques and the test data are provided in Appendix I.

Bottom seal leakage was 928 gpm (2.07 cfs) at 40 ft and 1,292 gpm (2.88 cfs) at 80 ft heads. This leakage was about 3% of the turbine flow at both conditions. Head loss coefficients were determined for the bottom seal leakage at these two turbine heads were calculated and the bottom seal leakage at the final engineering test turbine heads were estimated to the average of the head loss coefficients based on the two leakage measurements. As discussed in Appendix I, the accuracy of the leakage flow measurements was about 5%, which amounts to about 0.15% of the turbine flow. Since measured leakage was proportional to the square root of the turbine head, these measurements also indicate that bottom seal leakage did not contribute to the difference in turbine efficiency at the 40 ft and 80 ft heads. Bottom seal leakage was considered a non-scalable loss and was accounted for in developing the prototype turbine performance characteristics.

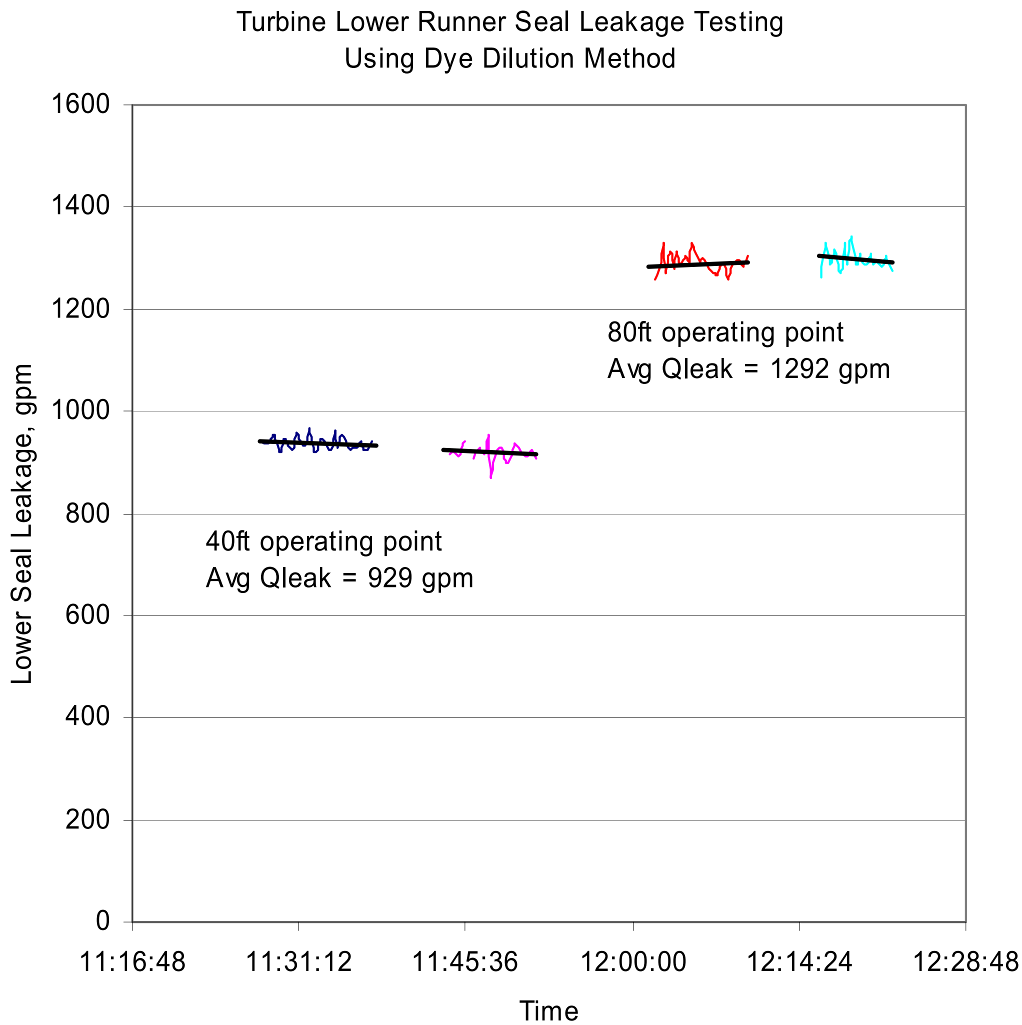


FIGURE 4-33 RUNNER BOTTOM SEAL LEAKAGE MEASUREMENTS

4.9 Final Engineering Tests with Wicket Gates

Final engineering tests with wicket gates were conducted in December 2002 to define the Alden/Concepts NREC turbine performance characteristics. These tests were conducted at wicket gate angles of 16°, 18.2°, 20°, 22°, 24°, and 26° open from the fully closed position. Tests at a 14º wicket gate angle were also attempted, but data could not be obtained because of severe turbine vibrations, similar to the problems encountered during the preliminary engineering tests with wicket gates in the spring 2002.

The final engineering data are presented in Table G-7 (Appendix G). The hill chart, which is discussed in Section 4.7, defines the performance characteristics of the pilot scale turbine at different gate positions in terms of φ (Equation 4-9) and p_{11} (Equation 4-10). The performance characteristics, including all losses associated with the turbine, are shown on Figure 4-34. All of the engineering tests discussed in Section 4.8 indicate that bottom seal leakage is the only loss in the pilot scale turbine which is not scalable to a prototype turbine.

As shown on Figure 4-34, the turbine BEP based on the final engineering tests is 84.5% at an 18.2º wicket gate position with a φ value of 1.000 and p_{11} equal to 0.058. The efficiency is reasonably uniform over a 0.990-1.100 range of φ values and 0.055-0.065 p_{11} values. The BEP operational setpoints selected for biological operation (φ values of 1.015 and 0.990 for 80 ft and 40 ft heads) with the 18.2º gate angle are near peak efficiency for the turbine.

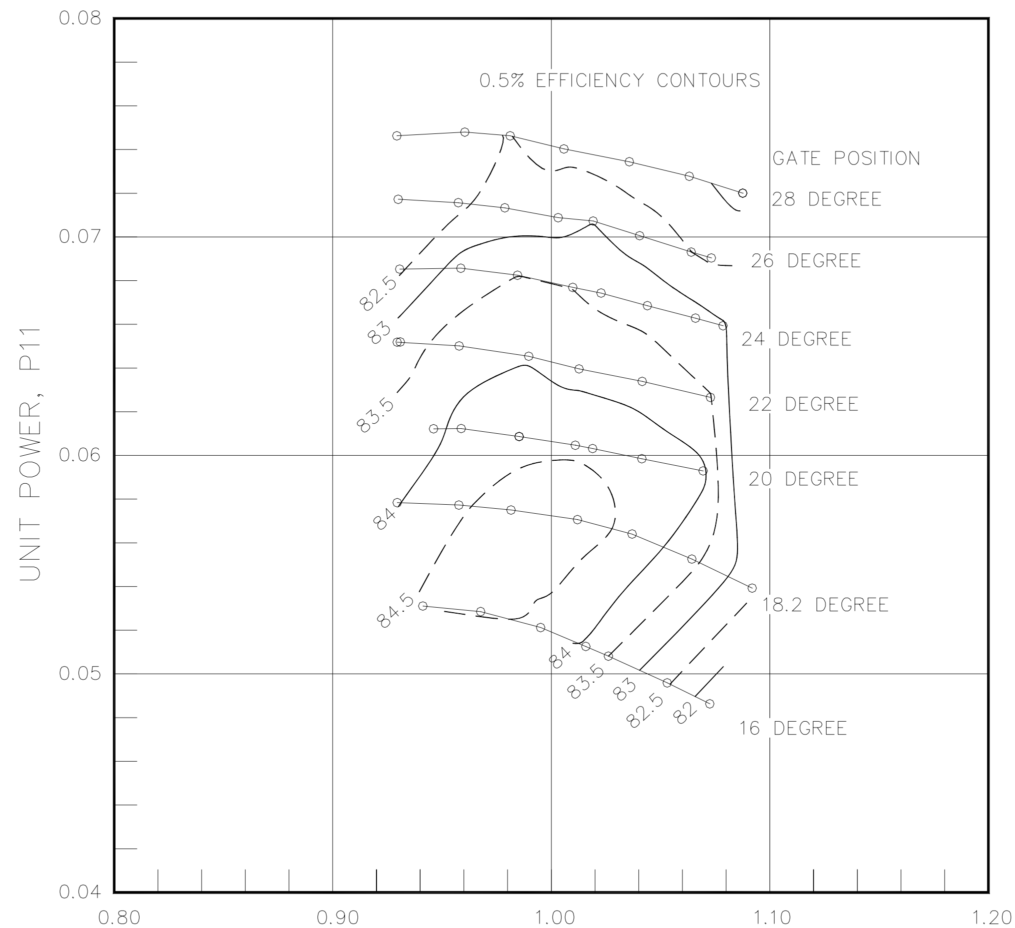


FIGURE 4-34 PILOT SCALE TURBINE HILL CHART

4.10 Efficiency Scale Effects

Efficiency of reduced scale (model) turbines is less than full size units due to "scale effects". These scale effects are caused by differences in friction and form losses in the model compared to the larger field units, with the difference in losses due to differences in Reynolds numbers and relative roughness.

Various "step up" formulas have been proposed to account for the increase in efficiency for prototype versus model turbines. The International Code for Model Acceptance Tests of Hydraulic Turbines IEC Publication 193, p55-(VI), Section 6, "Application of Scale Formula" gives formulas for a generally accepted increment in efficiency ($\Delta\eta$), which may be added to the maximum efficiency measured in the model (η_m), namely

$$\Delta\eta = (1 - \eta_m)\,[1 - K] \qquad 4\text{-}12$$

where: $$K = (1 - \eta_p)/(1 - \eta_m) \qquad 4\text{-}13$$

For Kaplan and propeller turbines, the Hutton formula is used

$$K = 0.3 + 0.7\{D_m\nu_p/D_p\nu_m(H_m/H_p)^{1/2}\}^{1/5} \qquad 4\text{-}14$$

where D is the diameter, ν is the dynamic viscosity of water and H is the head. Subscripts m and p refer to the model and the prototype turbine, respectively.

For prototype efficiencies at the same head as tested in the pilot scale turbine (80 ft), and assuming equal viscosities and η_m = 84.7% at the BEP, the prototype Alden/Concepts NREC turbine would have K = 0.853 and $\Delta\eta$ = 2.2% using the Hutton formula. If the measured efficiency during the fall 2002 tests at a head of 38 ft (η_m = 84.5%; average efficiency in Table G-5 (Appendix G)) is used to scale up to the design head of 80 ft in the pilot scale turbine (D_m = $D_{p)}$, K = 0.950 and $\Delta\eta$ = 0.8%, similar to the measured difference in BEP efficiencies during the spring 2002 at the two test heads, as shown in Tables G-3 and G-4 (Appendix G). Assuming all of the turbine efficiency losses are scalable, scaling effects may explain why the tests at the lower head had a lower efficiency than the higher head tests.

For Francis turbines, the Moody formula is used wherein

$$K = (D_m/D_p)^{1/5} \qquad 4\text{-}15$$

Using the Moody formula with η_m = 84.8%, K = 0.79 and $\Delta\eta$ = 3.2% for the prototype Alden/Concepts NREC turbine.

Since the Alden/Concepts NREC turbine is a mixed flow machine with inflow somewhere between axial and radial, the average $\Delta\eta$ from the Hutton formula and the Moody formula has been selected as a representative scale factor for predicting prototype turbine performance from pilot scale data. This average incremental efficiency is about 2.7% (2.2% with the Hutton formula and 3.2% with the Moody formula with the 1/5 exponent) at BEP without wicket gates. The predicted maximum efficiency is 87.4% for the prototype turbine, assuming all losses are scalable, compared to 84.7% measured for the pilot scale turbine.

The 1/5 exponent in the Moody formula, which is currently accepted and used by the industry, may be too high and an exponent of 1/10 may be more appropriate (Sheldon 1985). With this lower exponent in the Moody formula, K = 0.89 and $\Delta\eta$ = 1.7%. The average incremental efficiency using the Hutton formula and the Moody formula with this 1/10 exponent would be 2.0%. This lower exponent would result in a predicted peak efficiency of 86.7%, about 0.7% lower than the predicted efficiency scale up used by the industry and Alden to determine prototype turbine performance, as discussed in the next section.

4.11 Prototype Hill Chart

Prototype turbine performance characteristics have been predicted by adding scalable losses to the measured performance and then applying a scaling factor. As discussed in Section 4.8, bottom seal leakage was the only factor in the pilot scale testing that was identified as contributing to reduced power output and lower efficiency and that would not be scalable to the prototype turbine. Therefore, the performance of the prototype turbine has been predicted taking into account bottom seal leakage and the scale factor related to the pilot scale turbine data. Prototype efficiency (η_p) has been calculated by

$$\eta_p = \eta_m + 0_m (Q_L/Q_m) + \Delta\eta \qquad 4\text{-}16$$

where, η_m = measured efficiency (%)

Q_L = bottom seal leakage (cfs) (eq. H-2, Appendix H)

Q_m = measured total flow (cfs) 4-17

$\Delta\eta$ = average efficiency increment (eq. 4-19) with $(K_1 + K_2)/2$ 4-18

K_1 = Hutton scale coefficient (eq. 4-14)

K_2 = Moody scale coefficient (eq. 4-15)

The unit power (p_{11} defined by eq. 4-10 in Section 4.7) for the prototype hill chart has also been adjusted to reflect bottom seal leakage and runner bearing shaft friction. The prototype turbine p_{11} has been calculated using eq. 4-10 with

$$P = P_m + P_m (Q_L/Q_m) \qquad 4\text{-}19$$

where, P_m = measured power (HP)

The predicted prototype turbine performance is summarized in Table J-1 (Appendix J) and on Figure 4-35. The scale up of the pilot scale test results with wicket gates predicts that the BEP for the prototype (full scale) turbine is about 90.5%, and this occurs at a φ (phi) of about 0.97 and a unit power of about 0.055. These predicted values for the full size (prototype) turbine are somewhat different than the raw data for the pilot scale turbine presented in Section 4.7.

As discussed previously (Section 4.7), the unit power at the BEP of 0.055 predicted for the full sized unit is relatively low since the power out is relatively low for the runner diameter. This is caused by the relatively low flow through the turbine due to the small radial space height (i.e., wicket gate height) relative to the diameter of the runner. An increase in unit power may be achieved by increasing the height of the radial space as part of a runner redesign, assuming minimal detrimental effects on safe fish passage.

Using Equation 4-14 with a unit power of 0.055 at a turbine head of 80 ft and a full size runner of 13 ft indicates the prototype turbine would produce about 6,650 hp. Using this power and a full size runner speed of 100 rpm at 80 ft, Equation 4-15 indicates a specific speed of about 34. This is somewhat low compared to other turbines at this head due to the lower power density discussed above.

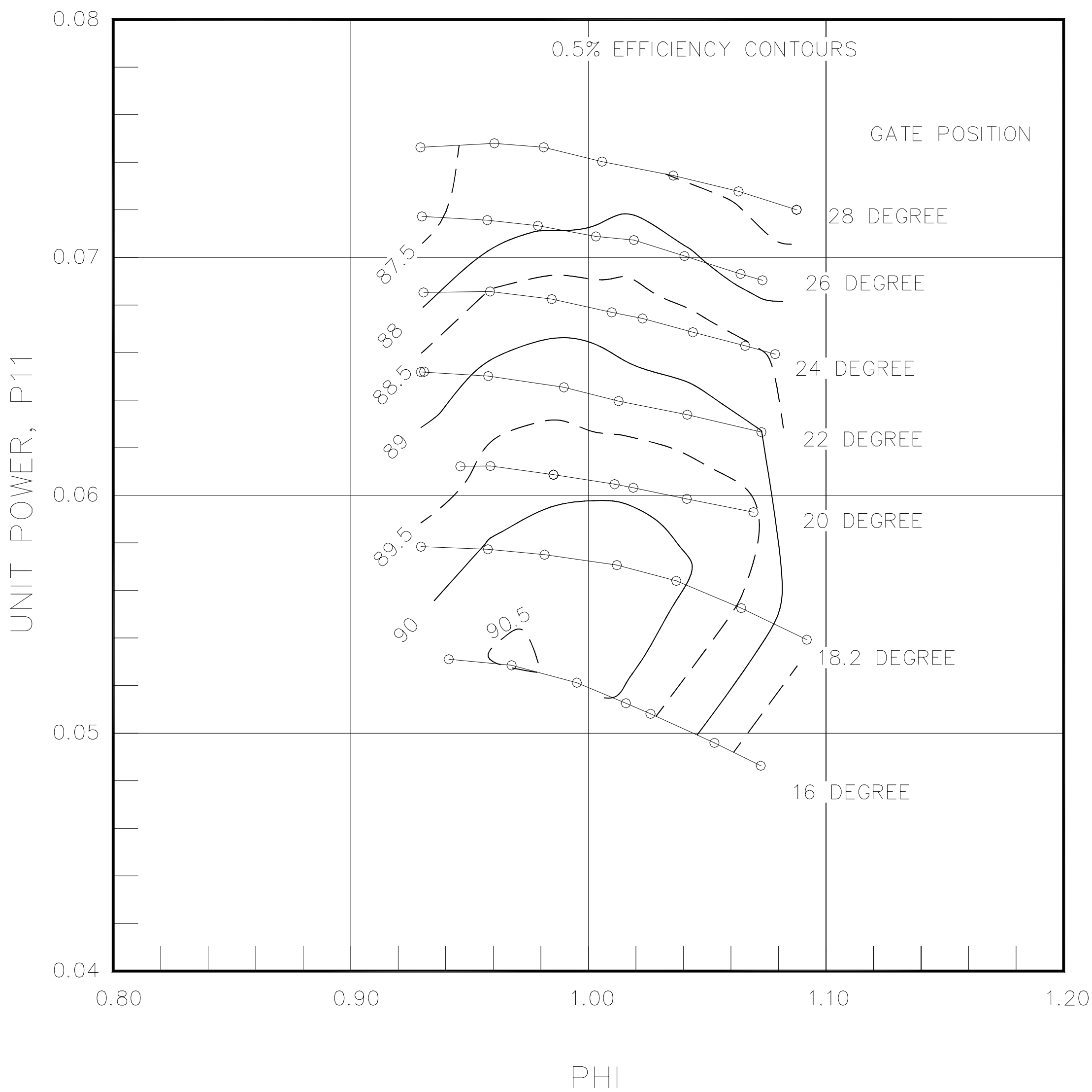


FIGURE 4-35 PROTOTYPE TURBINE HILL CHART (WITH GATES)

5.0 BIOLOGICAL TESTING - METHODS

The biological evaluation of the Alden/Concepts NREC turbine consisted of several test series that focused on specific operational and/or biological parameters considered to have potential for affecting turbine passage survival and injury rates. Biological testing was conducted during the fall of 2001 and the spring and fall of 2002. The primary goal of test series conducted in the fall of 2001 was to examine survival and injury rates for several test conditions (treatment fish release location, fish size, operating head) *without* wicket gates installed, whereas the primary goal for testing in the spring of 2002 was to evaluate similar test conditions (fish size, head) *with* wicket gates. With the exception of one test series conducted with American eels, all tests in the fall of 2001 and spring of 2002 were conducted with rainbow trout. Testing in the fall of 2002 focused on passage survival and injury rates of additional species and the effects of turbine operating efficiency. Specific test conditions evaluated during each test series are discussed in more detail below.

5.1 Evaluation Parameters

There are many biological and engineering parameters that affect the survival of fish passing through turbines. Fish size is perhaps the most important biological factor influencing injury and mortality rates (Turnpenny et al. 1992; Franke et al. 1997). Design and operational factors that have been shown to have direct or indirect effects on passage survival include runner type, head, runner rotational speed, blade spacing, and number of blades (EPRI 1987; Franke et al. 1997; Winchell et al. 2000). Some of these parameters contribute to hydraulic conditions and/or pressure regimes that can have adverse effects on survival rates (Cada et al. 1997). Others affect the probability of injury and mortality due to mechanical mechanisms (Cada et al. 1997). Based on the existing knowledge of parameters that contribute to mortality and injury of fish passing through turbines, a wide range of biological and engineering parameters were selected for the evaluation of the Alden/Concepts NREC turbine to provide a comprehensive information base that would be suitable for assessing the potential of the new turbine design to effectively minimize or eliminate turbine injury and mortality. Additionally, the focus of the biological evaluation was on direct turbine passage survival rates, not indirect effects that may be associated with increased predation or disease of disoriented or injured fish.

5.1.1 Biological Parameters

In order to effectively assess the probability of injury and mortality from direct contact with the turbine runner and/or fixed parts (e.g., stay vanes and wicket gates), it was considered necessary to evaluate fish sizes that were appropriate for the size of the pilot-scale test runner. The average size of many anadromous species (e.g., salmonid smolts, juvenile clupeids) is between 75 and

225 mm (3 and 9 inches) during their downstream migrations. This size range also covers the larger sizes of riverine species that are most commonly entrained at hydroelectric projects. Since the test runner was approximately one-third of the size of a full-scale runner designed for a flow of 1,000 cfs at 85 ft head, it was concluded that fish between 25 and 75 mm (1 to 3 inches) in length that were to be passed through the pilot turbine most likely would have a similar probability of strike as fish 75 to 225 mm (3 to 9 inch) in length passing through a full-size runner. Although the probability of strike would be slightly increased, we selected a larger target size range for most tests of 50 to 100 mm (2 to 4 inches), in part due to concerns that very small fish would be susceptible to injury or impingement on the inclined screen that was used to guide fish into the collection tank downstream of the turbine. However, to provide sufficient data for evaluating the effects of fish length on passage survival rates, larger fish (150 mm or greater) were also evaluated for three of the species that were selected for testing. To further support the evaluation of size effects, one series of tests with rainbow trout was conducted with fish that averaged less than 50 mm in length.

Most of the biological test program focused on estimating passage survival and injury rates for rainbow trout tested at different design and operational conditions. Rainbow trout was selected as the primary species for testing because they are widely available in several sizes during most times of the year, are relatively easy to handle, and the results obtained for this species would be considered representative for other members of the family Salmonidae (trout and salmon). Furthermore, recent studies of turbine passage survival indicate that differences in survival between fish species are generally small in comparison to those observed for different sizes of fish, or for turbines with different design characteristics (Franke et al. 1997). This suggests that the results obtained with trout may also be representative of survival rates for other species of fish (i.e., non-salmonids) of the same size and with similar morphology.

Despite the evidence that indicates species differences in turbine mortality may not be significant (Franke et al. 1997), there are some physiological differences among species that could affect their vulnerability to injury during turbine passage. Fish with different body shapes, skin and bone types, swimming abilities, and/or behaviors may be more or less vulnerable to strike injuries. Most species evaluated in past turbine passage studies have been representative bony fishes with similar body shapes, including fusiform, moderate dorso-ventral compression, or laterally compressed (Franke et el. 1997; Winchell et al. 2000). There is no existing information on turbine passage survival and injury for species like paddlefish and sturgeon, which are cartilaginous and have few scales. Very little information exists for American eel, which have small embedded scales and an elongated body type (i.e., anguilliform). Also, American eels are unique in that they move downstream at a large size (approximately 20 to 40 inches) during their spawning migration. Their large size makes them relatively susceptible to blade strikes in conventional turbines. Their elongated body shape, tough skin, and abundant mucous coating may also affect their vulnerability to injury compared to other species. Furthermore, a reported decline in the abundance of American eels has stimulated interest in the protection and restoration of this species. To determine if species with atypical body shapes and physical characteristics have survival rates that differ from more typical species, American eel and white sturgeon were selected for testing.

Pressure changes that occur as fish pass through turbines may adversely affect some species. Species that have a duct connecting the swim bladder to the esophagus (physostomous species) are generally more tolerant of pressure changes than species that lack a duct (physoclistous species) because they can control the volume of gas within the swim bladder more readily (Cada et al. 1997). However, the rapid decrease in pressure that typically occurs on the downstream side of a turbine runner has potential to damage physostomous and physoclistous fish (Cada et al. 1997). Physostomous species include salmon, trout, catfish and minnows, while most of the spiny rayed species, such as perch, bass and sunfish, are physoclistous. Since the Alden/Concepts NREC turbine is designed to minimize the magnitude of pressure changes experienced by fish during passage, large differences in survival rates between physostomous and physoclistous species are not anticipated. To verify this assumption, smallmouth bass, which is a physoclistous species, was selected for testing (all other species tested were physostomes).

In addition to tests with rainbow trout, coho salmon was selected as a test species for representing anadromous salmonids that may be more prone to scale loss and other stressors associated with turbine passage. However, only hatchery-reared coho salmon smolts were available for testing and are considered somewhat hardier than wild fish. Also, these fish may not have been undergoing some of the physiological changes associated with smoltification. Alewife were selected as a representative anadromous clupeid. Similar to salmonids, clupeid species (e.g., alewife, blueback herring, and American shad) are commonly entrained at hydro projects during juvenile outmigrations. Clupeids are also considered fragile species that are very prone to scale loss.

5.1.2 Engineering Parameters

Operating head, wicket gates, and turbine efficiency were considered design and operational parameters that had the greatest potential for influencing passage survival and injury rates of fish passed through the new runner design. Tests were conducted with one species (rainbow trout) to specifically evaluate the effects of each of these parameters. Turbine passage survival was evaluated for two heads (40 and 80 ft), with and without wicket gates, and at the best efficiency point (BEP) and five off-BEP settings (one below BEP and four above). Tests with other species, which were designed to evaluate the effects of biological parameters, were all conducted at a head of 40 ft, with wicket gates, and at the BEP.

The turbine runner that was tested at Alden was approximately one-third the size of a runner for the field design condition of 1,000 cfs at 85 ft of head. The prototype runner would be about 13 ft in diameter for these design conditions and would be too large to test in the pilot scale facility. Alden designed the pilot scale runner to have a diameter of about 4.0 ft giving a geometric scale ratio of about 3.25. Since the size of the fish relative to turbine passageways was expected to influence the probability of strike, fish in the 50- to 100-mm size range that were evaluated during biological testing represent the passage of 150- to 300-mm fish through a full scale turbine. There are, however, other factors that were considered to have potential to produce higher rates of injury in the pilot scale turbine than would occur in the full size turbine operated at the design head. Fish passing through the pilot scale turbine were subjected to the same blade tip speeds, water velocities and pressure changes as in the full scale turbine. However, the test fish experienced more rapid changes in velocity and pressure (in space and time) than they would in a larger turbine. These factors made the results of the pilot scale biological testing conservative (i.e., more likely to show injury) compared to larger turbine installations. Although predicting the magnitude of these effects on turbine injuries is difficult, scaling factors are considered later in the interpretation of biological test results.

5.2 Test Plan Design

In order to determine turbine passage survival and injury rates associated with the parameters discussed above, a test plan that included ten distinct test series for selected test conditions was developed. Modifications to this plan were implemented based on the results from testing conducted in the fall of 2001 and subsequent discussions with the DOE and Technical Committee members (Figure 5-1). Specifically, the following changes to the original test plan were made:

- All tests that did not include head as a test parameter were conducted at a head of 40 ft instead of 80 ft.

- The evaluation of head effects was conducted with two size groups (mean lengths = 93.4 and 173.4 mm) instead of three during tests without wicket gates (Test Series 2/3).

- Test Series 4 was eliminated because release location was shown not to be a factor during tests conducted without wicket gates (i.e., Test Series 1).

- Test Series 7 was conducted with three species instead of four and Test Series 8 was conducted with two species instead of three.

Test Series 2 and 3 and Series 5 and 6 were combined into two series to strengthen the statistical analysis of passage survival rates (i.e., replicate trials with multiple sizes of fish conducted at two heads were evaluated in random order, rather than separately). Test Series 1 and 2/3 were conducted without wicket gates (i.e., Fall 2001 tests). Test Series 5/6, 7, and 8 were conducted with wicket gates (i.e., Spring and Fall 2002 tests). More detailed descriptions of each test series, including preliminary tests conducted in the fall of 2001, are provided below.

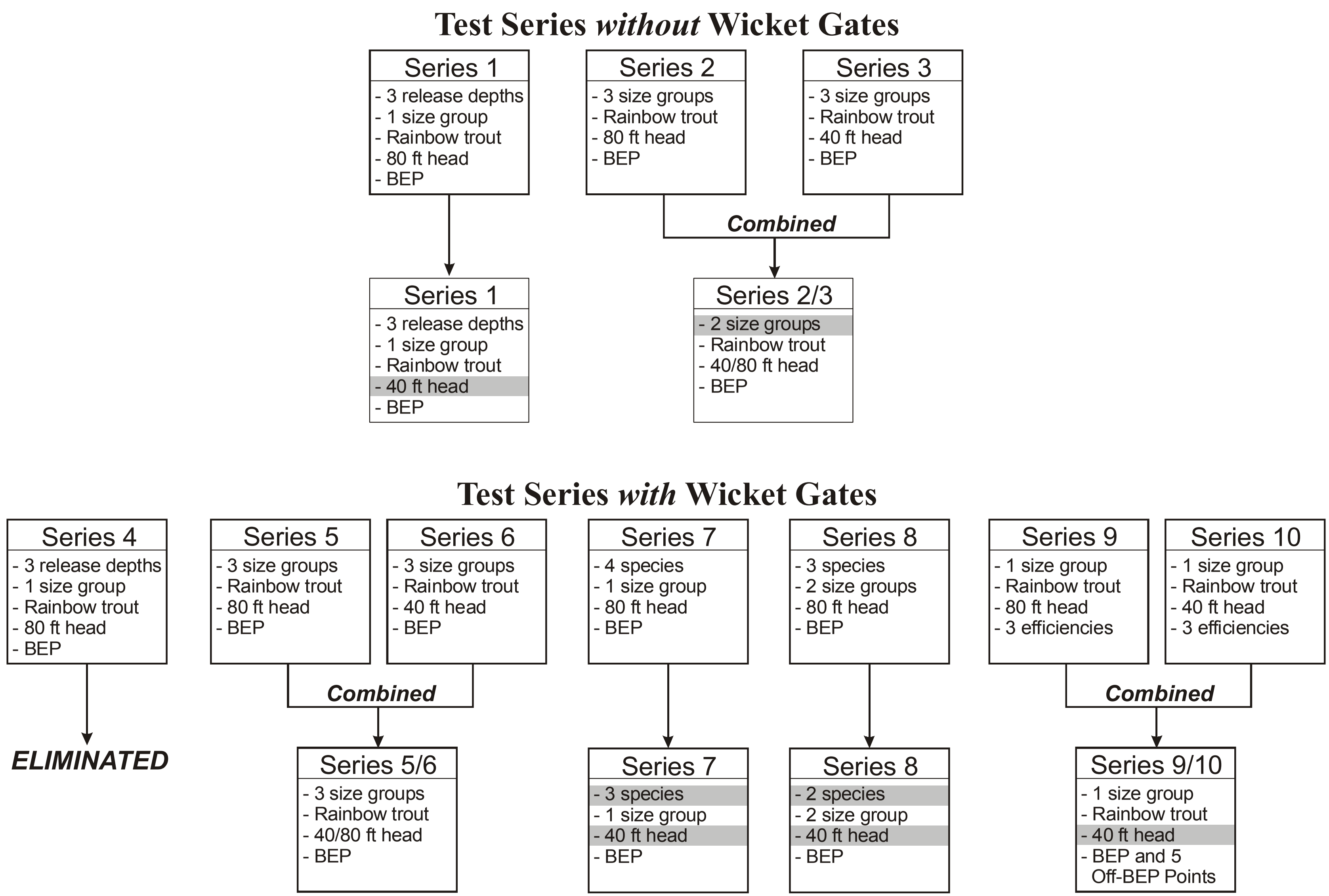


FIGURE 5-1 ORIGINAL AND MODIFIED STUDY PARAMETERS FOR EACH TEST SERIES CONDUCTED AS PART OF THE ALDEN/CONCEPTS NREC TURBINE EVALUATION

5.2.1 Preliminary Test Series (Fall 2001) – Test Procedures Evaluation

The purpose of preliminary tests was to train staff, refine testing procedures (marking, injection, and recovery of fish; evaluation of injury and delayed mortality), and to confirm that introduction and collection of fish from the test loop did not cause injury or mortality that could compromise an accurate estimation of survival rates associated with turbine passage alone. In 2001, preliminary tests were also used to determine where to release control fish (i.e., top, middle, or bottom of draft tube pipe). A control release depth at the bottom of the draft tube was selected for use in subsequent tests to provide a fish distribution in the pipe upstream of the Eicher screen and a velocity at the injection pipe exit similar to the treatment groups. Since the depth of injection for treatment fish probably does not affect the vertical distribution of treatment fish after they have passed through the turbine, the release depth selected for injection of control fish was not intended to correspond directly to any of the depths at which the treatment fish were released.

All preliminary tests in 2001 were conducted with rainbow trout approximately 75 to 150 mm (3 to 6 inches) in length. A set of three trials was conducted for four sets of test conditions (38 and 80 ft of head at two efficiency points). The survival data from these tests are included in the discussion of results.

5.2.2 Test Series 1 (Fall 2001) – Treatment Release Location Evaluation

The results of some field studies have indicated that the location at which fish approach a turbine runner may have an effect on turbine survival. Fish that pass through a runner near the hub may experience lower rates of injury and mortality compared to fish that pass near the blade tips, where strike and grinding may be more likely to occur. The design of the Alden/Concepts NREC turbine runner most likely minimizes effects related to the location of fish as they pass through the turbine due to the lack of gaps at the hub and the attached shroud. The goal of Test Series 1 was to examine whether release location of treatment groups, and the subsequent positions at which fish enter the runner, affects turbine survival and injury rates. Trials for this test series were conducted at a head of 38 ft using rainbow trout with a mean FL length of about 111 mm. Treatment fish were released at three depths (top, middle, and bottom) within the test loop pipe upstream of the turbine. Nine replicate trials were conducted at each of the three treatment fish release locations for a total of 27 tests. Based on the results of the preliminary tests, which included an assessment of control release depths, all control groups were released at the bottom depth location during Test Series 1 trials.

5.2.3 Test Series 2/3 (Fall 2001) - Operating Head and Fish Size Evaluation Without Wicket Gates

The primary goal of Test Series 2/3 was to evaluate the effect of fish size and operating head without wicket gates installed. The length ranges for the two size groups of rainbow trout that were evaluated were approximately 75 to 125 mm (3 to 5 inches) and 150 to 200 mm (6 to 8 inches). The two operating heads that were evaluated were 38 and 80 ft. Nine replicate trials were conducted with each of the four treatments for a total of 36 tests. Because the results of Test Series 1 indicated that there was no statistical difference in turbine survival rates with respect to treatment fish release location, treatment groups were released at the middle location for all Test Series 2/3 trials. Similar to Test Series 1, all control fish were injected at the bottom release location.

5.2.4 Test Series 5/6 (Spring 2002) - Operating Head and Fish Size Evaluation With Wicket Gates

The primary goal of Test Series 5/6 also was to evaluate the effect of fish size and operating head with wicket gates installed. The evaluation of similar-sized rainbow trout with and without wicket gates allows for separation of mortality and injury associated with the runner and wicket gates. For Test Series 5/6, a third size group of rainbow trout was included to provide additional survival and injury data for the evaluation of fish size effects. The length ranges for the three size groups that were evaluated were approximately 30 to 50 mm (1.2 to 2.0 inches), 70 to 100 mm (2.8 to 4 inches), and 150 to 200 mm (6 to 8 inches). The two operating heads that were evaluated were 40 and 80 ft. The three size groups of rainbow trout were evaluated separately because of constraints related to the capacity of the fish holding system and when fish of each target size were available. Within each size group, trials conducted at the two heads were performed randomly. Nine replicate trials were conducted with each of the five treatments (i.e., three size groups and two heads) for a total of 54 tests. Similar to Test Series 2/3, treatment groups were released at the middle release location and control fish were injected at the bottom location.

5.2.5 Test Series 7 (Fall 2002) – Evaluation of Additional Species

Test Series 7 was designed to evaluate turbine survival and injury rates for species other than trout that are commonly entrained at hydroelectric projects. The species selected for this test series included alewife, coho salmon, and white sturgeon. Approximate length ranges were 50 to 100 mm (2 to 4 inches) for alewife and 75 to 125 mm (3 to 5 inches) for white sturgeon and coho salmon. All Test Series 7 trials were conducted at a head of 40 ft. Nine replicate trials were conducted with each species, which were tested separately due to differences in when fish were available. All treatment groups were released in the middle of the test loop pipe and control fish were released at the bottom.

5.2.6 Test Series 8 (Spring and Fall 2002) – American Eel and Smallmouth Bass Size-Effect Evaluation

Evaluations of American eel and smallmouth bass were conducted as part of Test Series 8 to examine the effects of fish size on turbine survival and injury rates for species other than rainbow trout. American eel tests also provide data for a physically unique species that migrates to the sea as adults from riverine habitats. Smallmouth bass, which are physoclistous, provide survival and injury data for a species that may be more susceptible to pressure changes than the other species that were evaluated. Two size groups were evaluated for tests with each species. Yellow eels were acquired for testing in order to evaluate eels that were of a length appropriate for tests with the pilot-scale turbine. Length ranges of the two size groups of American eel were approximately 200 to 300 mm (8 to 12 inches) for the smaller fish and 375 to 550 mm (15 to 18 inches) for the larger fish. Smallmouth bass length ranges for the two size groups were about 50 to 100 mm (2 to 4 inches) and 125 to 175 mm (5 to 7 inches). The length ranges of smallmouth bass were selected to correspond as closely as possible to those of rainbow trout in order to determine if size effects differ between species. Based on availability from suppliers, tests with the smaller size group of American eels were conducted in the spring. The larger eels and both size groups of smallmouth bass were evaluated in the fall of 2002. All Test Series 7 trials were conducted at a head of 40 ft. Nine replicate trials were conducted with each species and size group. All treatment fish were released at the middle release location and controls were released at the bottom.

5.2.7 Test Series 9/10 (Fall 2002) – Evaluation of Turbine Operating Efficiency

The primary goal of Test Series 9/10 was to determine the effect of turbine efficiency on passage survival and injury rates of one size group of rainbow trout. Six turbine efficiency settings were evaluated, including BEP, one point below BEP, and four points above BEP. Efficiency settings were represented by wicket gate openings measured in degrees from the closed position (i.e., 0^o). Wicket gate positions that were evaluated included 16^o, 18.2^o (BEP), 20^o, 22^o, 24^o, and 26^o. Test fish ranged in length from approximately 70 to 110 mm (2.8 to 4.3 inches). All tests were conducted at a head of 40 ft. Treatment fish were released at the middle release depth and control fish at the bottom.

5.3 Test Fish Sources

All rainbow trout were purchased from the Red Wing Meadow Trout Farm located in Montague, Massachusetts. Alewife were wild fish collected from freshwater ponds in New Jersey and delivered by Benbrook Bait. Coho salmon were hatchery fish (Domsea strain) reared by AquaSeed Corporation of Seattle, Washington. White sturgeon also were hatchery-reared fish and were supplied by Professional Aquaculture Services of Chico, California. The smaller American eels were obtained from the Swimming Rockfish and Shrimp Farm located in Meggett, South Carolina, and the larger eels were supplied by Delaware Valley Fish of Norristown, Pennsylvania. All American eels acquired for testing were wild fish collected by bait suppliers. Smallmouth bass were pond-reared by Hicklings Fish Farm located in New York. Fish were delivered at least 24 hours prior to being handled for marking and three days before testing was conducted. All fish were fed a standard pellet feed at a rate of about 0.5-1.0% of body weight. This was intended as a maintenance diet that would minimize growth without comprising the health of fish.

5.4 Fish Holding Facilities

All fish were held in a 10,000 gallon re-circulating fish holding facility located adjacent to the turbine test facility. Water quality was maintained through the use of Zeolite, sand, activated carbon, and DE filters. Water changes of about 5 to 10% were also performed every one to three days. Prior to testing, fish were held in 400-gallon stock tanks supplied with a continuous flow of about 10 gallons/min each. About 750 to 2000 fish were held in each tank depending on fish size. After marking and testing, treatment and control groups were held in 200-gallon circular tanks that received about 3 to 6 gallons/min of continuous flow.

5.5 Water Quality

Water quality was monitored on a daily basis for the holding facilities and typically on a weekly basis for the test loop during each evaluation period. The water quality parameters that were measured are presented in Appendix L. Depending on time of year and the species being held, water temperature was generally maintained between 9 and 17 ^{o}C (48 and 62 ^{o}F) in both the holding and test facility with the use of chillers. Dissolved oxygen levels fluctuated between about 6 and 11 ppm in the holding tanks, depending on water temperature and the number of fish in the system. Dissolved oxygen concentrations in the test loop were fairly constant throughout each test period with differences in weekly minimum and maximum levels typically less than 2.0 ppm.

Other water quality parameters (pH, alkalinity, hardness, total and un-ionized ammonia) were typically held at levels close to or within ranges recommended for rainbow trout (Piper et al. 1992). There were occurrences of high levels of ammonia in 2002 during the first three weeks of testing. More frequent water changes and zeolite re-charging were conducted during this time. Based on low control mortalities and the condition and behavior of untested fish, it was evident that these conditions were not negatively affecting fish health. Calcium chloride and sodium bicarbonate were used to increase the hardness and alkalinity of the holding facility water because the source tap water was relatively soft. Salinity levels in the holding facility generally were maintained between about 2.0 and 3.5 ppt to reduce physiological stress symptoms and the potential for fungal infections. Low daily mortality rates of untested fish (less than 0.5% for most species) and high control survival rates (often greater than 99%) demonstrated that the holding facility design and operation produced water quality conditions that met established standards maintaining healthy fish for research purposes.

5.6 Fish Marking

A BMX 1000 POW'R-Ject marking gun (New West Research and Engineering Laboratories, Santa Rosa, CA) was used to mark treatment and control fish. This marking system uses compressed CO_2 to inject biologically inert, micro-encapsulated photonic dyes at the base of individual fins. Injection pressure and dye volume are adjustable to facilitate marking different species and sizes of fish. Six colors and four fin locations were used to provide 24 unique marks. This resulted in each combination of color and fin location being used once during three days of testing (based on four tests per day, two release groups per test). Marking each release group for each trial allowed for the identification of treatment and control fish after recovery and the identification of fish that were collected during tests conducted after the one for which they were released.

All fish were marked two days before being tested. Fish were anesthetized prior to marking using a clove oil solution (1 part clove oil to 9 parts ethanol). The target concentration of clove oil in the anesthetic bath was 30 mg/L. After marking, pairs of treatment and control groups were held in circular net pens placed in 200 gal holding tanks (i.e., one treatment and one control group per tank). Treatment and control fish were placed in separate net pens within each tank to facilitate counting and separation of the two groups prior to being released. Marking and test information were recorded on datasheets for each group processed. Each paired group was assigned to a scheduled test prior to marking based on the planned sequence of testing two days from the marking date (e.g., the first group of fish that was marked each day was assigned to the first test scheduled to be conducted two days from the marking date). Marking information that was recorded for each treatment and control group included date and time of marking, fin location, mark color, number of fish marked, personnel who performed marking, and holding tank and net pen numbers. Test information included date of testing, turbine head, fish size (target range), test group (treatment or control), and the release location of each group (i.e., top, middle, or bottom). All marked groups were monitored over the two days that preceded testing; any mortalities or injured fish were removed and recorded on the appropriate data sheets.

5.7 Fish Release and Collection

When turbine operating conditions were stabilized for a given test, treatment and control groups were transferred from the holding tanks into separate 5-gallon buckets for counting. Portable aerators were used to provide a continuous supply of air for the entire time that fish were in the buckets. If an initial count did not match the count of the number of fish that were marked, additional counts were conducted until matching back-to-back counts were obtained. Any fish that died during the 2-day pre-test holding period and any fish that did not appear to be swimming properly or had visible injuries were removed prior to counting. After counting, each group of fish was carried to the test facility and transferred into the appropriate injection system canister (Figure 5-2). Each canister was filled with water prior to fish being placed inside.

After fish were placed in the canisters, the lids were secured and the injection process was initiated. Control fish were the first group to be injected for all tests. The injection of both release groups involved pressurizing the canisters to the levels that existed at each location in the test loop (i.e., upstream and downstream of the turbine) over a 2-3 minute period, then opening a ball valve that separated the canister from the pressurized injection pipe and forcing air into the system to push the fish and water out of the canister and pipe. Video cameras located underneath each pipe were used to determine when all fish had exited the injection pipes (Figure 5-3). The injection of both release groups took approximately 15 minutes from the time they were placed in the canisters to the time the last treatment fish exited the injection pipe.

In 2001, test conditions were maintained for 30 minutes from the time the control fish injection was completed (this corresponded to about 15 to 20 minutes from the time of test fish release). In attempts to maximize the recovery of treatment and control fish (i.e., minimize the number of fish remaining upstream of the collection at the end of a test), the test period was increased for Spring and Fall 2002 tests to one hour from the time treatment fish exited the release system. At the end of a test, the gate at the entrance to the collection tank was closed and the tank was drained. After most of the water was drained from the collection tank, a pipe that led to a smaller collection tank was opened and the remaining water and fish from the main tank entered the smaller tank (Figure 5-4). Fish were dip-netted from the smaller tank and placed into 5-gallon buckets with aerators (Figure 5-5).

FIGURE 5-2 CONTROL INJECTION SYSTEM (TOP) WITH FISH INSIDE CANISTER PRIOR TO RELEASE (BOTTOM)

FIGURE 5-3 TREATMENT FISH EXITING INJECTION RELEASE PIPE
(175 MM FISH TESTED AT A HEAD OF 38 FT)

When the collection process was completed, all fish were transferred to the holding facility where immediate mortality data were collected and injury evaluations were conducted. After being evaluated for injury, all live fish were returned to one of the 200-gallon holding tanks (usually to the one they were held in prior to testing) and held for 96-hours to evaluate delayed mortality. Treatment and control fish recovered at the end of each test remained together as one group from the time they entered the main collection tank until the end of the 96-hour delayed mortality holding period. This means that fish from both groups were subject to the same handling, holding, and collection conditions for the entire testing process. The only time the fish from the two groups were separated was when they were removed from stock tanks for marking and held in separate net pens (within the same holding tank) prior to testing.

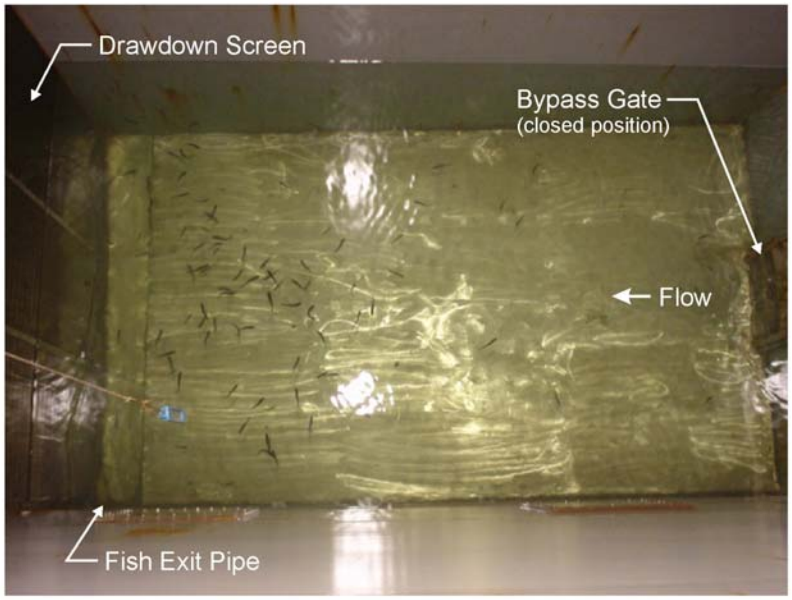


FIGURE 5-4 COLLECTION TANK BEING DRAINED AT THE END OF A TEST

FIGURE 5-5 FISH COLLECTION PROCESS

5.8 Survival, Injury, and Scale Loss Evaluations

Survival, injury, and scale loss evaluations were conducted on all recovered fish to enumerate immediate mortalities, external injuries, and percent scale loss. Immediate mortalities were classified as any fish that died within in 1 hr from the completion of a test. External injuries were recorded by type (bruising/hemorrhaging, lacerations, severed body, eye damage) and location (Figure 5-6). Using methods similar to those reported by Basham et al. (1982) and Neitzel et al. (1985), percent scale loss (< 3%, 3 – 20%, 20 – 40%, and > 40%) was recorded for each of three locations along the length of the body (Figure 5-6). Fish that had greater than 20% scale loss in two or more locations on one side of the body were classified as descaled. Because hatchery rainbow trout are relatively hardy and are not overly susceptible to scale loss, the rates of occurrence for this type of injury should not be considered representative of anadromous salmonids that are in a smolted condition (i.e., smolts are more prone to scale loss due to abrasion, shear, and/or handling procedures than rainbow trout are). During the injury and scale loss evaluation fish were also measured for fork length to the nearest mm.

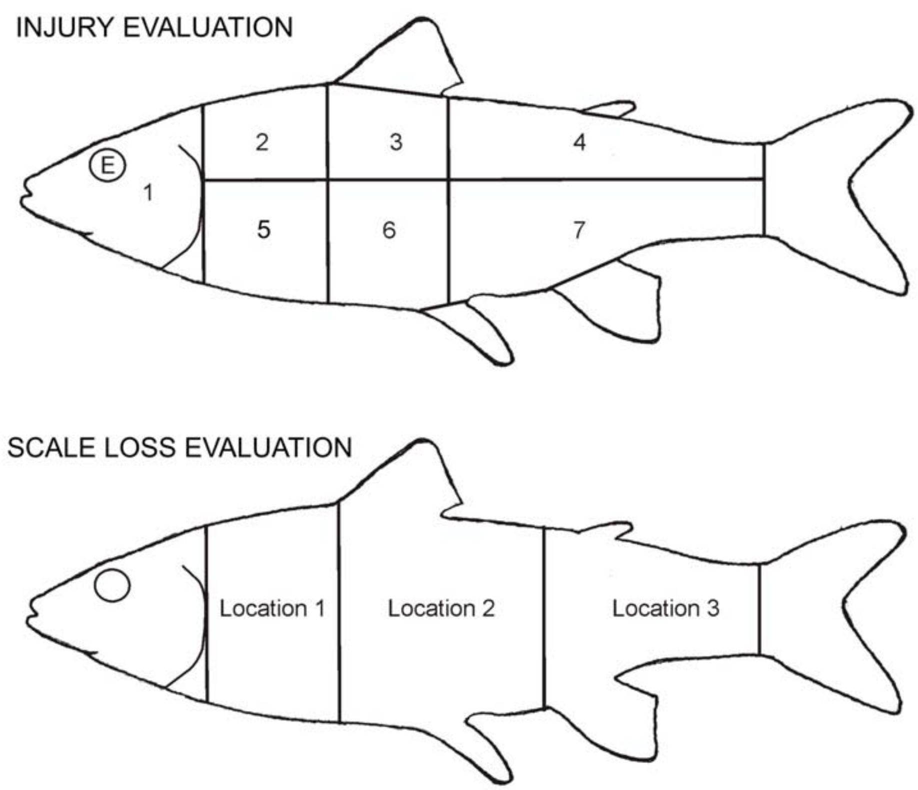


FIGURE 5-6 BODY ZONES USED TO CLASSIFY THE LOCATION OF EXTERNAL INJURIES (TOP) AND TO ASSESS PERCENT SCALE LOSS (BOTTOM)

Immediate mortalities from each test were evaluated for injuries and scale loss and were photographed to catalog the types of injuries that were observed. Live fish were evaluated for external injuries and scale loss and then returned to a holding tank and held for 96-hours to assess latent mortality. Treatment and control fish remained together from the time of collection until the end of the delayed mortality holding period. Fish were anesthetized for the injury and scale loss evaluations using the same procedures described for the marking process.

5.9 Data Analysis

The data analysis for the biological evaluation of the turbine involved assessments of immediate and delayed mortalities and injury and scale loss for selected turbine operating conditions, species, and fish size groups. Nine replicate trials were conducted for each condition evaluated during all test series with a target sample size of 100 treatment and 100 control fish per trial (i.e., $N = N_t = N_c = 100$). Actual sample sizes varied depending on the accuracy of marking counts and the occurrence of mortality between marking and testing; for some trials, the availability of fish limited samples sizes to 50 to 75 fish. This level of replication and sample size was based on an assessment of appropriate statistical techniques provided by a professional statistician (Dr. John Skalski, University of Washington; Appendix A). Because the 2001 Preliminary Test Series was primarily designed to evaluate the efficacy of marking and testing procedures, and not to be used as a rigid statistical evaluation of turbine survival, only three replicate trials with 50 treatment and 50 control fish per trial were conducted per treatment (four combinations of head and efficiency).

Immediate and total (immediate plus 96-hour) turbine survival rates were estimated and statistically analyzed using maximum likelihood estimation (MLE) techniques (Appendix A). Turbine survival estimates for individual replicates were generated as described in Section 2.1 of Appendix A and pooled-replicate estimates for each test condition were calculated using methods described in Section 2.2 of the same appendix. The input parameters for survival estimates included the following:

N_c = total number of control fish recovered (live and dead);

c = number of control fish recovered live;

N_t = total number of treatment fish recovered (live and dead); and

t = number of treatment fish (i.e., turbine passed) recovered live.

The total number of fish recovered for each release group was used instead of the number released because some fish were able to maintain position in the draft tube and were not recovered until later tests. Although most unrecovered fish were later collected live during a subsequent test, a small number of unrecovered treatment and control fish were collected dead during later tests. The source or time of death could not be determined for these fish. Defining N_c and N_t as the number of fish released would have assumed that all unrecovered fish were mortalities, leading to over-estimations of turbine passage mortality.

Marks on a small number of fish could not be located or identified after recovery. With the exception of a few replicate trials, the number of fish without identifiable marks recovered during each trial was very low (typically less than 0.5% of fish recovered) and the vast majority of unmarked recoveries were collected live. As a conservative approach for the estimation of turbine passage survival, fish recovered live without a detectable mark were assigned to control groups up to a 100% recovery rate, after which unmarked live fish were classified as treatment fish. Fish recovered dead without a mark were assigned to treatment groups.

A software program developed by Dr. John Skalski and his staff was used to perform the calculations for turbine survival and the evaluation of statistically significant differences among treatments. This program, The Passage Analysis of Turbine Survival Studies program (PATSS; Appendix B), estimated control and turbine survival rates, determined if control and treatment survival rates were homogeneous among replicates and treatments, and performed an analysis of deviance (ANODEV) to determine if there were statistically significant differences in turbine survival estimates among the treatments. If the ANODEV results demonstrated a statistical difference, 95% confidence intervals were adjusted for dispersion in the data and compared for overlap among the treatments. Non-overlapping confidence intervals indicated a statistical difference in the turbine survival estimates.

5.10 Video Techniques and Observations

Separate fish releases were made to evaluate high-speed and conventional video techniques for observing fish entering the scroll case inlet and possibly at the runner inlet. These releases were conducted after testing was completed for each test period (i.e., Fall 2001, Spring and Fall 2002). Some of the video releases were conducted with untested fish, while others were conducted with fish tested during the survival evaluation. A high speed camera (Olympus Encore Model MAC-1000S B/W; up to 20,000 frames per second) was installed in special ports located at two positions; one was about 1/4 of the distance around the scroll case horizontal centerline and other was on the draft tube about 6 inches down from the turbine runner exit. The frame rate used for recording turbine passage with the high speed camera was about 750 frames per second. A handheld digital camera (Sony Model DCR-TRV520 Digital Handycam) was used at viewing ports in the scroll inlet about 1/4 of the distance around the scroll, at the draft tube exit, at the treatment and control fish release locations, and above the inclined screen. Conventional underwater cameras (GENWAC GW-103 B/W progressive scan) were used to view fish exiting both the treatment and control fish injection tubes.

6.0 BIOLOGICAL TESTING - RESULTS

6.1 Preliminary Test Series (Fall 2001) – Test Procedures Evaluation

The Preliminary Test Series conducted in 2001 was successful in providing initial data and information that were used to finalize testing procedures (marking, fish release and recovery, and injury and scale loss evaluations) for Test Series 1 and 2/3. Twelve tests (3 replicate trials conducted with four operating conditions) were completed during the preliminary series. The four operating conditions included heads of 38 and 80 ft with turbine efficiency set at the BEP and an off-BEP condition. The average fork length of rainbow trout evaluated during the preliminary tests was 104 mm (SD = 18.6 mm). Average lengths of treatment and control fish for each test condition are presented in Table 6-1.

6.1.1 Test Procedures Evaluation

Immediate and delayed control mortality for fish recovered during the trial of their release was 0% for all twelve replicates conducted during preliminary tests (Table 6-1). Delayed mortality of treatment fish was also low (< 3% of fish recovered live for tests conducted at 38 ft of head and 0% for tests conducted at 80 ft of head; Table 6-1). The low control fish mortality rates demonstrated that the marking and testing procedures were effective in minimizing fish stress and non-turbine related injury and mortality.

Recovery rates for each test condition (i.e., three replicate trials combined per condition) ranged from 93.4 to 99.3% for treatment groups and 84.5 to 99.3% for control groups (Table 6-1). These tests were conducted for a duration of 10 minutes from the time the last group of fish was released (i.e., time that all fish had exited the release system to the time that the collection bypass gate was closed). Most fish that were not collected during the test in which they were released were recovered during following tests (see Table O-1 in Appendix O). Most of these post-test recoveries were live, but treatment and control fish mortalities were recovered during tests conducted after the one in which they were released. Live fish recovered during later tests were probably able to maintain a position within the test loop for extended periods of time (either upstream or downstream of the turbine for treatment fish and downstream of the turbine for control fish) before moving downstream and into the collection tank. Immediate post-test mortalities may have been impinged on the Eicher (bypass) screen or could have been fish that passed through the turbine after the test in which they were released was completed. Because recovery rates were lower than target goals (> 98%) during some trials and fish were being recovered during subsequent tests, the test duration for Test Series 1 and 2/3 was expanded to about 20 minutes from the time the treatment fish were released (treatment groups were released after controls for all trials conducted during Test Series 1 and 2/3).

TABLE 6-1
SUMMARY OF FISH RELEASE AND RECOVERY DATA FOR THE FALL 2001 PRELIMINARY TEST SERIES WITH RAINBOW TROUT

Head (ft)	Turbine Efficiency	Runner Speed (rpm)	Number of Trials	Test Group	Total Number of Fish Released	Mean FL and SD (mm)	Percent Recovered During Test of Release	Number Recovered Live	Number of Immediate Mortalities (1 hr)	Number of Delayed Mortalities (48 hr)
38	Off-BEP	226	3	T	150	100.7 (15.6)	99.3	147	2	1
				C	156	98.0 (17.5)	96.2	150	0	0
38	BEP	240	3	T	151	103.7 (19.2)	93.4	130	11	3
				C	148	108.1 (18.4)	84.5	125	0	0
80	Off-BEP	322	3	T	150	99.8 (18.4)	97.3	137	9	0
				C	150	101.5 (18.1)	99.3	149	0	0
80	BEP	345	3	T	150	111.4 (18.4)	98.0	135	12	0
				C	153	112.7 (17.9)	97.4	149	0	0

6.1.2 Turbine Survival Estimates

Although the Preliminary Test Series was not designed to generate robust turbine survival estimates, the data that were collected were useful in assessing the appropriateness of the selected statistical models and the effects of the operating conditions that were evaluated. Control group survival rates were homogeneous within and among treatments and turbine survival estimates were homogenous within treatments (chi-square contingency table test of homogeneity, $P > 0.05$). These results demonstrated that release and collection procedures were adequate for producing consistent recovery rates among replicate trials.

Immediate turbine survival was highest at a head of 38 ft and with the turbine operating off-BEP at the lowest turbine runner speed that was evaluated (Table 6-2). The lowest turbine survival rate was observed at a head of 80 ft with the turbine operating at the BEP and the highest runner speed evaluated (Table 6-2). The immediate turbine survival estimates for 38 ft head/BEP and 80 ft head/off-BEP were between 92 and 94% (Table 6-2). Despite a difference of almost 8% in immediate survival rates between the lowest and highest estimates, there were no statistically significant differences among treatment conditions. Total turbine survival estimates (i.e., immediate and 96-hr mortality combined) were 1-2% lower than the immediate survival rates for tests at a head of 38 ft (Table 6-2). Total turbine survival at 38 ft of head was significantly lower for tests at BEP than for tests at off-BEP (ANODEV; $P < 0.05$). For the tests at 80 ft of head, there was no difference between immediate and total turbine survival because there was no treatment fish mortality during the 96-hr post test holding period. The differences in total turbine survival rates at a head of 80 ft were not statistically different between tests at the two turbine efficiency points (ANODEV; $P < 0.05$).

TABLE 6-2
TURBINE SURVIVAL ESTIMATES FOR THE FALL 2001 PRELIMINARY TEST SERIES CONDUCTED AT TWO HEADS AND TWO TURBINE OPERATING EFFICIENCIES

Survival rates without a letter in common are significantly different ($P < 0.05$)

Head (ft)	Mean Fish Length (mm)	Turbine Efficiency	Runner Speed (rpm)	Immediate Turbine Survival (%) ± 95% CI	Total Turbine Survival (%) ± 95% CI
38	99.5	Off-BEP	226	98.7 ± 1.8^{a}	98.0 ± 2.3^{a}
38	105.9	BEP	240	92.2 ± 4.4^{a}	90.1 ± 4.9^{b}
80	100.8	Off-BEP	322	93.8 ± 3.9^{a}	93.8 ± 3.9^{a}
80	112.0	BEP	345	91.8 ± 4.4^{a}	91.8 ± 5.2^{a}

6.2 Test Series 1 (Fall 2001) – Treatment Release Location Evaluation

Test Series 1 was designed to evaluate the potential effects of treatment fish depth as they approach the turbine inlet and scroll case and pass through the runner. For this Test Series, treatment fish were released at three depths within the pipe leading to the turbine. The three depths were classified as top (12 inches from the top of the pipe), middle (centerline depth of pipe), and bottom (12 inches from the bottom of the pipe). Control groups were released at the bottom depth within the draft tube portion of the pipe for all trials conducted during this test series. The control release location was selected based on the results of the preliminary tests that demonstrated there was no difference in control mortality related to release location, and velocity measurements that indicated flows near the bottom of the pipe may best represent the conditions that treatment fish were exposed to after injection.

The average length of all rainbow trout evaluated during Test Series 1 was 111.3 mm (SD = 19.4 mm). The range of average fish lengths for treatment and control groups was 109 to 113 mm (Table 6-3).

6.2.1 Turbine Survival Estimates

Recovery rates of treatment and control groups evaluated during Test Series 1 ranged from 96.5 to 98.6% (Table 6-3). The recovery rate of treatment fish was lower than control fish for all three test conditions. Most unrecovered fish were collected live in later tests (i.e., tests conducted after the test in which a fish was released) (see Table O-2 in Appendix O). Live fish comprised about 90% of post-test recoveries for both treatment and control groups. Consequently, the number of post-test recoveries that were collected dead was less than 1% of the total number of fish released. Recovery rates of treatment and control fish were also affected by fish which did not have detectable marks. Twenty-five fish recovered in Test Series 1 trials did not have marks that could be identified during the post-test injury evaluation (Table 6-3). Twenty-four of these fish were recovered live and one was recovered dead.

Immediate mortalities accounted for about 74 to 81% of the total number of treatment fish that died during the evaluation of the three release locations. Delayed mortality was most prevalent during the first 48 hrs of the 96 hour post-test holding period (see Table O-3 in Appendix O). Immediate survival of control fish exceeded 99% and total survival (immediate and 96-hour combined) was 98.9% or greater for all three test conditions. Immediate turbine passage survival rates ranged from 92.7 to 92.9% and total turbine survival ranged from 90.3 to 91.0% (Table 6-4). Statistical comparisons of the immediate and total turbine survival rates revealed no significant differences among the three release locations (ANODEV, $P > 0.05$).

TABLE 6-3
SUMMARY OF FISH RELEASE AND RECOVERY DATA FOR FALL 2001 TESTS WITH RAINBOW TROUT
TEST SERIES 1 – WITHOUT WICKET GATES

All tests were conducted at an operating head of 38 ft and at the BEP.
Test Group codes are: T, treatment; C, control; and NM, no identifiable mark.

Treatment Fish Release Location	Number of Trials	Test Group	Total Number of Fish Released	Mean FL and SD (mm)	Percent Recovered During Test of Release	Number Recovered Live	Number of Immediate Mortalities (1 hr)	Number of Delayed Mortalities (96 hr)
top	9	T	871	109.2 (20.0)	97.5	788	61	21
		C	873	111.6 (20.1)	98.6	861	0	0
		NM	--	94.2 (20.2)	--	14	0	0
middle	9	T	889	112.2 (19.9)	96.5	791	67	16
		C	897	112.7 (19.4)	98.4	879	4	6
		NM	--	94.6 (20.0)	--	9	1	0
bottom	9	T	900	111.6 (18.2)	98.3	820	65	15
		C	898	110.4 (18.6)	98.6	885	0	5
		NM	--	130.0 (--)	--	1	0	0

TABLE 6-4
TURBINE SURVIVAL ESTIMATES FOR TEST SERIES 1 (WITHOUT WICKET GATES)

All tests were conducted with at a head of 38 ft and the best efficiency point (BEP).
Survival rates for three release locations are not significantly different.

Treatment Release Location	Immediate Turbine Survival (%) ± 95% CI	Total Turbine Survival (%) ± 95% CI
top	92.9 ± 1.7	90.4 ± 2.0
middle	92.1 ± 1.8	90.3 ± 2.0
bottom	92.7 ± 1.7	91.0 ± 1.9

6.2.2 Injury and Scale Loss Evaluation

Approximately 90% of treatment fish and greater than 95% of control fish recovered during Test Series 1 were classified as uninjured based on an absence of visible external injuries (Table 6-5). Depending on test condition, about 95% or more of treatment fish recovered live exhibited no external injuries (Table 6-5). In contrast, only 6.5 to 12.7% of immediate treatment mortalities were classified as uninjured. Immediate mortalities that did not have any external injuries may have suffered from some type of internal injury. About 70% or greater of immediate treatment mortalities were observed with bruising and/or hemorrhaging. Bruising was also the most common injury observed on live treatment fish. The next most common injury suffered by immediate mortalities was lacerations, followed by severed bodies and eye injuries (Table 6-5). The occurrence of lacerations and eye injuries was about 1% or less for live treatment fish. Based on the high rate of bruising and relatively high rates of lacerations and severed bodies, the primary mechanism for injuries suffered by immediate mortalities was most likely strike-related.

The percent of control fish that did not have visible injuries (96.5-98.3%) was greater than for treatment fish for each of the test conditions evaluated (Table 6-5). Similar to treatment fish, the most common injury observed on control fish was bruising. Unlike turbine survival rates, the injury rates reported for treatment fish are not adjusted for control data. Based on the control fish injury rates, it is likely that a similar proportion of treatment fish injuries can be attributed to marking and testing procedures.

The percent of scale loss estimated for treatment fish was generally higher than scale loss rates estimated for control fish (see Table O-4 in Appendix O). However, the percent of treatment and control groups that had less than 3% scale loss was typically between 80 and 90% for each of the three body sections for which it was measured. Greater than 95% of treatment and control fish for all three test conditions had less than 20% scale loss in each location. The percent of fish that were classified as descaled (i.e., greater than 20% scale loss in two or more locations on one side of the fish) was less than 2% for treatment fish and less than 1% for control fish (Table 6-6). The percent of treatment fish mortalities that were classified as descaled was considerably greater than it was for live fish (Table 6-6), ranging from 7.0 to 11.3% for the three test conditions. None of the four control fish immediate mortalities were classified as being descaled.

TABLE 6-5
PERCENT OF RAINBOW TROUT RECOVERED DURING TEST SERIES 1 (WITHOUT WICKET GATES) THAT WERE OBSERVED WITH EXTERNAL INJURIES

T = treatment fish; C = control fish

Treatment Release Location	Live/ Dead	Total Number Recovered		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
		T	C	T	C	T	C	T	C	T	C	T	C
Top	L	788	861	96.5	98.3	2.5	0.9	0.5	0.7	--	--	0.8	0.2
	D	61	0	6.5	--	79.0	--	8.1	--	14.5	--	16.1	--
	Total	849	861	90.1	98.3	8.0	0.9	1.0	0.7	1.0	0.0	1.9	0.2
middle	L	791	879	94.8	96.5	3.2	1.9	1.1	0.3	--	--	0.5	0.8
	D	67	4	12.7	40.0	69.0	60.0	16.9	0.0	7.0	0.0	9.9	0.0
	Total	858	883	88.2	96.2	8.5	2.2	2.4	0.3	0.7	0.0	1.3	0.8
bottom	L	820	885	96.3	97.0	3.1	2.6	0.5	0.2	--	--	0.4	0.1
	D	65	0	11.9	0.0	76.1	0.0	17.9	0.0	10.5	0.0	1.5	100.0
	Total	885	885	89.9	96.9	8.6	2.6	1.8	0.2	0.8	0.1	0.5	0.2

TABLE 6-6
PERCENT OF RAINBOW TROUT RECOVERED DURING TEST SERIES 1 (WITHOUT WICKET GATES) THAT WERE CLASSIFIED AS DESCALED

Treatment Release Location	Live/Dead	Treatment Number Recovered	Treatment % Classified as Descaled	Control Number Recovered	Control % Classified as Descaled
top	Live	788	0.5	861	0.2
	Dead (1 hr)	61	11.3	0	0.0
	Total	849	1.3	861	0.2
middle	Live	791	0.6	879	0.1
	Dead (1 hr)	67	7.0	4	0.0
	Total	858	1.1	883	0.1
bottom	Live	820	1.5	885	0.8
	Dead (1 hr)	65	7.5	0	0.0
	Total	885	1.9	885	0.8

6.3 Test Series 2/3 (Fall 2001) – Operating Head and Fish Size Evaluation without Wicket Gates

Test Series 2/3 was designed to evaluate differences in turbine survival rates associated with fish size and turbine operating head without wicket gates installed. For these tests, two size groups of rainbow trout were each evaluated at 38 and 80 ft of head. The study plan called for Test Series 2 to be conducted with fish that were 50 to 100 mm in length, and Test Series 3 was designed to evaluate fish between 125 and 175 mm in length. Due to scheduling delays, the average length of the two size groups were about 25 mm greater than originally planned. The average length of the smaller fish was 93.4 mm (SD = 8.7 mm) and the average length of the larger fish was 173.4 mm (SD = 24.7). Mean lengths of treatment and control fish tested with each set of conditions are presented in Table 6-7. To strengthen the statistical comparisons made between the survival rates estimated for the two size groups and turbine heads, the nine replicate trials conducted with each combination of fish size and head were combined into one test series and performed in random order.

TABLE 6-7
SUMMARY OF FISH RELEASE AND RECOVERY DATA FOR FALL 2001 TESTS WITH RAINBOW TROUT
TEST SERIES 2/3 – WITHOUT WICKET GATES

Test group codes are: T, treatment; C, control; and NM, no identifiable mark.

Head (ft)	Fish Size Group	Number of Trials	Test Group	Total Number of Fish Released	Mean FL and SD (mm)	Percent Recovered During Test of Release	Number Recovered Live	Number of Immediate Mortalities (1 hr)	Number of Delayed Mortalities (96 hr)
38	small	9	T	882	94.1 (9.5)	98.9	827	45	19
			C	883	93.2 (8.3)	96.5	852	0	0
			NM	--	--	--	0	0	0
80	small	9	T	851	92.9 (8.0)	98.0	771	63	12
			C	862	93.3 (8.9)	99.3	856	0	0
			NM	--	--	--	0	0	0
38	large	9	T	890	174.0 (24.3)	90.6	714	92	18
			C	885	173.7 (25.5)	93.6	823	5	9
			NM	--	169.5 (22.8)	--	63	1	0
80	large	9	T	897	173.3 (24.1)	100.6[a]	746	156	15
			C	897	172.7 (24.8)	98.7	869	16	8
			NM	--	--	--	0	0	0

[a] A recovery rate greater than 100% indicates that more fish were recovered than were released. This occurred during one or more trials for most of the treatment conditions. Sources of sampling error that may have contributed to overestimates of recovery rates include miscounts of the number of fish released and/or errors in data recording during the injury evaluation.

6.3.1 Turbine Survival Estimates

Recovery rates of treatment and control groups evaluated during Test Series 2/3 ranged from 96.5 to 99.3% for smaller size group and 90.6 to 100.6% for the larger size group (Table 6-7). Most unrecovered fish were collected live during subsequent trials (see Table O-5 in Appendix O). Additionally, the percentage of fish that were unrecovered was smaller for tests conducted at the higher head for both size groups that were evaluated. This was likely due to higher velocities that made it difficult for fish to remain upstream of the collection area for extended periods of time (i.e., longer than a test period). The lowest recovery rates observed for treatment and control groups occurred with larger fish evaluated at a head of 38 ft (Table 6-7). These relatively low recovery rates were due to one trial in which the marks of 65 fish could not be identified. The lack of visible marks for some of the fish tested during this trial was attributed to a marking gun that malfunctioned resulting in a lack of pressure to properly inject the photonic dye into the base of the targeted fins. For the purposes of estimating turbine survival, unmarked live fish were assigned to the control group up to a recovery rate of 100%, after which they were assigned to the treatment group. There was one immediate mortality that did not have a mark; this fish was assumed to be from the treatment release. Including the unmarked fish in the survival analysis prevented the need for statistically evaluating turbine survival rates among the treatments with unequal replication (i.e., the alternative to assigning unmarked fish to the treatment and control groups would have been to eliminate the data collected during this trial from the survival analysis).

Control survival (immediate and 96 hr) was 100% for the evaluation of the two heads with smaller fish and was greater than 97% for tests with larger fish (Table 6-7). Most treatment fish delayed mortalities occurred within the first 48 hours of the 96-hour holding period (see Table O-6 in Appendix O). Immediate and total turbine survival was higher for smaller fish at both of the operating heads and survival of both size groups was higher at the lower head (Table 6-8). The statistical evaluation of the immediate and total turbine survival rates resulted in significant differences for several comparisons of test conditions (i.e., fish size and head). Immediate survival of smaller fish evaluated at 38 ft of head was significantly greater than survival of larger fish evaluated at both heads (ANODEV, $P > 0.05$). Immediate survival of smaller fish tested at 80 ft of head also was significantly greater than survival of larger fish tested at 80 ft of head ($P < 0.05$), but it was not significantly different from the estimate of survival for larger fish evaluated at 38 ft of head ($P > 0.05$). The differences in immediate and total turbine survival rates estimated for the two head conditions were not statistically significant for either size group ($P > 0.05$). However, total turbine survival was significantly greater for smaller fish evaluated at both heads than for the larger fish at evaluated at 80 ft of head ($P > 0.05$). There was no statistical difference between the total turbine survival rates of the smaller fish at both head levels and larger fish evaluated at the lower head ($P > 0.05$).

TABLE 6-8
TURBINE SURVIVAL ESTIMATES FOR TEST SERIES 2/3 (WITHOUT WICKET GATES)

All tests were conducted at the best efficiency point (BEP).
Survival rates without a letter in common are significantly different ($P < 0.05$)

Mean Fish Length (mm)	Head (ft)	Immediate Turbine Survival (%) ± 95% CI	Total Turbine Survival (%) ± 95% CI
93.7	38	94.8 ± 1.5[a]	92.7 ± 1.7[a]
93.1	80	92.5 ± 1.8[ab]	91.0 ± 1.9[a]
173.8	38	89.1 ± 2.1[bc]	88.4 ± 2.4[ab]
173.0	80	84.2 ± 2.6[c]	83.3 ± 2.8[b]

6.3.2 Injury and Scale Loss Evaluation

The percent of recovered fish that had no visible injuries was lower for treatment fish (79.4 - 92.2%) than for controls (98.5 – 99.7%) for each of the test conditions evaluated (Table 6-9). Fish size and head also influenced treatment group injury rates. A greater percent of smaller fish were classified as uninjured compared to larger fish and both size groups also exhibited higher levels of injury at the higher head. Bruising was the most common injury observed for treatment fish, followed by lacerations and severed bodies (Table 6-9). About 17% of the treatment fish mortalities had eye injuries, but less than 1% of live recoveries had eye damage. The occurrence of each type of injury was generally less than 4% for treatment fish (live and dead combined) and less than 2% for control fish. The high rate of bruising that was observed for immediate mortalities, combined with observations of lacerations and severed bodies, indicates that physical strikes (most likely with the leading edge of the runner) were the primary cause of turbine-related injury and mortality.

The percent of control fish recovered live that did not have visible injuries ranged from 99.1 to 99.7%. The percent of control fish that were uninjured was greater than for treatment fish for each of the test conditions evaluated (Table 6-9). Similar to treatment fish, the most common injury observed sustained by control fish was bruising. Unlike turbine survival rates, the injury rates reported for treatment fish are not adjusted for control data. However, because the injury rates of control fish in this test series were very low (<1%), any adjustments to the treatment data to account for handling related injury would have been minor.

The percent of fish with less than 3% scale loss in each of the three locations that were examined was greater for treatment fish than for controls for all of the test conditions that were evaluated in Test Series 2/3 (see Table O-7 in Appendix O). Greater than 90% of all treatment and control fish evaluated during this test series had less than 20% scale loss for each of the three locations. The percent of fish that were classified as descaled was slightly higher for treatment groups than for control groups for each of the test conditions (Table 6-10). Also, the larger fish had higher rates of descaling than did the smaller fish. Within each size group, a greater percent of fish were classified as descaled for tests at the higher head level (Table 6-10).

TABLE 6-9

PERCENT OF RAINBOW TROUT RECOVERED DURING TEST SERIES 2/3 (WITHOUT WICKET GATES) THAT WERE OBSERVED WITH EXTERNAL INJURIES

T = treatment fish; C = control fish

Head (ft)	Mean Fish Length (mm)	Live/ Dead	Total Number Recovered		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
			T	C	T	C	T	C	T	C	T	C	T	C
38	93.7	L	827	852	96.7	99.2	2.5	0.5	0.5	0.1	--	--	0.4	0.1
		D	45	0	10.9	--	80.4	0.0	15.2	0.0	8.7	0.0	17.4	0.0
		Total	872	852	92.2	99.2	6.6	0.5	1.2	0.1	0.5	0.0	1.2	0.1
80	93.1	L	771	856	96.3	99.7	3.5	0.1	0.3	0.0	--	--	0.1	0.1
		D	63	0	0.0	--	68.3	0.0	42.9	0.0	39.7	0.0	15.9	0.0
		Total	834	856	89.1	99.7	8.3	0.1	3.4	0.0	3.0	0.0	1.3	0.1
38	173.8	L	714	823	95.9	99.3	3.5	0.5	0.3	0.0	--	--	0.7	0.5
		D	92	5	12.9	30.0	71.0	60.0	14.0	30.0	16.1	30.0	9.7	0.0
		Total	806	828	86.7	98.5	10.9	1.2	1.8	0.4	1.8	0.4	1.7	0.5
80	173.0	L	746	869	94.7	99.1	4.3	0.8	0.3	0.1	--	--	0.9	0.0
		D	156	16	7.0	87.5	67.7	12.5	34.8	0.0	36.7	0.0	12.0	0.0
		Total	902	885	79.4	98.9	15.3	1.0	6.3	0.1	6.4	0.0	2.9	0.0

TABLE 6-10
PERCENT OF RAINBOW TROUT RECOVERED DURING TEST SERIES 2/3 (WITHOUT WICKET GATES) THAT WERE CLASSIFIED AS DESCALED

Head (ft)	Mean Fish Length (mm)	Live/Dead	Treatment Number Recovered	Treatment % Classified as Descaled	Control Number Recovered	Control % Classified as Descaled
38	93.7	Live	827	2.6	852	1.8
		Dead	45	37.0	0	0.0
		Total	872	4.4	852	1.8
80	93.1	Live	771	1.7	856	0.6
		Dead	63	46.0	0	0.0
		Total	834	5.0	856	0.6
38	173.8	Live	714	3.3	823	2.2
		Dead	92	29.0	5	40.0
		Total	806	6.2	828	2.7
80	173.0	Live	746	3.9	869	2.8
		Dead	156	31.1	16	18.8
		Total	902	8.6	885	3.0

6.4 Test Series 5/6 (Spring 2002) – Operating Head and Fish Size Evaluation with Wicket Gates

Test Series 5/6 was designed to evaluate differences in turbine survival rates associated with fish size and turbine operating head with wicket gates installed. For these tests, three size groups of rainbow trout were each evaluated at 40 and 80 ft of head. The target size ranges for the two larger size groups evaluated in this test series was the same as the two size groups tested during Test Series 2/3 (tests at the same heads without wicket gates installed). The average lengths for the larger size groups evaluated in Test Series 5/6 were 85.0 mm (SD = 8.6 mm) and 172.3 mm (SD = 18.9 mm), compared to 93.4 mm (SD = 8.7 mm) and 173.4 mm (SD = 24.7 mm) for Test Series 2/3. The smallest size group was included in Test Series 5/6 to provide additional data for assessing relationships between fish length and turbine survival and injury rates. The average length of these fish was 38.2 mm (SD = 3.6 mm). The mean lengths of treatment and control fish for each set of test conditions are presented in Table 6-11. The 18 trials (2 heads x 9 trials) conducted with each size group were performed in random order.

6.4.1 Turbine Survival Estimates

Recovery rates of treatment and control groups evaluated during Test Series 5/6 ranged from 96.7 to 99.3% (Table 6-11). Most unrecovered fish (about 88% for all test groups and conditions combined) were collected live during subsequent trials (see Table O-8 in Appendix O). The percent of fish that were unrecovered typically was less for tests conducted at the higher head for all three size groups. However, differences in recovery rates between tests at the two heads were typically less than 1%. Similar to previous test series, some recovered fish did not have detectable marks for several of the trials conducted with each size group. The lack of visible marks for these fish most likely was due to inadequate amounts of the photonic dye being injected into the base of the targeted fins. As described previously, fish recovered live without a detectable mark were assigned to control groups up to a 100% recovery rate, after which, unmarked live fish were classified as treatment fish. Fish recovered dead without a mark were assigned to treatment groups. This approach was chosen primarily because several unmarked fish recovered during tests with the largest size group were immediate mortalities that most likely were treatment fish that were killed during turbine passage. With the exception of two trials (one during the evaluation of smallest size group at a head of 80 ft and the other during the evaluation of the largest size group at 80 ft), the number of fish recovered without detectable marks was extremely low (Table 16-11).

Immediate survival of control fish was high (> 99%) for all test conditions evaluated during Test Series 5/6 (Table 6-11), including 100% survival for tests at both heads with the medium-sized fish. Delayed control survival was also high (> 99%) for tests with the two larger size groups, but approached 10% for tests with the smallest size group (Table 6-11). High rates of delayed mortality (about 10%) for treatment fish were also observed during tests with this size group. These delayed mortality rates were attributed to a relatively rapid increase in the holding facility water temperature that occurred after the chiller was tripped off during a thunderstorm on the night of the last day of testing with small fish. The relationship between delayed mortality for tests with the smallest size group and the temperature increase is demonstrated in Figure 6-1. With the exception of these tests, most treatment fish delayed mortalities occurred within the first 48 hours of the 96-hour holding period (see Table O-9 in Appendix O).

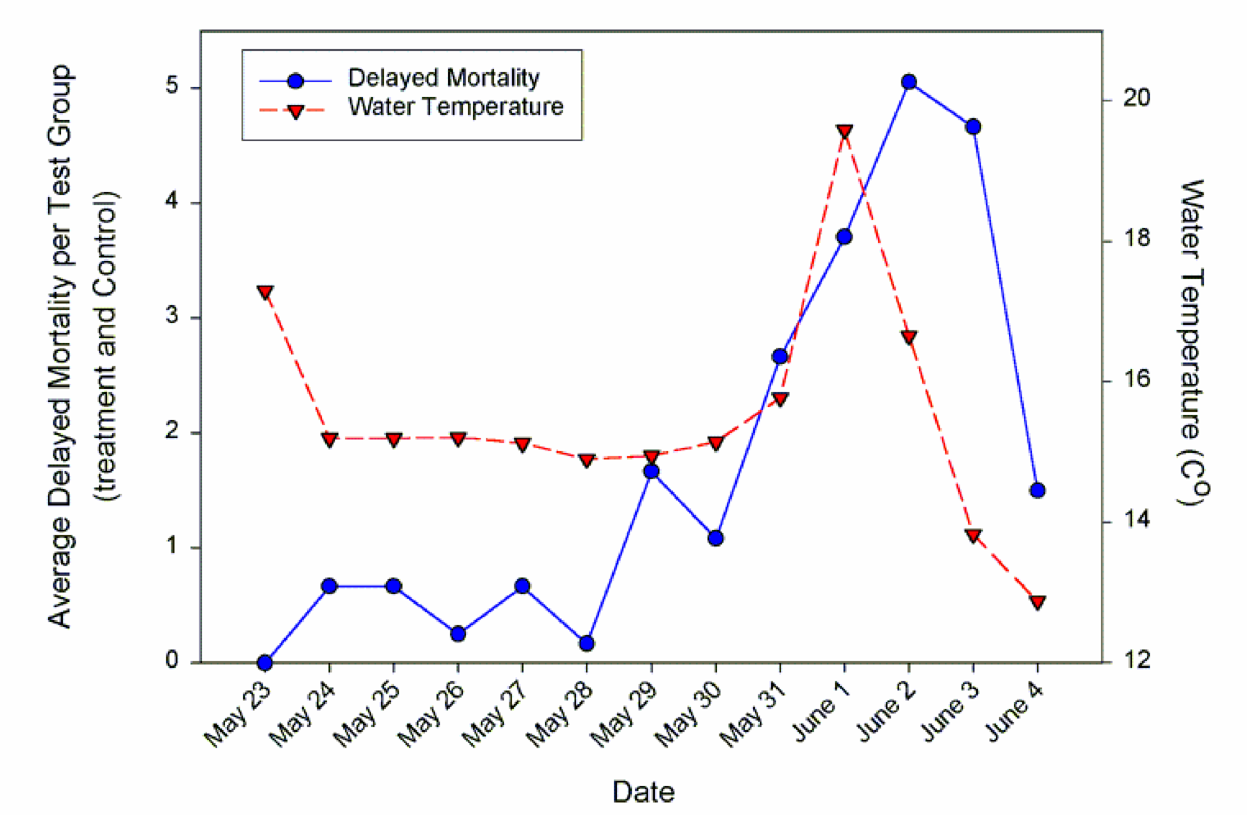


FIGURE 6-1 AVERAGE NUMBER OF DAILY DELAYED MORTALITIES PER TEST GROUP (TREATMENT AND CONTROL) FOR SMALL RAINBOW TROUT (MEAN FL = 38 MM) EVALUATED AT HEADS OF 40 AND 80 FT

TABLE 6-11
SUMMARY OF FISH RELEASE AND RECOVERY DATA FOR SPRING 2002 TESTS WITH RAINBOW TROUT
TEST SERIES 5/6 - WICKET GATES INSTALLED

Test group codes are: T, treatment; C, control; and NM, no identifiable mark.

Target Fish Size (mm)	Head (ft)	Number of Trials	Test Group	Total Number of Fish Released	Mean FL and SD (mm)	Percent Recovered During Test of Release	Number Recovered Live	Number of Immediate Mortalities (1 hr)	Number of Delayed Mortalities (96 hr)
40-60	40	9	T	890	38.1 (3.6)	98.0	836	36	71
			C	884	37.8 (3.7)	98.5	863	8	81
			NM	--	34.0 (2.8)	--	2	1	12
	80	9	T	891	38.3 (3.6)	96.7	825	37	88
			C	890	38.4 (3.6)	98.0	867	5	81
			NM	--	37.1 (3.9)	--	18	2	4
80-110	40	9	T	876	85.1 (8.3)	99.3	829	41	7
			C	874	84.9 (9.0)	99.1	866	0	2
			NM	--	73.0 (--)	--	1	0	0
	80	9	T	859	84.8 (8.8)	98.6	775	72	8
			C	858	85.0 (8.5)	98.3	843	0	1
			NM	--	--	--	0	0	0
150-200	40	9	T	899	170.3 (18.7)	97.9	803	77	18
			C	877	169.0 (18.8)	97.6	856	0	4
			NM	--	--	--	0	3	0
	80	9	T	898	173.6 (18.7)	97.7	724	153	25
			C	864	175.6 (18.3)	99.2	853	4	6
			NM	--	180.1 (16.0)	--	7	5	0

Similar to Test Series 2/3, immediate and total turbine survival rates for Test Series 5/6 decreased with increasing fish size at both heads and decreased with head for each size class (Table 6-12). Survival rates were not significantly different between the two heads for the small and medium size groups of rainbow trout, whereas survival rates at the lower head were significantly greater than at the higher head for the large size group ($P < 0.05$; Figure 6-2). Additionally, at each head, the smaller and medium-sized fish had significantly greater survival rates than fish of the largest size group ($P < 0.05$; Figure 6-2). The survival rates of the smaller fish were greater than the medium size group at both heads. However, the differences between these two size groups were not statistically different at either head, despite a difference in mean length of about 47 mm (almost 2 inches). The results of these tests indicate that size may have a greater effect on survival for fish with lengths about 150 to 200 mm and that the effects of head are more evident for fish of this size than for fish less than 100 mm.

TABLE 6-12
TURBINE SURVIVAL ESTIMATES FOR TEST SERIES 5/6 (WICKET GATES INSTALLED)

All tests were conducted at the best efficiency point (BEP).
Survival rates without a letter in common are significantly different ($P > 0.05$)

Head (ft)	Mean Fish Length (mm)	Immediate Turbine Survival (%) ± 95% CI	Total Turbine Survival (%) ± 95% CI
40	38.0	97.6 ± 1.4[a]	96.2 ± 2.8[a]
80	38.4	96.6 ± 1.6[ab]	96.0 ± 2.7[a]
40	85.0	96.5 ± 1.4[ab]	95.5 ± 1.6[a]
80	84.9	93.3 ± 1.9[bc]	92.2 ± 2.0[ab]
40	169.8	91.7 ± 2.1[c]	90.4 ± 2.2[b]
80	174.7	82.9 ± 2.9[d]	80.7 ± 3.0[c]

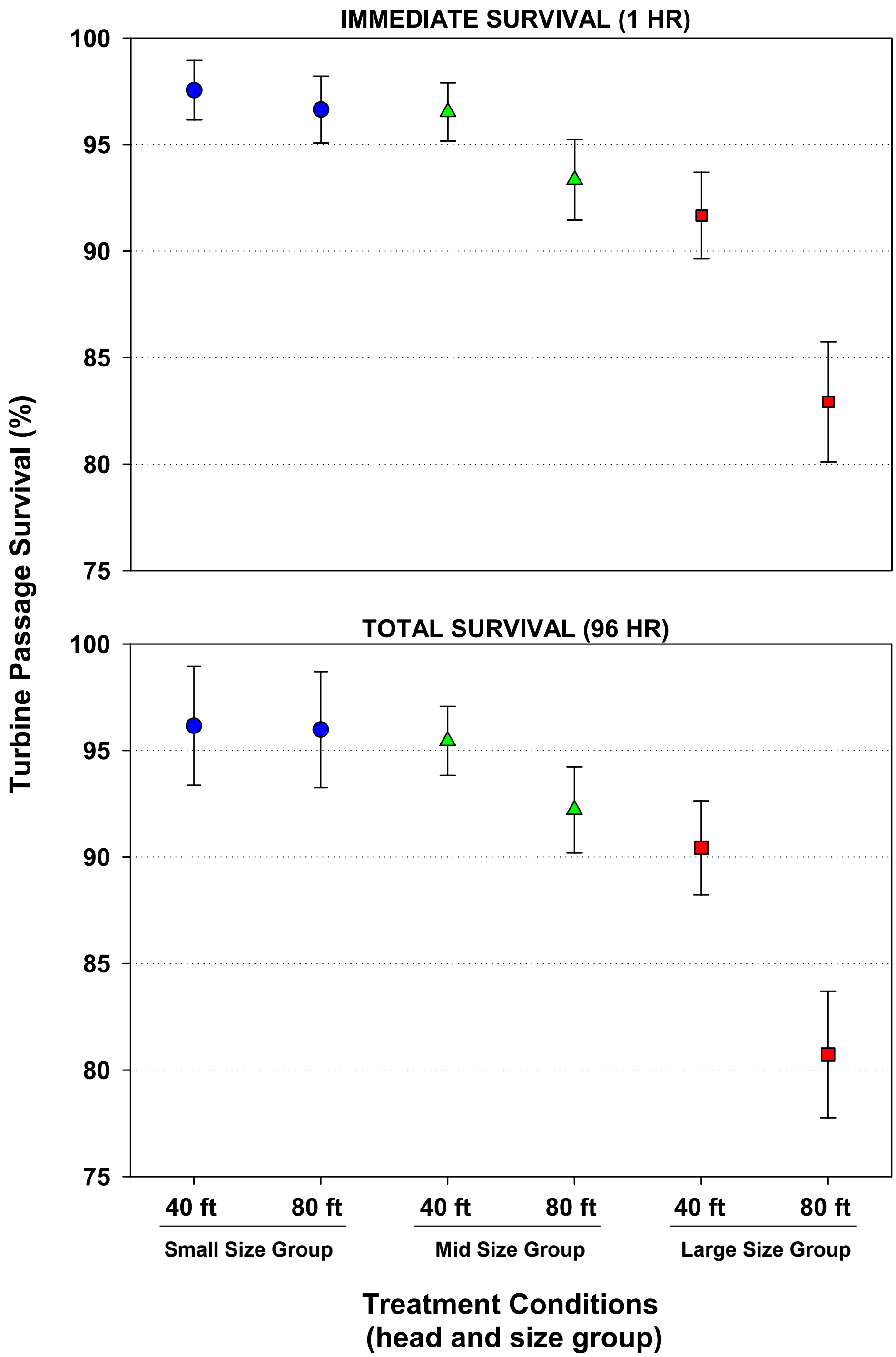


FIGURE 6-2 IMMEDIATE (1 HR) AND TOTAL (1 HR AND 96 HRS COMBINED) TURBINE SURVIVAL ESTIMATES (± 95% CI) FOR TEST CONDITIONS EVALUATED DURING TEST SERIES 5/6 (WITH WICKET GATES)

NOTE: Confidence intervals are adjusted to account for dispersion in the survival estimates. Survival rates that have non-overlapping confidence intervals are significantly different ($P < 0.05$).

6.4.2 Injury and Scale Loss Evaluation

The percent of all recovered fish that were classified as uninjured (i.e., had no visible injuries) was lower for treatment fish than for controls for each of the test conditions evaluated during Test Series 5/6 (Table 6-13). For the small (mean FL = 38.2 mm) and medium (mean FL = 85.0 mm) size groups, the percent of treatment fish recovered live that did not exhibit any external injuries exceeded 98% for tests at both heads. Bruising was the most common injury observed on live treatment fish, but the rate of occurrence for this injury type never exceeded 5.4% for any of the test conditions, and was less than 2% for tests with the small and medium size fish. Lacerations, severed bodies, and eye injuries occurred at rates of less than 1% for live treatment fish. The percent of immediate treatment mortalities without visible injuries was low (7 to 18%) for all test conditions, and decreased with head for the medium and large size groups (Table 6-13). Similar to tests conducted in 2001, bruising was the most common injury observed for treatment fish that were recovered dead. Although the rate of bruising generally was similar among tests at each head, the percentages of immediate treatment mortalities with lacerations, severed bodies, and eye injuries were considerably greater at the higher head for tests with all three size groups. In particular, severed bodies were not observed during tests at the 40 ft head with the small and medium size fish, but occurred at rates exceeding 20% for the tests at 80 ft of head. A similar increase in the rate of severed bodies was also observed for the largest size group (mean FL = 172.3 mm).

The percent of fish with less than 3% scale loss in each of the three body locations that were examined typically was greater for control fish than for treatment fish for all of the test conditions that were evaluated in Test Series 5/6 (see Table O-10 in Appendix O). This difference was more notable for tests with the two larger size groups of fish and for tests at the higher head within each size group. Additionally, control fish scale loss increased with fish size, but was similar between tests at each head within each size class. Scale loss greater than 3% was rare for treatment fish of the smallest size group, most likely because rainbow trout of this size are not prone to scale loss, even when exposed to stressful conditions and excessive handling. Scale loss greater than 20% was infrequent for treatment fish of the medium and large size groups.

The percent of control fish classified as descaled was 0% for all tests with the small and medium size rainbow trout and less than 0.5% for tests with the large trout (Table 6-14). The percent of treatment fish that were classified as descaled also was 0% for tests with the smallest size group of rainbow trout. The highest rates of treatment fish descaling occurred with immediate mortalities during tests with the largest size group (Table 6-14). However, the total percent of treatment fish that were descaled did not exceed 2.2% for all recovered fish (i.e., live and dead recoveries combined) within each set of test conditions.

TABLE 6-13
PERCENT OF RAINBOW TROUT RECOVERED DURING TEST SERIES 5/6 (WICKET GATES INSTALLED) THAT WERE OBSERVED WITH EXTERNAL INJURIES

T = treatment fish; C = control fish

Head (ft)	Mean Fish Length (mm)	Live/ Dead	Total Number Recovered		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
			T	C	T	C	T	C	T	C	T	C	T	C
40	38.0	L	836	863	99.9	100.0	0.0	0.0	0.0	0.0	--	--	0.1	0.0
		D	36	8	8.1	22.2	89.2	55.6	5.4	33.3	0.0	0.0	8.1	0.0
		Total	872	871	96.0	99.0	3.7	0.6	0.23	0.3	0.0	0.0	0.5	0.0
80	38.4	L	825	867	99.8	99.9	0.1	0.1	0.0	0.0	--	--	0.1	0.0
		D	37	5	18.4	42.9	76.3	28.6	15.8	14.3	21.1	0.0	15.8	14.3
		Total	862	872	96.2	99.4	3.4	0.3	0.7	0.1	0.9	0.0	0.8	0.1
40	85.0	L	829	866	98.7	100.0	1.3	0.0	0.0	0.0	--	--	0.0	0.0
		D	41	0	12.2	--	75.6	--	24.4	--	0.0	--	9.8	--
		Total	870	866	94.6	100.0	4.8	0.0	1.1	0.0	0.0	0.0	0.5	0.0
80	84.9	L	775	856	98.6	99.6	1.3	0.2	0.1	0.1	--	--	0.0	0.1
		D	72	0	6.9	--	81.9	--	48.6	--	29.2	--	9.7	--
		Total	847	856	91.0	99.6	8.1	0.2	4.2	0.1	2.5	0.0	0.8	0.1

TABLE 6-13 (CONTINUED)

Head (ft)	Mean Fish Length (mm)	Live/ Dead	Total Number Recovered		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
			T	C	T	C	T	C	T	C	T	C	T	C
40	169.8	L	803	856	96.3	99.3	3.2	0.6	0.2	0.1	--	--	0.2	0.0
		D	77	0	11.5	0.0	79.5	100.0	10.3	100.0	3.8	0.0	12.8	0.0
		Total	897	856	89.0	99.0	9.8	0.7	1.1	0.2	0.3	0.0	1.3	0.0
80	174.7	L	724	853	93.6	99.3	5.4	0.6	1.0	0.0	--	--	0.1	0.1
		D	153	4	7.5	20.0	68.4	40.0	37.9	20.0	30.5	50.0	14.4	20.0
		Total	877	857	78.4	98.4	16.5	1.0	7.5	0.2	5.4	0.5	2.6	0.3

TABLE 6-14
PERCENT OF RAINBOW TROUT RECOVERED DURING TEST SERIES 5/6 (WICKET GATES INSTALLED) THAT WERE CLASSIFIED AS DESCALED

Head (ft)	Mean Fish Length (mm)	Live/Dead	Treatment Number Recovered	Treatment % Classified as Descaled	Control Number Recovered	Control % Classified as Descaled
40	38.0	Live	836	0.0	863	0.0
		Dead	36	0.0	8	0.0
		Total	872	0.0	871	0.0
80	38.4	Live	825	0.0	867	0.0
		Dead	37	0.0	5	0.0
		Total	862	0.0	872	0.0
40	85.0	Live	829	0.5	866	0.0
		Dead	41	2.4	0	0.0
		Total	870	0.6	866	0.0
80	84.9	Live	775	0.3	843	0.0
		Dead	72	0.0	0	0.0
		Total	847	0.2	843	0.0
40	169.8	Live	803	0.1	856	0.2
		Dead	77	5.1	0	0.0
		Total	880	0.6	856	0.2
80	174.7	Live	724	0.1	853	0.4
		Dead	153	12.1	4	0.0
		Total	877	2.2	857	0.4

6.5 Test Series 7 (Fall 2002) – Evaluation of Additional Species

Test Series 7 was designed to assess turbine passage survival and injury rates for several fish species with distinct differences in morphology, swimming ability, and behavior, all of which may contribute to differences in turbine survival rates among species. The species that were selected for testing – alewife, coho salmon, and white sturgeon – represent fishes commonly entrained at hydro projects with recreational and/or commercial importance. To allow direct comparisons with the trout data, the target size range for the each of the additional species was between 75 and 100 mm. Mean lengths of species evaluated during Test Series 7 were 75.6 mm (SD = 8.4) for alewife, 102.3 mm (SD = 16.0 mm) for coho salmon, and 102.8 mm (SD = 15.1) for white sturgeon. Mean lengths of treatment and control fish for tests with each species are included in Table 6-15.

6.5.1 Turbine Survival Estimates

Recovery rates for treatment and control groups during Test Series 7 exceeded 98% for alewife and white sturgeon (Table 6-15). Recovery rates of coho salmon were 93.1% for treatment fish and 92.3% for controls (Table 6-15). With the exception of larger American eels evaluated as part of Test Series 8, the recovery rates of coho salmon were the lowest that were recorded during the biological evaluation of the turbine. It is unclear why coho salmon had lower recovery rates than other species (including larger rainbow trout and smallmouth bass), however, these rates may have resulted from stronger swimming abilities and/or avoidance of the collection tank entrance. Most un-recovered coho salmon (treatment and controls) were collected live during later tests (see Table O-11 in Appendix O), indicating fish were maintaining positions between the turbine outlet and collection tank for extended periods of time. The lower recovery rates did not affect turbine passage survival estimates for coho salmon because they were similar between treatment and control groups and most fish were eventually recovered live.

Six of nine alewife recovered during tests after the one in which they were released were collected dead (see Table O-11 in Appendix O). This number of post-test recovery mortalities was higher than observed for tests with other species. However, these mortalities represent less than 1% of the total number of alewife released and, although some of these fish may have died during turbine passage, the exclusion of these data from the survival analysis does not result in a large positive bias for the survival rates calculated for this species (i.e., if post-test recoveries were included, the estimated passage survival rates for alewife would decrease by less than 1%).

TABLE 6-15
SUMMARY OF FISH RELEASE AND RECOVERY DATA FOR FALL 2002 TESTS WITH ALEWIFE, COHO SALMON, AND WHITE STURGEON
TEST SERIES 7 – WITH WICKET GATES

All tests were conducted at an operating head of 40 ft and at the BEP.
Test Group codes are: T, treatment; C, control; and NM, no identifiable mark.

Species	Number of Trials	Test Group	Total Number of Fish Released	Mean FL and SD (mm)	Percent Recovered During Test of Release	Number Recovered Live	Number of Immediate Mortalities (1 hr)	Number of Delayed Mortalities (96 hr)
alewife	9	T	891	75.4 (8.3)	99.1	843	40	21
		C	887	75.6 (8.0)	99.9	886	0	2
		NM	--	--	--	0	1	0
coho salmon	9	T	902	101.5 (15.1)	93.1	801	39	14
		C	905	102.5 (15.8)	92.3	835	0	0
		NM	--	--	--	--	--	--
white sturgeon	9	T	888	102.8 (15.1)	99.0	864	15	16
		C	892	103.2 (15.0)	98.5	879	0	5
		NM	--	85.1 (13.2)	--	13	0	0

Immediate and delayed survival rates of control fish were high for all three species evaluated during Test Series 7, with no immediate mortalities and only two delayed mortalities for alewife and five for white sturgeon (Table 6-15). All immediate treatment mortalities recovered during tests with each species appeared to be due to turbine passage based on the immediate survival rates of 100% for control fish. Most delayed treatment mortalities occurred during the first 48 hrs of the 96-hr holding period (see Table O-12 in Appendix O). Delayed mortality of control fish indicated that testing and handling contributed to some of the observed delayed treatment mortality of alewife and white sturgeon, whereas coho salmon, which experienced no delayed control mortality, appeared to be less susceptible to experimental procedures.

The estimated immediate turbine passage survival rates of alewife and coho salmon were nearly equivalent (95.4 and 95.5%, respectively; Table 6-16), despite alewife having a mean length that was about 33 mm less than coho salmon. Total turbine passage survival rates for these two species were also similar (Table 6-16). The similarity in survival rates between alewife and coho salmon resulted in no statistically significant differences ($P > 0.05$). In contrast, white sturgeon immediate and total turbine passage survival rates (98.3 and 97.0%, respectively) were significantly greater than the rates for alewife and coho salmon ($P > 0.05$).

TABLE 6-16
TURBINE SURVIVAL ESTIMATES FOR TEST SERIES 7 (WITH WICKET GATES)

All tests were conducted with at a head of 40 ft and the best efficiency point (BEP).
Survival rates without a letter in common are significantly different ($P < 0.05$)

Species	Immediate Turbine Survival (%) ± 95% CI	Total Turbine Survival (%) ± 95% CI
alewife	95.4 ± 1.4[a]	93.7 ± 1.6[a]
coho salmon	95.4 ± 1.4[a]	93.1 ± 1.7[a]
white sturgeon	98.3 ± 0.9[b]	97.0 ± 1.3[b]

6.5.2 Injury And Scale Loss Evaluation

Of the three species tested during Test Series 7, alewife had the lowest percent of treatment fish (live and dead recoveries combined) classified as uninjured (87.6%) and white sturgeon had the highest percent uninjured (92.4%) (Table 6-17). The higher rate of uninjured white sturgeon was due, in part, to a larger percent of immediate treatment mortalities that were classified as uninjured compared to alewife and coho salmon (Table 6-17). White sturgeon treatment mortalities did not exhibit bruising to the extent that species with scales did (including rainbow trout and smallmouth bass evaluated during other test series). Their tough skin and lack of scales may have resulted in lower rates of bruising and/or made bruising more difficult to detect.

Bruising was the most common injury sustained by turbine-passed fish recovered live and dead during tests with all three species evaluated in Test Series 7 (Table 6-17). Less than 10% of live treatment recoveries from tests with each species suffered bruising, whereas greater than 75% of alewife and coho salmon immediate mortalities and about 47% of white sturgeon mortalities had bruising (Table 6-17). Control fish of each species that were recovered live exhibited bruising at rates less than 3%. Additionally, other types of external injuries were not sustained by control fish or occurred at rates less than 1% (Table 6-17).

Coho salmon immediate mortalities demonstrated a considerably higher laceration rate compared to alewife and white sturgeon. The lower laceration rate for alewife may have been due to their smaller size, whereas the lower rate for white sturgeon may have been due to physical characteristics associated with having no scales, tough skin, and a cartilaginous skeleton. The smaller size of alewife probably contributed to this species not being severed during turbine passage. However, similar rates of severed bodies observed for coho salmon and white sturgeon indicate that sturgeon did not have a physical advantage for avoiding this type of injury, which probably resulted from direct turbine blade strikes.

The occurrence rate of eye injuries was relatively high for alewife and white sturgeon immediate treatment mortalities (20 and 22.5%, respectively; Table 6-17). Eye injuries were less common for coho salmon (about 10%). In addition to being greater than coho salmon, the rates of eye injuries observed for alewife and white sturgeon were higher than rates observed for species evaluated during other test series, which typically ranged between 10 and 20%. There was no indication as to why alewife and white sturgeon appeared to be more prone than other species to eye damage caused by turbine passage.

The percent of alewife and coho salmon (white sturgeon do not have scales) with less than 3%, 3-20%, and 20-40% descaling in each of the three locations that were examined was generally comparable between treatment and control fish (see Table O-13 in Appendix O). However, there were apparent differences in descaling rates between the two species. The percent of alewife with less than 3% descaling in each location ranged from about 18 to 42%, whereas less than 10% of coho salmon had this low level of descaling. Alewife had considerably lower percentages of fish with descaling between 3-20%. Conversely, descaling of 20-40% and greater than 40% were nearly twice as common for alewife than for coho salmon. Treatment fish of both species suffered descaling greater than 40% at higher rates than control fish, but this difference was more pronounced for alewife.

The high percentages of alewife with 20-40% and greater than 40% descaling resulted in greater numbers of this species being classified as descaled compared to coho salmon (Table 6-18). This is not unexpected given that *Alosa* species are known to be prone to scale loss. Most of the scale loss observed with alewife was most likely due to handling and testing procedures given that control fish also sustained rates of descaling that were only slightly lower than treatment fish (Table 6-18). The number of coho salmon recovered live that were classified as descaled was similar for treatment and control fish. Immediate treatment mortalities of both species suffered much higher rates of descaling than did live recoveries (Table 6-18).

TABLE 6-17

PERCENT OF FISH RECOVERED DURING TEST SERIES 7 (WITH WICKET GATES) THAT WERE OBSERVED WITH EXTERNAL INJURIES

Species	Live/Dead	Total Number Recovered		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
		T	C	T	C	T	C	T	C	T	C	T	C
alewife	L	843	886	91.5	97.3	8.2	2.7	0.2	0.0	--	--	0.4	0.0
	D	40	0	7.5	--	85.0	--	10.0	--	0.0	--	22.5	--
	Total	883	886	87.6	97.3	11.7	2.7	0.7	0.0	0.0	0.0	1.4	0.0
coho salmon	L	801	835	94.0	98.8	5.0	1.2	0.0	--	--	--	0.2	0.0
	D	39	0.0	10.2	--	76.9	--	28.2	--	7.7	--	10.2	--
	Total	840	835	90.1	98.8	8.3	1.2	1.3	0.0	0.4	0.0	0.7	0.0
white sturgeon	L	864	879	93.3	98.5	6.4	1.3	0.0	0.0	--	--	0.0	0.1
	D	15	0.0	40.0	--	46.7	--	6.7	--	6.7	--	20.0	--
	Total	879	879	92.4	98.5	7.1	1.3	0.1	0.0	0.1	0.0	0.3	0.1

TABLE 6-18
PERCENT OF FISH RECOVERED DURING TEST SERIES 7 (WITH WICKET GATES) THAT WERE CLASSIFIED AS DESCALED

		Treatment		Control	
Species	Live/Dead	Number Recovered	% Classified as Descaled	Number Recovered	% Classified as Descaled
alewife	Live	843	24.6	886	20.1
	Dead (1 hr)	40	85.0	--	--
	Total	883	27.3	886	20.1
coho salmon	Live	801	9.5	835	8.5
	Dead (1 hr)	39	28.2	--	--
	Total	840	10.4	835	8.5

6.6 Test Series 8 (Spring and Fall 2002) - American Eel Size-Effect Evaluation

American eels were evaluated as part of Test Series 8, which was designed to evaluate the effects of fish size on turbine survival and injury rates for species other than rainbow trout. The mean lengths of the two size groups of eels that were evaluated were 249 mm (SD = 24 mm) and 431 mm (SD = 41 mm). Mean lengths of treatment and control fish are presented in Table 6-19. The smaller size group was evaluated in the spring of 2002 and the larger group in the fall. Eel tests consisted of nine trials per size group conducted at a head of 40 ft and with the turbine operating at the BEP.

6.6.1 Turbine Survival Estimates

Recovery rates for treatment and control fish of the smaller size group of American eels were 99% and 96%, respectively (Table 6-19). Recovery rates for the larger eels were lower (about 90% for treatment fish and 86% for controls), most likely due to stronger swimming abilities that allowed the larger fish to maintain positions within the test loop for longer periods of time. For both size groups, all fish collected during later tests were recovered live except for two control fish of the smaller size group (see Table O-14 in Appendix O). A small number of eels of both size groups did not have identifiable marks when recovered, but all of these fish were collected live.

All of the smaller eels that were recovered during the test of their release were recovered live (i.e., no immediate mortality occurred for treatment or control fish) and all but two treatment and two control fish were recovered live during tests with the larger fish (Table 6-19). There were six treatment and two control delayed mortalities for tests with the smaller eels (Table 6-19). Delayed mortality of larger eels was higher than the smaller fish for treatment and control groups. Most of the treatment delayed mortality for smaller fish occurred within 48 hours of recovery, whereas delayed mortality of larger fish was relatively uniform over the 96-hour post-test holding period (see Table O-15 in Appendix O).

The estimated immediate and total turbine passage survival rates for the smaller size group of American eel were 100% and 99.6%, respectively (Table 6-20). The larger eels also had an estimated immediate survival rate of 100% (Table 6-20). The total turbine passage survival rate of the larger fish was 98.2%. The total survival rates for the two size groups of American eel were not statistically different ($P > 0.05$). Turbine passage survival rates of American eel are in strong contrast to other species that were evaluated for size effects (i.e., rainbow trout and smallmouth bass) given that eels were considerably longer in length and there were no differences in survival rates between the two size groups evaluated. The high survival rates of eels probably are due to physical and behavioral characteristics that contribute to reduced injury during passage. In particular, American eels have very small embedded scales, their integument is relatively tough, and they are extremely flexible (this is demonstrated to some degree by their undulating swimming motion). Eels may also behave in a manner that reduces the potential for strike (e.g., they may curl into a position that effectively reduces exposure to blade strike as they enter the runner).

TABLE 6-19
SUMMARY OF AMERICAN EEL RELEASE AND RECOVERY DATA
TEST SERIES 8 - WICKET GATES INSTALLED

All tests were conducted at an operating head of 40 ft and at the BEP.
Test Group codes are: T, treatment; C, control; and NM, no identifiable mark.

Fish Size Group	Number of Trials	Test Group	Total Number of Fish Released	Mean FL and SD (mm)	Percent Recovered During Test of Release	Number Recovered Live	Number of Immediate Mortalities (1 hr)	Number of Delayed Mortalities (96 hr)
small	9	T	901	249 (23)	99.0	892	0	6
		C	902	249 (23)	96.0	866	0	2
		NM	--	--	--	6	0	0
large	9	T	894	429 (42)	90.2	804	2	20
		C	891	433 (41)	86.1	765	2	5
		NM	--	421 (26)	--	2	1	0

TABLE 6-20
TURBINE SURVIVAL ESTIMATES FOR AMERICAN EEL TESTS
TEST SERIES 8 - WICKET GATES INSTALLED

All tests were conducted at a head of 40 ft and at the best efficiency point (BEP).

Mean Fish Length (mm)	Immediate Turbine Survival (%) ± 95% CI	Total Turbine Survival (%) ± 95% CI
249	100.0 ± 0.0	99.6 ± 0.8
431	100.0 ± 0.4	98.3 ± 0.8

6.6.2 Injury Evaluation

The percent of treatment and control fish that were classified as uninjured was 83.3% and 88.2%, respectively, for tests with the smaller eels (Table 6-21). The percent of larger eels that were classified as uninjured was greater than it was for the smaller fish for treatment and control groups (Table 6-21). Bruising was the most common injury sustained by treatment and control fish of both size groups, but the larger fish exhibited this injury type at rates that were about half of those observed for the smaller fish (Table 6-21). The incidence of bruising on control fish, although less than for treatment fish, indicates that handling and/or pre-existing injuries were prevalent for both size groups, particularly for the smaller fish. Lacerations were rare for both size groups and treatment fish did not sustain severed bodies or eye injuries (Table 6-21).

TABLE 6-21
PERCENT OF RECOVERED AMERICAN EELS THAT WERE OBSERVED WITH EXTERNAL INJURIES
TEST SERIES 8 - WICKET GATES INSTALLED

T = treatment; C = control

Fish Size Group	Live/ Dead	Total Number Recovered		Uninjured (%		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
		T	C	T	C	T	C	T	C	T	C	T	C
small	L	892	866	83.3	88.2	16.3	11.4	0.3	0.1	--	--	0.0	0.0
	D	0	0	--	--	--	--	--	--	--	--	--	--
	Total	892	866	83.3	88.2	16.3	11.4	0.3	0.1	0.0	0.1	0.0	0.0
large	L	804	765	91.2	95.4	8.5	4.1	0.2	0.5	--	--	0.0	0.0
	D	2	2	50.0	50.0	50.0	0.0	50.0	0.0	0.0	0.0	0.0	0.0
	Total	806	767	91.2	95.3	8.5	4.0	0.2	0.7	0.0	0.0	0.0	0.0

6.7 Test Series 8 (Fall 2002) – Smallmouth Bass Size-Effects Evaluation

Similar to American eel, smallmouth bass tests were conducted with two distinct size groups to examine the effects of fish size on turbine passage survival and injury rates. Smallmouth bass was the only species evaluated that was physoclistous (i.e., smallmouth bass do not have a duct that connects the esophagus and air bladder). Physoclistous species are more susceptible to pressure-related injuries during turbine passage due to their inability to adjust to rapid decreases in pressure that occur on the downstream side of runner blades. The two size groups of smallmouth bass that were tested were similar in length to size groups of rainbow trout that were evaluated during tests with and without wicket gates. The mean length of the smaller groups was 68.7 mm (SD = 7.8 mm) and mean length of the larger group was 154.5 mm (SD = 18.4 mm). The mean lengths of treatment and control groups are included in Table 6-22.

6.7.1 Turbine Survival Estimates

Recovery rates of smallmouth bass treatment and control fish ranged from about 96 to 99% (Table 6-22). Two fish recovered during tests with the smaller size group did not have identifiable marks; both of these fish were recovered live. One immediate mortality recovered during tests with the larger bass had no identifiable mark. All treatment fish of both size groups that were recovered during a test after the one in which they were released were collected live (see Table O-16 in Appendix O).

Control fish survival was high for both size groups, with only three mortalities (one immediate and two 96-hr) during tests with the smaller fish and one mortality (96-hr) during tests with the larger fish (Table 6-22). The majority of treatment fish delayed mortalities occurred during the first 24 hrs of the 96-hr holding period for tests with smaller fish and during the first 48 hrs for tests with larger fish (see Table O-17 in Appendix O). Immediate and total turbine passage survival rates of the smaller smallmouth bass were high (greater than 97%) and significantly greater than the survival rates of the larger fish (Table 6-23). Survival rates of the smaller bass were greater than slightly larger and smaller size groups of rainbow trout, whereas survival rates for the larger bass were similar to rainbow trout that were larger in length by about 20 mm (see previous sections for rainbow trout survival estimates).

TABLE 6-22
SUMMARY OF FISH RELEASE AND RECOVERY DATA FOR FALL 2002 TESTS WITH SMALLMOUTH BASS
TEST SERIES 8 – WITH WICKET GATES

Test group codes are: T, treatment; C, control; and NM, no identifiable mark.

Fish Size Group	Number of Trials	Test Group	Total Number of Fish Released	Mean FL and SD (mm)	Percent Recovered During Test of Release	Number Recovered Live	Number of Immediate Mortalities (1 hr)	Number of Delayed Mortalities (96 hr)
small	9	T	902	68.1 (7.0)	96.3	852	17	9
		C	894	69.2 (8.4)	97.9	874	1	2
		NM	--	71.0 (7.1)	--	2	0	0
large	9	T	901	154.6 (18.6)	98.9	827	64	29
		C	898	154.2 (18.1)	96.2	864	0	1
		NM	--	83.0 (--)	--	0	1	0

TABLE 6-23
TURBINE SURVIVAL ESTIMATES FOR TESTS WITH SMALLMOUTH BASS (TEST SERIES 8; WITH WICKET GATES)

All tests were conducted at a head of 40 ft and the best efficiency point (BEP).

Mean Fish Length (mm)	Immediate Turbine Survival (%) ± 95% CI	Total Turbine Survival (%) ± 95% CI
69	98.2 ± 0.9	97.4 ± 2.2
155	92.6 ± 1.7	89.5 ± 2.0

6.7.2 Injury and Scale Loss Evaluation

The percent of treatment fish that were classified as uninjured was greater for smaller smallmouth bass (92.1%) than for the larger fish (76.2%) (Table 6-24). The percent of control fish that were uninjured was also greater for the smaller fish, but exceeded 92% for both size groups. Treatment fish of the smaller size group did not suffer lacerations or severed bodies, whereas larger fish experienced both of these types of injuries. These data (i.e., percent uninjured and occurrence of lacerations and severed bodies) indicate that the smaller bass experienced less strike-related injury and mortality due to their smaller size. However, bruising rates for immediate mortalities were similar between the two size groups of bass (70.6 and 73.4%, respectively), demonstrating that the main cause of passage mortality for each group was most likely blade strike. Similar to other species, bruising was the predominant injury sustained by immediate mortalities and fish recovered live during tests with both size groups of bass (Table 6-24). The rate of eye injuries was greater for immediate mortalities of the smaller size group (Table 6-24), but the overall percent of treatment fish (immediate mortalities and live recoveries combined) with damaged eyes was less than 1% for both size classes of bass.

The percent of fish with less than 3% scale loss in each of three locations examined was greatest for the smaller fish and for controls (see Table O-18 in Appendix O). For the smaller bass, more than 93% of treatment fish had less than 3% scale loss in each body location. Greater levels of scale loss that were observed for the larger size group of bass occurred for treatment and control fish. This demonstrates that the larger fish were more susceptible to scale loss from handling, as well as from passage through the turbine, than were the smaller fish. Despite the apparent greater susceptibility to scale loss experienced by larger fish, the percent of control fish that were classified as descaled was similar between the two size groups (Table 6-25). The percent of live treatment fish that were classified as descaled, although greater for the larger bass, was low for both size groups (less than 4%; Table 6-25). The percent of immediate mortalities that were classified as descaled for tests with both size groups was nearly equivalent (Table 6-25).

TABLE 6-24

PERCENT OF SMALLMOUTH BASS RECOVERED DURING TEST SERIES 8 (WITH WICKET GATES) THAT WERE OBSERVED WITH EXTERNAL INJURIES

Fish Size Group	Live/ Dead	Total Number Recovered		Uninjured (%		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
		T	C	T	C	T	C	T	C	T	C	T	C
small	L	852	874	93.3	97.4	6.5	2.6	0.1	0.0	--	--	0.4	0.0
	D	17	1	29.4	0.0	70.6	100.0	0.0	0.0	0.0	0.0	17.6	0.0
	Total	869	875	92.1	97.3	7.7	2.7	0.1	0.0	0.0	0.0	0.7	0.0
large	L	827	864	80.4	92.9	19.0	6.9	0.6	0.2	--	--	0.2	0.0
	D	64	0	21.9	--	73.4	--	9.4	--	4.7	--	6.3	--
	Total	891	864	76.2	92.9	22.9	6.9	1.2	0.2	0.3	0.0	0.7	0.0

TABLE 6-25
PERCENT OF SMALLMOUTH BASS RECOVERED DURING TEST SERIES 8 (WITH WICKET GATES) THAT WERE CLASSIFIED AS DESCALED

		Treatment		Control	
Fish Size Group	Live/Dead	Number Recovered	% Classified as Descaled	Number Recovered	% Classified as Descaled
small	Live	852	1.3	874	0.7
	Dead	17	23.5	1.0	100.0
	Total	869	1.7	875	0.8
large	Live	827	3.6	864	0.5
	Dead	64	23.4	0.0	0.0
	Total	891	5.1	864	0.5

6.8 Test Series 9/10 – Evaluation of Turbine Operating Efficiency

Test Series 9/10 was designed to evaluate the effect of turbine operating efficiency (as measured by wicket gate angle relative to the closed position [0^{o}], with BEP being 18.2^{o}) on turbine survival and injury rates. The evaluation of turbine efficiency effects included trials conducted at BEP and five off-BEP points (one below BEP and four above). As with the other evaluations of turbine operation and design effects (i.e., assessments of head and wicket gate effects), the off-BEP evaluation was conducted with rainbow trout. The mean length of trout used in these tests was 91.2 mm (SD = 10.7 mm). The mean length of treatment and control group for each test condition (i.e., gate position) are presented in (Table 6-26).

6.8.1 Turbine Survival Estimates

Recovery rates of treatment and control fish during Test Series 9/10 were similar to previous tests with rainbow trout, ranging from about 96 to 99% (Table 6-26). Most fish that were not recovered during the test in which they were released were collected live in subsequent tests (Table 6-45). There were only two treatment fish immediate mortalities and one control immediate mortality that were recovered during later tests (see Table O-19 in Appendix O). As with other test series, because most post-test recoveries were collected live, the exclusion of these data from survival estimate calculations did not effect the results of this test series.

Immediate survival rates for control fish were high (greater than 99.5%) for all six turbine efficiency test conditions that were evaluated (Table 6-26). However, disease problems were encountered during the 96-hour post-test holding period of the first six replicate trials conducted at each turbine efficiency setting resulting in high delayed mortality rates for treatment and control fish (Tables 6-26 and Table O-20 in Appendix O). Increasing mortality of treatment and control fish over time during the delayed mortality holding period demonstrated that some type of pathogen was causing the high mortality rates (i.e., delayed mortality attributed to turbine passage typically decreased with time during post-test holding periods). The disease problem initially was noticed for fish taken from one of the five pre-test holding tanks, after which it spread to other tanks, eventually affecting all fish in the holding facility. After six replicate trials had been completed for each turbine efficiency test condition, all of the rainbow trout that were being held (tested and un-tested) were sacrificed and the holding facility was disinfected. Additional fish were acquired from the supplier to complete the final three replicates for each test condition.

TABLE 6-26

SUMMARY OF FISH RELEASE AND RECOVERY DATA FOR FALL 2002 TESTS WITH RAINBOW TROUT AT BEP AND FIVE OFF-BEP WICKET GATE POSITIONS (TEST SERIES 9/10; ALL TESTS WERE CONDUCTED AT 40 FT HEAD)

Test group codes are: T, treatment; C, control; and NM, no identifiable mark.

Wicket Gate Position	Number of Trials	Test Group	Total Number of Fish Released	Mean FL and SD (mm)	Percent Recovered During Test of Release	Number Recovered Live	Number of Immediate Mortalities (1 hr)	Number of Delayed Mortalities (96 hr)
18.2° (BEP)	9	T	892	91.1 (10.9)	97.5	838	32	90
		C	907	91.7 (11.4)	97.4	880	3	57
		NM	--	98 (--)	--	1	0	1
16°	9	T	896	91.0 (10.4)	98.5	845	38	127
		C	901	91.9 (11.1)	97.0	874	0	89
		NM	--	73.0 (7.1)	--	2	0	3
20°	9	T	902	89.6 (10.7)	95.8	837	27	24
		C	902	90.4 (10.5)	96.5	869	1	5
		NM	--	83.1 (9.2)	--	22	0	1
22°	9	T	906	91.5 (10.4)	97.9	863	24	119
		C	902	91.5 (10.7)	98.8	890	1	96
		NM	--	--	--	--	--	1
24°	9	T	910	91.2 (10.6)	98.9	870	30	0
		C	906	91.1 (10.3)	96.9	878	0	18
		NM	--	--	--	--	--	1
26°	9	T	900	91.0 (10.9)	98.6	853	34	140
		C	898	91.6 (10.1)	99.2	891	0	121
		NM	--	80.0 (--)	--	0	0	4

Because the disease problem resulted in high rates of delayed mortality that were not due to test-related handling or turbine passage, replicate trials for which delayed control mortality was greater than 5% or delayed treatment mortality was greater than 10% were excluded from the estimation of total turbine survival rates. These levels of delayed mortality were considered to be reasonable criteria for determining the validity of test results based on delayed mortality rates from previous test series conducted with rainbow trout (i.e., during which disease problems did not occur). Using these criteria, between one and five replicate trials were excluded from the estimation of total turbine survival rates for each turbine efficiency setting, except for estimates generated for a wicket gate position of 20°, which included all nine replicates that were conducted. Immediate survival data were not affected by the disease problem and, therefore, include data from all of the nine replicate trials that were conducted for each efficiency setting.

Immediate turbine passage survival rates for the six turbine efficiency settings ranged from 95.8 to 97.4% (Table 6-27). The narrow range of immediate survival estimates resulted in no statistical differences among efficiency settings ($P > 0.05$). Despite the lack of statistical significance, there appeared to be a trend in immediate survival rates associated with the range of wicket gate openings tested. Immediate survival was lowest at the boundaries of the efficiency range and peaked at a wicket gate position of 22° (Figure 6-3). Similar to immediate survival estimates, total turbine passage survival rates for the six test conditions were within a narrow range (1.4%; Table 6-27) and were not statistically different ($P > 0.05$). However, the same peaking trend that was observed for immediate survival did not occur with total survival estimates (Figure 6-3).

TABLE 6-27
TURBINE SURVIVAL ESTIMATES FOR TEST SERIES 9/10 (WICKET GATES INSTALLED)

Wicket Gate Position	Immediate Turbine Survival (%) ± 95% CI	Total Turbine Survival (%) ± 95% CI
18.2° (BEP)	96.4 ± 1.3	94.0 ± 2.0
16°	95.8 ± 1.3	94.9 ± 1.9
20°	97.0 ± 1.2	94.7 ± 1.6
22°	97.4 ± 1.1	95.5 ± 2.1
24°	96.8 ± 1.2	95.6 ± 1.9
26°	96.3 ± 1.3	95.4 ± 2.1

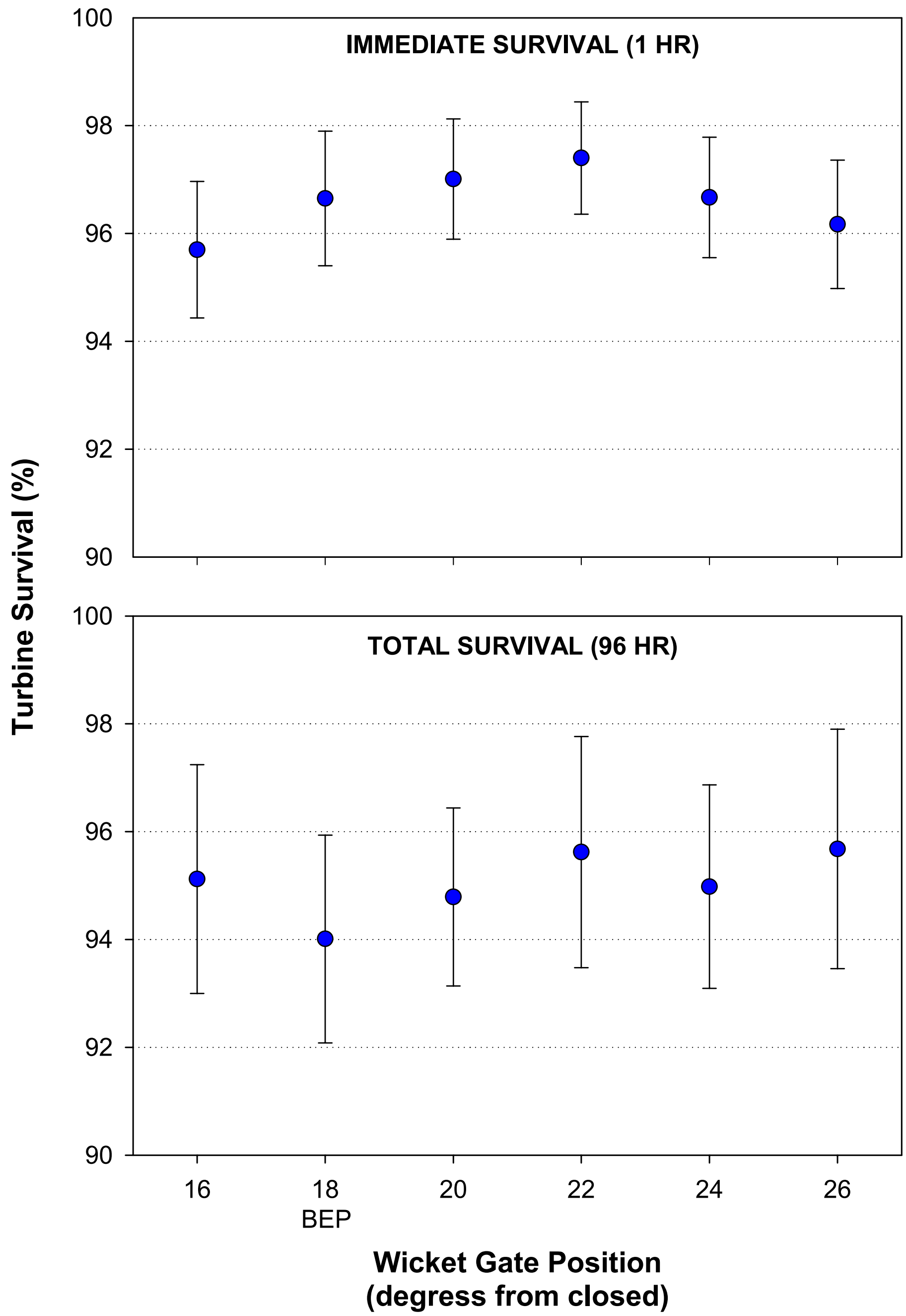


FIGURE 6-3 IMMEDIATE (1 HR) AND TOTAL (1 HR AND 96 HRS COMBINED) TURBINE SURVIVAL ESTIMATES (± 95% CI) FOR TEST CONDITIONS EVALUATED WITH RAINBOW TROUT DURING TEST SERIES 9/10

NOTE: Confidence intervals are adjusted to account for dispersion in the survival estimates. Survival rates that have non-overlapping confidence intervals are significantly different ($P < 0.05$).

6.8.2 Injury and Scale Loss Evaluation

The percent of live treatment fish that were classified as uninjured was high (greater than 95%) and did not vary considerably among the six turbine efficiency conditions evaluated (Table 6-28; Figure 6-4). Also, the percent of treatment fish recovered live that exhibited bruising was similar among the test conditions (Figure 6-4). Other types of injuries were rare for all test conditions (i.e., less than 1% of live treatment fish had lacerations or eye injuries) (Table 6-28). The percent of control fish that were classified as uninjured exceeded 99% for tests at each efficiency setting (Table 6-28; Figure 6-4) and, similar to treatment fish, other types of injuries were not observed or occurred at rates less than 1%. Low control injury rates indicate that handling and testing procedures during this test series generally did not contribute to the injuries sustained by treatment fish.

Similar to previous tests with rainbow trout and the other species that were tested, bruising was the most common injury sustained by immediate treatment mortalities for each turbine efficiency condition evaluated (Table 6-28; Figure 6-5). The percent of immediate mortalities with bruising, lacerations, and severed bodies increased with increasing wicket gate opening before peaking at wicket gate positions of either 20 or 22°, depending on injury type (Figure 6-5). The lowest rates observed for these injury types occurred at either the lowest or highest wicket gate opening (Figure 6-5). A similar trend (i.e., peaking at the middle efficiencies) was not observed for the percent of immediate mortalities that sustained eye injuries. Eye injury rates for immediate mortalities were greatest for the two largest wicket gate openings evaluated (Figure 6-5). The lowest rate of eye injuries occurred at the smallest wicket gate opening.

TABLE 6-28
PERCENT OF RAINBOW TROUT RECOVERED DURING TEST SERIES 9/10 TRIALS THAT WERE OBSERVED WITH EXTERNAL INJURIES

T = treatment; C = control

Wicket Gate Position	Live/ Dead	Total Number Recovered		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
		T	C	T	C	T	C	T	C	T	C	T	C
18° (BEP)	L	838	880	95.2	99.7	4.3	0.3	0.1	0.0	--	--	0.2	0.0
	D	32	3	6.3	0.0	90.6	100.0	9.4	0.0	3.1	0.0	12.5	33.3
	Total	870	883	92.0	99.3	7.5	0.7	0.5	0.0	0.1	0.0	0.7	0.1
16°	L	845	874	95.6	99.3	3.8	0.5	0.0	0.1	--	--	0.2	0.0
	D	38	0	7.9	--	89.5	--	5.3	--	0.0	--	2.6	--
	Total	883	874	91.8	99.3	7.5	0.5	0.2	0.1	0.0	0.0	0.3	0.0
20°	L	837	869	96.3	99.4	3.3	0.6	0.0	0.0	--	--	0.0	0.0
	D	27	1	0.0	0.0	96.3	100.0	18.5	0.0	3.7	0.0	11.1	0.0
	Total	864	870	93.3	99.3	6.3	0.7	0.6	0.0	0.1	0.0	0.3	0.0
22°	L	863	890	95.8	99.6	3.4	0.1	0.0	0.0	--	--	0.0	0.0
	D	24	1	8.3	0.0	91.7	100.0	16.7	0.0	4.2	0.0	8.3	0.0
	Total	887	891	93.5	99.4	5.7	0.2	0.5	0.0	0.1	0.0	0.2	0.0

TABLE 6-28 (CONTINUED)

Head (ft)	Live/ Dead	Total Number Recovered		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
		T	C	T	C	T	C	T	C	T	C	T	C
24°	L	870	878	97.4	99.8	2.3	0.2	0.0	0.0	--	--	0.1	0.0
	D	30	0	0.0	--	90.0	--	10.0	--	0.0	--	13.3	--
	Total	900	878	94.1	99.8	5.2	0.2	0.3	0.0	0.0	0.0	0.6	0.0
26°	L	853	891	95.8	99.6	3.5	0.4	0.0	0.1	--	--	0.4	0.0
	D	34	--	2.9	--	85.3	--	8.8	--	0.0	--	14.7	--
	Total	887	891	92.2	99.6	6.7	0.4	0.3	0.1	0.0	0.0	0.9	0.0

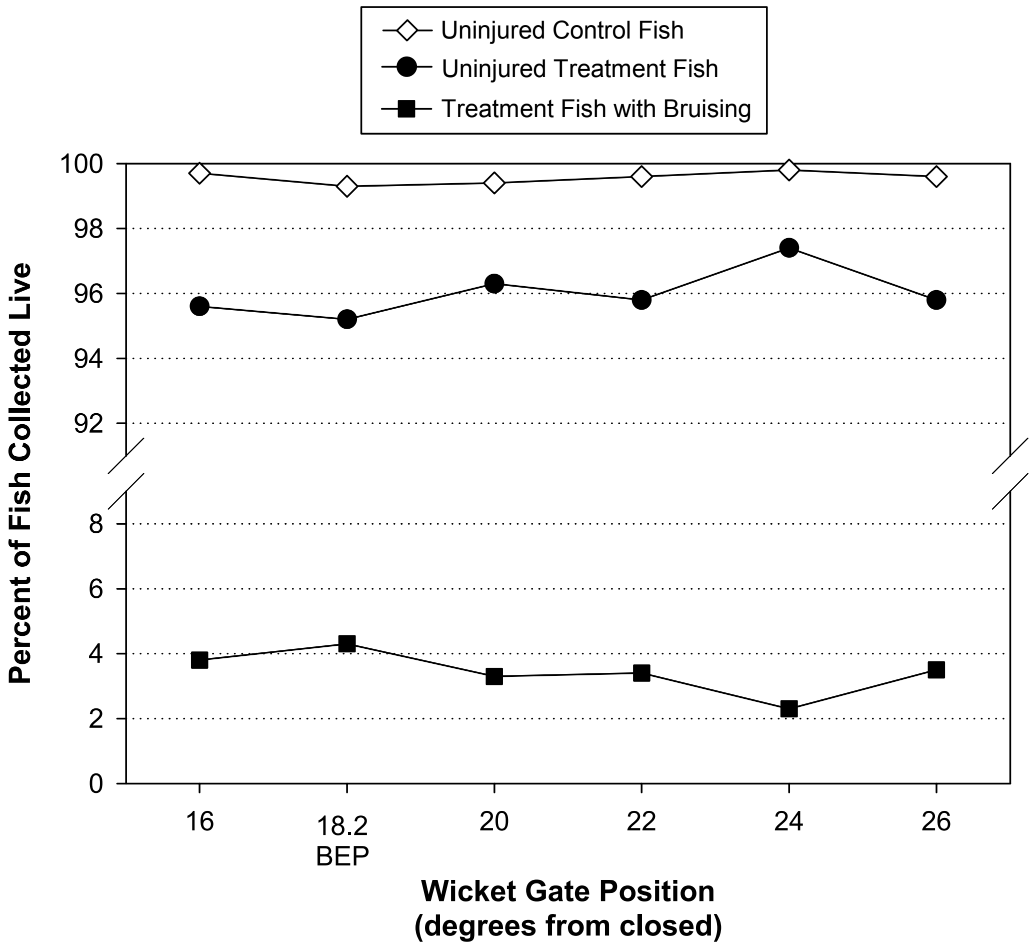


FIGURE 6-4 PERCENT OF LIVE RECOVERIES FROM TEST SERIES 9/10 TRIALS THAT WERE CLASSIFIED AS UNINJURED OR THAT HAD VISIBLE BRUISING

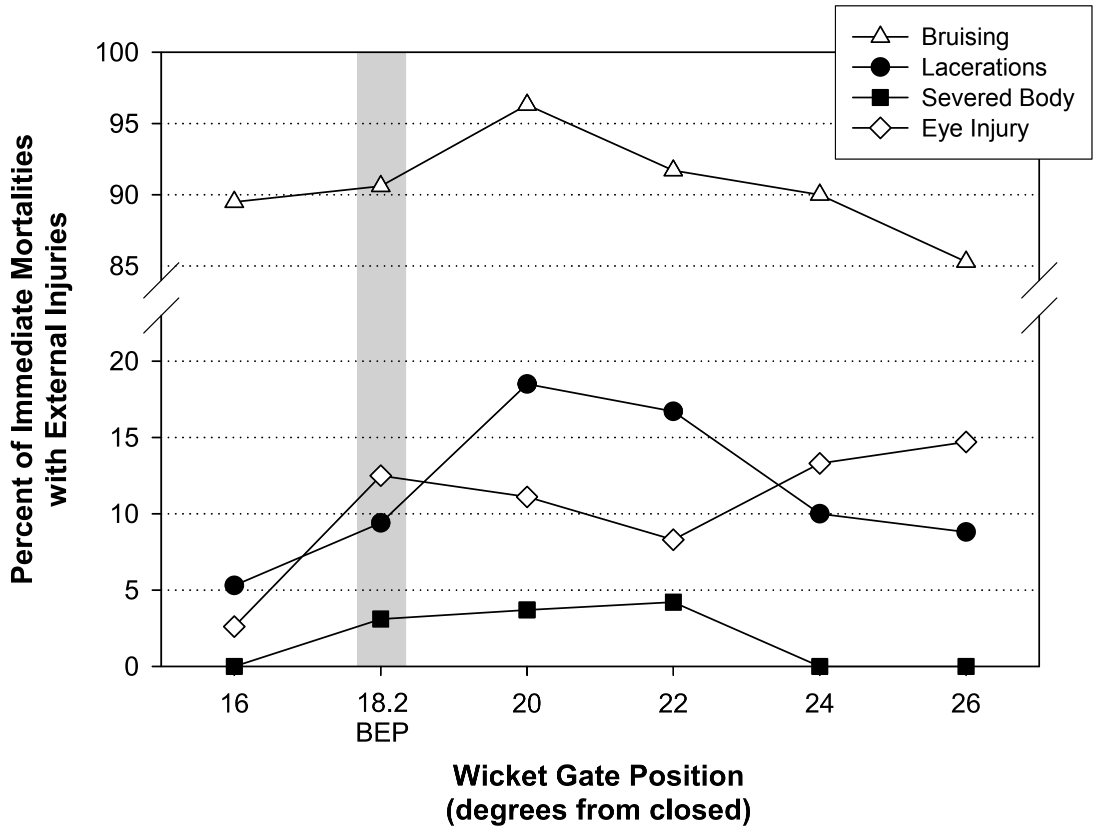


FIGURE 6-5 PERCENT OF IMMEDIATE TREATMENT MORTALITIES RECOVERED DURING TEST SERIES 9/10 TRIALS THAT HAD VISIBLE EXTERNAL INJURIES

Although bruising, lacerations, and severed bodies were more prevalent among immediate mortalities during trials conducted at wicket gate positions of 20^{o} and 22^{o}, immediate passage survival was highest at these efficiency settings. The higher rates of these injury types experienced by fish that died during passage at the middle wicket gate positions suggests that changes in efficiency may affect the susceptibility of fish to injury when struck by a blade (i.e., assuming blade strike is the primary injury mechanism). However, based on the immediate and total turbine passage survival rates that were estimated for each wicket gate opening, this effect did not appear to contribute to significantly greater or less mortality (i.e., the probability of mortality from blade strike did not change among the wicket gate openings tested). Injury rates of fish that survived turbine passage demonstrate that the probability of injury associated with each wicket gate opening only changed for immediate mortalities.

Percent scale loss was similar among the six turbine efficiency test conditions for treatment groups and control groups (see Table O-21 in Appendix O). In general, about 50 to 60% of treatment fish had descaling rates of less than 3% for each of the three body locations that were examined and about 97% or greater had less than 20% scale loss (numbers of fish with less than 3% and 3-20% combined) for each location. The percent of control fish with less than 3% descaling in each location was typically between 55 and 65%.

The percent of live treatment fish that were classified as descaled was low (less than 1.5%) and did not vary considerably among the six turbine efficiency settings or from the percent of control fish that were descaled (Table 6-29; Figure 6-6). The similarity in descaling rates between live treatment and control fish indicates that turbine passage did not contribute to extensive descaling of fish that survived passage. The percent of immediate treatment mortalities that were classified as descaled was 10% or lower at five of the six efficiency settings (including BEP) (Table 6-29; Figure 6-6). Similar to injury rates, the lowest rates of immediate mortalities that were descaled occurred at the lowest and highest efficiency settings (Figure 6-6). The highest rate of descaling was observed at one of the middle efficiencies (wicket gate position of 20^{o}; Figure 6-6).

TABLE 6-29
PERCENT OF RAINBOW TROUT RECOVERED DURING TEST SERIES 9/10 (WICKET GATES INSTALLED) THAT WERE CLASSIFIED AS DESCALED

Wicket Gate Position	Live/Dead	Treatment Number Recovered	Treatment % Classified as Descaled	Control Number Recovered	Control % Classified as Descaled
18° (BEP)	Live	838	1.4	880	0.8
	Dead	32	9.4	3	33.3
	Total	870	1.7	883	0.9
16°	Live	845	1.3	874	0.9
	Dead	38	2.6	0	--
	Total	883	1.4	874	0.9
20°	Live	837	1.3	869	0.5
	Dead	27	22.2	1	0.0
	Total	864	2.0	870	0.5
22°	Live	863	0.9	890	0.7
	Dead	24	4.2	1	0.0
	Total	887	1.0	891	0.7
24°	Live	870	0.6	878	0.7
	Dead	30	10.0	0	--
	Total	900	0.9	878	0.7
26°	Live	853	0.8	891	0.7
	Dead	34	2.9	0	--
	Total	887	0.9	891	0.7

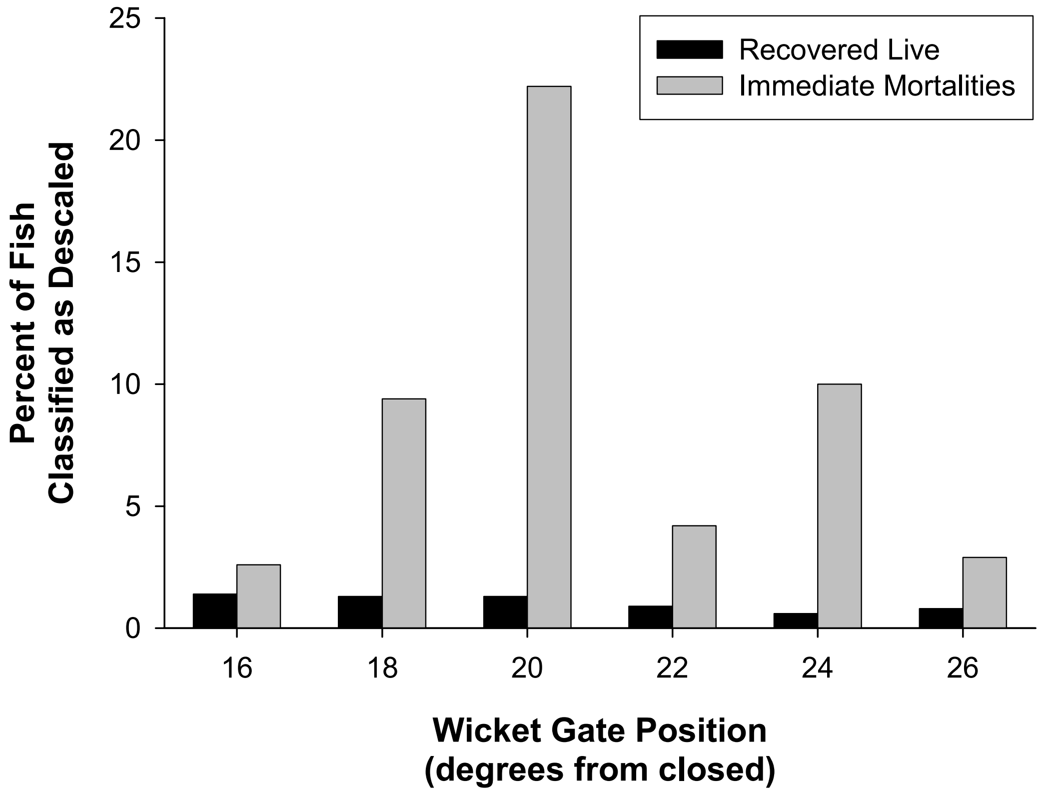


FIGURE 6-6 PERCENT OF IMMEDIATE TREATMENT MORTALITIES RECOVERED DURING TEST SERIES 9/10 TRIALS THAT WERE CLASSIFIED AS DESCALED

6.9 Video Observations

Video recordings taken at several locations were used to qualitatively evaluate fish behavior and passage through the turbine. High-speed video was recorded at the turbine inlet and outlet to assess fish position and orientation as they entered and exited the turbine. In 2001, high-speed video was recorded for releases of small and large rainbow trout (same sizes as the fish evaluated in Test Series 2/3) at two heads (38 and 80 ft). Similar recordings were made in 2002 with large rainbow trout (150-200 mm) and the other species that were tested. However, the presence of the wicket gates in 2002 severely restricted the view of fish approaching the runner. Fish passage in 2001 was also recorded using a handheld digital video camera at the exit of the treatment injection pipe, at the turbine inlet, over the inclined bypass screen, and in the draft tube. In 2002, video with the handheld camera was recorded only at the turbine inlet.

Rainbow trout that were videotaped exiting the treatment injection pipe quickly oriented in the upstream direction, with several fish from each group swimming upstream past the injection pipe before returning downstream and passing through the turbine. Upstream movement was more prevalent at the lower head, most likely due lower flow velocities. Video from the handheld camera also demonstrated that fish entering and moving around the scroll case were facing upstream. Video from the draft tube demonstrated that fish passing downstream towards the inclined screen swam or drifted along straight paths. This indicates that the flow in the draft tube was relatively free of large scale eddies and turbulence within the field of view of the camera. A review of fish passing over the inclined screen leading to the collection tank did not reveal any fish contacting or impinging on the screen. However, only a small portion of the screen was within the field of view of the camera, resulting in most fish passing into the bypass without being visible.

Observations from the high speed video recorded in 2001 (without wicket gates) revealed that many fish approached the turbine facing upstream (i.e., positive rheotaxis) (Figure 6-7). Most fish that were observed entering the inlet and approaching the runner were actively swimming (i.e., tail beating was visible when the high-speed video was slowed down). Smaller fish appeared to be more likely to drift passively, particularly at the higher head and flow. Many fish were observed shifting to a head-downstream orientation just as they were about to enter the turbine and leave the view of the camera. Several fish also were observed being struck by a runner blade just after they exhibited this behavior. Patterns associated with the location of fish as they passed by or contacted runner blades were difficult to assess because the high-speed video only captured a relatively small proportion of fish actually approaching the runner. Fish exiting the turbine were difficult to observe due to turbulent flows immediately downstream of the runner, but many fish appeared to be facing upstream after passing through the turbine.

Video observations from fish releases with the wicket gates installed demonstrated that most fish followed flow paths that took them between wicket gates without making contact. Very few fish were observed striking or contacting the wicket gates. Most fish that were observed approaching the wicket gates tail first. One large trout was observed impinged on a wicket gate and eventually was severed from the force of the flow. The injury evaluation of larger trout indicated that severed fish may have been torn in this manner rather than suffering a turbine blade strike (i.e., based on the roughness of the injury, severed fish appeared to be pulled apart, not cut by a blade strike).

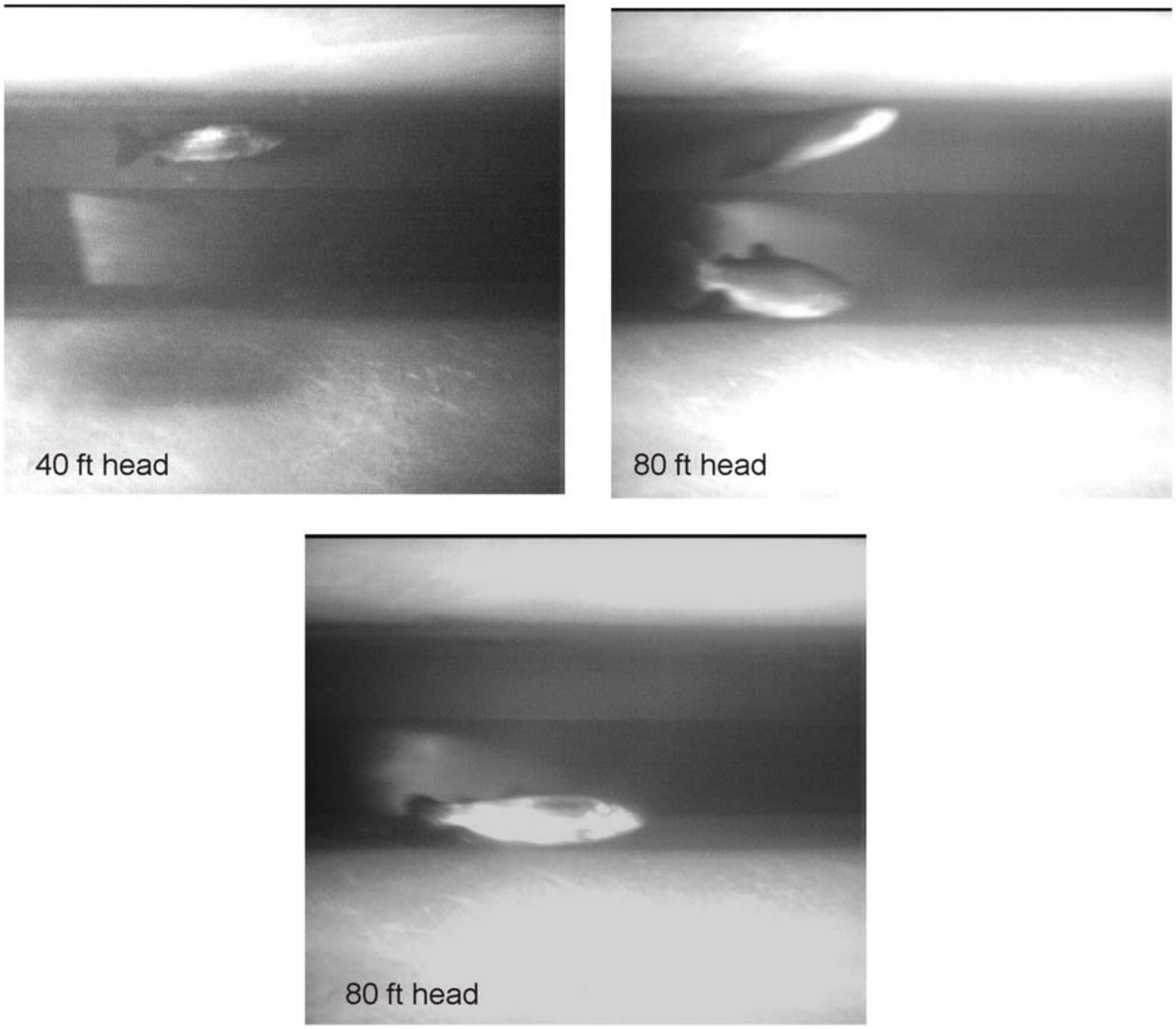


FIGURE 6-7 STILL IMAGES FROM HIGH-SPEED VIDEO OF RAINBOW TROUT (150-200 MM) APPROACHING RUNNER (A SINGLE TURBINE BLADE IS VISIBLE IN EACH PHOTO; FLOW PASSES FROM RIGHT TO LEFT)

6.10 Effects of Turbine Design and Operational Parameters on Passage Survival and Injury Rates

Turbine passage survival of rainbow trout was estimated for several turbine design and operational parameters during the biological evaluation of the Alden/Concepts NREC Turbine. Tests were conducted at two heads, with and without wicket gates, and at BEP and five off-BEP points. Head and turbine operating efficiency have been identified as parameters that may influence turbine passage survival rates, but previous studies have not conducted evaluations of fish mortality and injury associated with the presence and absence of wicket gates. In general, the results of the pilot-scale turbine evaluation, as related to turbine design and operation, correspond to the results of previous studies that have examined the relative importance of various engineering parameters to survival of fish passing through turbines (EPRI 1987; Franke et al. 1997; Winchell et al. 2000; Headrick 2001).

Turbine operating head has been identified as a factor that influences passage survival rates, with greater mortality occurring at higher heads. Operating head, in and of itself, does not directly contribute to lower or higher mortality, but it can create conditions associated with pressure regimes and turbine operation (runner rotational speed) that are detrimental to fish. Recent studies have shown that pressure changes may be inconsequential at relatively low operating heads (less than 60 ft). The Alden/Concepts NREC turbine was specifically designed to meet criteria that were expected to minimize pressure-related injuries (i.e., minimum pressures that were at least 30% of acclimation pressure). The types of injuries that were observed did not appear to be related to pressure changes experienced by fish. This observation was supported by high survival rates of smallmouth bass which is a physoclistous species that does not have the ability to rapidly adjust air bladder volume in response to rapid pressure decreases. The differences in survival rates observed between tests at the two heads evaluated during the study probably were the result of differences in runner rotational speeds. The higher rotational speed at 80 ft of head most likely resulted in a greater probability of strike and, consequently mortality. Prevalent injuries that were sustained by turbine-passed fish also indicated strike was the leading cause of death (e.g., bruising, lacerations, and severed bodies). Based on greater differences in survival rates between the two heads, the effect of head, as represented by rotational speed, was more noticeable for larger fish than it was for smaller fish.

Test Series 2/3 and 5/6 evaluated turbine survival and injury with and without wicket gates for two size groups of rainbow trout. The evaluation of these data allows for sources of mortality and injury associated with wicket gates to be separated from those associated with the turbine runner. The mean lengths of the two size groups tested without wickets in the fall of 2001 and with wicket gates in the spring of 2002 were within 9 mm of each other for tests at 40 ft of head and within 4 mm for tests at 80 ft of head. Although Alden has statistically analyzed the data for differences, there is the possibility that the results are confounded by factors associated with the test conditions being separated in time and because fish were not from the same lots. These constraints were unavoidable because of the logistics involved with installing and uninstalling the wicket gates (i.e., it was not possible to randomize tests with and without wicket gates).

Within each set of test conditions (fish size and operating head), there were no statistically significant differences in turbine passage survival rates between tests with and without wicket gates (Table 6-30; Figure 6-8). With the exception of fish recovered dead during tests at 80 ft of head with the smaller size group, the percent of live and dead fish that were classified as uninjured was similar (within 3%) between tests with and without wicket gates for each combination of fish size and turbine head (Table 6-31). With few exceptions, bruising and lacerations were the most common injuries sustained by both live and dead fish for tests with and without wicket gates. The rate of severed bodies was greater for tests without wicket gates for all combinations of fish size and head. This was the only injury type that was consistently higher at all test conditions in the absence of wicket gates.

TABLE 6-30

COMPARISON OF TURBINE SURVIVAL ESTIMATES FOR TESTS WITH (TEST SERIES 2/3) AND WITHOUT WICKET GATES (TEST SERIES 5/6)

Survival rates for tests with and without wicket gates were not significantly different within any of the test condition combinations (i.e., operating head and fish size).

Head (ft)	Mean Length (mm)	Wicket Gates	Immediate Survival (%) ± 95% CI	Total Survival (%) ± 95% CI
40	93.7	no	94.8 ± 1.5	92.7 ± 1.7
	85.0	yes	96.5 ± 1.4	95.5 ± 1.6
80	93.1	no	92.5 ± 1.8	91.0 ± 1.9
	85.0	yes	93.3 ± 1.9	92.2 ± 2.0
40	169.8	no	89.1 ± 2.1	88.4 ± 2.4
	173.8	yes	91.7 ± 2.1	90.4 ± 2.2
80	173.0	no	84.2 ± 2.6	83.3 ± 2.8
	174.7	yes	82.9 ± 2.9	80.7 ± 3.0

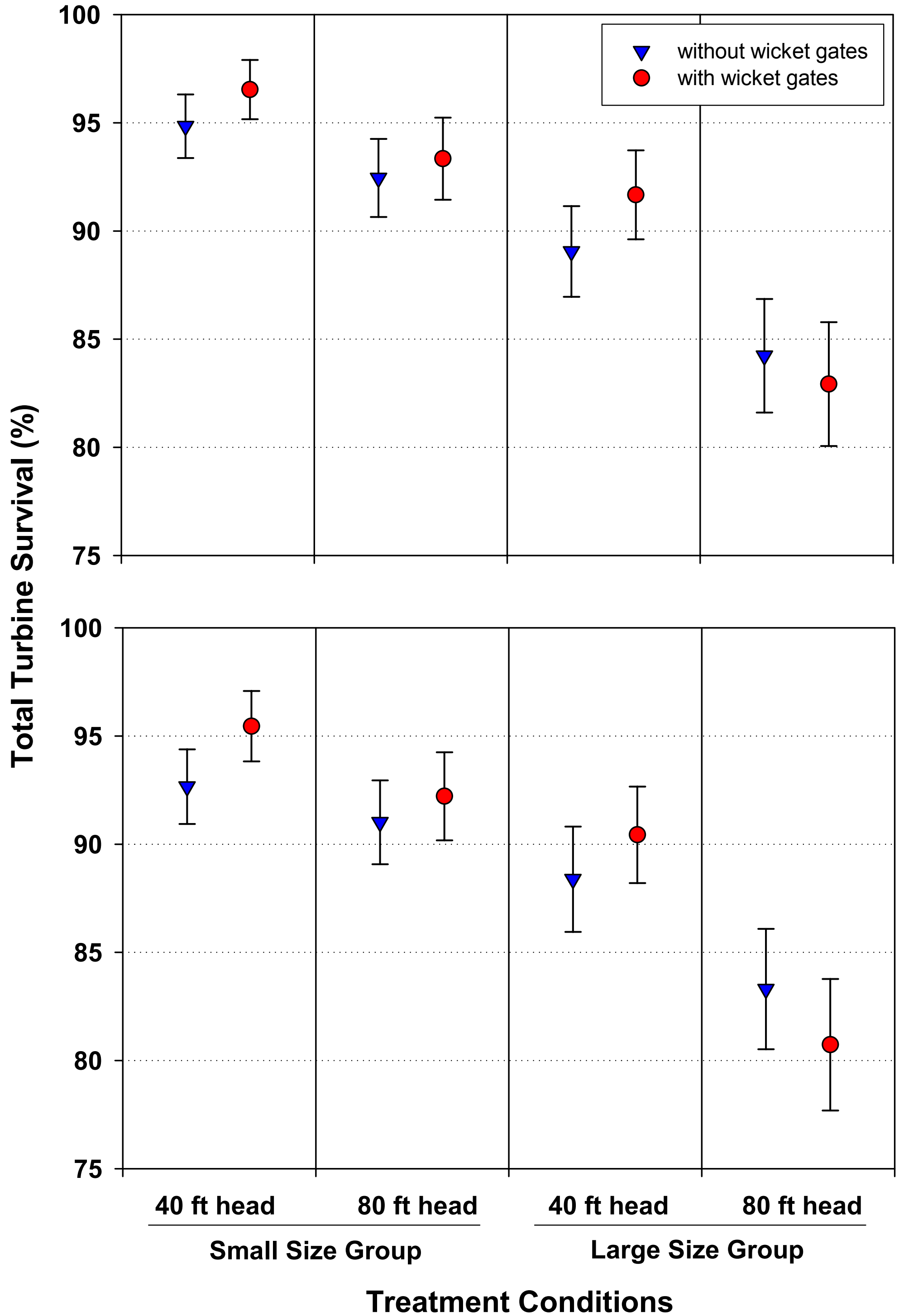


FIGURE 6-8 IMMEDIATE (1 HR) AND TOTAL (1 HR AND 96 HRS COMBINED) TURBINE SURVIVAL ESTIMATES (± 95% CI) FOR RAINBOW TROUT TESTS WITH AND WITHOUT WICKET GATES

TABLE 6-31
COMPARISON OF TREATMENT FISH INJURY RATES FOR TESTS WITH (TEST SERIES 2/3) AND WITHOUT WICKET GATES (TEST SERIES 5/6)

Turbine Head (ft)	Mean Fish Length (mm)	Wicket Gates	Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
			Live	Dead	Live	Dead	Live	Dead	Live	Dead	Live	Dead
40	93.7	no	96.7	10.9	2.5	80.4	0.5	15.2	0.0	8.7	0.4	17.4
	85.0	yes	98.7	12.2	1.3	75.6	0.0	24.4	0.0	0.0	0.0	9.8
80	93.1	no	96.3	0.0	3.5	68.3	0.3	42.9	0.0	39.7	0.1	15.9
	84.9	yes	98.6	6.9	1.3	81.9	0.1	48.6	0.0	29.2	0.0	9.7
40	173.8	no	95.9	12.9	3.5	71.0	0.3	14.0	0.0	16.1	0.7	9.7
	169.8	yes	96.3	11.5	3.2	79.5	0.2	10.3	0.0	3.8	0.2	12.8
80	173.0	no	94.7	7.0	4.3	67.7	0.3	34.8	0.0	36.7	0.9	12.0
	174.7	yes	93.6	7.5	5.4	68.4	1.0	37.9	0.0	30.5	0.1	14.4

For all combinations of fish size and head, the percent of fish that were classified as descaled was greater for live and dead fish when the wicket gates were not installed (Table 6-32). Differences between the rates of descaled fish were particularly notable for fish recovered dead (Table 6-32). The large differences in descaling for dead fish may be partially due to differences in personnel (i.e., the estimation of scale loss is somewhat subjective and can vary among evaluators) or fish condition that occurred between years. Alternatively, the wicket gates may have altered the turbine environment in a manner that affected the conditions that lead to high rates of scale loss when fish were fatally injured in the absence of wicket gates.

Although passage survival rates varied among the six efficiency points that were evaluated during Test Series 9/10, variability in survival rates was relatively small and there was no statistical difference among the rates estimated for the six set points (see Section 6.8). Evaluations of fish passage data for Kaplan turbines have also found no relationship between operating efficiency and survival rates (Skalski et al. 2002). However, despite a lack of a statistical significance, the results from an analysis of data from Columbia River projects indicated that peak passage survival may occur at efficiencies above the peak operating point (Skalski et al. 2002). Immediate survival rates of rainbow trout evaluated at BEP and the five off-BEP settings suggest peak survival rates for the Alden/Concepts NREC turbine may also occur at efficiency points above BEP.

TABLE 6-32

COMPARISON OF THE PERCENT OF FISH DESCALED FOR TESTS WITH (TEST SERIES 2/3) AND WITHOUT WICKET GATES (TEST SERIES 5/6)

Head (ft)	Mean Fish Length (mm)	Wicket Gates	Percent of Fish Classified as Descaled	
			Live	Dead
40	93.7	no	2.6	37.0
	85.0	yes	0.5	2.4
80	93.1	no	1.7	46.0
	84.9	yes	0.3	0.0
40	173.8	no	3.3	29.0
	169.8	yes	0.1	5.1
80	173.0	no	3.9	31.1
	174.7	yes	0.1	12.1

6.11 Effects of Fish Size and Species on Turbine Passage Survival and Injury Rates

Turbine passage survival and injury data were collected for several distinct size groups and species of fish under similar turbine operating conditions (i.e., head, turbine efficiency). These data allow for relationships between biological parameters and passage survival and injury rates to be explored. With the exception of American eel, all of the species that were evaluated were included in an analysis of fish size and species effects. American eel were the largest species evaluated (with respect to length) and had the highest survival rates (100% immediate survival). Additionally, despite a difference of about 180 mm in mean length, immediate and total turbine survival rates were not statistically different between the two eel size groups. This demonstrates that, for American eel, fish size did not influence turbine passage survival rates within the length range tested. Conversely, tests with multiple size groups of rainbow trout and smallmouth bass demonstrated that size was a statistically significant factor that affected passage survival for these two species.

The survival data collected for rainbow trout were the most comprehensive with respect to the number of size groups and operating conditions that were evaluated. There is a statistically significant straight line relationship when turbine survival rates are plotted versus mean fish length (simple linear regression; $P < 0.05$) for the two turbine heads that were evaluated with and without wicket gates (Figure 6-9). These data clearly demonstrate the negative relationship that exists between fish length and turbine survival for rainbow trout evaluated with the Alden/Concepts NREC runner. Based on the coefficient of determination (r^2) values, approximately 98% of the variation in survival rates at the higher head and about 71% at the lower head was due to fish length. When tests conducted at off-BEP settings are excluded from the analysis of survival rates at the lower head, the strength of the straight line relationship increased, with about 80% of the variation in survival being due to fish length (Figure 6-9). The results of the regression analyses with rainbow trout demonstrate that fish length is the primary factor affecting turbine passage survival at the operating heads that were evaluated. This conclusion is supported by previous analyses of turbine passage survival data, which have identified fish length as an important parameter in determining and/or predicting survival rates for fish passing through turbines (Franke et al. 1997; Winchell et al 2000; Headrick 2001).

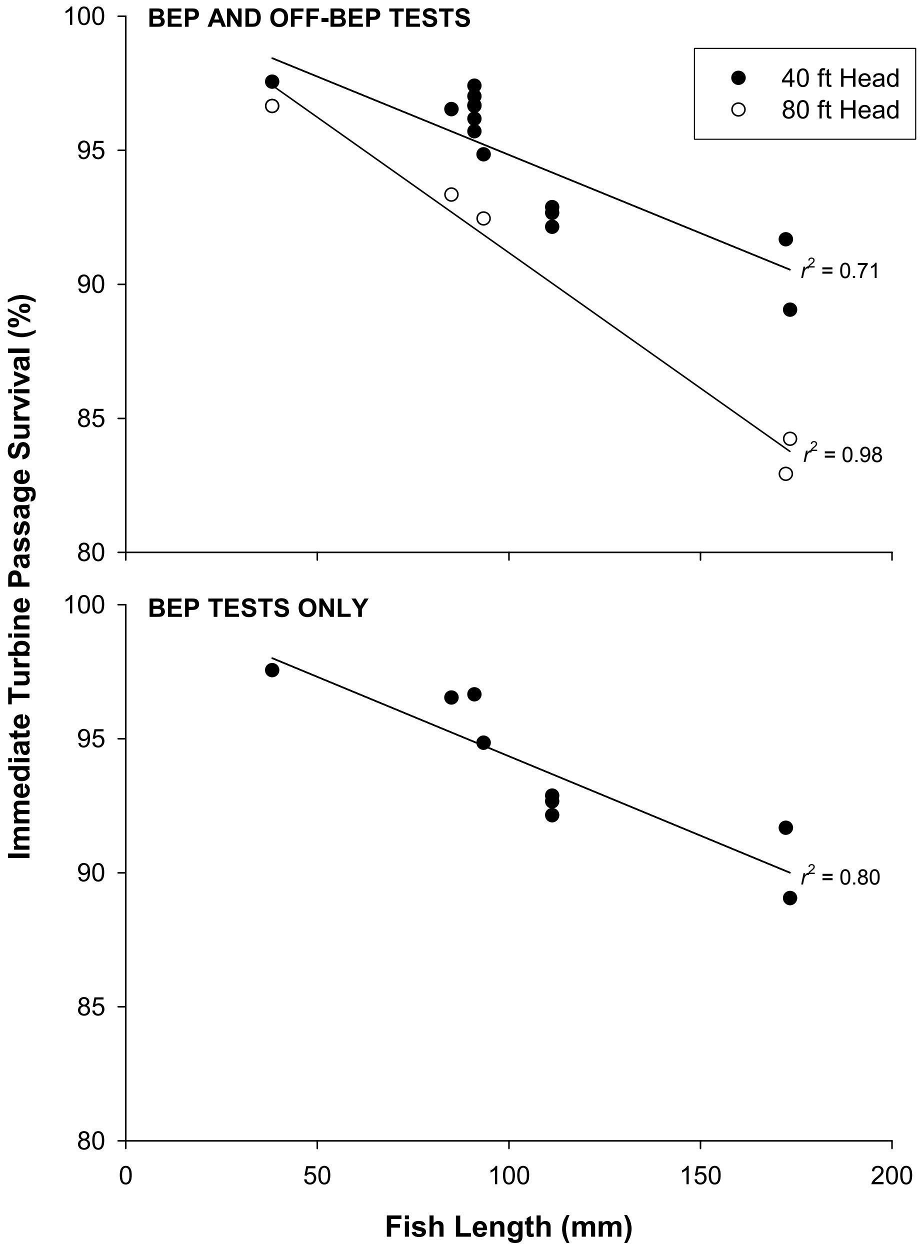


FIGURE 6-9 TURBINE SURVIVAL VERSUS FISH LENGTH FOR RAINBOW TROUT EVALUATED AT 40 AND 80 FT OF HEAD. TOP GRAPH INCLUDES DATA FROM ALL TESTS CONDUCTED AT BEP AND OFF-BEP SETTINGS; BOTTOM GRAPH INCLUDES TESTS CONDUCTED AT 40 FT HEAD AND BEP ONLY

Tests with two size classes of smallmouth bass also demonstrated the relationship between fish length and passage survival that was evident with rainbow trout. This relationship is further supported when data from tests with all species are combined and survival rates are regressed against fish length (Figure 6-10). The results of this analysis show that about 68% of the variation in passage survival rates is due to fish length. When white sturgeon are excluded, the percent of variation attributed to fish length increases to 78%. Significantly higher survival rates for white sturgeon (i.e., compared to the other two species evaluated as part of Test Series 7) were unexpected given that their mean length was similar to coho salmon and about 34 mm greater than alewife.

Previous studies have indicated that turbine survival rates are not highly species-specific (Franke et al. 1997). However, Alden's data suggest that when very precise estimates of turbine mortality are obtained, there are significant differences among some species. These differences do not appear to be considerable for species with similar body shapes and physical characteristics (i.e., presences of scales and true bones). But for species with more distinct differences, such as sturgeons and American eel, passage survival rates may be significantly greater if the differences include characteristics that reduce the potential for injury (e.g., lack of scales, cartilaginous skeleton, atypical body shape).

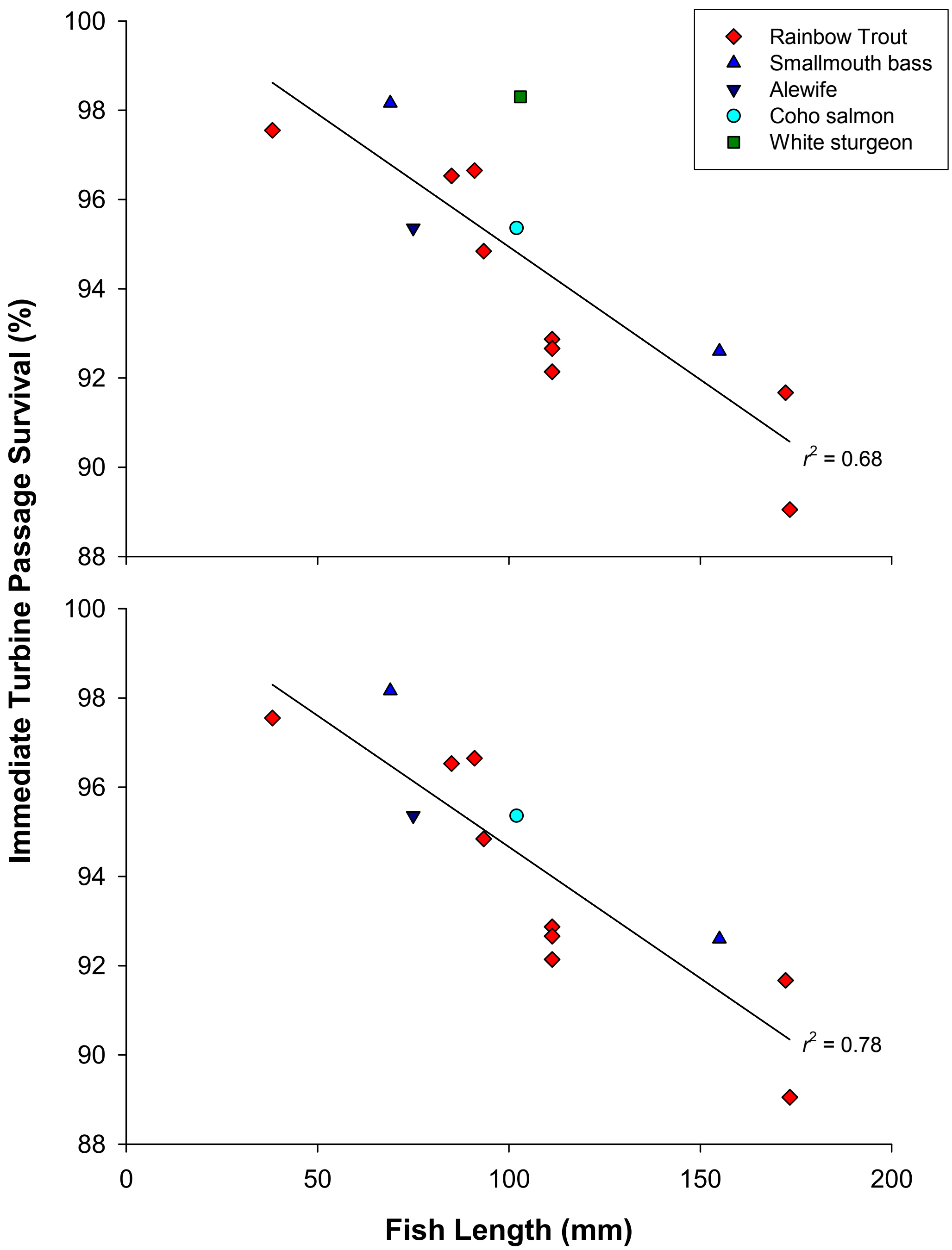


FIGURE 6-10 TURBINE SURVIVAL VERSUS FISH LENGTH FOR TESTS CONDUCTED AT A HEAD OF 40 FT AND BEP. TOP GRAPH INCLUDES DATA FOR ALL SPECIES EVALUATED UNDER THESE CONDITIONS; BOTTOM GRAPH INCLUDES DATA FOR ALL SPECIES EXCEPT WHITE STURGEON

6.12 Injury Mechanisms

The primary mechanisms of turbine-related fish injury and mortality include mechanical strike and grinding, shear and turbulence, pressure, and cavitation (Cada et al. 1997). Most injuries that were sustained by fish passing through the model Alden/Concepts NREC turbine appeared to be strike-related based on the types and frequencies of external injuries that were observed. Also, the model mortalities were reasonably well predicted by the usual strike probability equation when transposed to a mortality probability form (see Section 6.13). The majority of fish that were immediate mortalities suffered bruising, and to a lesser extent, lacerations and severed bodies. In designing the Alden/Concepts NREC turbine, gaps at the blade “tips” were eliminated by attaching a shroud to the outside of the blades over their entire length. The blades are also attached to the hub over their entire length. Therefore, there are no gaps that cause injury to fish due to mechanical grinding.

Flow shear can cause injury if the strain rate is sufficiently high. Tests at the Pacific Northwest National Laboratory (Nietzel et al. 2000) showed that no significant injury to the three fish species tested occurred for strain rates below 500/sec. CFD analysis of the Alden/Concepts NREC turbine runner (Cook et al. 2000) predicted that the volumes wherein the strain rate is greater than 500/sec is relatively small. Additionally, of the three species evaluated by Neitzel et al. (2000), steelhead and rainbow trout were found to be the most resistant to shear-related injuries. Injuries that have been attributed to shear forces include missing eyes and torn operculi (Neitzel et al. 2000), neither of which were common among immediate mortalities recovered during the laboratory evaluation of the Alden/Concepts NREC pilot-scale turbine. Therefore, the CFD analysis and the injury observations from biological testing support the view that shear is not an injury mechanism of obvious concern and did not appear to contribute to the mortality observed in the pilot scale testing.

Adverse pressure conditions within the turbine environment can result in ruptured swim bladders or instantaneous bubble formation in the gills or blood vessels, both of which can lead to mortality (Abernethy et al. 2001). The minimum pressure in the Alden/Concepts NREC runner was designed to be relatively high compared to conventional turbines to avoid fish injury due to rapid pressure reductions and cavitation. At the exit of the runner, the minimum local pressure predicted by the CFD analysis is about 10 psia when the average exit pressure at the runner discharge is slightly under atmospheric pressure, typical of runner settings. No obvious injuries related to pressure decreases (e.g., extruded swim bladders) were observed during testing, but external injury evaluations, which would have detected ruptured swim bladders and gas bubble formations, were not conducted. The CFD analysis results and the available injury data, although limited, indicate that pressure reductions probably are not an injury mechanism of concern for the new turbine.

6.13 Prediction of Full Scale Turbine Survival

Most of the fish injury observed in testing the pilot scale Alden/Concepts NREC turbine was believed to be due to blade strike. Since the pilot scale turbine was tested at actual heads and, therefore, actual velocities, the runner rpm was increased (compared to the full sized turbine) to obtain the same blade tip speeds as will occur in full scale. This produced the correct velocity triangle at the leading blade edge and the correct engineering performance (see Section 4.7). However, the distance between the leading edges in the pilot scale turbine was reduced from the full scale runner by the geometric scale factor, 3.25, while the fish lengths tested were similar to the full size. Therefore, the probability of strike and strike-related fish mortality is higher in the pilot scale than in the full size turbine and a method is needed to predict the lower fish mortality expected in the full size turbine. This prediction was made using a previously published strike equation, developed below, with a mortality factor which accounts for what fraction of the fish that encounter the blade actually die. The final mortality factor used also accounts for the differing relative (blade to fish) velocities at different heads.

Figure 6-11 shows flow conditions approaching the leading edge of the Alden/Concepts NREC turbine. The actual approach velocity is V_1 which, together with the blade tip velocity u, produces a relative velocity essentially in line with the blade leading edge angle. V_r is the radial component of the approach velocity and is equal to the turbine flow divided by the circumferential turbine area at the leading edges. With no wicket gates, the angle α between V_1 and u is fixed and equals 21°. With gates, this angle may be slightly different depending on the best (BEP) gate position. If a fish of length l is transported in line with the inflow, its projected length in the radial direction is $l \sin\alpha$.

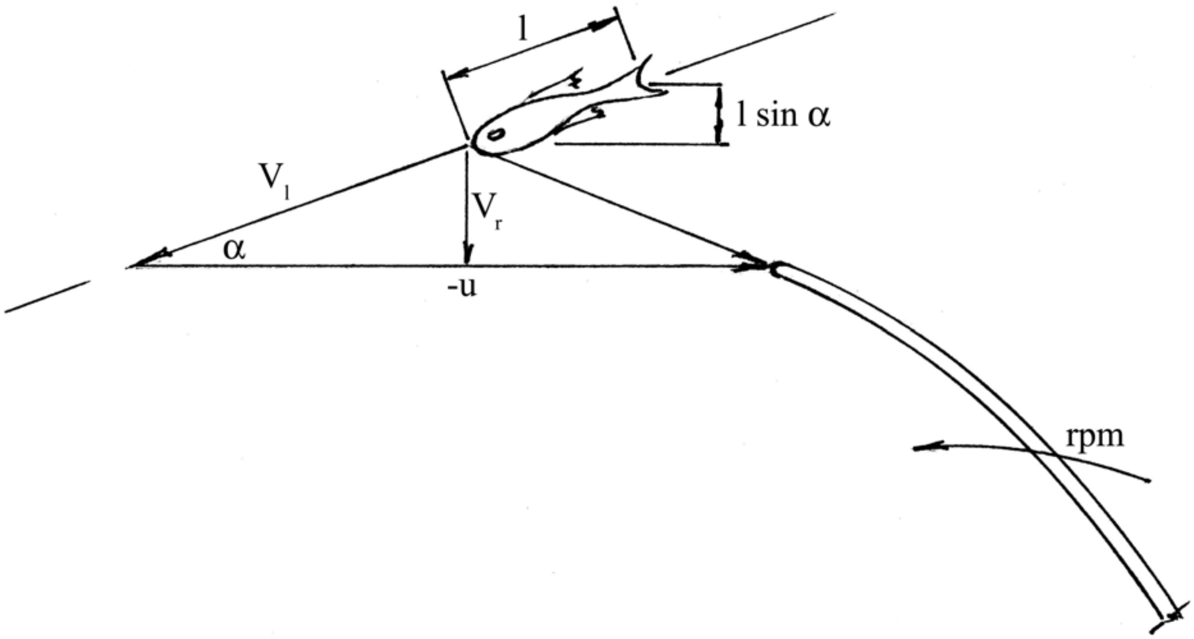


FIGURE 6-11 VELOCITIES AND FISH AT LEADING EDGE

The probability of strike may be taken as the fraction of the total distance along the arc between leading edges that the blade tip moves in the time it takes for the fish to pass through the critical arc of the blade edges (Bell 1991). Therefore,

$$P = \Delta s / S \qquad 6\text{-}1$$

where:

- P = probability of strike (dimensionless)
- Δs = distance blade edge moves in Δt (ft)
- Δt = time for fish to pass arc of leading edges (sec)
- S = distance (along arc) between leading edges (ft)

That is, if the blade were to only move 10% of the distance between blade tips in the time for a fish to pass through the critical arc, then the probability of strike would be only 10%, and 90% of the fish would pass into the runner without encountering the leading edges. If the leading edges were to move a distance equal to the distance between blade edges in the time for a fish to pass the critical arc, then the fish would have a 100% chance of being struck.

Note that

$$\Delta s = u\Delta t \qquad 6\text{-}2$$

and

$$S = \pi D/(\text{Number of Blades}) \qquad 6\text{-}3$$

The blade leading edges move at a speed u, which is equal to

$$u = \pi Dn/60 \qquad 6\text{-}4$$

where:

- u = blade tip speed (ft/sec)
- D = runner diameter (ft)
- n = rotational rate (rpm)

The time (Δt) for a fish to pass through the critical blade arc is

$$\Delta t = l \sin\alpha \;/\; V_r \qquad 6\text{-}5$$

where:

- l = fish length (ft)
- α = angle between V_1 and u
- V_r = radial component of turbine inflow (ft/sec)

Note that the radial projection of the fish length moving at the radial velocity is used in the formulation since the radial velocity can easily be calculated from the turbine geometry and flow. If the fish body is not aligned with the inflow near the blade leading edges, a different factor than $\sin\alpha$ would be applied to the fish length.

By substituting Equations 6-2 through 6-5 into Equation 6-1, the probability of strike, P, is

$$P = n\,(l \sin\alpha)\,N \,/\, (60\,V_r) \qquad 6\text{-}6$$

where N = number of leading blade edges.

Note that the diameter of the turbine has canceled out, but its effect is embodied in the turbine rpm, n, since n times D is proportional to the blade tip speed. Equation 6-6 indicates that the probability for strike increases if the runner rpm increases, if the fish length increases, and if the number of blades increases, all other thing being equal, and vice versa. In contrast, the probability of strike decreases if the radial velocity (or head) increases because fish are transported more quickly through the critical arc of the turbine blade tips. Essentially the same equation may be derived by considering the length of a streamline between blade passes compared to the fish length (Von Raben 1957) or the time between blade passes compared to the time for the fish to pass the critical blade tip arc.

Because not all strikes result in fatal damage to fish (Turnpenny et al. 2000), Equation 6-6 may be transposed to an equation to predict mortality (due to strike) using a relationship between strike and related fish mortality. For this purpose, Equation 6-6 can be written in the following form:

$$P_m = K_T\, n\, (l \sin\alpha)\, N / (60\, V_r) \qquad 6\text{-}7$$

where:

P_m = probability of mortality due to strike
K_T = mortality to strike ratio (Turnpenny et al. 2000)

The factor K_T has been experimentally investigated (Turnpenny et al. 1992), resulting in the following regression equation (Turnpenny et al. 2000)

$$K_T = 0.153(\log_n l) + 0.012 \qquad 6\text{-}8$$

where:

K_T = Turnpenny mutilation (mortality to strike) ratio
$\log_n$ = natural logarithm
l = fish length (cm)

In the Turnpenny experiments, brown trout and bass were anesthetized and held in position by a short line until a blade was propelled (along rails) into the fish at velocities of from 17 to 23 ft/sec. These velocities are similar to the 24 ft/sec relative velocity approaching the model turbine blade at 40 ft of head. Because damaged fish were not retained in Turnpenny's experiments to evaluate delayed mortality, use of the mortality to strike ratio, K_T, infers immediate mortality. Table 6-33 provides the information needed to calculate immediate mortality using Equation 6-7. The latter equation, with $\sin\alpha = \sin 21° = 0.36$, results in the immediate survival predictions for the model turbine shown by the line(s) in Figure 6-12. Survival is 100% minus the percent mortality. The predictive equation is essentially the same for both BEP head/rpm conditions tested since the ratio n/V_r is essentially constant at the two

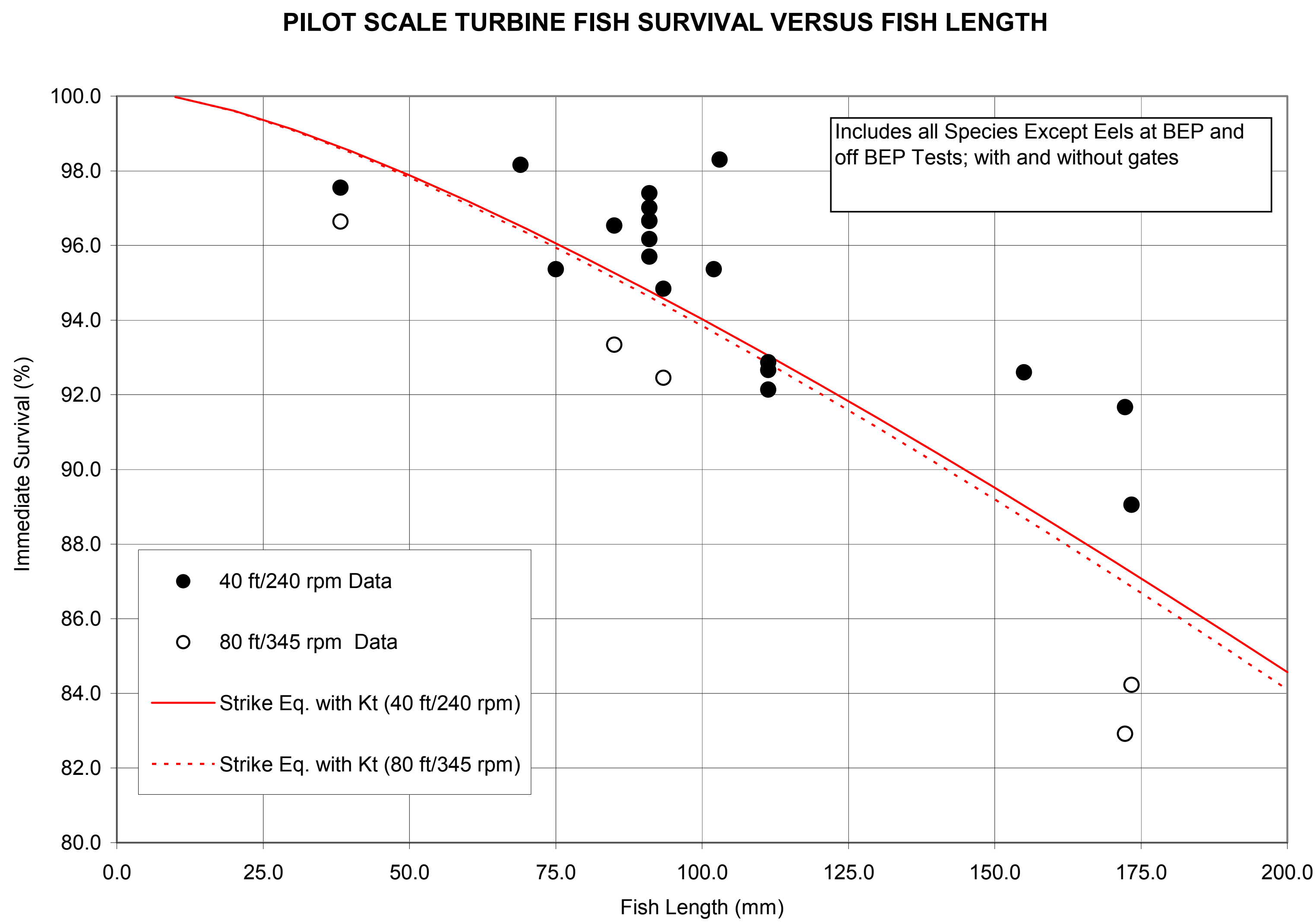


FIGURE 6-12 COMPARISON OF PREDICTED IMMEDIATE SURVIVAL (EQUATION 6-7) TO TEST DATA WITH AND WITHOUT WICKET GATES

TABLE 6-33
INPUT TO IMMEDIATE MORTALITY
PREDICTIVE EQUATIONS 6-7 AND 6-10

For Pilot Scale Model At BEP:

@ H = 80 ft, n = 345 rpm, Q = 91 cfs, V_r = 12 ft/sec, V_{rel} = 35 ft/sec

@ H = 38 ft, n = 240 rpm, Q = 64.5 cfs, V_r = 8.6 ft/sec, V_{rel} = 24 ft/sec

selected BEP test conditions. This is analogous to a constant phi (Equation 4-9) used in presenting the engineering data (Section 4.7). Given the new design of the Alden/Concepts NREC turbine (e.g., only three blades), the relatively high rpm of the pilot scale turbine, and that the test data include all species, with and without gates, and off-BEP as well as BEP conditions, it is noteworthy that the test data follow the predictive strike mortality equation fairly well. Considering the complex factors involved in fish passage mortality, the general agreement between the strike mortality equation and the test data is considered reasonably accurate for a new turbine design and supports the view that the majority of the observed mortality in the model was strike related.

More carefully comparing the predicted immediate mortality with the actual immediate mortality data from the model tests with and without wicket gates indicates that Equation 6-7, with the coefficients K_T, generally under-predicts immediate survival at the lower head/rpm tests condition (40 ft/240 rpm) and generally over-predicts immediate survival at the higher head/rpm test condition (80 ft/345 rpm). There are a number of factors not included in the strike mortality equation which would account for this difference. First, there may be some other fish damage mechanisms, such as flow shear and abrasion, which increase fish mortality at the higher head/rpm. Second, fish swim behavior would vary at the different turbine velocities of the different head/rpm conditions. Especially for the larger fish sizes tested, fish would be more able to orient upstream and try to avoid the turbine leading edge at the lower velocities associated with the lower head/rpm, and vice versa. The predictive equation assumes one and the same fish orientation for both head/rpm test conditions. Third, the coefficient of strike mortality, K_T, developed by Turnpenny et al.(2000) and used in the above analysis does not consider that the relative velocity of strike increases with head and vice versa.

To improve the strike mortality equation so that it may be used to predict the full scale turbine fish survival, including considerations mentioned above which change with head/rpm, a new coefficient of strike mortality, K_A, was developed by Alden using the pilot scale test data. This new coefficient has a term based on fish length (as did the Turnpenny coefficient) and a term based on the relative fish to blade strike velocity, which varies with head. The best fit to the pilot scale test data was given by the following equation:

$$K_A = 1.0x10^{-3}\, l^{1.1} + 1.57x10^{-4}\,(V_{rel})^{1.15} \qquad 6\text{-}9$$

where:

K_A = Alden strike mortality coefficient
l = fish length (cm)
V_{rel} = relative fish to blade velocity (cm/sec), assuming that fish move at water velocity

At the 80 ft/345 rpm test condition, the relative velocity is about 35 ft/sec (165 cm/sec) while at the 40 ft/240 rpm test condition, the relative velocity is about 24 ft/sec (113 cm/sec).

Using this coefficient in the strike equation results in the following strike mortality equation:

$$P_m = K_A\, n\, (l \sin\alpha)\, N / (60\, V_r) \qquad 6\text{-}10$$

where K_A is defined above. The resulting immediate survival (survival equals 100% minus % mortality) is shown versus the pilot scale test data on Figure 6-13. Two distinct lines result from the coefficient K_A varying with head/rpm, and these lines represent a good fit to the data, with some scatter due to the data from off-BEP tests and results with different species. If only BEP tests with rainbow trout are considered, equation 6-10 results in a very close fit to the data, as shown in Figure 6-14 where equation 6-10 is compared to the best fit lines for each head/rpm data set.

The close agreement between equation 6-10 and the pilot scale data allows use of this equation to predict the full scale turbine survival with considerable confidence. It should be recalled that the pilot scale turbine was tested at full scale heads and velocities, and with non-scaled fish lengths. Therefore, the same relationship given in equation 6-9 for K_A would apply in the full scale turbine. However, a thicker blade in the full scale turbine will result in more survival than predicted, as discussed further below.

Equations 6-9 and 6-10 were used to predict the immediate fish survival for the full scale Alden/Concepts NREC turbine. As shown on Figure 6-15, the predictions indicate that 6 inch (about 150 mm) fish will have a survival of about 96% at 80 ft (100 rpm) and above 97% at 40 ft (71 rpm). Three-inch fish (about 75 mm) may have a survival of 98% or more at both head conditions. Some species, especially sturgeon and eel, are expected to have a higher survival since the predictive equation was mainly based on the test results for rainbow trout. The predictions in Figure 6-15 are for direct survival of fish and do not consider potential effects of the tailrace and predation.

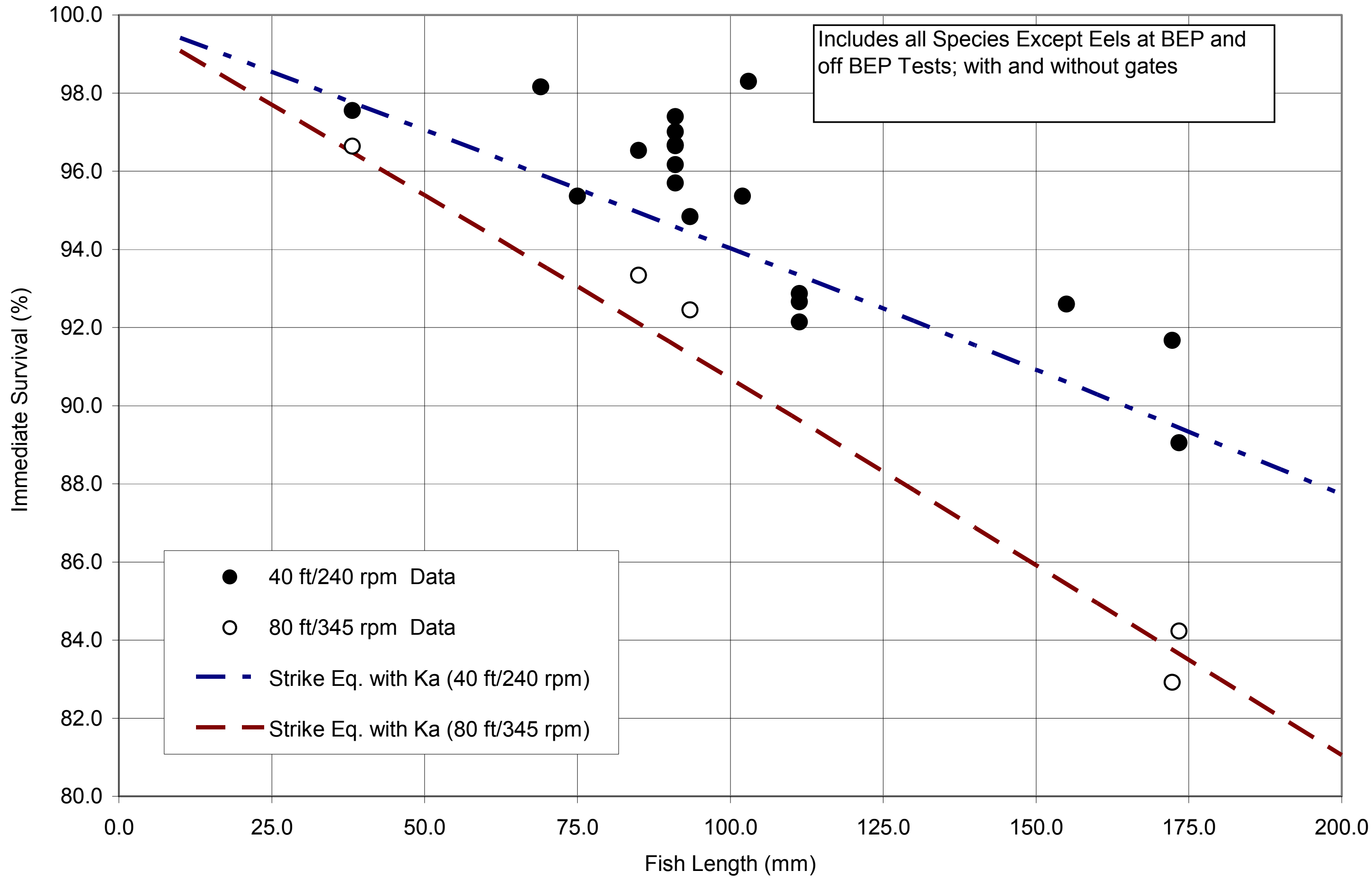


FIGURE 6-13 COMPARISON OF IMMEDIATE FISH SURVIVAL (EQUATION 6-10) TO TEST DATA, WITH AND WITHOUT GATES

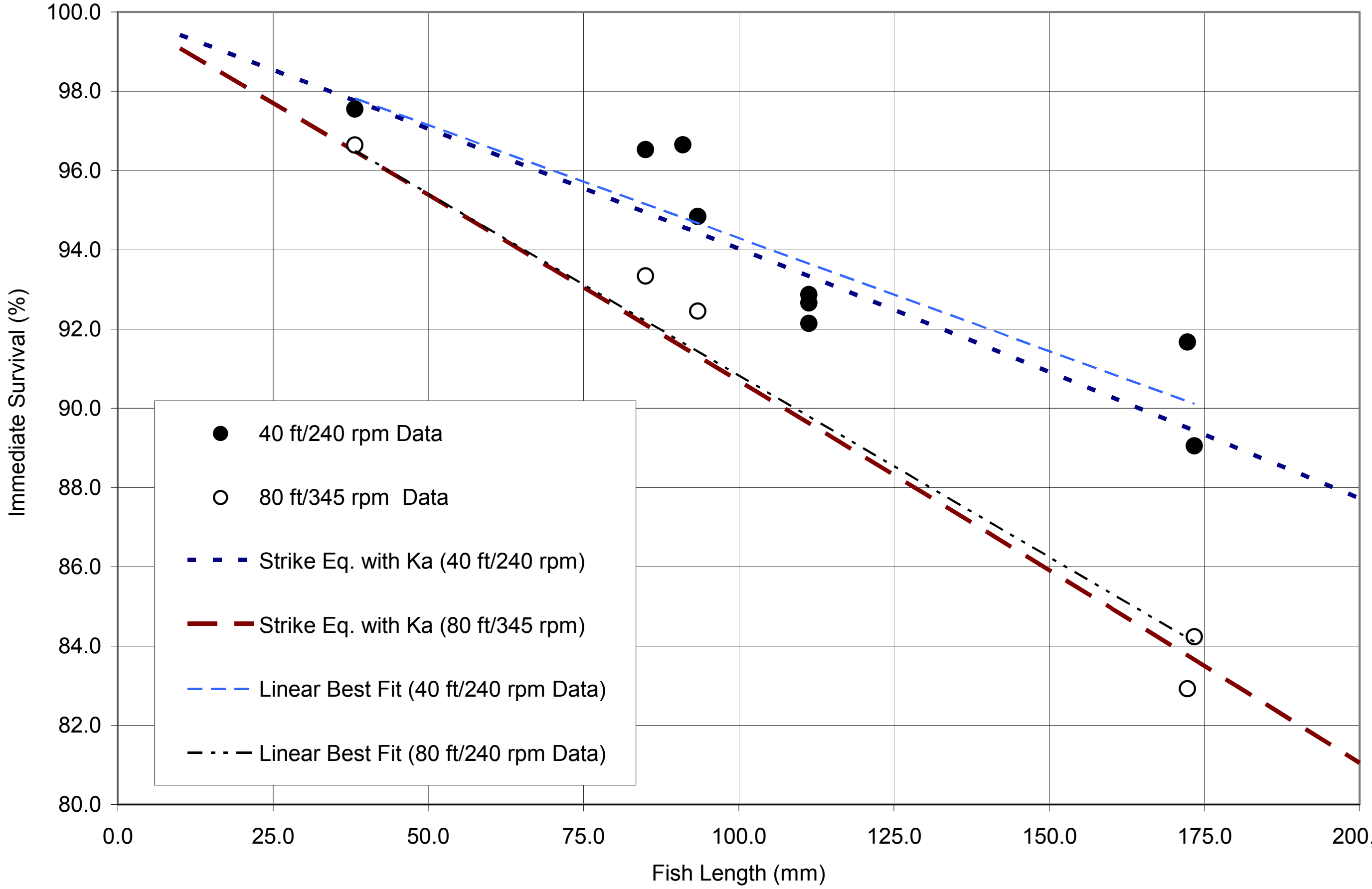


FIGURE 6-14 PILOT SCALE TURBINE RAINBOW TROUT SURVIVAL VERSUS FISH LENGTH AT BEP

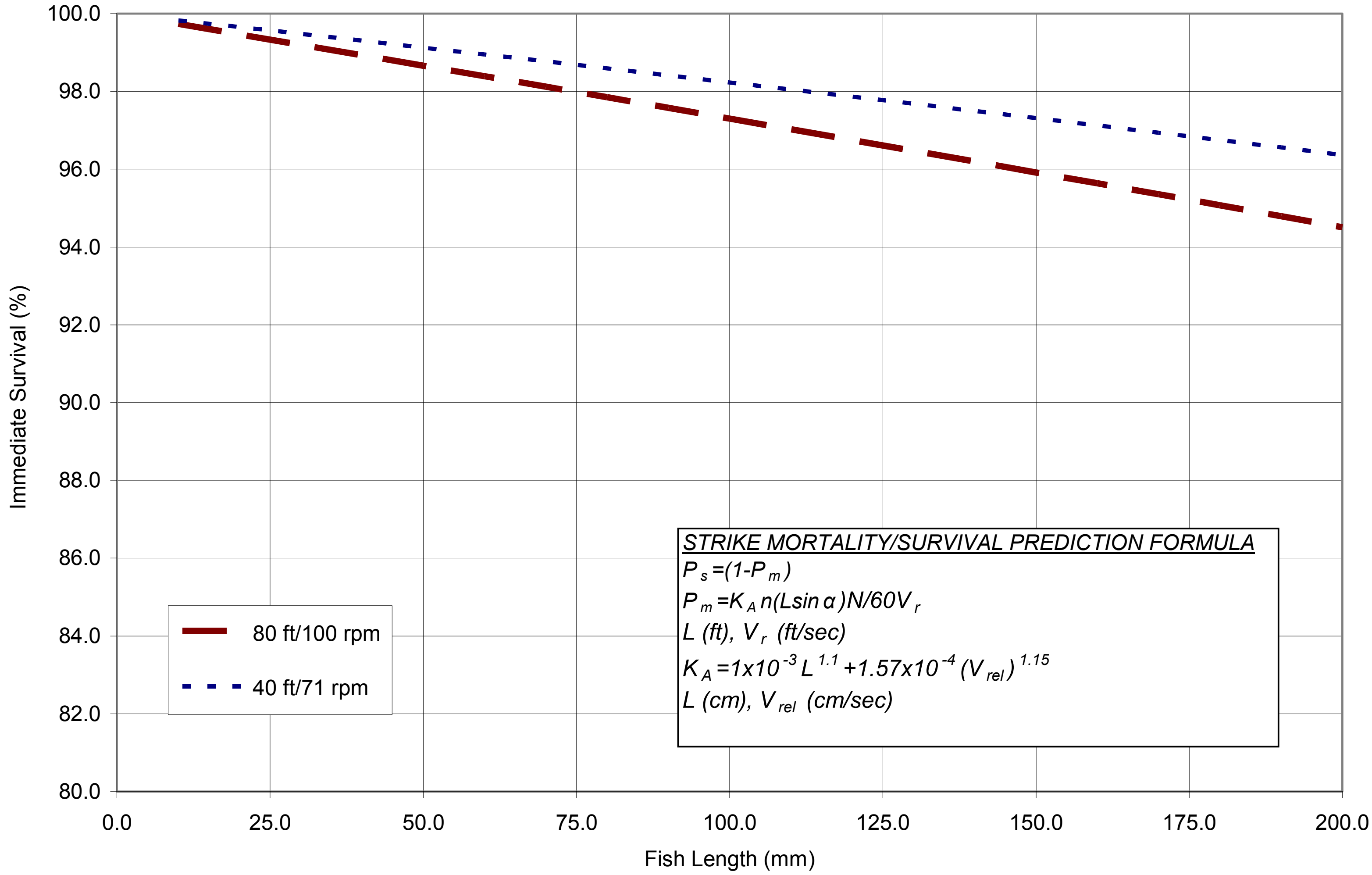


FIGURE 6-15 PREDICTED FULL SIZE TURBINE FISH SURVIVAL VERSUS FISH LENGTH

As mentioned above, another factor that will influence full scale strike mortality for the same size fish (i.e., non-scaled fish lengths) is the difference in leading edge blade thickness between the model and field runner. This factor is not included in the above predictions of full size turbine survival because no data are available on how K_T or K_A change with *l/t*, the fish length to blade thickness ratio. Figure 6-16 shows that the model blade thickness was about 3/8 inch (9.5 mm) and that the field blade thickness is expected to be about 1.5 inches (38 mm), depending on the manufacturing method. Experiments have shown (Turnpenny et al. 1992) that, for a given fish size group and a relative velocity of about 22 ft/sec (7 m/sec), fish injury decreased with increasing thickness of the leading edge. This additional factor will increase the survival of fish in the full size turbine compared to the pilot scale turbine beyond what is shown on Figure 6-15.

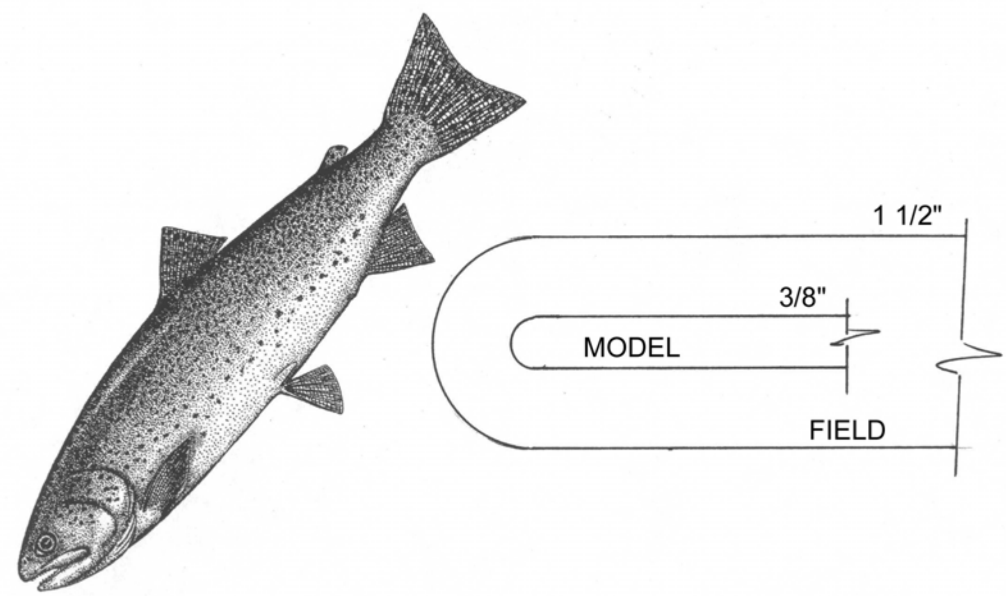


FIGURE 6-16 MODEL VERSUS FIELD LEADING EDGE BLADE THICKNESS

6.14 Alden/Concepts NREC Turbine Fish Survival Compared to Other Turbines

The report entitled "Development of Environmentally Advanced Hydropower Turbine System Design Concepts", prepared by the Idaho National Engineering Laboratory (INEEL) (Franke et al. 1997) provides a database that summarizes most of the available fish survival data for hydroelectric projects. Alden has compared fish survival results presented in this database, which is provided in Appendix Q, to fish survival predicted for the full size Alden/Concepts NREC turbine.

Immediate survival data in the INEEL database was grouped by Alden according to turbine type, fish length and runner rotation rate (rpm). All data within each group was averaged to represent the entire range of the various field studies and identify basic trends in the data. Head was not used to group the data since prior analysis (Franke et al. 1997) had shown that survival was not correlated with turbine head. Studies were not grouped according to statistically significance of the data resulting from different methods (e.g., fish injection location and fish retrieval techniques) and different numbers of replicate tests associated with each study.

Fish survival from the database is summarized on Table 6-34 and is plotted on Figure 6-17. Figure 6-17 shows that Francis turbines have a lower average immediate survival than Kaplan turbines for all fish sizes and turbine rotational speeds (rpm). The average immediate survival generally increases with decreasing rpm and decreasing fish length for both Francis and Kaplan turbines.

To allow a direct comparison with the available database of immediate fish survival described above, the immediate (rather than total) survival results predicted for the Alden/Concepts NREC turbine, as discussed in Section 6.13, are also plotted on Figure 6-17. Comparing the average results (both turbine heads for each range of fish length) for immediate survival for the Alden/Concepts NREC turbine to the average immediate survival from the available database shows that the full scale Alden/Concepts NREC turbine operating at 70-100 rpm is expected to have a higher fish survival than the average survival for the other turbine types operating at any speed. This is particularly true when the predicted survival for the Alden/Concepts NREC turbine is compared to the survival for Francis turbines. Due to the mixed inflow design, the Alden/Concepts NREC turbine may be designed for higher heads and, thus, overlap the operating range of Francis turbines at lower heads.

TABLE 6-34
IMMEDIATE FISH SURVIVAL BY SIZE AND RUNNER SPEED CLASS FOR KAPLAN AND FRANCIS UNITS (FIELD DATA; FRANKE ET AL. 1997)

Size Class (mm)	Runner Speed (rpm)	Parameter	Kaplan Turbines	Francis Turbines
<100	<100	*N**	2	11
		mean (range)**	93.3 (89.0-97.5)	87.3 (62.0-100.0)
	101 – 200	*N*	20	12
		mean (range)	94.4 (89.7-100.0)	77.9 (32.3-100.0)
	201 – 300	*N*	1	16
		mean (range)	96.0 (--)	71.4 (27.0-100.0)
	>300	*N*	1	8
		mean (range)	89.0 (--)	56.1 (3.0-87.8)
101 – 150	<100	*N*	6	14
		mean (range)	95.4 (93.0-97.5)	90.7 (59.5-100.0)
	101 – 200	*N*	8	23
		mean (range)	96.0 (91.0-100.0)	80.0 (36.4-96.0)
	201 – 300	*N*	9	6
		mean (range)	91.0 (82.1-99.3)	82.5 (58.1-98.2)
	>300	*N*	1	4
		mean (range)	87.1 (--)	66.0 (43.0-78.1)
151 – 200	<100	*N*	21	18
		mean (range)	94.9 (88.5-100.0)	86.0 (16.4-100.0)
	101 – 200	*N*	11	21
		mean (range)	93.7 (86.4-98.7)	83.5 (68.4-95.5)
	201 – 300	*N*	4	15
		mean (range)	90.6 (86.0-93.2)	63.6 (14.0-95.0)
	>300	*N*	1	6
		mean (range)	83.7 (--)	33.4 (1.0-58.9)

*N = number of data points
**Range = minimum and maximum survival (%)

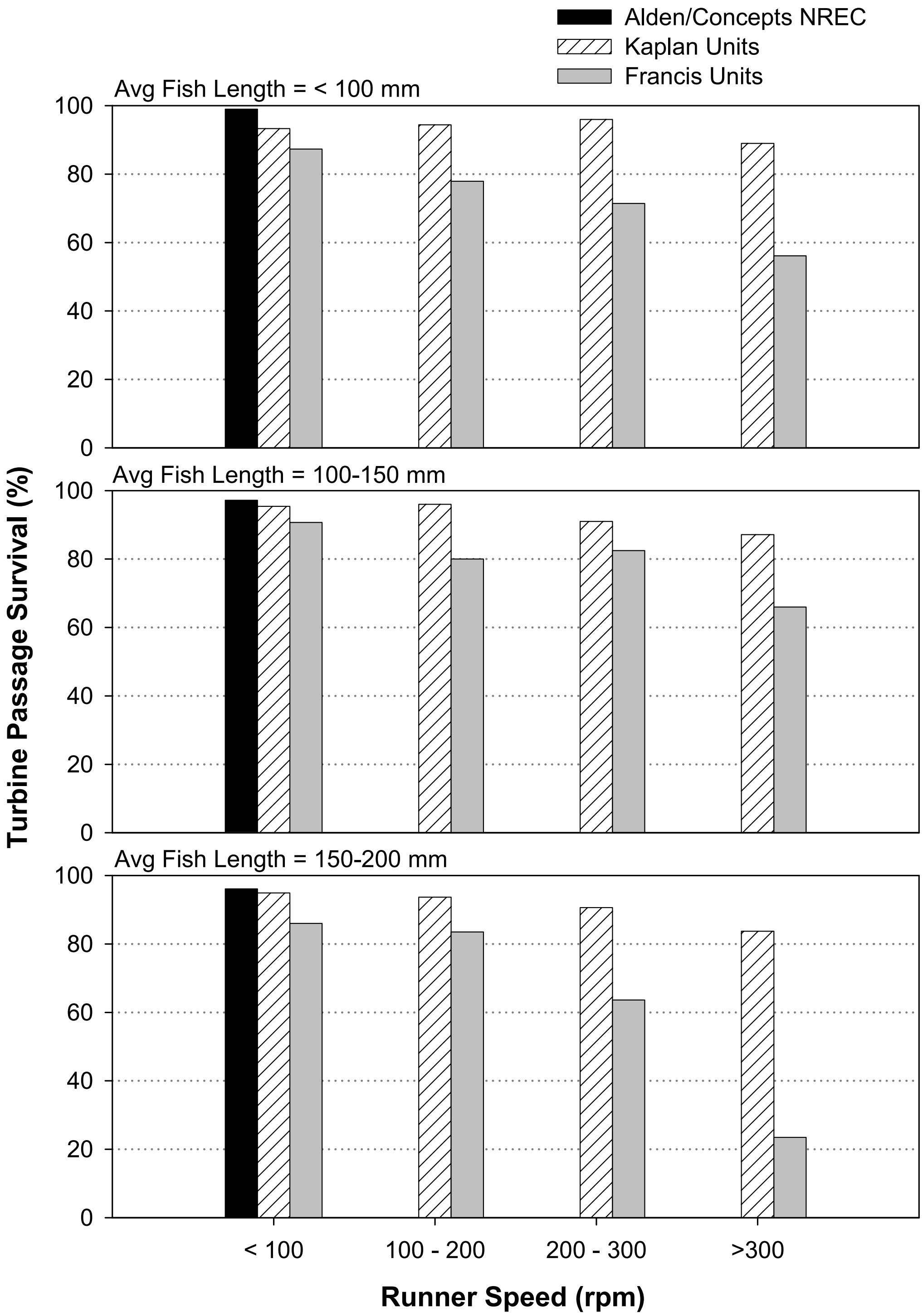


FIGURE 6-17 FISH SURVIVAL VERSUS TURBINE RUNNER SPEED

NOTE: Francis and Kaplan estimates are averages of field data reported by Franke et al. (1997); Alden data are predicted based on pilot scale data (Section 6.13).

7.0 COMPUTER ANALYSIS OF BEP AND OFF-BEP OPERATION

7.1 Objectives of CFD Analysis

Final Computation Fluid Dynamic (CFD) analyses were performed to address the objectives listed below. Since the original CFD analysis was performed, advances in software and hardware allowed the complex flow conditions through the entire turbine (including the scroll case, wicket gates, runner, and draft tube) to be included in one simulation. Each simulation was at a predefined wicket gate position, runner rpm and flow. All other parameters, such as turbine head, power and efficiency were determined by the CFD simulation.

The objectives of this analysis were to:

1) Evaluate flow conditions at the actual best efficiency point (BEP) wicket gate setting (18.2^o) and runner rpm for the pilot scale turbine compared to the "theoretical" gate setting (22^o) and runner speed originally derived as the BEP.

2) Determine the flow fields for different off-BEP operating conditions to evaluate why similar fish survival was observed during these pilot scale test conditions.

3) Relate observed fish injury for BEP and off-BEP tests to internal runner flow characteristics, such as the minimum absolute pressure, strain rates and pressure change rates.

4) Evaluate whether the turbine design could be improved for fish passage and power.

A total of five turbine operation scenarios were simulated, as shown in Table 7-1. Two high (nominally 80 ft) head cases (Case Nos. 1 and 2) were studied to better understand the differences in turbine performance between the "theoretical" BEP (22^o gate setting, 325 rpm, and 95 cfs) and the actual measured BEP (18.2^o gate setting, 345 rpm, and 84.1 cfs), and to identify any turbine features that could be further improved. Three low (nominally 40 ft) head cases (Case Nos. 3, 4 and 5) were simulated to cover the range of turbine operation tested with fish at the 240 rpm rotational speed at the different gate positions, from the most wide open wicket gate position (26^o) to the most closed wicket gate position (16^o). The results of these simulations were used to correlate flow characteristics with fish survival.

TABLE 7-1
CFD CASES ANALYZED

Case No.	High Head		Low Head		
	1	2*	3	4*	5
Wicket Gate Setting (° from fully closed)	22	18.2	26	18.2	16
Speed, *n* (rpm)	325	345	240	240	240
Flow, *Q* (cfs)	95.0	84.1	76.9	60.7	54.7

*Actual BEP wicket gate position

A summary of the results and evaluations thereof will be provided in this section. Appendix P provides a more complete presentation of the CFD methods and results.

7.2 Methodology for Flow Simulations

A widely used commercial software program, FLUENT (Version 6), was used to perform the CFD simulations. This CFD package solves the Navier-Stokes equations and turbulence closure equations in both stationary and rotating reference frames to simulate three-dimensional flows. The standard κ–epsilon turbulence model was used with a wall function for the boundary layer. The 2.7 million computational meshes for this study were generated using Gambit (Version 2.0) and the CFD results were post-processed using FieldView (Version 8.0).

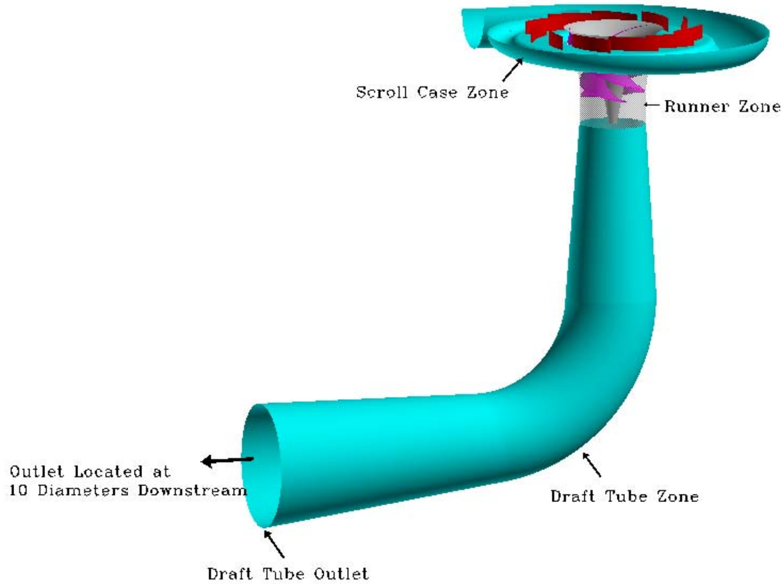
Flow characteristics through a hydraulic turbine are difficult to simulate accurately because the upstream and downstream components (scroll case and draft tube) are stationary while the runner is rotating. There are important interactions between flow in the scroll case and runner inlet as well as between flow in the runner exit and the draft tube. For the final CFD analysis, two methods were used to simulate the interaction between flows in stationary and rotating parts of the turbine: 1) a mixing plane method and 2) a multiple frame of reference (MFR) method. The mixing plane and MFR methods both assumed the flow field was steady-state, with the stator-rotor interactions being accounted for by different approximations. Due to greater accuracy and ease of convergence, only the MFR model results are presented herein. The time average values reported herein do not fully represent the extreme values that turbulent flow may produce.

As shown in Figure 7-1(a), the MFR method simulated the whole turbine in a single model. Figure 7-1(b) indicates that there were two grid interfaces. One interface was located between the end of the scroll case zone and the beginning of the runner zone and the other interface was located between the end of the runner zone and the beginning of the draft tube zone. At these interfaces, the flow-field variables are directly transferred from the upstream zone to the downstream zone for each calculation iteration. Therefore, flow and momentum are strictly conserved between the zones.

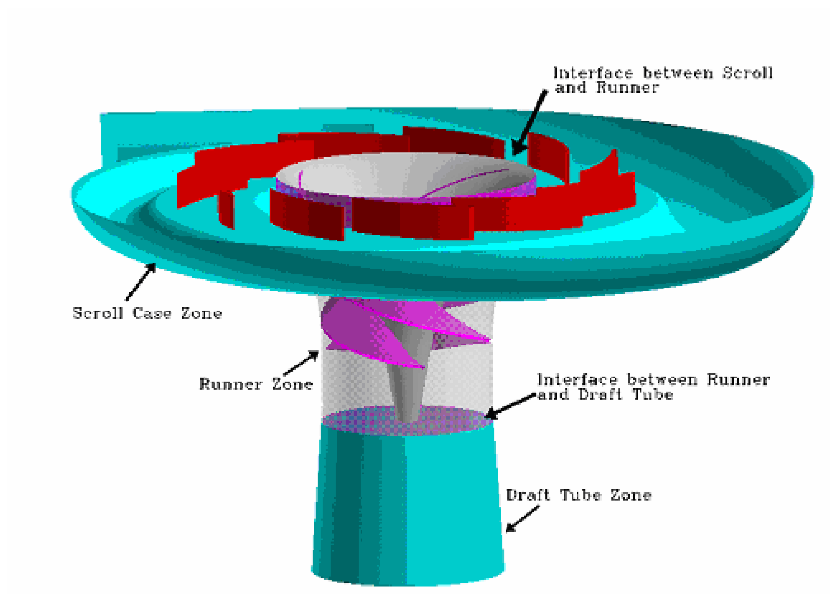
A uniform velocity inlet boundary condition was imposed at the scroll case inlet and an outflow pressure boundary condition was applied at the model outlet, which extended 10 pipe diameters downstream from the draft tube exit. The value of the pressure used at the outflow boundary was selected to produce a cross-sectional average pressure at the runner outlet of slightly less than atmospheric, which is typical for turbine settings and the pilot scale tests. A non-slip wall boundary condition was applied on all walls and the rotational speed was specified for each wall (zero for fixed surfaces and turbine speed (rpm) for the runner surfaces).

7.3 CFD Predicted Turbine Operating Characteristics

Turbine performance predicted with CFD is summarized in terms of runner torque (*T*), turbine power (*P*), turbine head (*H*), runner head (*Hr*), actual turbine head (*Ha*), turbine efficiency ($\eta = Ha/H$), runner efficiency ($\eta_r = Ha/Hr$), hydraulic losses in the scroll case and draft tube (ΔHs and ΔHd), and the averaged velocity angle from the radial direction at the downturn entrance in the plan view (β). The turbine head (*H*) is defined as the difference in total head (static plus kinetic) between the scroll inlet and draft tube outlet. The runner head (*Hr*) is defined as the difference in total head between runner inlet and runner outlet. The actual turbine head (*Ha*) is the actual power head of the turbine and is defined as $P/(Q\gamma)$, where Q is the flow rate and γ is the specific weight of the water.



(a) Whole Computational Domain



(b) Detailed View

FIGURE 7-1 COMPUTATIONAL DOMAIN AND TURBINE GEOMETRY
(TOP OF SCROLL NOT SHOWN FOR CLARITY

7.3.1 BEP Performance

The predicted turbine performance based on the CFD model at the high head condition is compared to the measured pilot scale turbine performance in Table 7-2. The predicted turbine efficiency at a 325 rpm rotational speed with the wicket gates set at 22° (Case No. 1; "theoretical" BEP) was 83.5%. At 345 rpm with the gates at 18.2° (Case No. 2; actual test BEP), the predicted efficiency was 84.8%. The turbine efficiency at the actual BEP was predicted to be 1.3% higher than the "theoretical" BEP, similar to the difference in measured turbine efficiencies for these two cases.

The CFD analysis predicted reasonably well the measured efficiencies at the higher head. However, the CFD analysis did not include leakage, viscous losses external to the runner flow path, and mechanical losses. Although CFD predicted efficiencies are close to the measured efficiencies, the CFD values are more meaningful in showing trends between operating conditions.

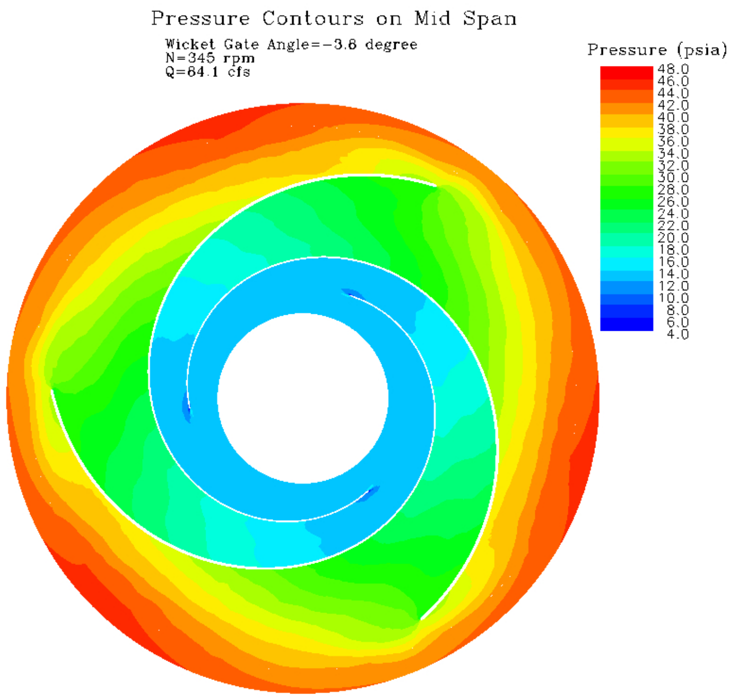
Figure 7-2 shows the pressure variation along a blade mid-span for the actual high head BEP (18.2° gate position) case. There is an area near the trailing edge where the pressure on the pressure side of the blade is less than the pressure on the suction side of the blade. This reversal is smaller than the one observed for the "theoretical" BEP case (see Appendix P). Changes to the blade shape would eliminate this pressure reversal and would produce higher turbine efficiencies than the current design.

TABLE 7-2
COMPARISON OF HIGH HEAD CFD RESULTS TO
PILOT SCALE TURBINE MEASUREMENTS

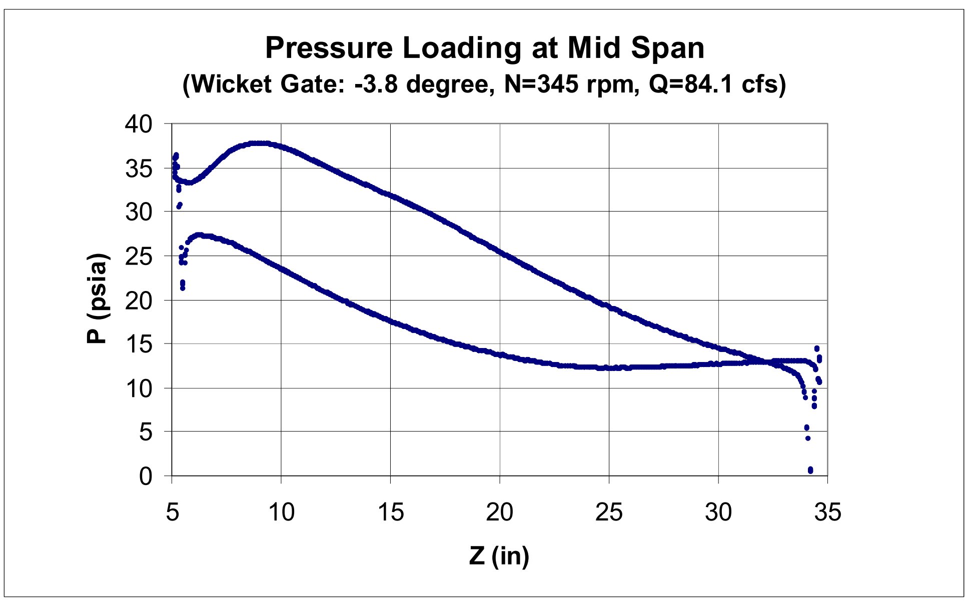
	Case No. 1		Case No. 2	
	CFD*	Measured**	CFD*	Measured**
Wicket Gate Setting (^{o} from fully closed)	22	22	18.2	18.2
Speed, n (rpm)	325	325	345	345
Flow, Q (cfs)	95.0	96.9	84.1	84.8
Runner Torque, T (N-m)	15194		13605	
Power, P (hp)	693.2	719.7	658.9	651.2
Turbine Head, H (ft)	77.1	78.2	81.5	79.8
Runner Head, Hr (ft)	74.5		79.5	
Actual Head, Ha (ft)	64.4		69.2	
Turbine Efficiency, η (%)	83.5	83.7	84.8	84.7
Runner Efficiency, η_r (%)	86.5		87.0	
Loss at Scroll, ΔHs (ft)	1.11		1.26	
Loss at Draft Tube, ΔHd (ft)	1.56		0.74	
Average Velocity Angle at Down Turn Entrance, β (^{o})	67.5	69.4	71.4	71.2

* CFD input parameters identified above double line.

** Measured in pilot scale turbine final engineering tests (Table G-7). Measured turbine efficiency has not been adjusted for runner bottom seal leakage and other mechanical/viscous losses.



(a) Pressure Contours on Mid-Span Plane



(b) Pressure Loading at Mid-Span Surface

FIGURE 7-2 PRESSURE VARIATION ALONG BLADE LENGTH
(18.2° WICKET GATE ANGLE FROM FULL CLOSED)

Figure 7-3(a) for the actual BEP gate position (18.2°) shows that the flow deceleration zone extends a considerable distance from the blade leading edge towards the trailing edge. This zone was smaller than for the "theoretical" BEP gate position (22°) (see Appendix P). This deceleration zone is related to the pressure reversal near the trailing edge. Figures 7-3(b) shows some tendency for flow separation on the suction side near the leading edges. Again, this tendency is less for the actual BEP gate position (18.2^o) than for the "theoretical" BEP gate position (22^o). The stagnation point locations for both the actual BEP and the "theoretical" BEP are similar.

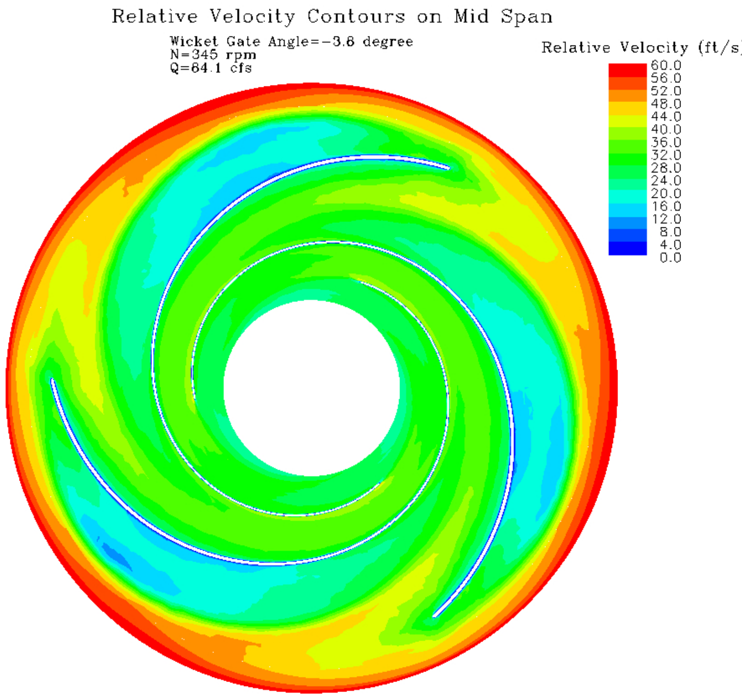
Figure 7-4 shows flow streamlines in the draft tube and indicates that Case No. 2 (actual BEP) has stronger swirl in the draft tube than Case No. 1 ("theoretical" BEP). The swirl angle at the draft tube exit for the "theoretical" BEP gate is relatively small (about 5-10^o). However, the swirl angle at the draft tube exit for the actual BEP gate (Case No. 2) is about 40-45^o because the tangential velocity component is relatively high compared to the axial velocity component (see Appendix P). This difference in the draft tube swirl agrees with measurements obtained in the pilot scale test facility and indicates that changes to the blade shaping would reduce the residual swirl and increase the efficiency at the BEP.

The CFD analysis confirmed the flow patterns and efficiency trends that were observed the pilot scale turbine test facility. The results demonstrate that the flow patterns at the leading and trailing edges and within the runner for the actual BEP gate position result in a higher turbine efficiency than for the "theoretical" BEP gate position. The higher residual swirl at the actual BEP gate position does not appear to be a major contributor to turbine power losses, probably because losses in the draft tube are small and some swirl helps the flow from separating in the expanding draft tube.

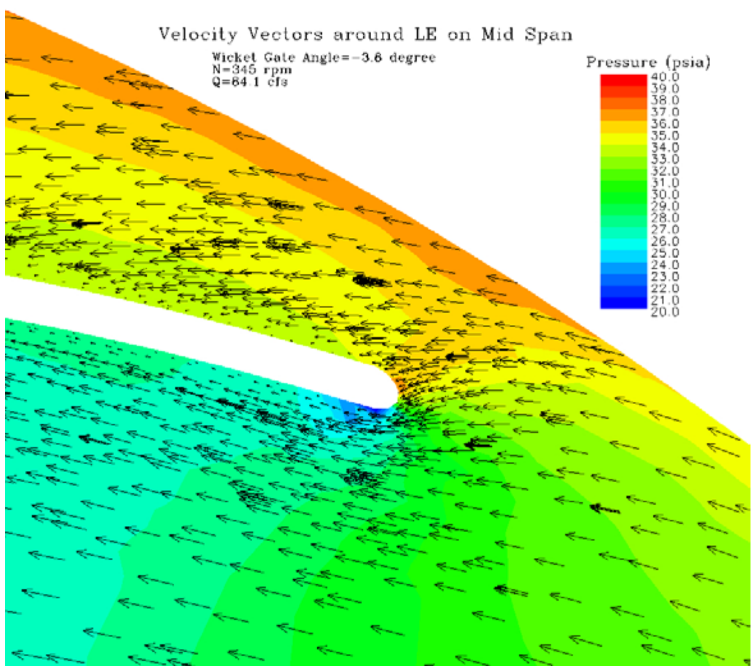
7.3.2 Turbine Performance at Off-BEP Conditions

Three off-BEP conditions were simulated with CFD for comparison to the fish survival test results. The simulations were completed with the lower head and a runner speed of 240 rpm at three wicket gate positions (26°, 18.2°, and 16°) to cover the full range of conditions tested with fish. Turbine performance parameters under these conditions are summarized in Table 7-3. The main objective for this off-BEP analysis was to evaluate differences in flow characteristics that the fish were exposed to at the different gate positions.

As shown in Table 7-3, CFD results for the actual BEP gate position of 18.2° (Case No. 4) had higher turbine efficiency (84.2%) than the other two cases with the wicket gates at the 26° gate setting (82.3% for Case No. 3) and at the 16° gate position (83.4% for Case No. 5). These results confirm the ability of CFD to simulate the entire turbine and to predict efficiency trends and the operating condition for best efficiency.

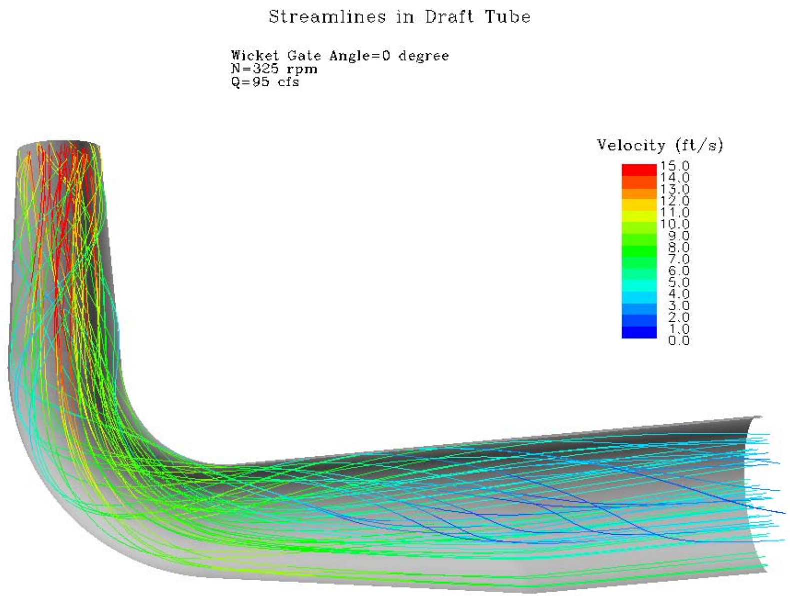


(a)

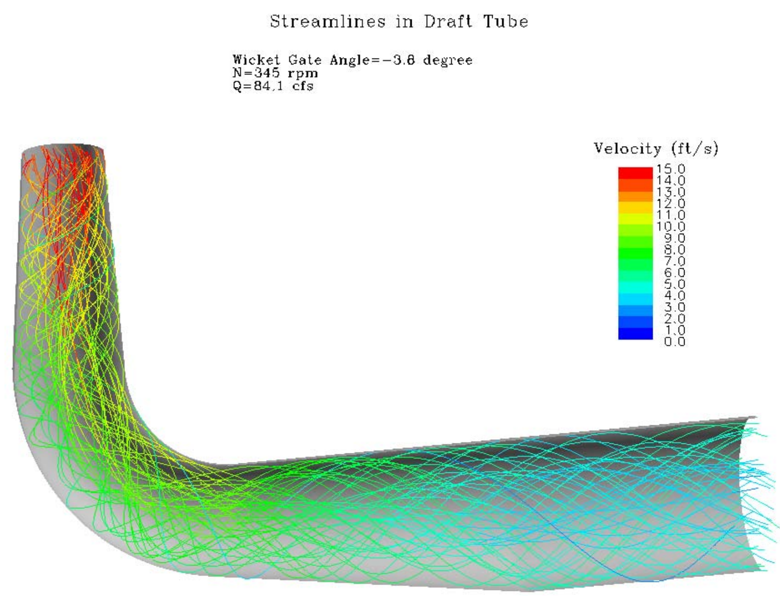


(b)

FIGURE 7-3 RELATIVE VELOCITY CONTOURS AND VECTORS ON MID-SPAN (CASE NO. 2, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)



(a) 22° Wicket Gate Angle from Full Closed



(b) 18.2° Wicket Gate Angle from Full Closed

FIGURE 7-4 STREAMLINES IN DRAFT TUBE (CASE NOS. 1 AND 2)

TABLE 7-3
COMPARISON OF LOW HEAD CFD RESULTS TO
PILOT SCALE TURBINE MEASUREMENTS

	Case No. 3		Case No. 4		Case No. 5	
	CFD*	Measured**	CFD*	Measured**	CFD*	Measured**
Wicket Gate Setting (^{o} from fully closed)	26	26	18.2	18.2	16	16
Speed, n (rpm)	240	240	240	240	240	240
Flow, Q (cfs)	76.9	77.6	60.7	60.8	54.7	53.9
Runner Torque, T (N-m)	8696		7184		6440	
Power, P (hp)	293	296	242	236	217	197
Turbine Head, H (ft)	40.9	40.3	41.8	40.3	42.0	38.5
Runner Head, Hr (ft)	39.1		40.8		40.9	
Actual Head, Ha (ft)	33.6		35.2		35.0	
Turbine Efficiency, η (%)	82.3	83.4	84.2	84.1	83.4	83.6
Runner Efficiency, η_r (%)	86.0		86.4		85.6	
Loss at Scroll, ΔHs (ft)	0.65		0.68		0.74	
Loss at Draft Tube, ΔHd (ft)	1.13		0.39		0.34	
Average Velocity Angle at Down Turn Entrance, β (^{o})	63.3		71.4		73.7	

* CFD input parameters identified above double line.

** Actual BEP from pilot scale turbine preliminary engineering test in June 2002 (Table G-6). Turbine efficiency has not been adjusted for runner bottom seal leakage and other mechanical losses.

A plot of pressures along the pressure and suction sides of the blades at the 40 ft head/240 rpm and the BEP gate position is shown on Figure 7-5. Similar plots for other gate positions are provided in Appendix P. A summary discussion on the effects of differences in these pressure distributions in the runner at the various wicket gate positions are presented in Section 7.4.

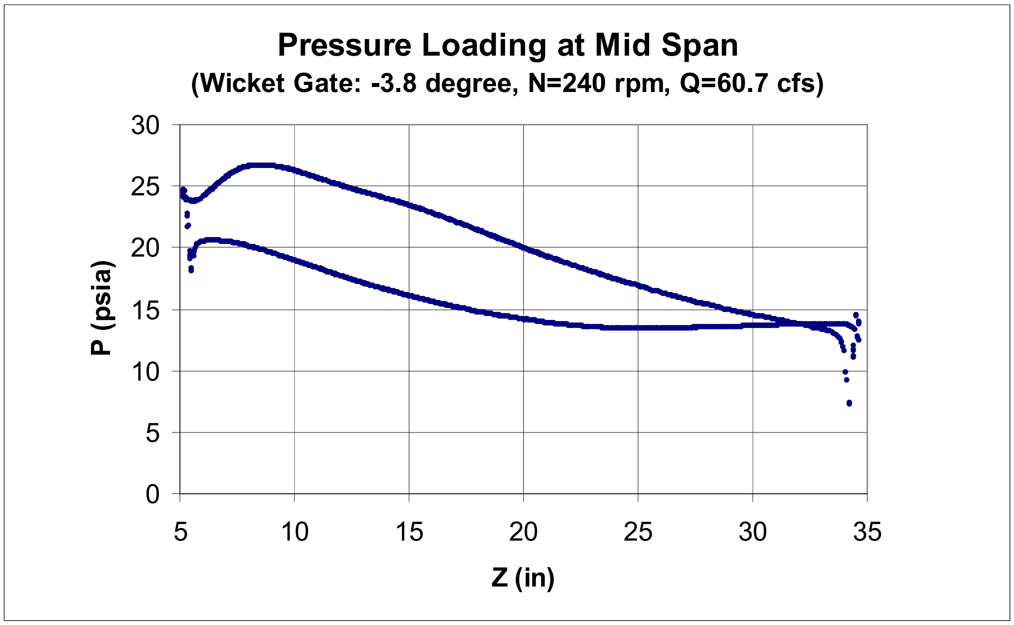


FIGURE 7-5 PRESSURE LOADING AT MID SPAN (CASE NO. 4, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)

7.3.3 Potential Turbine Improvements

The CFD analysis predicted that flow patterns and pressures at the leading/trailing edges of the blades and within the runner are more favorable at the actual BEP wicket gate position and runner rpm than at the "theoretical" BEP gate position (determined from the original CFD design). The results show that there is a pressure reversal on the runner blade trailing edges and this would decrease the overall turbine efficiency. The turbine blade shaping could be refined to eliminate the pressure reversal problem and reduce the residual swirl leaving the runner, and these changes in blade shape would increase the turbine efficiency.

Other areas for potential improvement in the turbine design would be to minimize the length of the downturn, increase the thickness of the blade leading edge, and increase the power density, i.e., power output per turbine size. Reducing the downturn at the runner inlet would decrease the overall diameter of the scroll case. Thicker leading edges on the runner blades could improve fish survival. Increasing the height of the radial space at the runner inlet (i.e., the wicket gate height) would increase the flow and the power density, but would require additional and shorter wicket gates. These refinements would decrease the size of the turbine for a given power output, or increase the power output for a given size. Changes in runner geometry to accommodate these changes would be determined using CFD.

7.4 Factors Related to Fish Survival

7.4.1 Biological Design Criteria

The CFD computed flow field characteristics were compared to available fish survival criteria and to actual fish survival in the pilot scale test facility. Results summarized in this section define flow parameters in the runner related to fish survival for comparison to critical values defined by other investigators' experiments and used as biological criteria for safe fish passage through turbines. The flow parameters that have discrete values that can be used to evaluate fish survival are: minimum pressures, pressure change rates, and flow shear stress (strain rate).

7.4.2 Minimum Pressures

The CFD analysis (see Figures 7-2 and 7-5) indicates that the minimum local absolute pressure in the runner is about 10 psia (the minimum pressure that was selected for the original design of the turbine) for all of the wicket gate positions evaluated and the high and low turbine head/rpm conditions (see Appendix P). These figures show that the lowest pressure zones are located near the trailing blade edge. Local pressures less than 10 psia only occur in limited spots at the trailing edge. These lower pressure spots are still consistent with the published minimum value for safe fish passage (Abernethy et al. 2002) of 0.5 atm or 7.4 psia, even for the off-design conditions.

7.4.3 Pressure Change Rate

For steady flow, the local pressure change with time ($\Delta p/\Delta t$) can be calculated based on the product of the local spatial pressure gradient ($\Delta p/\Delta s$) and the local velocity ($\Delta s/\Delta t$). The pressure change rate is a measurement of the change of pressure experienced by a fish moving along a streamline. Tests results (Abernethy et al. 2002) indicted that fish survived a pressure reduction of 3.5 atm over 0.1 second, or slightly greater than 500 psi/sec.

Pressure change rates determined with the CFD simulations were plotted as three-dimensional volumes ("clouds") within which the pressure rate of change is more than 500 psi/sec. Because positive pressure changes are known not to harm fish, the emphasis for evaluating the CFD results has been placed on negative pressure rate changes.

The pressure change rate clouds are shown on Figures 7-6 and 7-7 for Case Nos. 2 and 4, respectively. Additional similar figures for the other cases are presented in Appendix P. In these plots, the volumes where the pressure change rate exceeds -500 psi/sec (i.e., have greater negative values) are shown in red. All of these figures show that high negative pressure change rates occur mainly near the leading edge, with smaller volumes near the trailing edge. The high head/rpm condition (Case No. 2) has larger volumes where the negative pressure change rate exceeds -500 psi/second than low head/rpm case (Case No. 4).

The pressure change volumes shown on Figures 7-6 and 7-7 are relatively small compared to the flow volume, and a fish would pass through these volumes so quickly that no physical response may be possible. For example, using pilot scale dimensions, the volume may have a maximum length of 0.5 ft and the local velocity is about 40 ft/sec. Therefore, fish may pass through the volume in 0.0125 seconds (0.04 seconds in the full scale turbine).

As shown on figures in Appendix P, the volumes of pressure change rate exceeding -500 psi/sec are similar for the BEP wicket gate position (Cases Nos. 1 and 2) and the off-BEP conditions (Case Nos. 3, 4, and 5). These similar pressure change rates may partially explain why there was not a significant change in fish mortality over the turbine operating range tested.

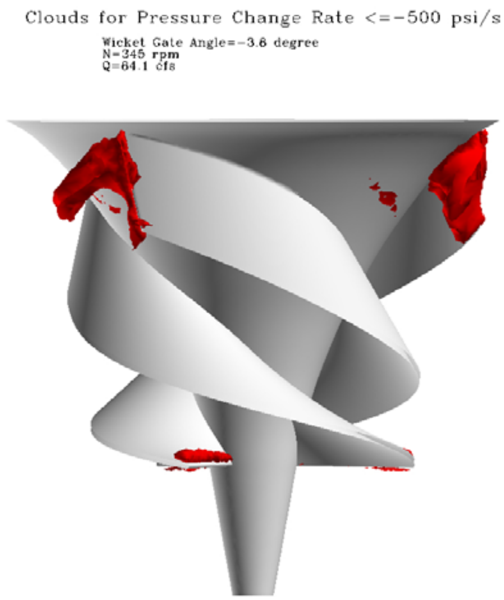


FIGURE 7-6 CLOUDS FOR NEGATIVE PRESSURE CHANGE RATE EXCEEDING -500 PSI/SEC (CASE NO. 2, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)

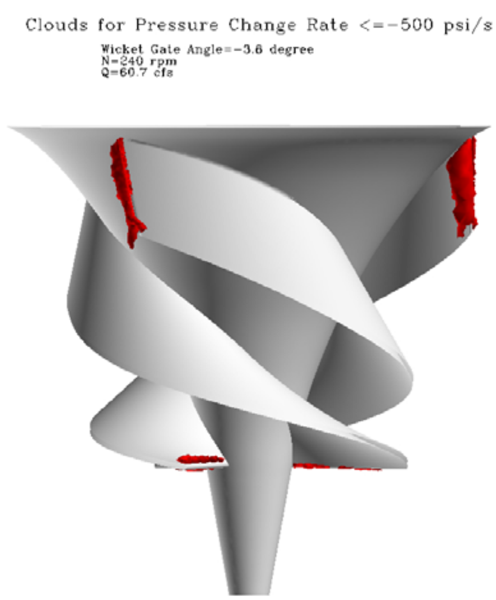


FIGURE 7-7 CLOUDS FOR NEGATIVE PRESSURE CHANGE RATE EXCEEDING -500 PSI/SEC (CASE NO. 4, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)

7.4.4 Maximum Strain Rate

When fish are subjected to velocities that vary over relatively short distances, they experience different forces on different parts of their body, which may result in injury. Experiments (Nietzel et al. 2000) concluded that "juvenile salmonids and American shad should survive shear environments where strain rates do not exceed 500 cm/sec/cm" (500/sec). Therefore, the results of the CFD simulations have been presented as volumes ("clouds") in which the strain rate is 500/sec or larger.

Figure 7-8 shows the strain rate on the central plane of the scroll case in the radial space (wicket gates) for Case No. 2. Areas where the shear rate exceeds 500/sec are limited and located very close to the leading edge of the wicket gates.

The volumes and areas where the strain rate exceeds 500/sec in the runner for the different wicket gate operating conditions simulated are shown as red clouds and strain rate contours on the mid-span surfaces on figures in Appendix P. Figures 7-9 and 7-10 in this section for Cases No. 2 and 4, respectively, show that the high strain rate volumes are relatively small and limited to spots near the leading edges, the trailing edges and the blade surfaces. There are no areas of excessive strain rate within the main flow of the turbine. Therefore, the small volumes of strain rates at the runner surfaces that are over 500/sec should not cause significant fish injury.

The volume of strain rates over 500/sec is reasonably constant at the BEP and the off-BEP operation at given head/rpm conditions (see Appendix P). These essentially constant strain rates at the different gate positions may explain why fish injury/survival in the pilot scale turbine tests was similar for the different gate positions. The volume of strain rates over 500/sec was only slightly larger at the higher head scenarios compared to the lower head conditions (i.e., Case Nos. 1 and 2 versus Case Nos. 3, 4 and 5).

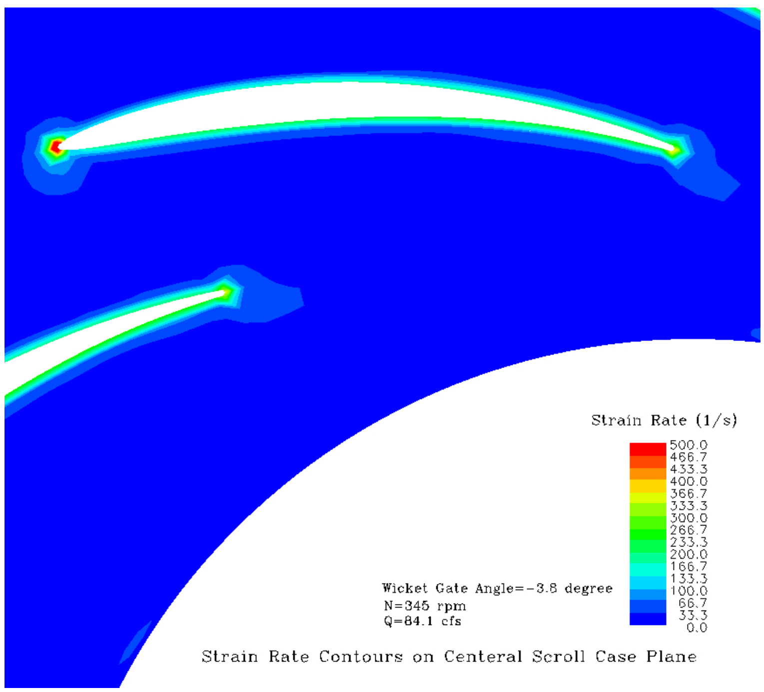
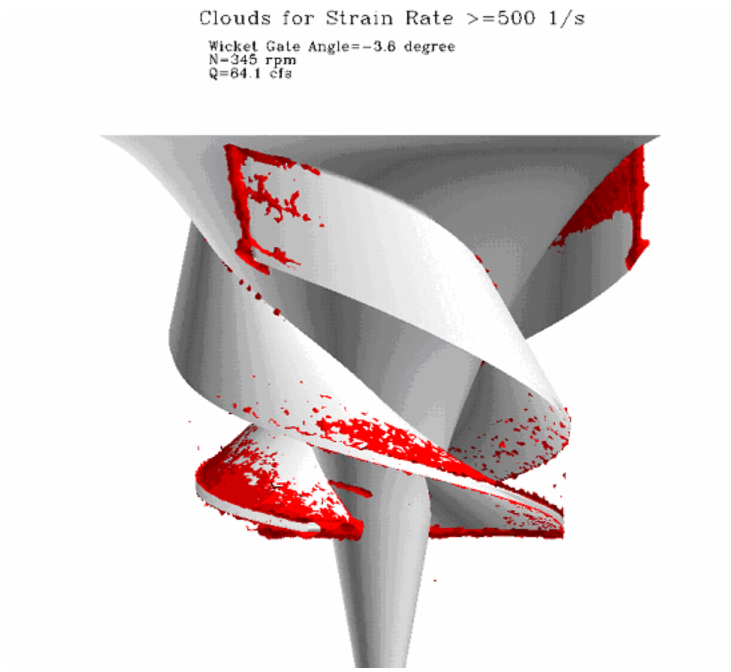
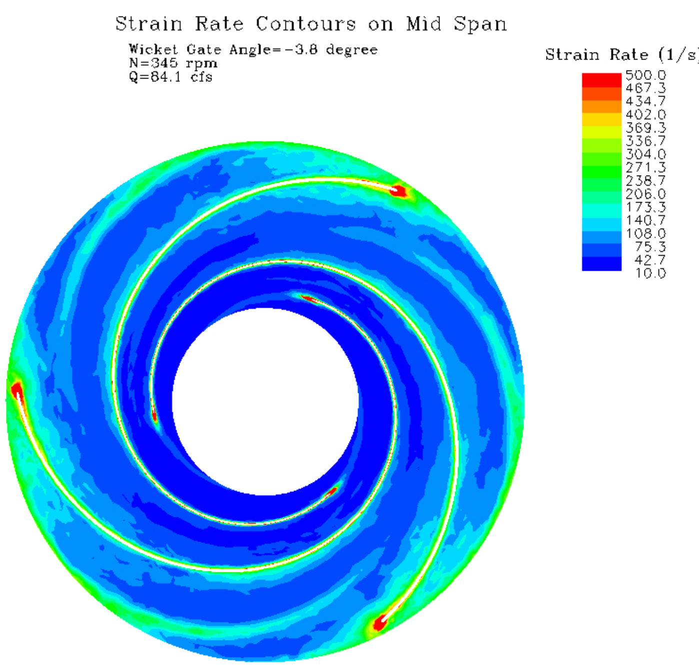


FIGURE 7-8 STRAIN RATE CONTOURS ON CENTRAL SCROLL CASE PLANE, 18.2° WICKET GATE ANGLE FROM FULL CLOSED

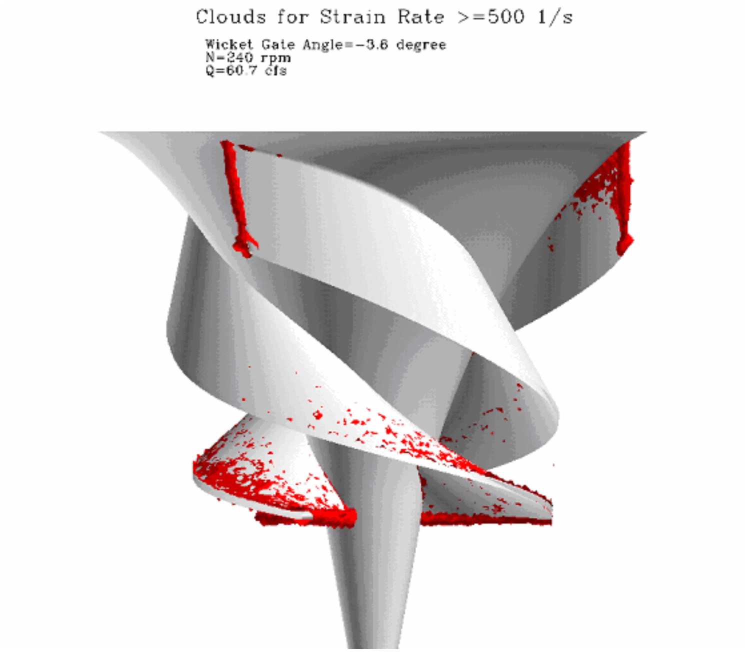


(a)

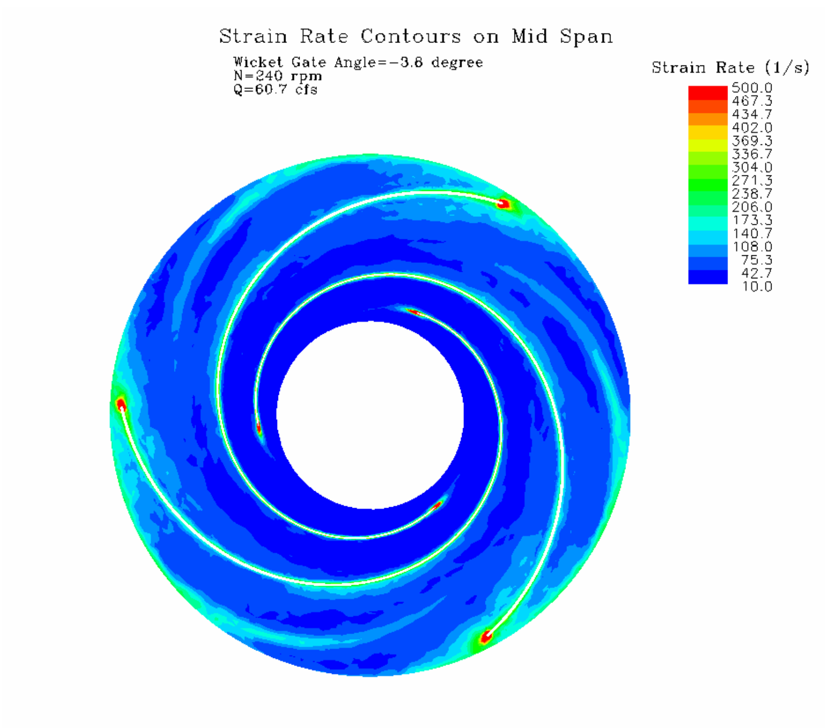


(b)

FIGURE 7-9 STRAIN RATES IN TURBINE RUNNER (CASE NO. 2, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)



(a)



(b)

FIGURE 7-10 STRAIN RATES IN TURBINE RUNNER (CASE NO. 4, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)

8.0 CONCLUSIONS

8.1 Turbine Performance

Engineering tests on the 1 to 3.25 reduced scale Alden/Concepts NREC turbine have documented the performance characteristics of the new turbine design. Conclusions relative to performance of the Alden/Concepts NREC turbine are:

- The predicted full sized turbine hill chart indicates that the maximum turbine efficiency will be about 90.5% (see Figure 4-35). This includes the normal step-up in efficiency from pilot scale to full sized turbine (scale effects) and a correction for the measured excess leakage (3% of turbine flow) in the pilot scale turbine due to a worn bottom seal.

- Tests with and without wicket gates did not result in any practical changes in turbine efficiency. Similarly, no changes in efficiency resulted from changing the pressure under the head cover, indicating the bearing losses were not sensitive to downthrust. Also, the efficiency was not effected by changes to the oil hose connected to the dynamometer or the cooling oil temperature.

- A thorough uncertainty analysis indicated that the uncertainty of the efficiency measurements was about 0.5% at the 95% confidence interval.

- The measured velocity distribution (axial and tangential) at the exit of the draft tube and the CFD results showed considerable swirl in the flow leaving the runner at the BEP, indicating that the turbine efficiency may be improved by reshaping the blades.

- CFD analysis showed that the best predicted turbine efficiency was at the gate angle and runner rpm actually measured for the BEP.

- Final CFD analysis also showed that a pressure reversal from the high to low pressure side occurred over a small section of the trailing blade length. This further indicates that improvements to the turbine efficiency may be realized by some reshaping of the blades.

- The turbine unit power (p_{11}) is lower than for typical units at the design head due to the flow restriction resulting from the selected wicket gate height relative to the turbine diameter. A greater power density may be achieved by increasing the height of the radial space (wicket gates) and redesigning the turbine blades accordingly.

Comparison of the CFD predictions to the biological design criteria indicates that:

- Minimum local pressures in the runner over the range of wicket gate positions analyzed (16°-26° from full closed) were consistent with the design value (about 10 psia). Some spots of lower pressures were consistent with the minimum recommended value of 0.5 atmospheres (7.4 psia) (Abernethy 2002).

- Areas of high negative pressure change rates exceeding -500 psi/sec occurred near the leading edge of the runner blades with smaller areas near the blade trailing edges at all wicket gate positions analyzed (16°-26°) and tested with fish. Areas exceeding -500 psi/sec were larger at the high head (80 ft) than the lower head (40 ft). Studies indicated fish survived pressure change rates of 500 psi/sec (Abernethy 2002).

- High strain rate areas (strain rates greater than 500/sec) were predicted to be relatively small and were limited to spots near the leading and trailing edges and the blade surfaces at all wicket gate positions analyzed and tested with fish (16°-26°). The 2002 Abernethy studies found that salmon and American shad survived strain rates less than 500/sec (Nietzel 2002).

8.2 Fish Survival

The biological evaluation of the pilot-scale turbine produced a comprehensive data set of direct turbine passage survival and injury rates for a wide range of fish species and operating conditions. Over 40,000 fish of six species (two anadromous, one catadromous, and three freshwater species) were released and recovered during the two years of testing. The evaluation of passage survival rates with and without wicket gates and for two head conditions using the same turbine is unprecedented. Large sample sizes, extensive replication, and high levels of consistency in testing and data collection methods resulted in very precise estimates of turbine passage survival (95% confidence limits were typically ±2% or less). Consequently, analyses of the effects of biological and operational factors on survival rates for fish passed through the new turbine were very robust. The primary conclusions supported by these analyses include the following:

- Preliminary tests verified the acceptability of the test methods and procedures selected for the estimation and evaluation of turbine survival rates. Control survival during these tests was 100% (for fish recovered during the test of their release), indicating that handling and holding procedures were successful in minimizing fish injury and stress.

- Results of Test Series 1 demonstrated that treatment fish release depth within the test loop pipe did not affect rainbow trout survival rates.

- With the exception of American eel and within the size ranges tested, survival rates were strongly dependent on fish length. The results from tests with rainbow trout and smallmouth bass demonstrated that smaller size groups had significantly higher survival rates than did larger size groups, depending on the head and rpm condition evaluated. Additionally, when survival estimates of all species tested at the same operating conditions were combined, there was a strong correlation between passage survival and fish length.

- American eel immediate survival was 100% and total survival exceeded 98% for both size groups evaluated, indicating size did not affect mortality rates of this species within the size range tested.

- Significantly higher survival rates for white sturgeon and American eel compared to the other species that were tested demonstrate that species may be an important factor affecting passage survival rates, depending on species-specific physical characteristics and behaviors. Eel and sturgeon are morphologically and physically very different than the other species that were evaluated (i.e., bony fishes with more typical body shapes and physical features).

- The percent of treatment fish recovered live that were classified as uninjured was high (about 95% or greater) for all species and turbine conditions evaluated.

- The most prevalent injury observed among immediate treatment mortalities and live recoveries was bruising, which typically occurred between the gill arch and the posterior margin of the dorsal fin. The relatively high rates of bruising, combined with the relatively minor occurrence of lacerations and severed bodies, suggest that the primary mechanism of immediate fish mortality was physical strikes with the leading edge of the runner blades. Other injury mechanisms (shear, pressure, gaps) are believed to be minor.

- The percent of fish classified as descaled was low for treatment fish recovered live (less than 2% in Test Series 1 and less than 4% in Test Series 2/3). The percent of live control fish that were classified as descaled was between 0.1 and 2.8%, indicating that some of the treatment fish descaling was due to handling associated with marking, testing, and injury evaluations.

- Because the fish lengths tested were considered to represent the same fish length in the field (i.e., fish length was not scaled, with the exception of the smallest size group of rainbow trout evaluated with wicket gates), and since the test heads and therefore flow velocities and blade tip speeds are the same as in the field, the survival rates estimated for the pilot-scale runner are considered to be lower than those that will occur with a full scale turbine, mainly due to the higher rotational speeds and closer spacing of the blade leading edges in the pilot-scale turbine.

- Predictions of blade strike and subsequent survival suggest that passage survival rates experienced with a full-scale turbine would include the following:

	Predicted Passage Survival for a Full-Scale Alden/Concepts NREC Turbine	
Fish Length	40 ft Head	80 ft Head
100 mm (4 inches)	98.2	97.3
150 mm (6 inches)	97.3	95.9
200 mm (8 inches)	96.4	94.5

Note: Based on the test data, survival rates of sturgeon species and American eel likely would be greater than those presented above.

9.0 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

The pilot scale testing of the Alden/Concepts NREC turbine identified improvements in the runner design that would improve fish passage. These improvements and studies would include:

- A thicker and more streamlined leading edge at the runner inlet could improve survival of fish struck by the blades. Biological testing of the modified leading edge would be conducted in a linear flume, similar to the Turnpenny et al. studies (2000), or on the pilot scale runner in the turbine test loop.

- Reshaping of the runner blades could remove areas of pressure reversal and reduce residual swirl. The existing CFD model would be used to analyze changes in the blade shape.

- The power density on the runner could be increased (i.e., increase the wicket gate height) to raise the turbine efficiency. CFD analysis would be used to investigate changes to the blade geometry and check hydraulic characteristics relative to the biological criteria.

- Reducing the length of the wicket gates (i.e., increase the number of gates) would reduce the size of the scroll case. Changes in the gate design would depend on the possible increases in gate height. Wicket gate changes would also be analyzed using the CFD model.

- Decreasing the radial length of the downturn at the runner inlet would also reduce the size of the scroll case. CFD analysis would be used to investigate the effects of changes in the downturn geometry on turbine performance and fish survival relative to the biological criteria.

- The lower seal and the turbine bearing could be redesigned to minimize leakage between the rotating shroud and the turbine housing. Roller bearings or bushings could be incorporated around the lower shroud to minimize runout.

- A hydraulic model study could be conducted in a turbine test stand to expand the Hill chart developed from the pilot scale test data. The model study would determine changes in performance characteristics related to geometry changes resulting from the studies described above.

- Biological and engineering tests could be conducted with any changes in the runner design that are identified with computer modeling.

Full scale testing of the Alden/Concepts NREC turbine would be necessary to document fish passage through the new design, including any improvements to the runner. Full scale testing should be conducted with a 10-12 ft diameter runner at a site with 60-80 ft of head and 750-1,000 cfs. Prototype testing would include biological testing to confirm predicted fish survival and hydraulic testing to verify performance characteristics.

APPENDIX A

TEST LOOP FLOW METER CALIBRATION

APPENDIX A
TEST LOOP FLOW METER CALIBRATION

INTRODUCTION

To provide an accurate measurement of flow through the turbine, the test loop Venturi meter was calibrated in Alden's main gravimetric facility where primary flow measurement is traceable to NIST standards. The certified flow measurement uncertainty of this facility is better than 0.25% at the 95% confidence level. Since the amount of residual swirl from the test loop pump was not known at the time of the meter calibration, and since such swirl or velocity asymmetry may affect the flow meter performance, the flow meter calibration was performed using two different upstream piping arrangements. One upstream pipe configuration was a straight line, shown on Figure A-1, yielding minimal swirl and velocity asymmetry. The other configuration had a tee and a short radius bend, shown on Figure A-2, followed by 36 ft (12 diameters) of straight pipe to generate swirl in the pipe approaching the flow meter. Both upstream pipe configurations included the test loop pipe section located immediately upstream of the meter, which had ports for a velocity probe. Velocity measurements upstream from the meter were obtained for both calibration piping configurations.

VELOCITY MEASUREMENTS

In conjunction with the flow meter calibration with both piping configurations, velocity measurements were made along three of the four available traverses about 13 ft (4.3 pipe diameters) upstream from the meter entrance. These velocity measurements were later repeated when the turbine test facility was operational to select which of the flow meter calibrations, with or without swirl, would be most similar to conditions in the turbine test loop. During calibration, the measurements in the fourth traverse could not be obtained because the port was inaccessible in the calibration test loop.

The velocity measurements were obtained using Alden's United Sensors 5-hole probe, serial number C-3159. The probe calibration curve is provided in Appendix B. Alden's Calibration Department differential pressure (DP) cells were used for measuring the differential pressure between the probe ports. The DP cell calibrations are provided in Appendix C.

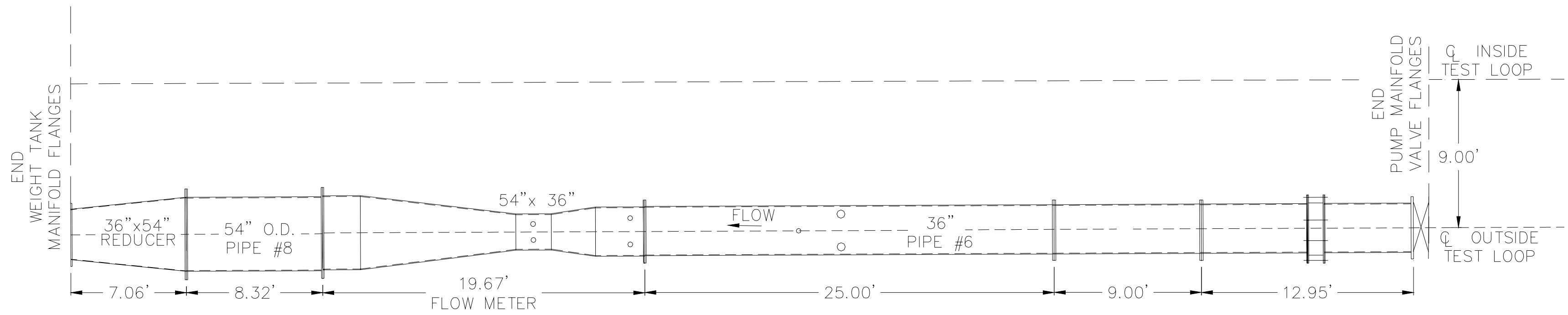


FIGURE A-1 TEST CONFIGURATION 1 (NO SWIRL) - TEST LOOP FLOW METER CALIBRATION

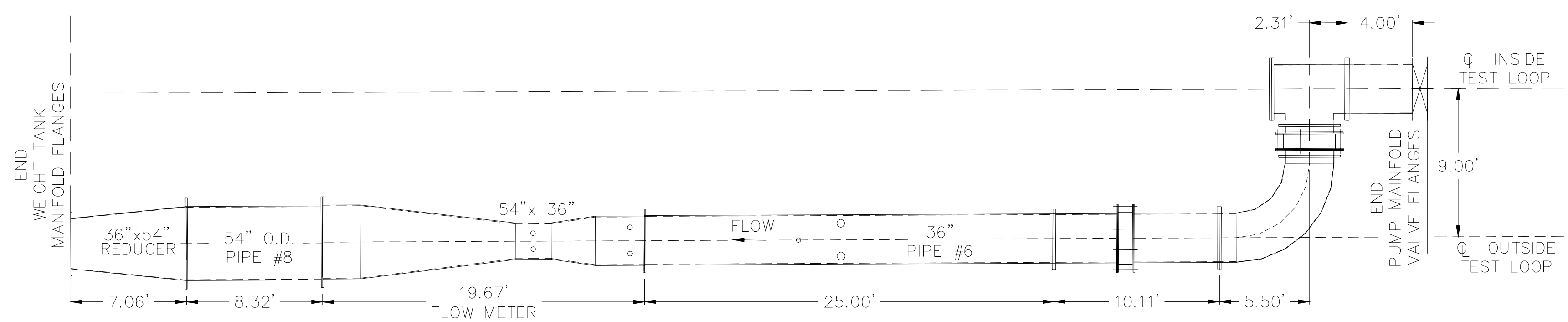


FIGURE A-2 TEST CONFIGURATION 2 (SWIRL) - TEST LOP FLOW METER CALIBRATION

APPROACH VELOCITY DISTRIBUTION WITH STRAIGHT PIPE CONFIGURATION

Measurements in the three velocity ports upstream of the flow meter with the calibration piping in a straight configuration are presented in Table A-1. The data are plotted on Figure A-3, with Port 3R being repeat measurements of Port 3. The non-dimensional velocity (v/Vc) is defined as the measured velocity (v) divided by the average of the velocity measurements (Vc). The non-dimensional radius (r/R) is defined as the radial distance (r) from the wall to the velocity measurement location divided by the pipe radius (R).

TABLE A-1
VELOCITY MEASUREMENTS FOR STRAIGHT PIPE CONFIGURATION CALIBRATION

Non-Dimensional Radius	Non-Dimensional Velocity, v/Vc				
r/R	Port 2	Port 3	Port 3R	Radial Average Velocity	Theoretical Velocity
0.04	0.75	0.73	0.72	0.73	0.83
0.17	0.97	0.94	0.93	0.95	0.96
0.29	1.08	1.02	1.01	1.04	1.02
0.44	1.14	1.05	1.08	1.09	1.06
0.71	1.21	1.16	1.19	1.19	1.12
1.00	1.31	1.27	1.25	1.28	1.16

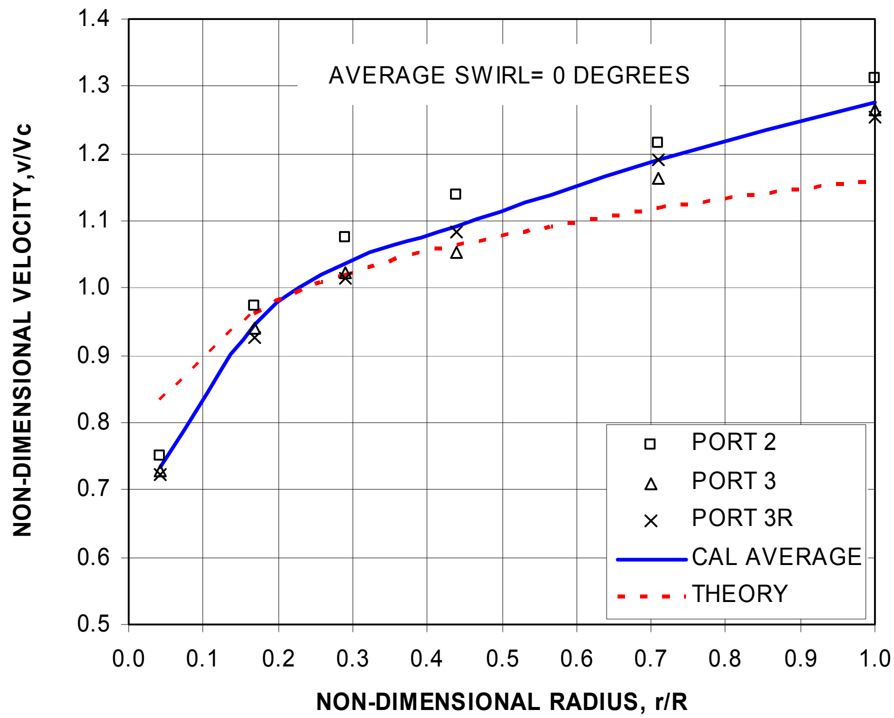


FIGURE A-3 FLOW METER CALIBRATION VELOCITY TRAVERSE
STRAIGHT PIPE, 42 CFS

A review of the data indicated that there was a discrepancy with the Port 1 data set. Due to time constraints, velocities at this port could not be re-measured. Based on the repeatability of the Port 3 data and its consistency with Port 2 data, Alden engineers concluded that there was a problem with the Port 1 data, probably due to air trapped in the probe pressure lines, and the Port 1 data were not included in the analysis.

The dotted line in Figure A-3 represents the theoretical distribution profile if the flow were fully developed. The theoretical distribution profile is based on the 1/x power equation:

$$V_r = \left(\frac{v_{CL}}{r}\right)^{1/k} \tag{A-1}$$

where:

V_r = the velocity at radius r,
v_{CL} = the centerline velocity,
r = the radial distance from the wall, and
k = a coefficient based on Reynolds Number, Re.

The pipe Reynolds Number (Re) during the traverse measurements was about 2.5×10^6. For this value of Re, k is approximately 9.5. Higher values of k, which would exist with higher pipe velocities and Re values, would result in a flatter profile. Based on this Re, the theoretical profile was calculated as shown by the dotted line in Figure A-3. The theoretical velocity profile indicates that the actual flow profile (shown by the solid line) with the straight pipe was not fully developed, since actual velocities decrease quicker towards the wall. A likely cause for this difference was the upstream flow straightener in the calibration test loop, which did not provide enough flow near the pipe wall.

To obtain the angle of any tangential velocity components, the probe was manually aligned to the flow by equalizing pressures on the two side ports. The probe angle with respect to the pipe was then measured externally using a taut line and protractor. The entire angle data set was corrected by 1.3 degrees, which was the average measured angle of the approach flow at the centerline of the pipe (where there should not be any flow angle). Corrected, the average approach flow angle was zero degrees, indicating that the approach flow had negligible swirl. Similarly, no radial velocity components of interest were measured.

APPROACH VELOCITY DISTRIBUTION TEE PIPING CONFIGURATION

Similar velocity measurements were conducted with a pipe Tee, which was installed just after the calibration test loop main header manifold, followed by a short radius bend to introduce swirl in the flow approaching the Venturi meter. These measurements were necessary to determine the effects of swirl on the flow meter discharge coefficient. The velocity data with swirl are presented in Table A-2 with the velocity traverse distribution shown on Figure A-4 for this configuration. The average (tangential) swirl angle in the approach flow was about 3.7 degrees. The swirl forced more flow towards the pipe wall as shown in the velocity data at about r/R = 0.3. Therefore, the measured velocities (shown by the solid line) are closer to the theoretical predicted values (shown by the dashed line). Measured pitch angles (radial) were negligible, with the average being less than 0.5 degrees.

TABLE A-2

VELOCITY MEASUREMENTS FOR TEE PIPING CONFIGURATION CALIBRATION

Non-Dimensional Radius	Non-Dimensional Velocity, v/Vc				
r/R	Port 1	Port 2	Port 3	Radial Average Velocity	Theoretical Velocity
0.04	0.83	0.76	0.79	0.79	0.85
0.17	1.00	1.01	0.93	0.98	0.98
0.29	1.10	1.04	1.07	1.07	1.04
0.44	1.10	1.07	1.05	1.07	1.08
0.71	1.07	1.10	1.07	1.08	1.14
1.00	1.13	1.11	1.11	1.12	1.18

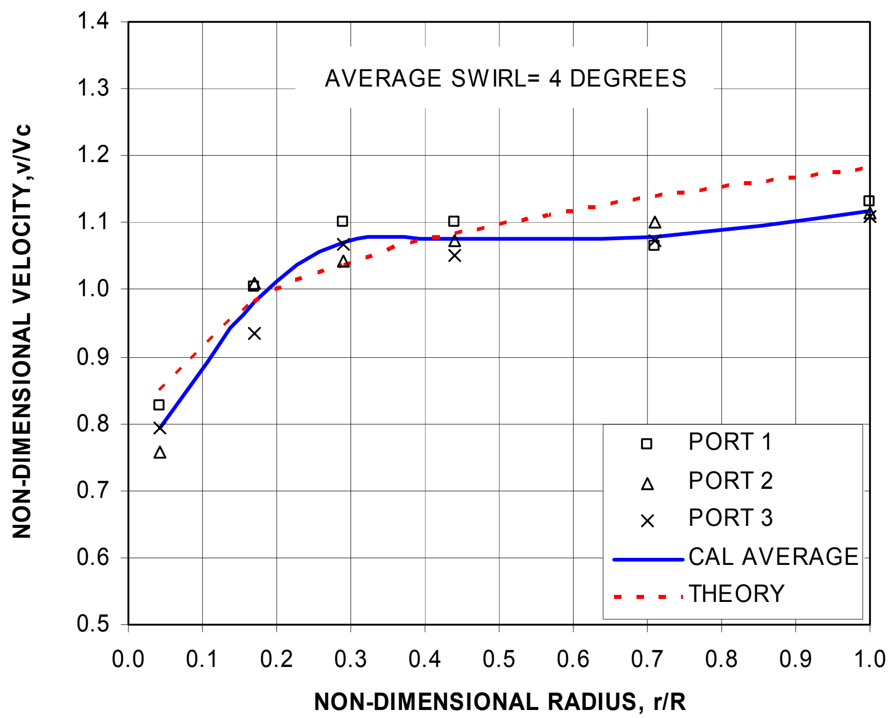


FIGURE A-4 FLOW METER CALIBRATION VELOCITY TRAVERSE TEE CONFIGURATION, 42 CFS

METER COEFFICIENTS

The flow meter calibration data for both straight pipe and Tee configurations are provided in Attachment 1. Figure A-5 shows the discharge coefficient versus Re for both upstream pipe configurations. Although there is a consistent shift in the coefficients with the straight pipe versus the upstream Tee, the overall change is within 0.2%.

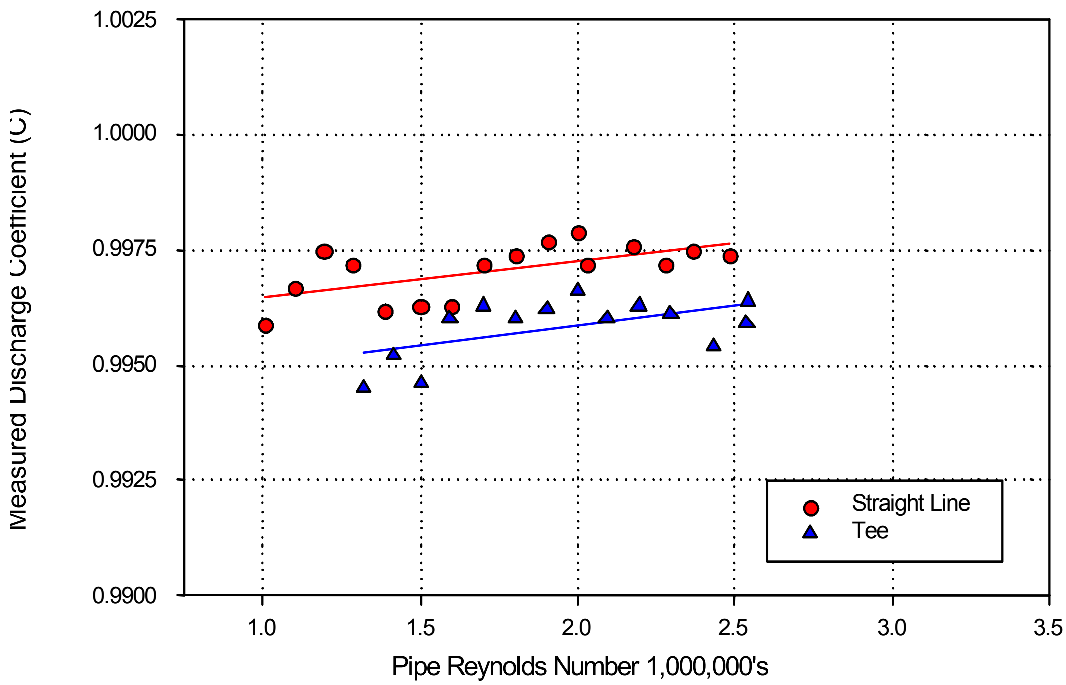


FIGURE A-5 36 INCH VENTURI METER MEASURED DISCHARGE COEFFICIENT (C_D)

The flow meter was calibrated in the main loop of Alden's Building #1 flow calibration facility, which is driven by two 300 HP pumps producing a maximum flow of about 42 cfs at about 100°F. This flow and temperature produced a maximum pipe Re of about 2.5 x 10^6. The maximum flow in the turbine test loop with the 2,000 HP pump was expected to be about 90 cfs at a water temperature of 60°F, producing a pipe Reynolds number (Re) of about 3.3 x 10^6. Since the meter would be used in the test loop at Reynolds numbers above those achieved in the calibration loop, the calibration data had to be extrapolated to the test loop operating Re. This extrapolation was done in accordance with ASME PTC 19.5, Draft VII -May 2000, Section 5.4.

For an ASME nozzle, the curve of meter coefficient versus throat Reynolds number (Re_d) is well understood and has the equation

$$C = C_o - 0.185/Re_d^{1/5}[1-361{,}239/Re_d]^{4/5} \qquad \text{A-2}$$

ASME PTC 19.5 requires that each measured coefficient value (C) be used to calculate C_o , and that the average value of C_o be used in the equation

$$C = \text{ave } C_o - 0.185/Re_d^{1/5}[1-361{,}239/Re_d]^{4/5} \qquad \text{A-3}$$

to generate a meter coefficient (C) versus throat Reynolds number curve over the range of meter use. The resulting curves of C from the two calibration piping configurations are shown on Figures A-6 and A-7.

Turbine flow (Q) was computed using either one of the calculated calibration curves (Figure A-3), depending on the flow meter approach flow conditions in the turbine test loop, using the following equation:

$$Q = C\, F_a\, K_m\, (H)^{1/2} \qquad \text{A-4}$$

where: F_a is the average thermal expansion coefficient factor, K_m is a meter constant, and H is the pressure difference across the meter taps. As shown in Attachment 1, F_a is 1.0006 for an ambient temperature of 68° F and the meter geometry and materials. The meter constant Km is 24.9087, which is a function of the inlet pipe and throat diameters.

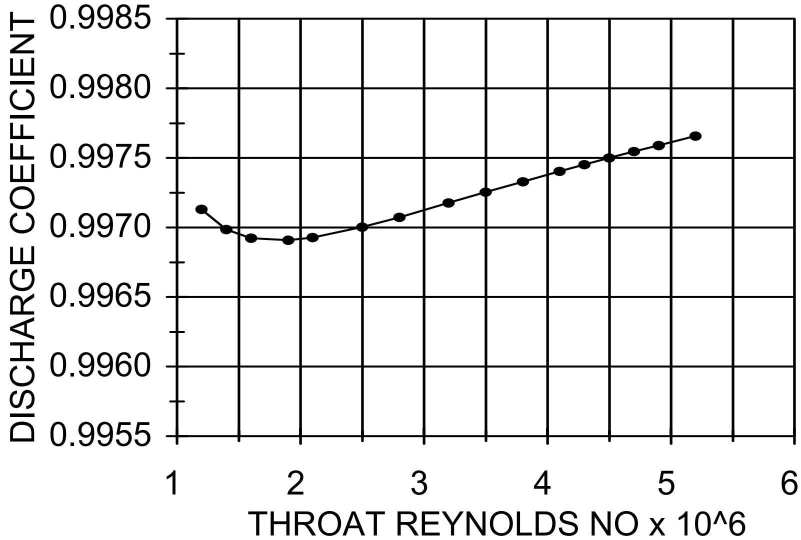


FIGURE A-6 CALCULATED FLOW METER COEFFICIENT (C_D)
UPSTREAM STRAIGHT PIPE

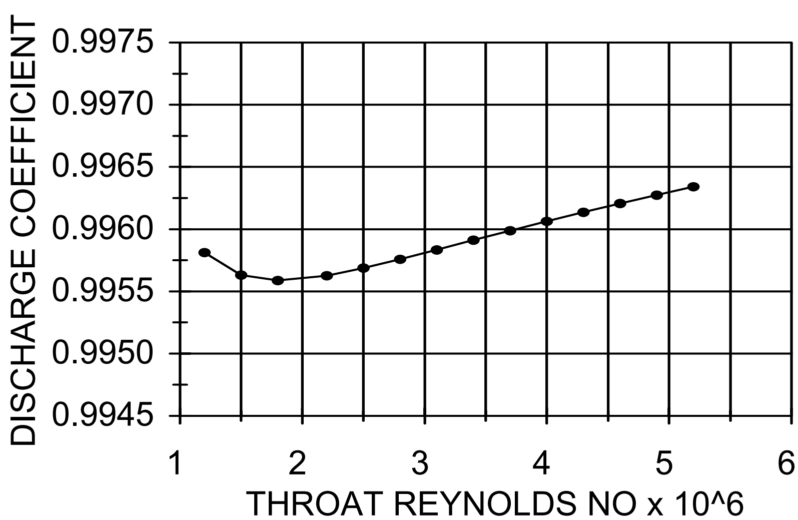


FIGURE A-7 CALCULATED FLOW METER COEFFICIENT (C_D)
UPSTREAM TEE CONFIGURATION

APPENDIX A

ATTACHMENT 1

FLOW METER CALIBRATION DATA

DOE TURBINE TEST STAND
36"X23" VENTURI

UPSTREAM ELBOWS

CALIBRATION
DATE: November 22, 2000
PIPE DIAMETER = 35.2140
THROAT DIAMETER = 22.7480

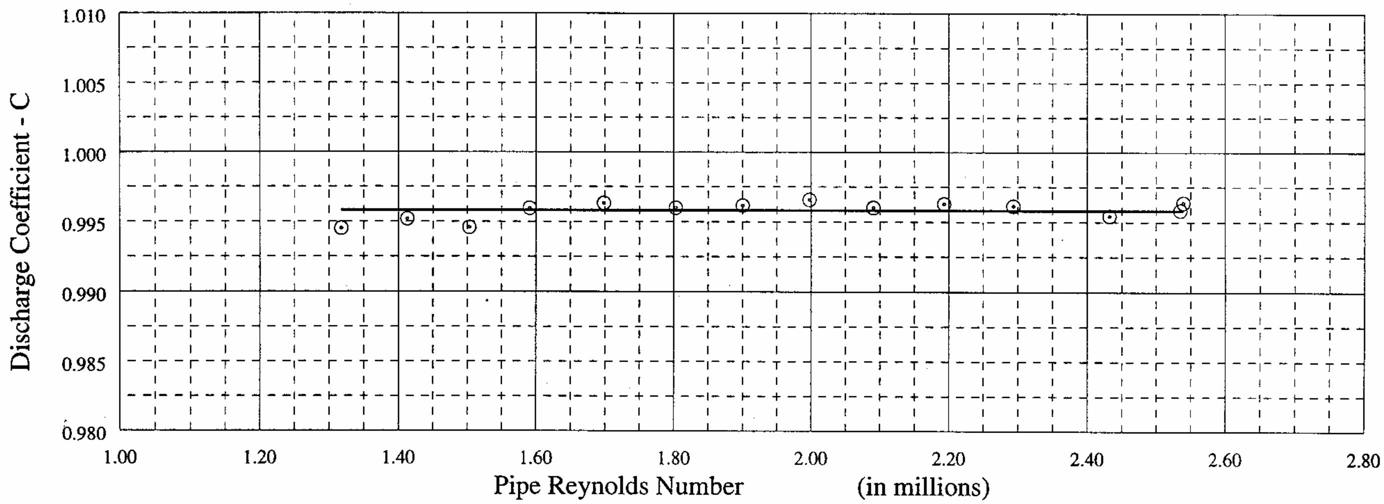
Run #	Line Temp Deg F	Air Temp Deg F	Net Weight lb.	Run Duration secs.	Output [see note]	Flow CFS	H Line FT H20	Pipe Rey. # x 10^6	Coef
1	102	62	98017	37.293	3.106~	42.46	2.927	2.5350	0.9959
2	102	62	97233	38.602	3.016~	40.69	2.691	2.4320	0.9954
3	102	62	97158	40.810	2.905~	38.46	2.400	2.2938	0.9961
4	102	62	96942	42.633	2.825~	36.73	2.189	2.1931	0.9963
5	102	62	96628	44.665	2.747~	34.95	1.983	2.0910	0.9960
6	102	62	96443	46.658	2.680~	33.39	1.808	1.9978	0.9966
7	102	62	96313	48.984	2.615~	31.76	1.637	1.9004	0.9962
8	102	62	96095	51.566	2.552~	30.10	1.471	1.8031	0.9960
9	102	62	95962	54.662	2.486~	28.36	1.305	1.6986	0.9963
10	102	62	95834	58.339	2.425~	26.54	1.143	1.5911	0.9960
11	102	62	95719	61.746	2.379~	25.04	1.021	1.5031	0.9946
12	103	62	95564	65.657	2.332~	23.51	0.899	1.4128	0.9952
13	103	62	95576	70.471	2.288~	21.91	0.782	1.3178	0.9945
14	103	62	97542	37.400	3.085~	42.14	2.880	2.5395	0.9964

~ dp transmitter volts

For Pipe Rey. #s above 1.30 x 10^6 Avg Coef = 0.9958 With Standard Deviation = 0.0006
The data reported on herein was obtained by measuring equipment the calibration of which is traceable to NIST , following the installation and test procedures referenced in this report, resulting in a flow measurement uncertainty of +/- 0.25% or less.

CALIBRATED BY: S.V.K.

CERTIFIED BY:



$$q_a = C F_a K_M \sqrt{\Delta h}$$

q_a =	Actual Flow (ft^3/sec)		
C =	Discharge Coefficient (Dimensionless)		
Δh =	Pressure Differential (Feet of Water at Run Temperature)		
K_M =	Meter Constant = $\frac{a\sqrt{2g}}{\sqrt{1 - \beta^4}}$	=	24.9087
F_a =	Average Thermal Expansion Factor	=	1.0006
a =	Throat Area (ft^2)	=	2.8224
g =	Local Acceleration of Gravity (ft/sec^2)	=	32.1625
ß =	Ratio of Throat to Pipe Diameter (Dimensionless)	=	0.6460
	Pipe Diameter (Inches)	=	35.2140
	Throat Diameter (Inches)	=	22.7480
	For Pipe Reynolds Number > 1.30 x 10^6 avg coefficient	=	0.9958
	Dimensions By: ARL		

DOE TURBINE TEST STAND
36"X23" VENTURI
November 22, 2000

UPSTREAM ELBOWS

Certified By: [signature]

ARL

DOE TURBINE TEST STAND

36" VENTURI

STRAIGHT LINE

CALIBRATION
DATE: November 20, 2000
PIPE DIAMETER = 35.2140
THROAT DIAMETER = 22.7480

Run #	Line Temp Deg F	Air Temp Deg F	Net Weight lb.	Run Duration secs.	Output [see note]	Flow CFS	H Line FT H20	Pipe Rey. # x 10^6	Coef
1	100	60	96778	45.612	2.711~	34.26	1.898	1.9978	0.9979
2	100	60	97854	37.163	3.102~	42.52	2.926	2.4793	0.9974
3	100	60	97289	38.676	3.005~	40.62	2.670	2.3634	0.9975
4	100	60	96911	40.115	2.926~	39.01	2.464	2.2747	0.9972
5	100	60	96788	41.994	2.842~	37.22	2.241	2.1750	0.9976
6	100	60	96564	45.059	2.727~	34.61	1.939	2.0267	0.9972
7	100	60	96390	47.999	2.636~	32.43	1.701	1.9031	0.9977
8	100	60	96291	53.757	2.505~	28.92	1.355	1.6975	0.9972
9	100	60	95656	65.563	2.332~	23.56	0.901	1.3841	0.9962
10	100	60	95497	76.186	2.242~	20.24	0.663	1.1903	0.9975
11	100	60	95202	90.146	2.169~	17.05	0.472	1.0029	0.9959
12	101	60	95473	82.558	2.205~	18.67	0.565	1.0993	0.9967
13	101	60	95729	71.026	2.281~	21.76	0.767	1.2812	0.9972
14	101	60	95808	60.896	2.388~	25.41	1.047	1.4972	0.9963
15	101	60	95980	57.301	2.441~	27.05	1.187	1.5956	0.9963
16	101	60	96194	50.961	2.561~	30.48	1.504	1.8000	0.9974

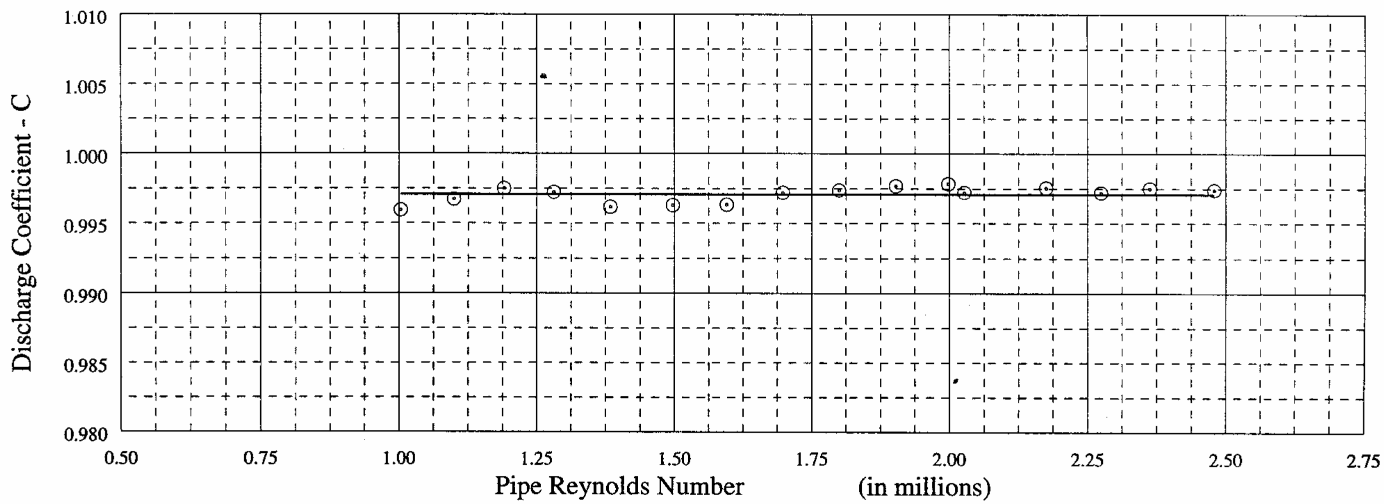
~ dp transmitter volts

For Pipe Rey. #s above 1.00 x 10^6 Avg Coef = 0.9971 With Standard Deviation = 0.0006
The data reported on herein was obtained by measuring equipment the calibration of which is traceable to NIST , following the installation and test procedures referenced in this report, resulting in a flow measurement uncertainty of +/- 0.25% or less.

CALIBRATED BY: S.V.K.

CERTIFIED BY:

ARL



$q_a = C F_a K_M \sqrt{\Delta h}$

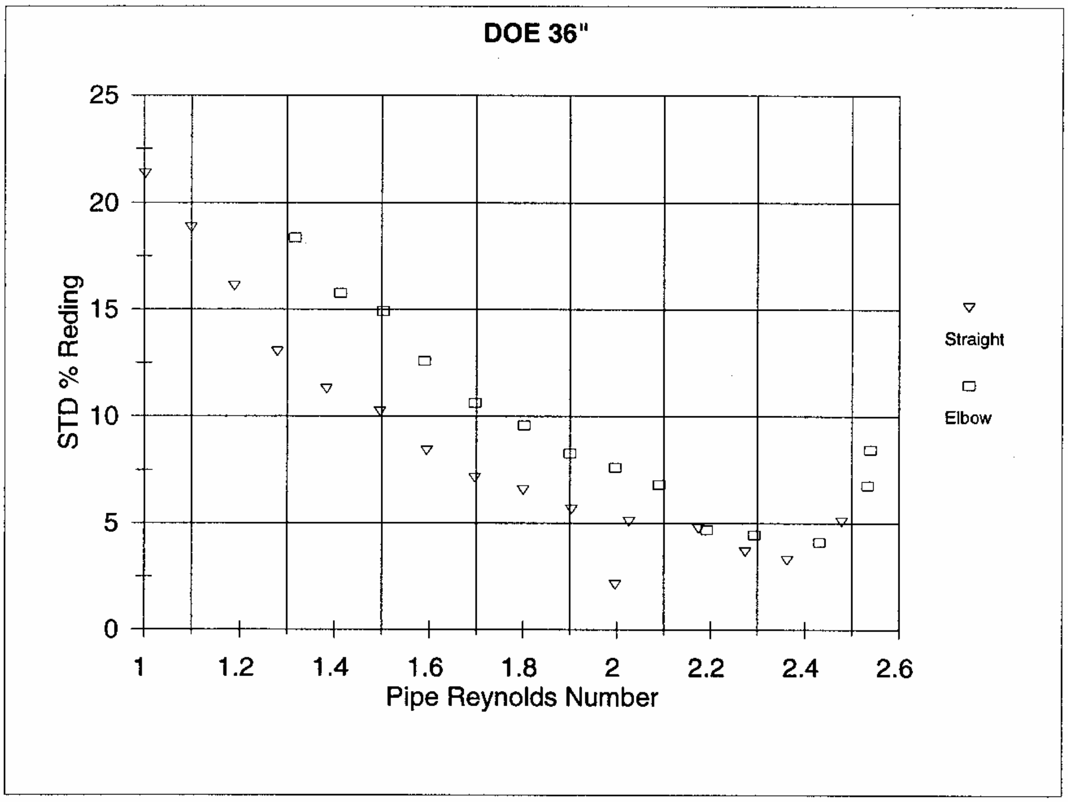
q_a = Actual Flow (ft^3/sec)		
C = Discharge Coefficient (Dimensionless)		
Δh = Pressure Differential (Feet of Water at Run Temperature)		
K_M = Meter Constant = $\frac{a\sqrt{2g}}{\sqrt{1 - \beta^4}}$	=	24.9087
F_a = Average Thermal Expansion Factor	=	1.0006
a = Throat Area (ft^2)	=	2.8224
g = Local Acceleration of Gravity (ft/sec^2)	=	32.1625
ß = Ratio of Throat to Pipe Diameter (Dimensionless)	=	0.6460
Pipe Diameter (Inches)	=	35.2140
Throat Diameter (Inches)	=	22.7480
For Pipe Reynolds Number > 1.00 x 10^6 avg coefficient	=	0.9971
Dimensions By: ARL		

DOE TURBINE TEST STAND
36" VENTURI
November 20, 2000

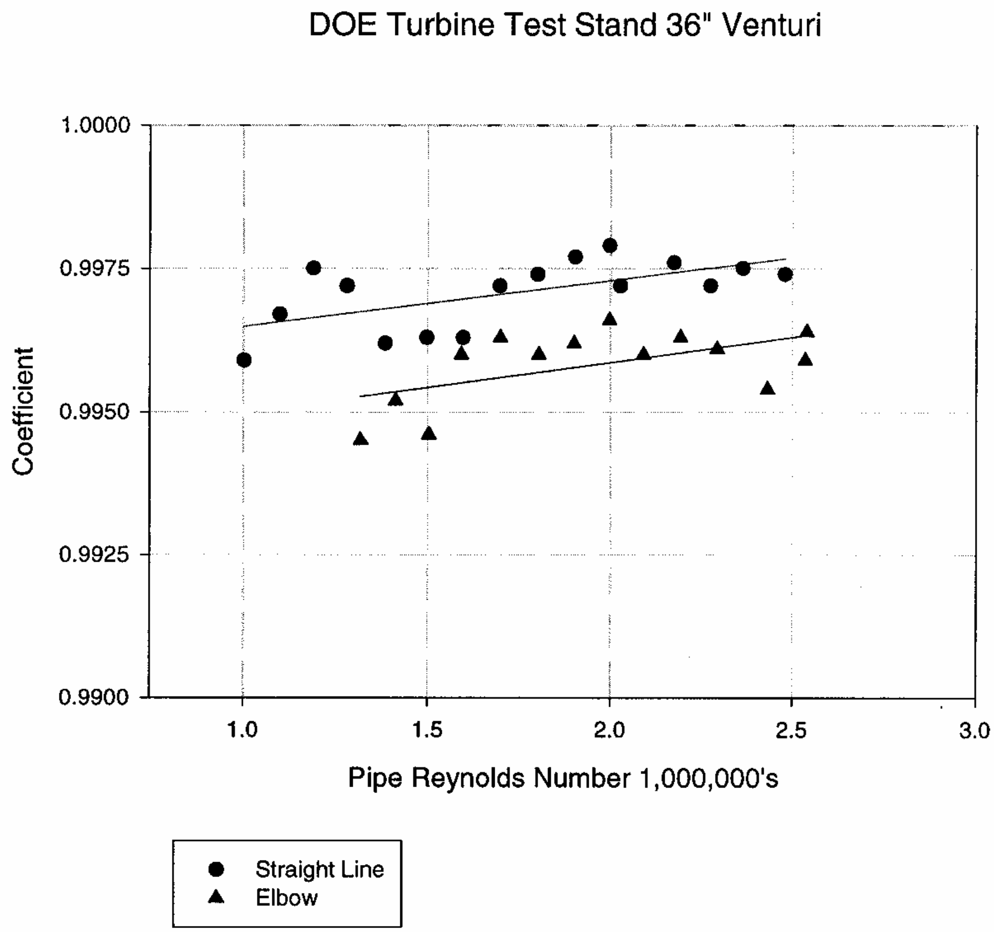
STRAIGHT LINE

Certified By: [signature]

ARL



DOE 36"
25
20
15
10
5
0
STD % Reding
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
Pipe Reynolds Number
Straight
Elbow

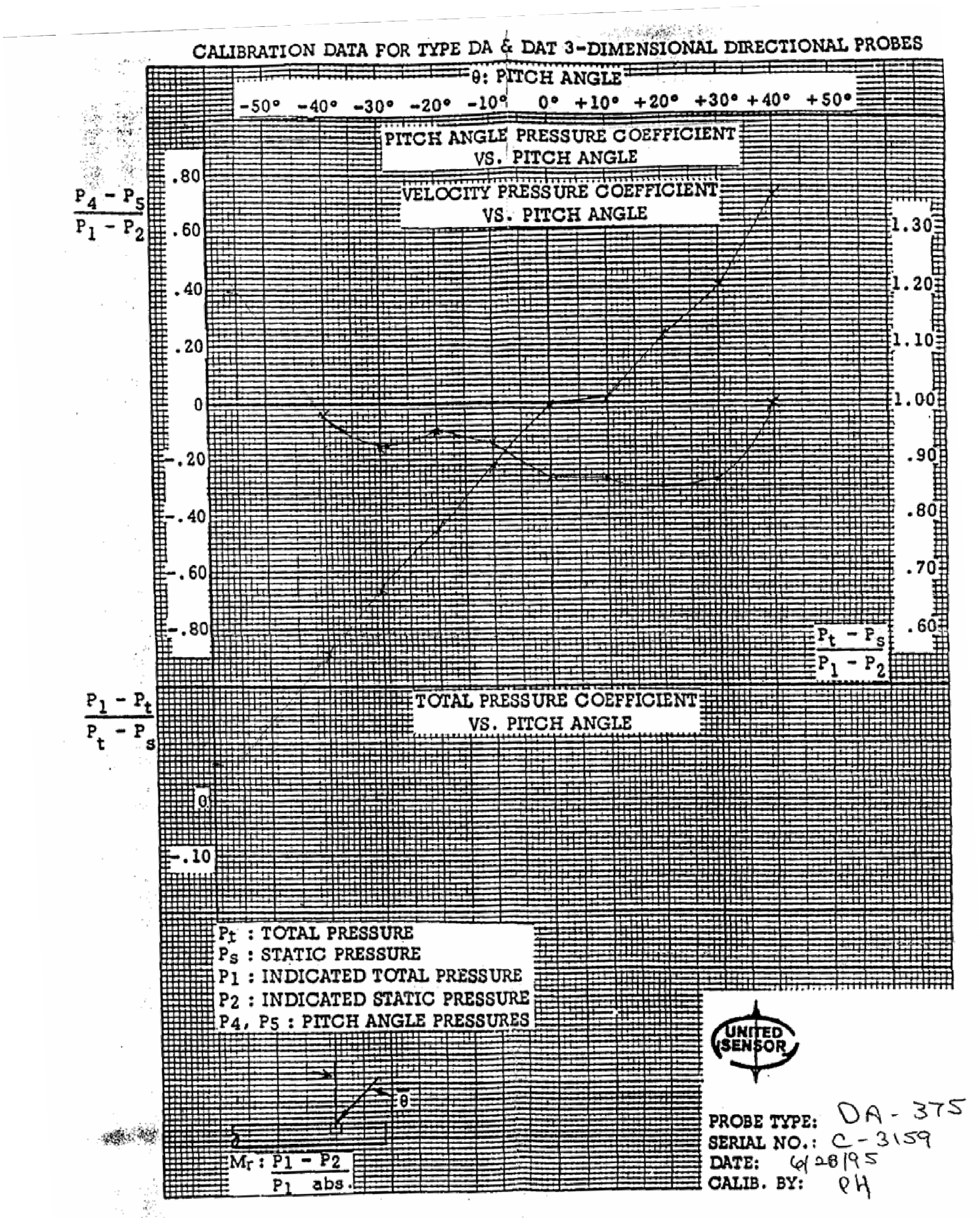


DOE Turbine Test Stand 36" Venturi
1.0000
0.9975
0.9950
0.9925
0.9900
Coefficient
1.0
1.5
2.0
2.5
3.0
Pipe Reynolds Number 1,000,000's
Straight Line
Elbow

APPENDIX B

VELOCITY PROBE CALIBRATION DATA

Velocity Probe 1 Calibration Data



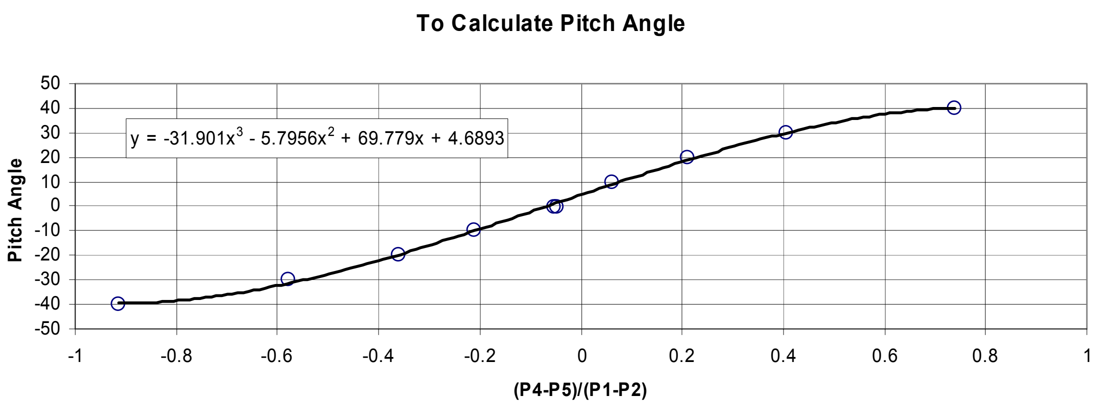
Velocity Probe 2 Calibration Data

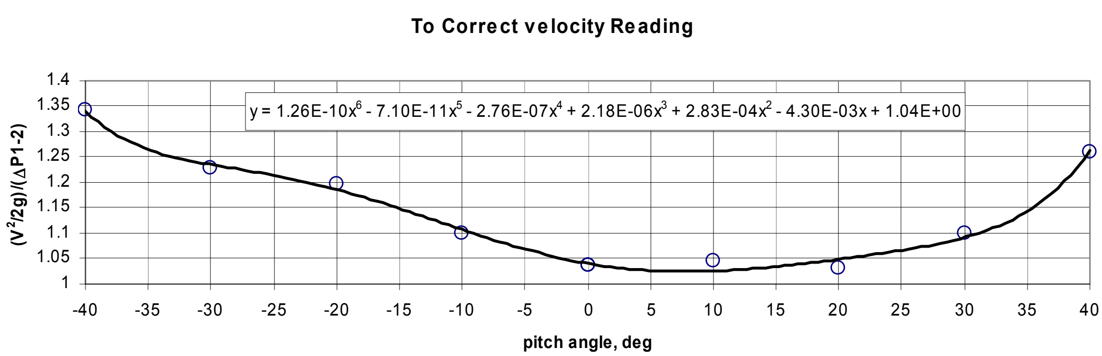
Method

Nov-02 DA-250 S/N: C-4355 ** S/N WAS SANDED OFF OF THE HEAD TO ATTACH A SPIRIT LEVEL GAGE

To Use This 5-hole probe:

1. **Align probe to flow by making P4=P5**
2. **Measure Differential pressures P1-P2, and P4-P5**
3. **Calculate x = (P4-P5)/(P1-P2)**
4. **Calculate Pitch angle using equation 1: Angle = $-31.901x^3 - 5.7956x^2 + 69.779x + 4.6893$**
5. **Correct the indicated Velocity Head $(V^2/2g)_I$, which is P1-P2, using equation 2:**
   $(V_2/2g)_{corrected}$ =(P1-P2)* $1.26E\text{-}10angle^6 - 7.10E\text{-}11angle^5 - 2.76E\text{-}07angle^4 + 2.18E\text{-}06angle^3 + 0.000283angle^2 - 0.0043angle + 1.0408$
6. **Calculate Velocity: $V=\mathrm{sqrt}(2gH_{vel})$**

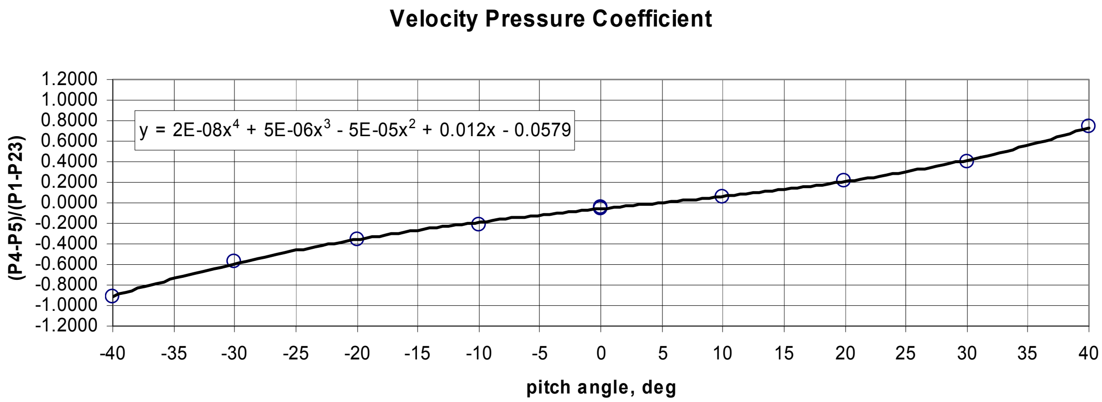


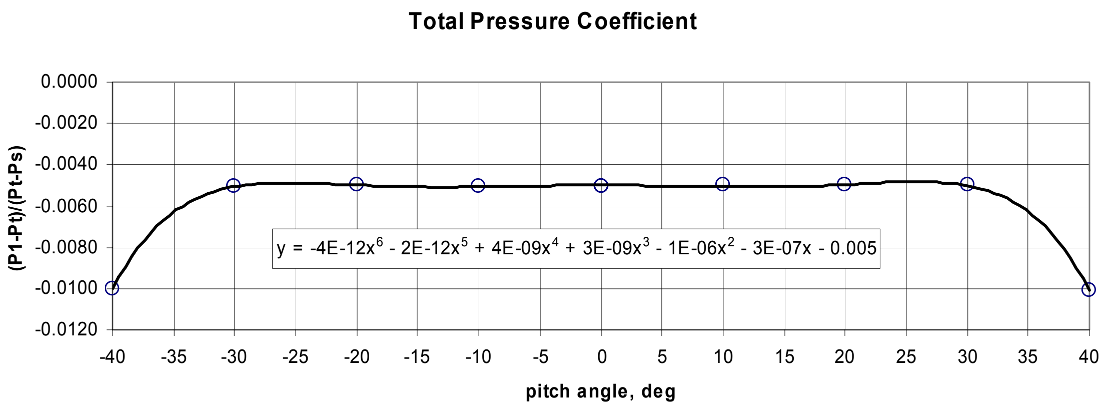


Velocity Probe 2 Calibration

ft water

1 Pt-Ps	2 P1-Pt	3 P23-Ps	4 P4-P5	5 Patm-Pt	6 Pitch Angle	7 2/1	8 3/1	9 4/1	10 1.0+7-8	11 9/10	12 1.0/10
20.0	-0.2	4.9	-13.6	3.9	-40	-0.0100	0.2450	-0.6800	0.7450	-0.9128	1.3423
19.8	-0.1	3.6	-9.3	3.9	-30	-0.0051	0.1818	-0.4697	0.8131	-0.5776	1.2298
20.0	-0.1	3.2	-6.0	3.9	-20	-0.0050	0.1600	-0.3000	0.8350	-0.3593	1.1976
19.9	-0.1	1.7	-3.8	3.8	-10	-0.0050	0.0854	-0.1910	0.9095	-0.2099	1.0994
19.9	-0.1	0.6	-0.9	3.7	0	-0.0050	0.0302	-0.0452	0.9648	-0.0469	1.0365
19.9	-0.1	0.6	-1.0	3.9	0	-0.0050	0.0302	-0.0503	0.9648	-0.0521	1.0365
20.0	-0.1	0.8	1.2	3.7	10	-0.0050	0.0400	0.0600	0.9550	0.0628	1.0471
20.0	-0.1	0.5	4.1	3.7	20	-0.0050	0.0250	0.2050	0.9700	0.2113	1.0309
20.0	-0.1	1.7	7.4	3.8	30	-0.0050	0.0850	0.3700	0.9100	0.4066	1.0989
19.8	-0.2	3.9	11.6	3.9	40	-0.0101	0.1970	0.5859	0.7929	0.7389	1.2611


Velocity Pressure Coefficient
y = 2E-08x^4 + 5E-06x^3 - 5E-05x^2 + 0.012x - 0.0579
(P4-P5)/(P1-P23)
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
-0.2000
-0.4000
-0.6000
-0.8000
-1.0000
-1.2000
-40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40
pitch angle, deg


Total Pressure Coefficient
y = -4E-12x^6 - 2E-12x^5 + 4E-09x^4 + 3E-09x^3 - 1E-06x^2 - 3E-07x - 0.005
(P1-Pt)/(Pt-Ps)
0.0000
-0.0020
-0.0040
-0.0060
-0.0080
-0.0100
-0.0120
-40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40
pitch angle, deg

APPENDIX C

CALIBRATION DATA FOR VELOCITY MEASUREMENT DIFFERENTIAL PRESSURE CELLS

APPENDIX C

CALIBRATION DATA FOR VELOCITY MEASUREMENT DIFFERENTIAL PRESSURE CELLS

TEST LOOP VELOCITY MEASUREMENT CELLS

Cell	Slope	Intercept
0	0.260417	-0.9375
1(9-20-01)	1.875	-3.75
1 (9-24-01 thru 9-28-01)	1.041667	-2.08333
2	1.041667	-6.25

CALIBRATION LOOP VELOCITY MEASUREMENT CELLS

Cell	Slope	Intercept
449	0.112771	-0.226322
450	0.112687	-0.225746

APPENDIX D

PRESSURE CELL CALIBRATION DATA

APPENDIX D

PRESSURE CELL CALIBRATION DATA

Calibration 1 Data 8/21/01

Calibration 1	Rg48/21/2001	
Differential Pressure Cell	Slope	Y Intercept
Pump Head	6.256559	-12.36250
Flow	1.126869	-2.24392
Turbine Head	6.251296	-12.48765
Tailwater Head	3.751875	-7.76915
Bypass Flow	0.540570	-1.07178

Pump Head

Volts	cal 1
4	12.6637
5	18.9203
6	25.1769
8	37.6900

Flow

Volts	cal 1
4	2.2636
5	3.3904
6	4.5173
8	6.7710

Turbine Head

Volts	cal 1
4	12.5175
5	18.7688
6	25.0201
8	37.5227

Tailwater

Volts	cal 1
4	15.0075
5	18.7594
6	22.5113
8	30.0150

Bypass Q

Volts	cal 1
4	1.0905
5	1.6311
6	2.1716
8	3.2528

Calibration 2 Data 2/01/02

Calibration 2	2/01/2002	
Differential Pressure Cell	Slope	Y Intercept
Pump Head	6.253841	-12.371291
Flow	1.126371	-2.241375
Turbine Head	6.250106	-12.491931
Tailwater Head	3.750887	-7.845037
Bypass Flow	0.540580	-1.071470

Pump Head		
volts	cal 2	% dev. CAL1/CAL2
3	12.6441	0.16
4	18.8979	0.12
6	25.1518	0.10
8	37.6594	0.08
Flow		
volts	cal 2	
4	2.2641	-0.02
5	3.3905	0.00
6	4.5169	0.01
8	6.7696	0.02
Turbine Head		
volts	cal 2	
4	12.5085	0.07
5	18.7586	0.05
6	25.0087	0.05
8	37.5089	0.04
Tailwater		
volts	cal 2	
4	15.0035	0.03
5	18.7544	0.03
6	22.5053	0.03
8	30.0071	0.03
Bypass Q		
volts	cal 2	
4	1.0909	-0.03
5	1.6314	-0.02
6	2.1720	-0.02
8	3.2532	-0.01

Calibration 3 Data 8/21/02

Calibration 3	8/21/02	
Differential Pressure Cell	Slope	Y Intercept
Pump Head	6.255971	-12.389982
Flow	1.126619	-2.241934
Turbine Head	6.251708	-12.516706
Tailwater Head	3.752393	-7.523787
Bypass Flow	0.540510	-1.071920

Pump Head		
volts	cal 3	% dev. CAL1/CAL3
3	12.6339	0.24
4	18.8899	0.16
6	25.1458	0.12
8	37.6578	0.09
Flow		
volts	cal 3	
4	2.2645	-0.04
5	3.3912	-0.02
6	4.5178	-0.01
8	6.7710	0.00
Turbine Head		
volts	cal 3	
4	12.4901	0.22
5	18.7418	0.14
6	24.9935	0.11
8	37.4970	0.07
Tailwater		
volts	cal 3	
4	15.0096	-0.01
5	18.7620	-0.01
6	22.5144	-0.01
8	30.0191	-0.01
Bypass Q		
volts	cal 3	
4	1.0901	0.03
5	1.6306	0.03
6	2.1711	0.02
8	3.2522	0.02

Calibration 4 Data 10/29/02

Calibration 4	10/29/02	
Differential Pressure Cell	Slope	Y Intercept
Flow	1.127118	-2.244301
Turbine Head	6.255504	-12.525732

Flow

volts	cal 4	% dev. CAL1/CAL4
4	2.2642	-0.03
5	3.3913	-0.03
6	4.5184	-0.02
8	6.7726	-0.02

Turbine Head

volts	cal 4	
4	12.4963	0.17
5	18.7518	0.09
6	25.0073	0.05
8	37.5183	0.01

Calibration 5 Data 2/12/03

Calibration 5	2/12/03	
Differential Pressure Cell	Slope	Y Intercept
Pump Head	6.255412	-12.419341
Flow	1.126137	-2.239355
Turbine Head	6.256369	-12.546642
Tailwater Head	3.751381	-7.653551
Bypass Flow	0.540528	-1.072235

Pump Head

volts	cal 5	% dev. CAL1/CAL5
3	12.6023	0.49
4	18.8577	0.33
6	25.1131	0.25
8	37.6240	0.18

Flow

volts	cal 5	
4	2.2652	-0.07
5	3.3913	-0.03
6	4.5175	0.00
8	6.7697	0.02

Turbine Head

volts	cal 5	
4	12.4788	0.31
5	18.7352	0.18
6	24.9916	0.11
8	37.5043	0.05

Tailwater

volts	cal 5	
4	15.0055	0.01
5	18.7569	0.01
6	22.5083	0.01
8	30.0110	0.01

Bypass Q

volts	cal 5	
4	1.0899	0.06
5	1.6304	0.04
6	2.1709	0.03
8	3.2520	0.02

APPENDIX E

DYNAMOMETER LOAD CELL CALIBRATION DATA

TURBINE TEST FACILITY DYNAMOMETER LOAD CELL CALIBRATION HISTORY

Cal Date	Slope (lbft/volt)	Change in Slope from Previous Cal (percent)		Piping Configuration	Air Temp (deg)	Cell Temp (deg)	Weights	Usage
8/28/2001	854.960			< fixed pipe				
10/3/2001	848.539			< original hose			h&n	pre - no gate tests
3/4/2002	850.839	0.27%		< original hose			h&n	post - no gate tests
4/5/2002	852.997	0.25%		< original hose			h&n	April gate tests
5/7/2002	856.047	0.36%		< 2nd hose	58-67		j&v	1/2 Biological
5/24/2002	851.165	-0.57%		<3rd hose	64 -71			2/2 Biological
7/15/2002-A	846.727	-0.52%		< 3rd hose w/vib	70		a&e	
7/15/2002-B	846.495	-0.03%		< 3rd hose w/o vib	81		a&e	
9/5/2002	848.465	0.23%		< 3rd hose w/o vib	72	91	dedicated DOE wieghts	
9/6/2002	848.915	0.05%		< 3rd hose w/o vib	78	94	dedicated DOE wieghts	
9/10/2002	848.592	-0.04%		< 3rd hose w/o vib	78	94	dedicated DOE wieghts	
9/16/2002	860.211	span change		< 3rd hose w/o vib	68	91	dedicated DOE wieghts	changed output signal for neg shift
9/18/2002	863.683	0.40%		"	68.5	91	"	"
9/19/2002	577.249	span change	0.00%	"	75	92	"	2nd shift
9/24/2002	577.418	0.029%	0.03%	"	70	90	"	"
9/27/2002	577.670	0.044%	0.07%	"	63	89	"	"
10/2/2002	576.317	-0.234%	-0.16%	"	77	92	"	"
10/9/2002	581.081	0.827%	0.66%	"	61	84	"	"
10/10/2002	577.883	-0.550%	0.11%		56	82	"	"
**				**New Load Cell and Electronics Installed**			**	
11/6/2002	626.964	new cell	-		44		"	50# increments: large hysteresis
11/7/2002	627.292	0.052%	0.05%		36		"	150# increments: small hysteresis
11/8/2002	639.032	span change	reference		56		"	150# increments
11/14/2002	637.517	-0.24%	-0.24%	WRT reference	48		"	150# increments
11/22/2002	637.318	-0.03%	-0.27%	WRT reference	44		"	150# increments
12/5/2002	637.492	0.03%	-0.24%	WRT reference	50		"	150# increments
12/12/2002	639.962	0.39%	0.15%	WRT reference	47		"	150# increments
1/14/2003	638.230	-0.27%	-0.13%	WRT reference	47		"	150# increments

APPENDIX F

VELOCITY MEASUREMENTS

APPENDIX F
VELOCITY MEASUREMENTS

UPSTREAM OF FLOW METER

Velocity measurements in the test loop upstream of the Venturi flow meter were taken in the fall of 2001 before the wicket gates were installed. The measurements were taken at the same traverse locations and with the same 5-hole pitot probe that was used during the flow meter calibration. Complete sets of measurements were made at two operating conditions: 1) a turbine head of about 80 ft and a corresponding flow of 93.7 cfs, and 2) a turbine head of about 38 ft and a corresponding flow of about 65.2 cfs. The measurements for each operating condition are summarized on Tables F-1 and F-2. The average axial velocities for the 80 ft and 38 ft head cases were about 13.7 and 9.6 ft/sec, respectively. Since the measured axial velocities along the four transects were very similar at each flow, each data set was averaged and is shown on Figures F-1 and F-2.

Part of the measurements, as performed during the meter calibrations, was to rotate the probe until the probe impact port was aligned into the flow and, thereby, obtain the tangential flow (swirl) angle at each measuring point. These swirl angles were small at all measuring locations and were averaged to obtain one value for each test condition. For the 80 ft and 38 ft heads, the swirl angles were 1.2 and 0.3 degrees, respectively. This indicated that flow swirl approaching the Venturi flow meter was negligible and, therefore, the flow meter calibration discharge coefficient for the straight pipe, Figure 4-6, was used during the turbine tests.

TABLE F-1

VELOCITY MEASUREMENTS IN TEST LOOP UPSTREAM OF FLOW METER AT 80 FT TURBINE HEAD

Non-Dimensional Radius	V_c=12.28 ft/sec Non-Dimensional Velocity, v/Vc					
r/R	Port 1	Port 2	Port 3	Port 4	Radial Average Velocity	Theoretical Velocity
0.04	0.85	0.78	0.75	0.84	0.81	0.84
0.17	0.97	0.95	0.96	1.01	0.97	0.96
0.29	1.05	1.03	1.04	1.08	1.05	1.02
0.44	1.08	1.07	1.08	1.10	1.08	1.06
0.71	1.09	1.09	1.08	1.10	1.09	1.11

TABLE F-2

VELOCITY MEASUREMENTS IN TEST LOOP UPSTREAM OF FLOW METER AT 38 FT TURBINE HEAD

Non-Dimensional Radius	V_c=8.93 ft/sec Non-Dimensional Velocity, v/Vc					
r/R	Port 1	Port 2	Port 3	Port 4	Radial Average Velocity	Theoretical Velocity
0.04	0.86	0.82	0.77	0.81	0.81	0.84
0.17	1.02	0.98	0.92	0.97	0.97	0.96
0.29	1.06	1.06	0.98	1.03	1.03	1.02
0.44	1.11	1.09	1.03	1.06	1.07	1.06
0.71	1.14	1.13	1.09	1.09	1.11	1.12

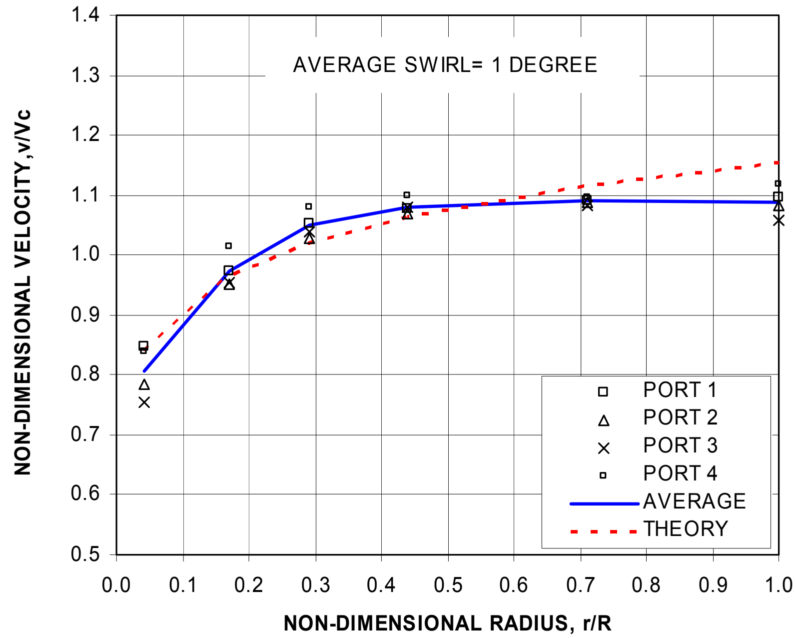


FIGURE F-1 VELOCITY DISTRIBUTION IN TEST LOOP APPROACHING FLOW METER AT 80 FT HEAD

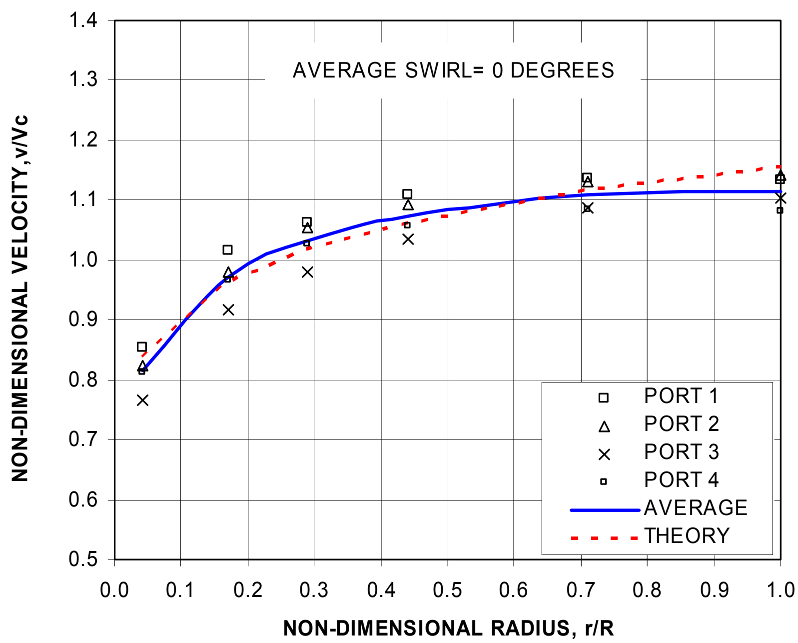


FIGURE F-2 VELOCITY DISTRIBUTION IN TEST LOOP APPROACHING FLOW METER AT 38 FT HEAD

TREATMENT FISH INJECTION

Velocity measurements were taken in the test loop just upstream of the treatment fish injection location during the fall 2001 preliminary engineering tests without wicket gates. The measurements, which are summarized in Tables F-3 and F-4, were obtained at two operating conditions: 1) a turbine head of about 80 ft and a corresponding flow of 93.7 cfs, and 2) at a turbine head of about 38 ft and a corresponding flow of about 65.2 cfs. The 80 ft measurements with 93.7 cfs showed a uniform distribution with an average velocity of about 5.9 ft/sec and a negligible swirl angle of 0.8 degrees. With 38 ft of turbine head and 65.2 cfs, the average velocity was 4.1 ft/sec. At these lower velocities, the pressure readings were somewhat low for the DP cell and the data were more scattered, but a generally uniform velocity distribution was evident as shown on Figures F-3 and F-4 for the 80 ft and 38 ft turbine head measurements, respectively.

TABLE F-3
VELOCITY MEASUREMENTS AT TREATMENT FISH INJECTION LOCATION
AT 80 FT TURBINE HEAD

Non-Dimensional Radius	V_c = 5.13 ft/sec Non-Dimensional Velocity, (v/V_c) and Tangential Flow Angles								
	Port 1		Port 2		Port 3		Port 4		Radial Average Velocity
r/R	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	
0.04	0.84	-1.20	n/a	n/a	0.87	-2.20	0.70	-2.20	0.80
0.17	1.01	-1.20	n/a	n/a	1.04	-2.20	0.90	-3.20	0.98
0.29	1.10	-1.20	n/a	n/a	1.06	-2.20	0.93	-1.20	1.03
0.44	1.13	-4.20	n/a	n/a	1.11	-1.20	1.00	-3.20	1.08
0.71	1.14	-3.20	n/a	n/a	1.12	-3.20	1.05	-2.20	1.10

TABLE F-4
VELOCITY MEASUREMENTS AT TREATMENT FISH INJECTION LOCATION
AT 38 FT TURBINE HEAD

Non-Dimensional Radius	V_c = 3.22 ft/sec Non-Dimensional Velocity, (v/V_c) and Tangential Flow Angles								
	Port 1		Port 2		Port 3		Port 4		Radial Average Velocity
r/R	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	
0.04	0.75	-5.20	n/a	n/a	0.73	-2.20	0.74	-7.20	0.74
0.17	0.92	-5.20	n/a	n/a	1.03	-4.20	1.00	-7.20	0.98
0.29	0.97	-3.20	n/a	n/a	1.15	-4.20	1.11	-5.20	1.08
0.44	0.92	-1.20	n/a	n/a	1.17	-4.20	1.08	-3.20	1.06
0.71	1.10	-3.20	n/a	n/a	1.17	-2.20	1.15	-3.20	1.14

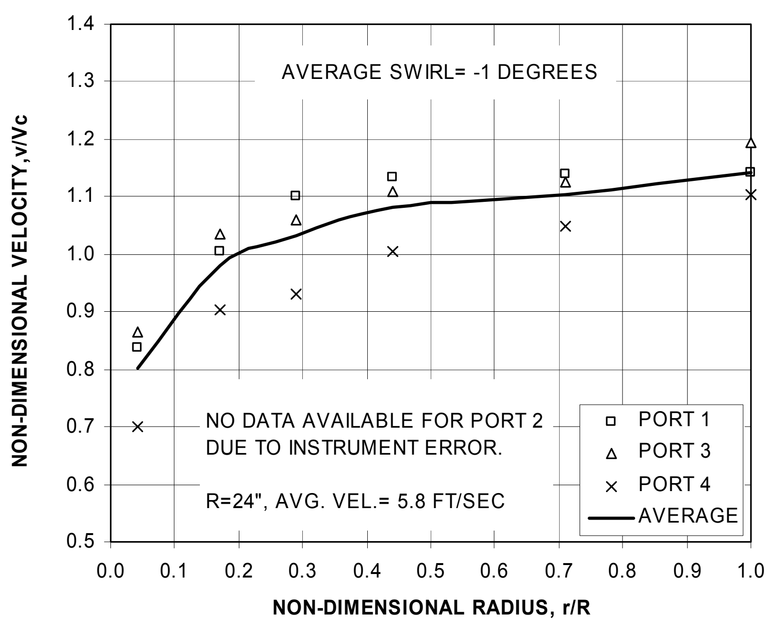


FIGURE F-3 VELOCITY DISTRIBUTION AT TREATMENT FISH INJECTION LOCATION WITH 80 FT HEAD, 92.7 CFS, 335 RPM

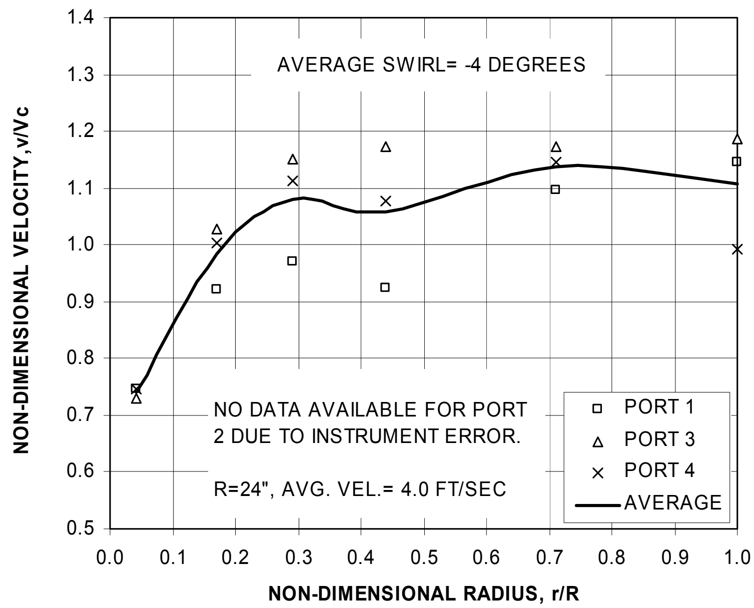


FIGURE F-4 VELOCITY DISTRIBUTION AT TREATMENT FISH INJECTION LOCATION WITH 38 FT HEAD, 65.7 CFS, 235 RPM

CONTROL FISH INJECTION

Velocity measurements were made just downstream from the control fish injection and slightly upstream from the end of the draft tube (see Figure 3-7) during the fall 2001 preliminary engineering tests without wicket gates. The purpose of these measurements was not only to determine the flow characteristics into which the control fish were injected but also to better understand the swirl leaving the turbine and to determine a kinetic energy correction factor (for the end of the draft tube) needed to calculate the head on the turbine.

Measurements of axial velocity and tangential swirl were made using the same 5-hole pitot probe (serial number C-3159) at 80 ft of turbine head for three turbine speeds without the wicket gates installed: essentially at the BEP rpm (335 rpm), somewhat above the BEP rpm (361 rpm), and somewhat below the BEP rpm (310 rpm). The data for these conditions are presented in Tables F-5, F-6, and F-7. Figures F-5 through F-10 show the non-dimensional axial velocity distributions and tangential swirl angles at the control fish injection location for these three cases noted on each figure.

At the BEP (335 rpm) and 80 ft head, the axial velocities shown in Figure F-5 are somewhat low in the center of the pipe and higher at the outside wall, especially near the bottom of the draft distribution. Time averaged swirl angles are shown on Figure F-6, indicating cells of flow rotating in different directions. The arithmetic average swirl angle was 2.7 degrees whereas the weighted average of the integrated angular momentum gave an average swirl angle of 14.5 degrees.

Similar measurements were made at the same 80 ft head at higher and lower rotation rates to determine the effects on axial velocity and swirl angle distributions. Axial velocity and swirl distributions at 310 rpm and 80 ft head, which are shown on Figures F-7 and F-8, indicated negligible axial flow in the center of the pipe but lower overall swirl angles. The negligible center velocities and the higher velocities at the pipe wall contribute to the lower turbine performance measured at the reduced speeds. A more uniform velocity distribution was measured at the speed associated with the measured BEP (Table F-5). Comparable data at 361 rpm and 80 ft head are shown on Figure F-9 and F-10, indicating a fairly uniform axial velocity distribution with higher values in the center of the pipe, but with high swirl angles of up to 45 degrees. These high swirl angles also resulted in lower measured power and efficiency at the higher speed than at the measured BEP speed.

TABLE F-5
VELOCITY MEASUREMENTS AT CONTROL FISH INJECTION LOCATION
WITH NO WICKET GATES, 335 RPM, AND 80 FT TURBINE HEAD

Non-Dimensional Radius	V_c = 4.70 ft/sec Non-Dimensional Velocity, (v/V_c) and Tangential Flow Angles								
	45° Port		135° Port		225° Port		315° Port		Radial Average Velocity
r/R	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	
0.04	1.2	-14.0	1.2	12.0	1.5	-6.0	1.7	-11.0	1.4
0.17	1.2	-9.0	1.1	8.0	1.3	-6.0	1.6	-10.0	2.0
0.29	0.9	0.0	1.0	2.0	1.0	-5.0	1.2	-10.0	1.0
0.44	0.8	6.0	0.8	0.0	0.7	-2.0	0.8	-9.0	0.8
0.71	0.7	14.0	0.6	-10.0	0.4	1.0	0.5	-4.0	0.5

TABLE F-6
VELOCITY MEASUREMENTS AT CONTROL FISH INJECTION LOCATION
WITH NO WICKET GATES, 310 RPM, AND 80 FT TURBINE HEAD

Non-Dimensional Radius	V_c = 4.45 ft/sec Non-Dimensional Velocity, (v/V_c) and Tangential Flow Angles								
	45° Port		135° Port		225° Port		315° Port		Radial Average Velocity
r/R	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	
0.043	1.7	-2.0	1.7	-4.0	1.4	-8.0	1.1	-3.0	1.5
0.170	1.7	-4.0	1.6	-2.0	1.3	-9.0	0.9	0.0	1.4
0.290	1.4	-6.0	1.5	-4.0	1.0	-4.0	0.8	-2.0	1.2
0.440	1.0	-7.0	0.4	-4.0	0.6	-1.0	0.6	-5.0	0.7
0.710	0.4	-5.0	0.4	-3.0	0.0	0.0	0.3	-6.0	0.3

TABLE F-7
VELOCITY MEASUREMENTS AT CONTROL FISH INJECTION LOCATION
WITH NO WICKET GATES, 361 RPM, AND 80 FT TURBINE HEAD

Non-Dimensional Radius	V_c = 4.45 ft/sec Non-Dimensional Velocity, (v/V_c) and Tangential Flow Angles								
	45° Port		135° Port		225° Port		315° Port		Radial Average Velocity
r/R	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	
0.04	1.0	25.0	0.7	49.0	0.6	52.0	0.8	27.0	0.8
0.17	1.1	27.0	0.9	44.0	0.8	44.0	1.1	21.0	0.9
0.29	1.2	23.0	0.9	37.0	0.9	35.0	1.0	23.0	1.0
0.44	1.2	21.0	1.0	27.0	0.9	23.0	1.2	21.0	1.1
0.71	1.3	10.0	1.1	13.0	1.1	10.0	1.3	10.0	1.2

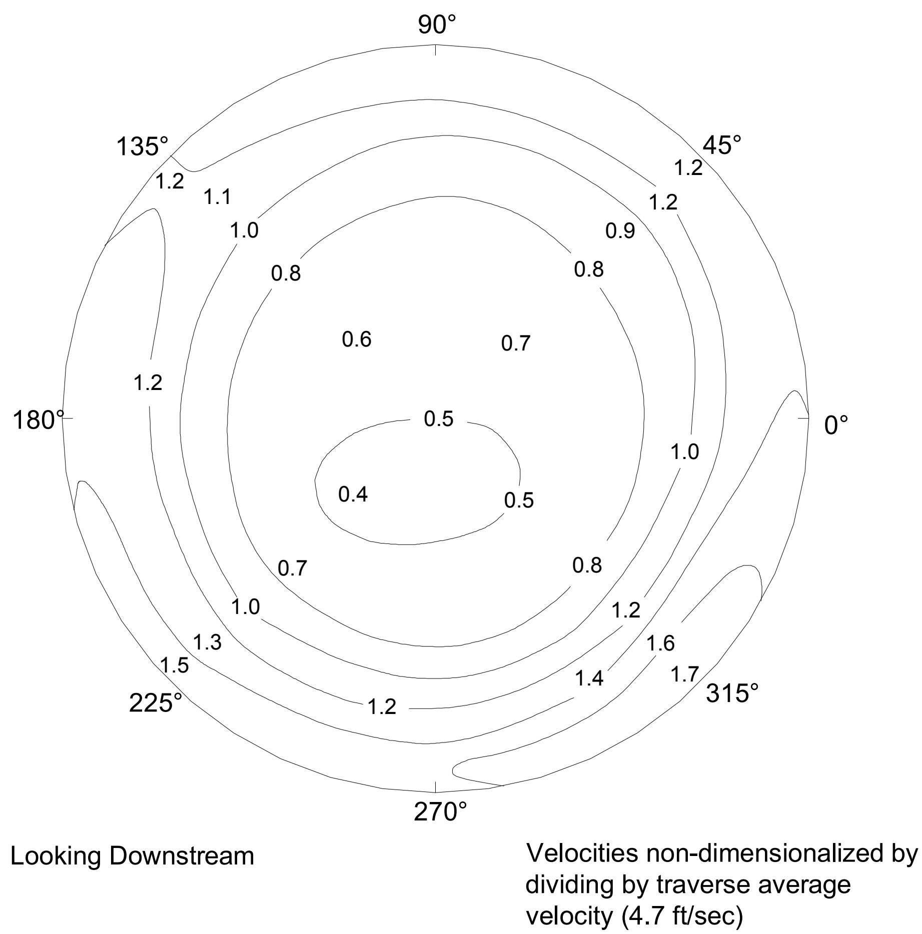


FIGURE F-5 VELOCITY PROFILE AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 80 FT HEAD, 92.7 CFS, 335 RPM (BEP)

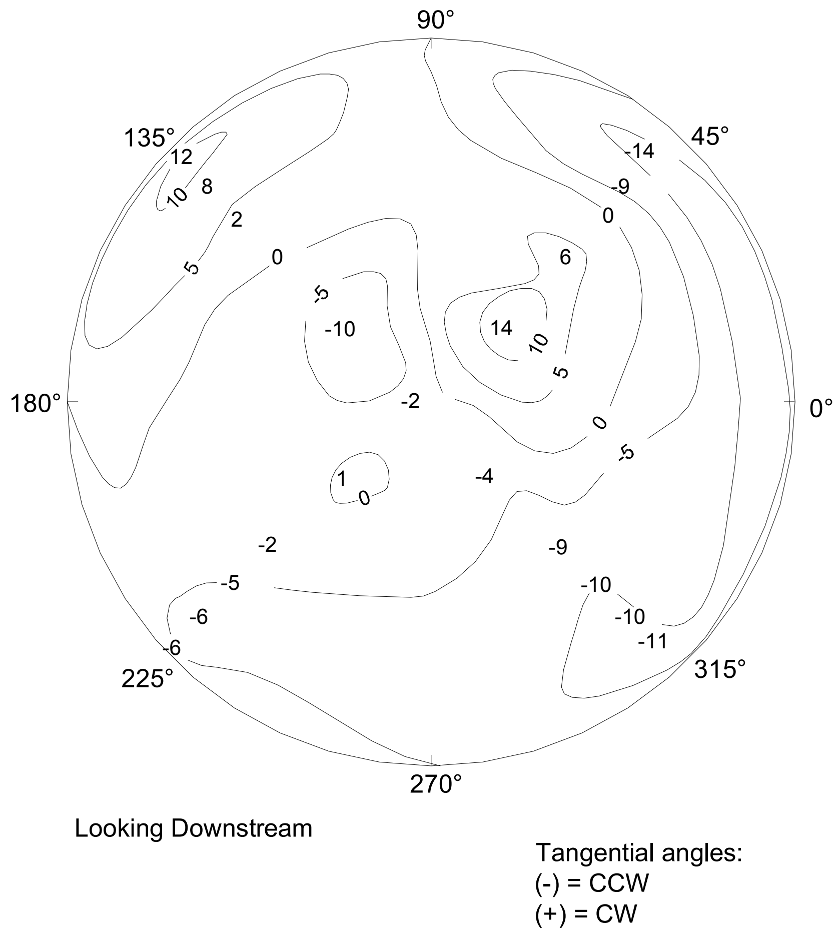


FIGURE F-6 TANGENTIAL FLOW ANGLES AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 80 FT HEAD, 92.7 CFS, 335 RPM (BEP)

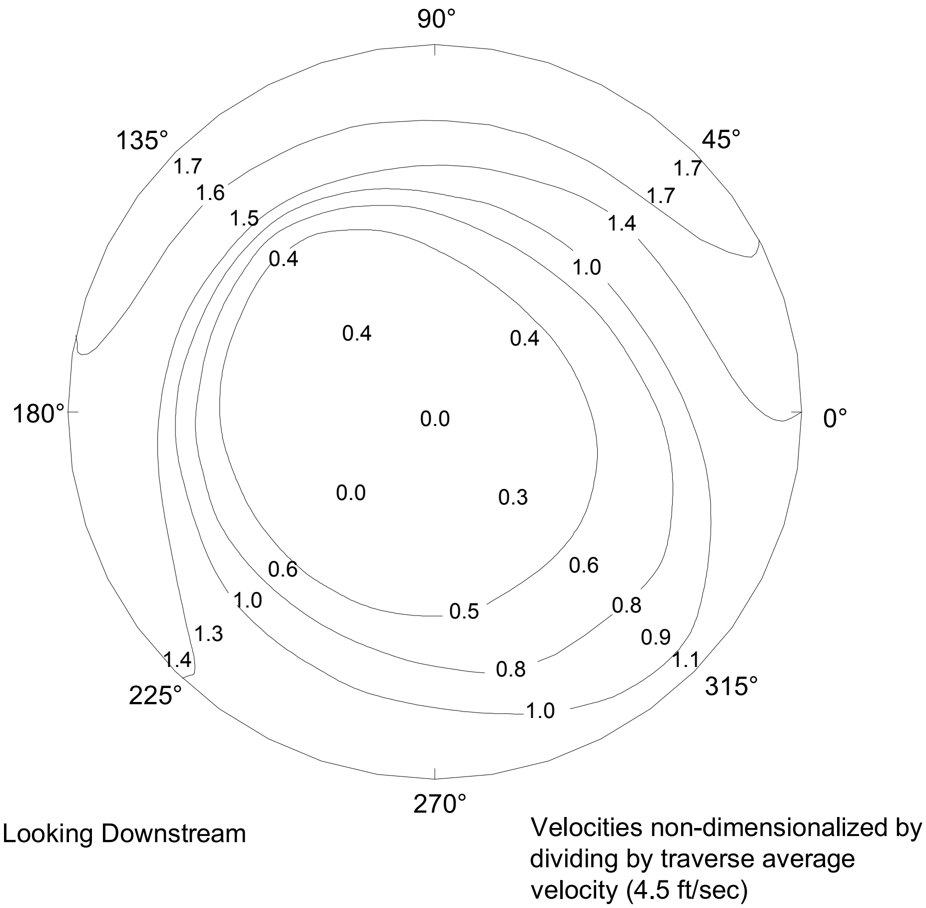


FIGURE F-7 VELOCITY PROFILE AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 80 FT HEAD, 94.7 CFS, 310 RPM

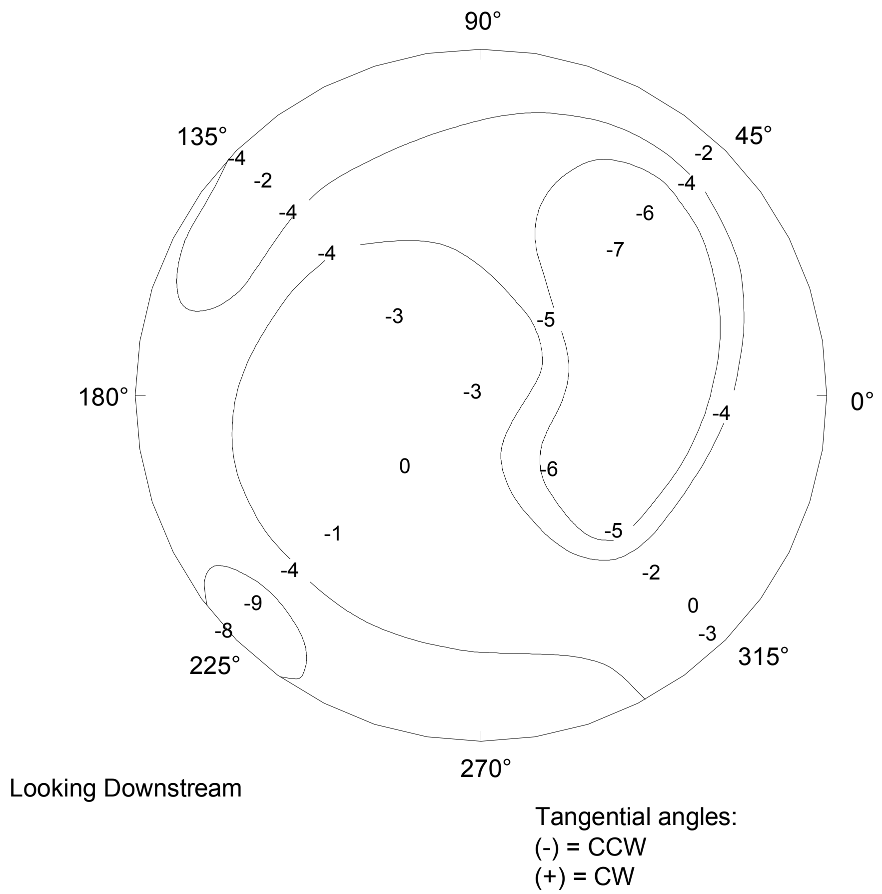


FIGURE F-8 TANGENTIAL FLOW ANGLES AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 80 FT HEAD, 94.7 CFS, 310 RPM

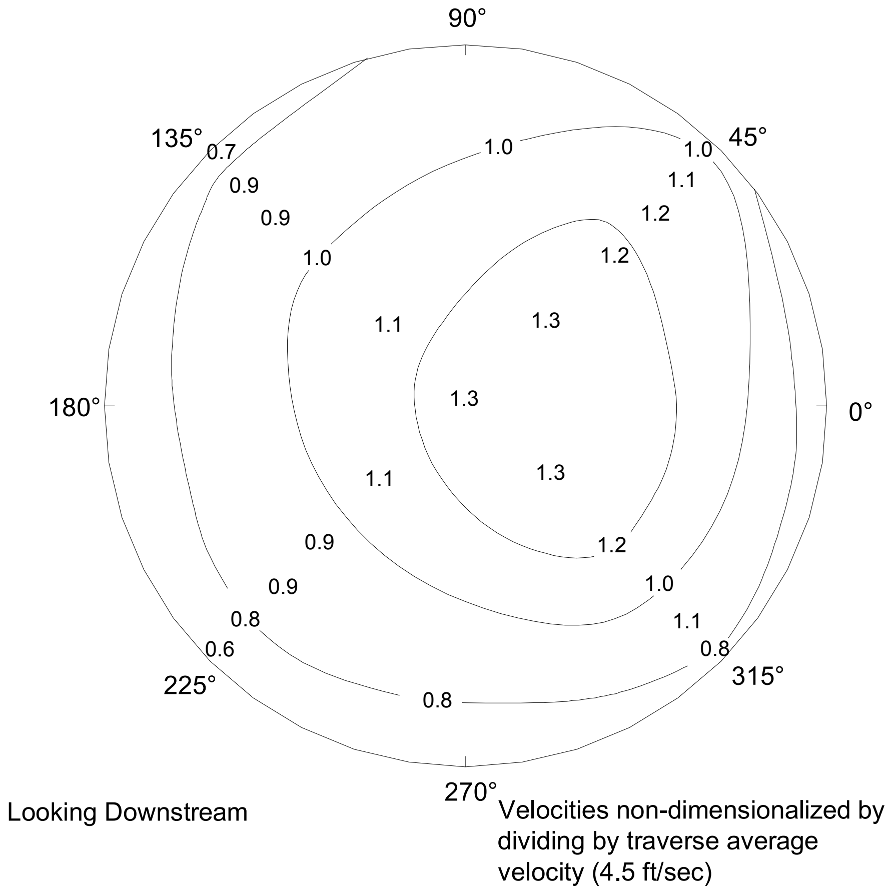


FIGURE F-9 VELOCITY PROFILE AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 80 FT HEAD, 92.7 CFS, 361 RPM

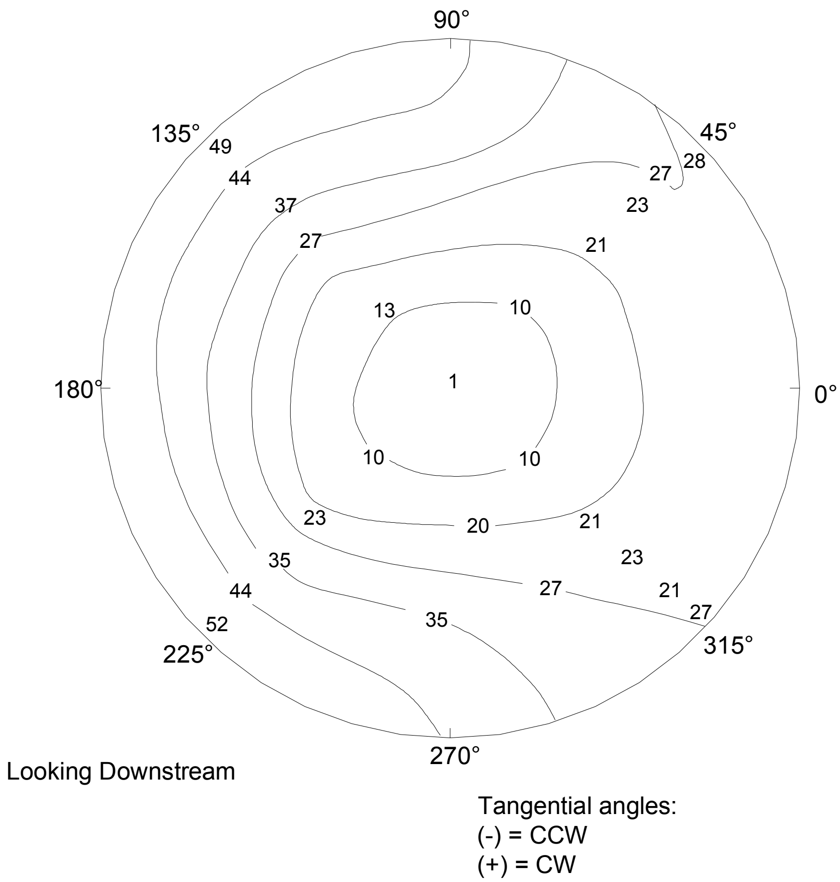


FIGURE F-10 TANGENTIAL FLOW ANGLES AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 80 FT HEAD, 92.7 CFS, 361 RPM

Theoretically, the flow pattern leaving the turbine should be the same at another head if tested at the BEP (i.e., the same φ) at that head. Velocity measurements at a 38 ft turbine head with 235 rpm and at an 80 ft head with 345 rpm confirmed the expected similar flow patterns. The resulting data, shown in Table F-8 and on Figures F-11 and F-12, indicate a similar axial velocity and tangential swirl angle distributions as for the 80 ft BEP data in Figures F-5 and F-6.

Axial velocity data obtained without wicket gates (Figures F-5 and F-11) were used to determine a kinetic energy correction coefficient (α) for the average velocity head ($V^2/2g$) at the end of the draft tube. The correction coefficient was calculated as the sum of kinetic energy per unit mass for each of the measurement areas divided by the total kinetic energy per unit mass over the entire draft tube exit area. This calculation produced a coefficient of about 1.5 and this value (times the average velocity head) was used to determine the total dynamic head ($TDH = \alpha\ V^2/2g$ plus static pressure) at the end of draft tube outlet for comparison of the turbine performance tests at BEP with and without wickets.

TABLE F-8
VELOCITY MEASUREMENTS AT CONTROL FISH INJECTION LOCATION
WITH NO WICKET GATES, 235 RPM, AND 38 FT TURBINE HEAD

Non-Dimensional Radius	V_c = 2.98 ft/sec Non-Dimensional Velocity, (v/V_c) and Tangential Flow Angles								
	45° Port		135° Port		225° Port		315° Port		Radial Average Velocity
r/R	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	
0.04	1.4	-15.0	1.1	15.0	1.5	-7.0	1.8	-10.0	1.5
0.17	1.3	-8.0	1.1	8.0	1.4	-10.0	1.8	-8.0	1.4
0.29	1.0	-5.0	1.0	2.0	1.1	-9.0	1.3	-5.0	1.1
0.44	0.8	7.0	0.7	0.0	0.6	-5.0	1.0	-9.0	0.8
0.71	0.5	29.0	0.1	-10.0	0.2	-7.0	0.3	0.0	0.3

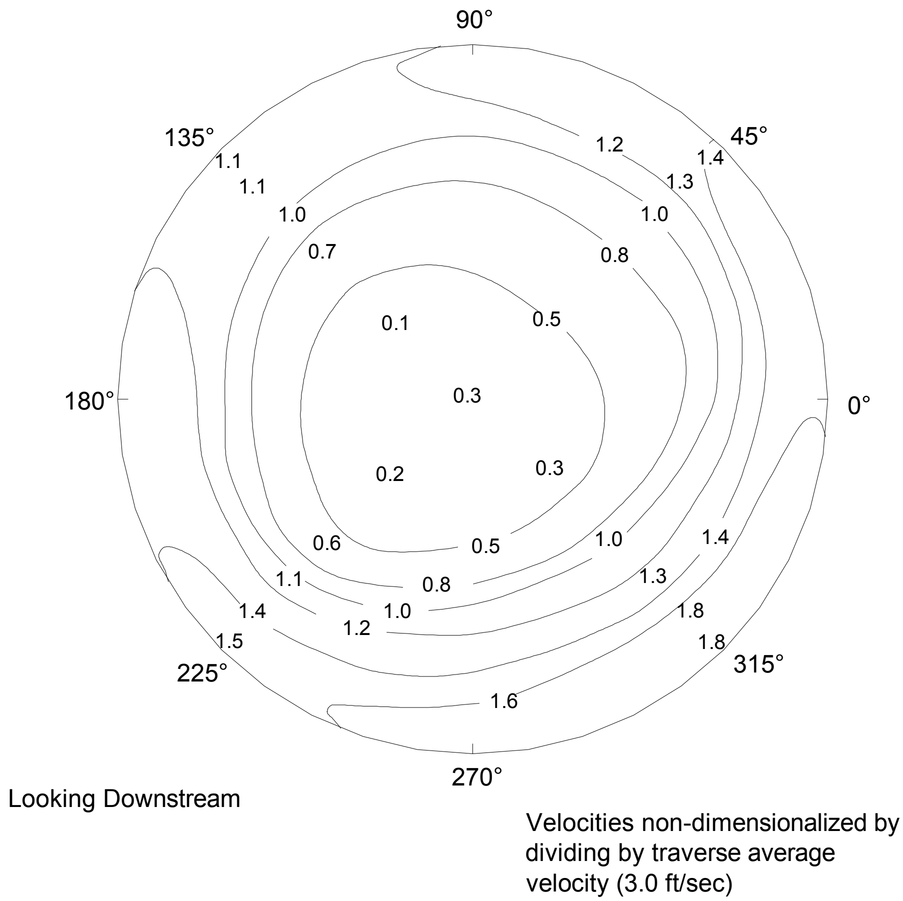


FIGURE F-11 VELOCITY PROFILE AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 38 FT HEAD, 65.7 CFS, 235 RPM

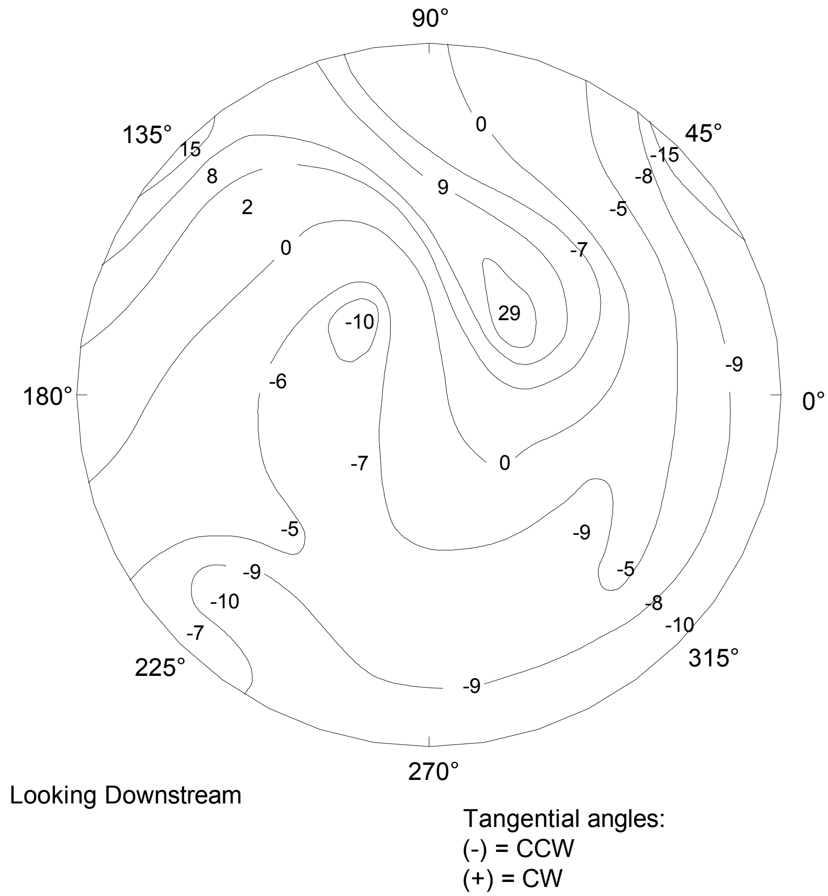


FIGURE F-12 TANGENTIAL FLOW ANGLES AT CONTROL FISH INJECTION LOCATION WITH NO WICKET GATES, 38 FT HEAD, 65.7 CFS, 235 RPM

Additional velocity measurements near the control fish injection location were obtained during the final engineering tests in fall 2002 with wicket gates for comparison to the measurements without wicket gates. Axial velocity and tangential swirl measurements were made using Alden's United Sensors 5-hole probe, serial number C-4402 (Probe No. C-3159, used for velocity measurements during the flow meter calibration and preliminary engineering without wicket gates, was not available). The probe calibration curve is provided in Appendix B. Alden's Calibration Department differential pressure (DP) cells were used for measuring the differential pressure between the probe ports. The DP cell calibrations are provided in Appendix C.

The velocity measurements at the control fish injection location were taken at 22° and 18.2° wicket gate positions, defined as the angle from fully closed, to investigate the impacts of gate angle on swirl exiting the turbine runner. As discussed in more detail in Section 4.8, the 22° wicket gate angle represents the theoretical design BEP position, and the 18.2° angle was determined to be the actual BEP gate position from preliminary test data measured with the pilot scale turbine. The turbine was operated at 80 ft head and 345 rpm for both gate positions. Velocity data for the 22° and 18.2° wicket gate positions are summarized in Tables F-9 and F-10 and plotted on Figures F-13 through F-16.

Comparison of the axial velocities in Figure F-15 (the actual measured BEP gate angle) with Figure F-13 (the theoretical BEP gate as determined from CFD analysis) indicates that the actual measured BEP gate angle produced a more uniform axial velocity distribution at the end of the draft tube. However, tangential swirl angles were higher for the actual measured BEP gate position (Figure F-14) than for the theoretical BEP gate position (Figure F-16), indicating that the residual swirl leaving the runner is sensitive to gate position. The kinetic energy correction coefficient at the actual BEP gate position was calculated to be about 1.0, lower than the 1.5 coefficient calculated without gates. A 0.5 change in the kinetic energy correction coefficient from 1.5 to 1.0 amounts to a 0.15 ft increase in the turbine head at the 80 ft test condition, corresponding to a 0.2% decrease in efficiency at BEP.

The American National Standard Code, ASME-PTC 18-1992, "Hydraulic Turbines" does not allow use of a kinetic energy correction coefficient (i.e., $\alpha=1.0$). In accordance with the code, turbine head and efficiencies reported in this document do not include a kinetic energy correction coefficient.

TABLE F-9
VELOCITY MEASUREMENTS AT CONTROL FISH INJECTION LOCATION
WITH 22° WICKET GATE ANGLE, 345 RPM, AND 80 FT TURBINE HEAD

Non-Dimensional Radius	V_c = 7.11 ft/sec Non-Dimensional Velocity, (v/V_c) and Tangential Flow Angles								
r/R	45° Port		135° Port		225° Port		315° Port		Radial Average Velocity
	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	
0.043	1.0	20.0	1.2	6.0	1.5	-6.0	1.6	-10.0	1.3
0.170	1.1	1.0	1.1	6.0	1.3	-4.0	1.5	-10.0	1.3
0.290	1.1	-2.0	1.0	4.0	1.0	-5.0	1.2	-11.0	1.1
0.440	1.0	-5.0	0.8	3.0	0.7	0.0	0.9	-5.0	0.9
0.710	0.9	0.0	0.8	3.0	0.7	1.0	0.9	16.0	0.8

TABLE F-10
VELOCITY MEASUREMENTS AT CONTROL FISH INJECTION LOCATION
WITH 18.2° WICKET GATE ANGLE, 345 RPM, AND 80 FT TURBINE HEAD

Non-Dimensional Radius	V_c = 4.67 ft/sec Non-Dimensional Velocity, (v/V_c) and Tangential Flow Angles								
r/R	45° Port		135° Port		225° Port		315° Port		Radial Average Velocity
	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	v/V_c	Tan. Angle	
0.04	0.9	32.3	1.1	16.3	0.6	44.3	0.8	43.3	0.9
0.17	1.1	28.3	1.1	20.3	0.8	36.3	0.8	39.3	0.9
0.29	1.1	24.3	1.2	18.3	0.9	30.3	0.8	31.3	1.0
0.44	1.1	23.3	1.1	20.3	0.9	21.3	1.2	14.3	1.1
0.71	1.1	21.3	1.1	14.3	1.1	5.3	1.2	10.3	1.1

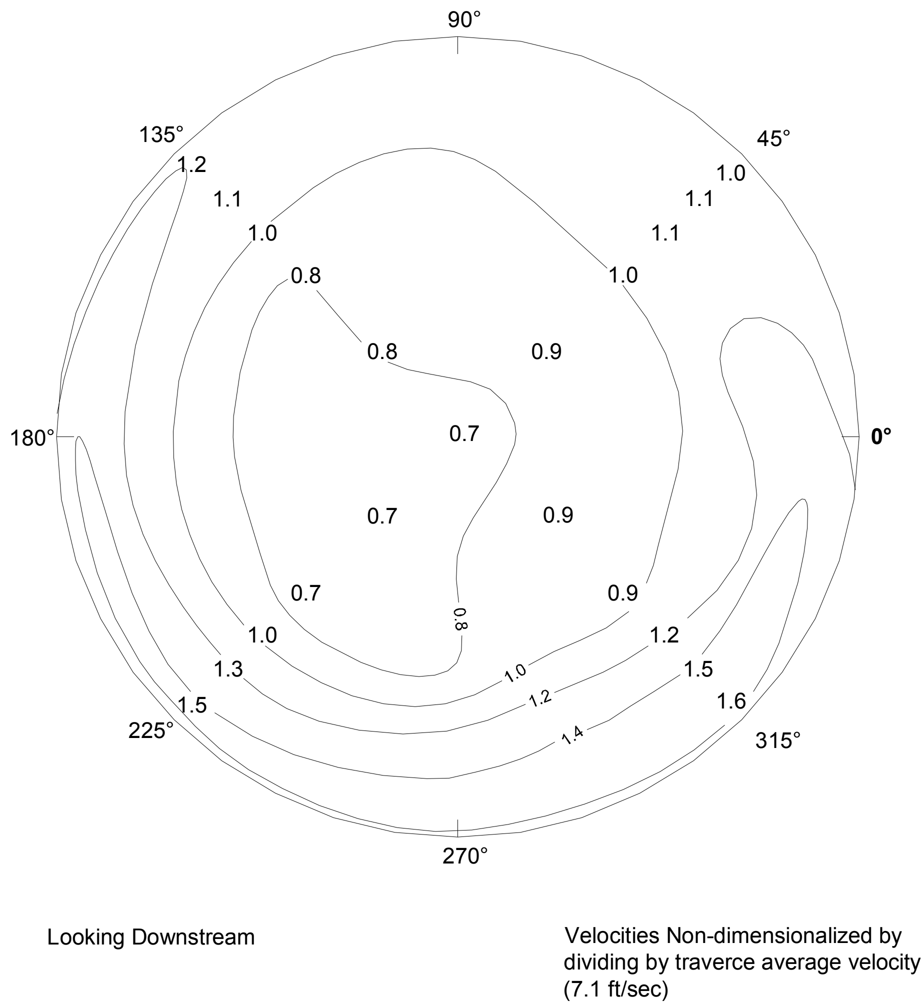


FIGURE F-13 VELOCITY PROFILE AT CONTROL FISH INJECTION LOCATION WITH 22° WICKET GATE ANGLE, 80 FT HEAD, 92.7 CFS; 345 RPM

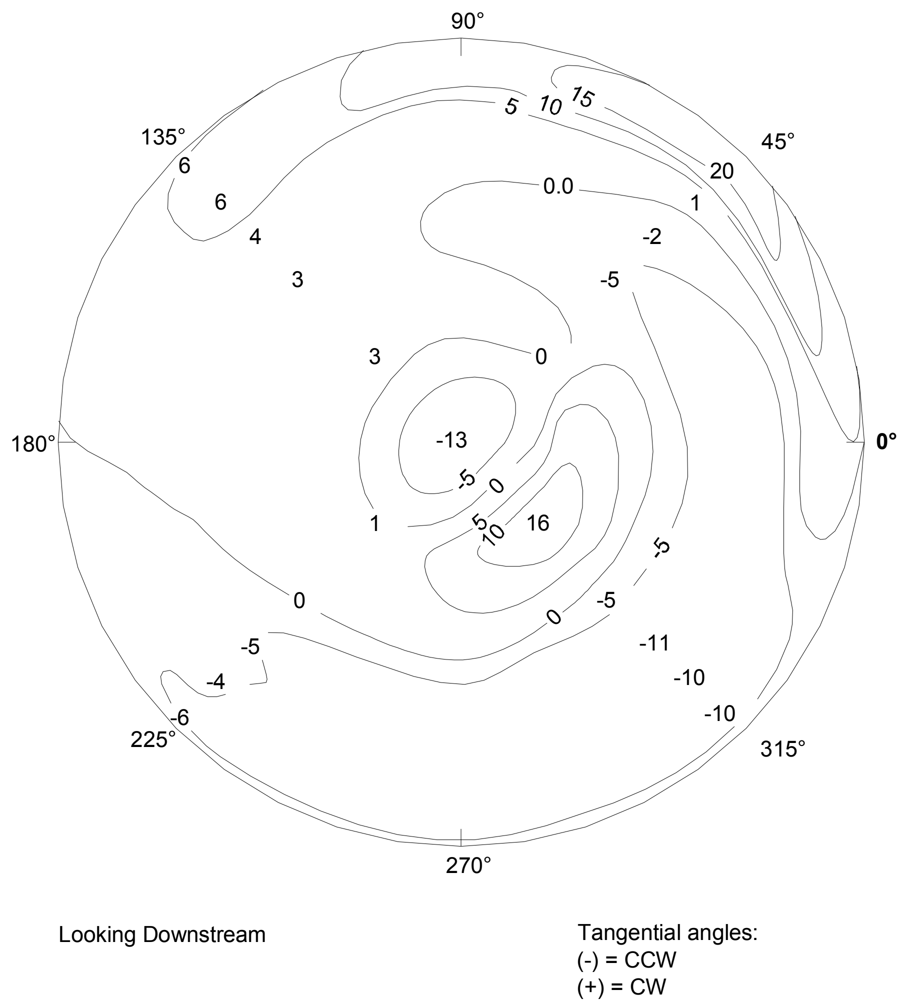


FIGURE F-14 TANGENTIAL FLOW ANGLES AT CONTROL FISH INJECTION LOCATION WITH 22° WICKET GATE ANGLE, 80 FT HEAD, 92.7 CFS, 345 RPM

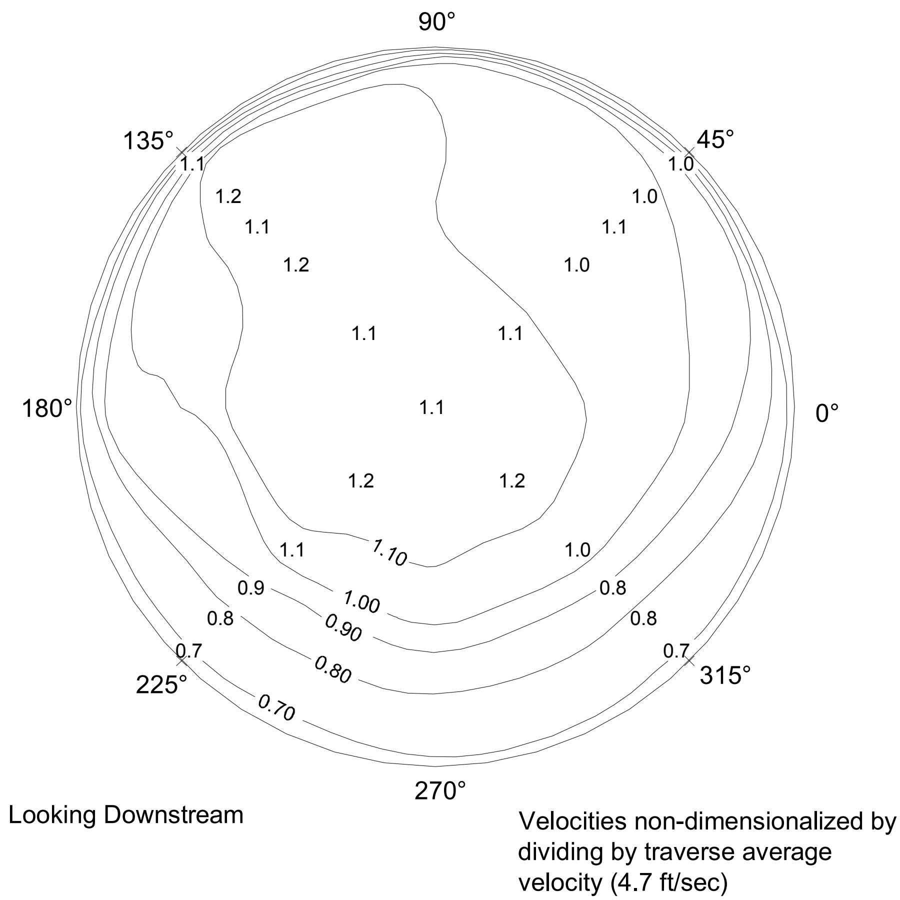


FIGURE F-15 VELOCITY PROFILE AT CONTROL FISH INJECTION LOCATION WITH 18.2° WICKET GATE ANGLE (ACTUAL BEP), 80 FT HEAD, 92.7 CFS, 345 RPM

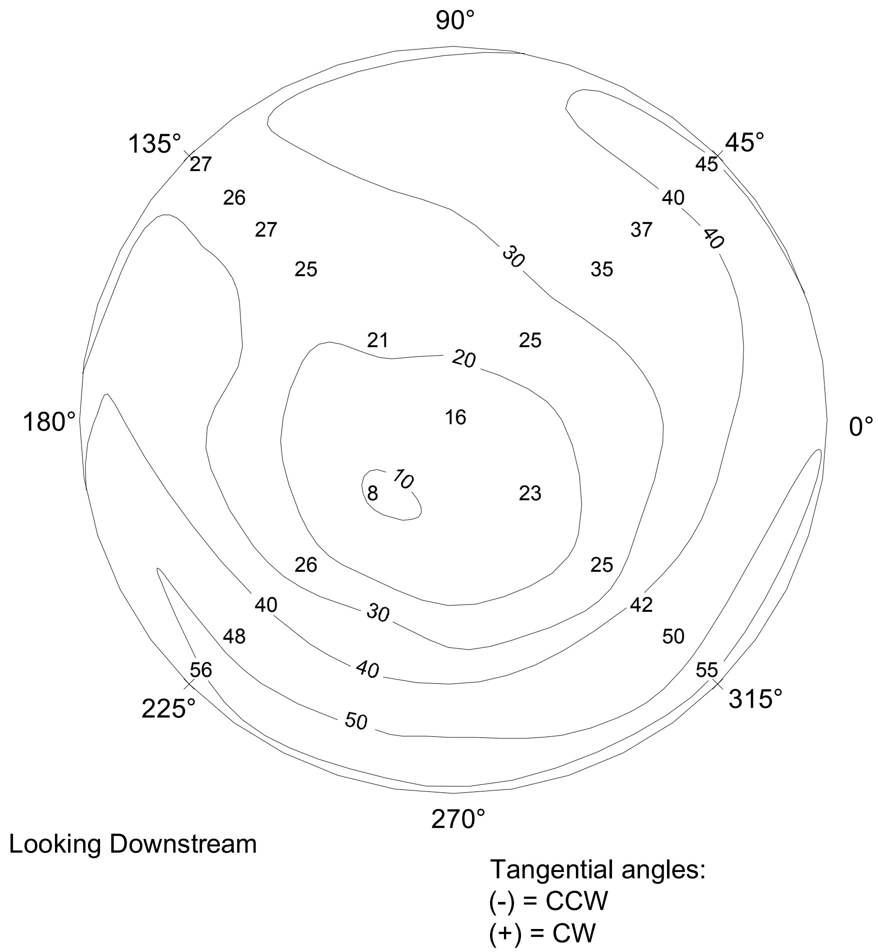


FIGURE F-16 TANGENTIAL FLOW ANGLES AT CONTROL FISH INJECTION LOCATION WITH 18.2° WICKET GATE ANGLE, 80 FT HEAD, 92.7 CFS, 345 RPM

TURBINE RUNNER INLET

Velocity measurements were obtained in the downturn at the runner inlet downstream of the wicket gates during final engineering tests. The measurements were obtained with United Sensor's 5-hole probe, serial number C-4355. The probe calibration curve and the differential pressure cell calibrations are provided in Appendices B and C, respectively.

The runner inlet measurements were taken at 22º and 18.2º wicket gate positions with the turbine operating at 40 ft of head, 61 cfs, and 240 rpm. Measurements were also taken at the 18.2º wicket gate positions with the turbine operating at 80 ft of head, 92.7 cfs, and 345 rpm. A plan and section of the velocity measurement locations at the runner inlet are shown on Figures F-17 and F-18, respectively.

The probe yaw angle, which is the angle of the velocity in the plane perpendicular to the probe axis, as shown on Figure F-19, was obtained by rotating the probe to zero pressures in ports 2 and 3 and physically measured with a protractor off horizontal. Impact velocity and pitch angle were measured with the probe and were used with the calibration curve to calculate the absolute (resultant) velocity. A three-dimensional AutoCad drawing of the measured velocity and angles was prepared to measure the radial and axial angles. The radial angle is the projection of the absolute velocity (V) in the horizontal plane (Figure F-17) and is comparable to the absolute inlet angle from the radius discussed in Section 4.7. The axial angle is defined as the projection of the absolute velocity in the vertical plane (Va) looking at a radial cross section of the runner (Figure F-18).

A summary of the runner inlet velocity measurement results is presented in Table F-11. Measured radial angles of the absolute velocity ranged between 68.2° and 73.0° with the 18.2° wicket gate position (actual BEP) at the 40 ft and 80 ft head operating conditions. At the actual BEP gate position, the average radial angle was 70.3°, agreeing with the 69° design angle predicted by the original CFD analysis.

Measured absolute velocities in the downturn were 20.7 to 23.4 ft/sec at 40 ft and 29.0 to 32.4 ft/sec at 80 ft heads with the wicket gates at the BEP position (18.2°). These velocities are lower than the leading edge velocities shown on Figure 4-21 because the probe was located some distance away from the leading edge and velocities within the scroll decrease with distance from the center of the runner. The predicted velocity at the location of the measurements is 22.7 ft/sec compared to the 22.6 ft/sec average measured velocity for 40 ft head with the 18.2° gate position. At 80 ft head, the predicted velocity at the measured location is 33.2 ft/sec compared to the 31.1 ft/sec average measured velocity with the wicket gates at 18.2°.

At a 22° wicket gate position, which was the BEP gate angle predicted with the original CFD design, the average measured radial angle was 68.5° for the 40 ft head operating condition, compared to the original 69° design angle. The average measured velocity was 20.8 ft/sec, compared to the 22.7 ft/sec predicted velocity during the original design.

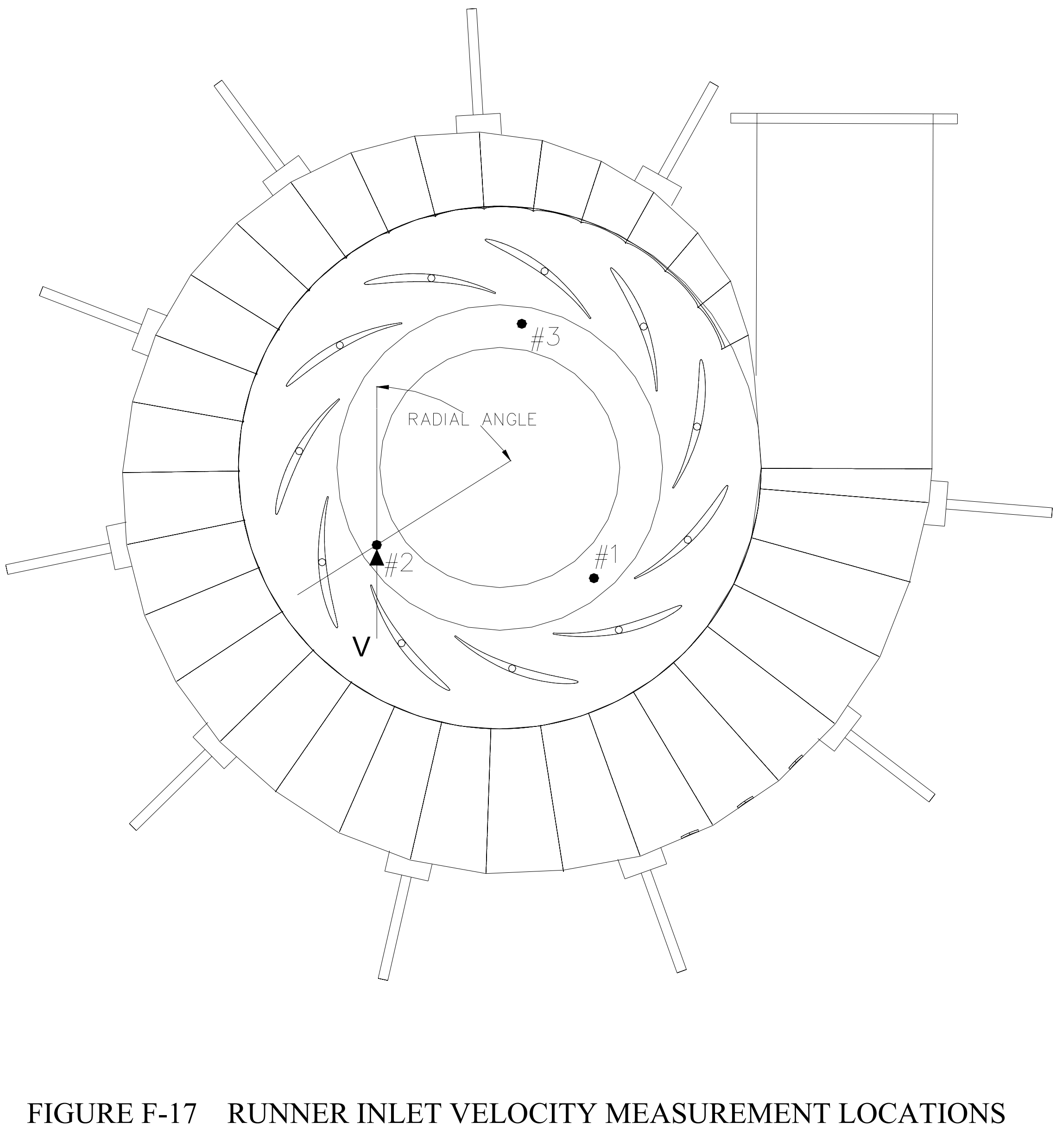


FIGURE F-17 RUNNER INLET VELOCITY MEASUREMENT LOCATIONS

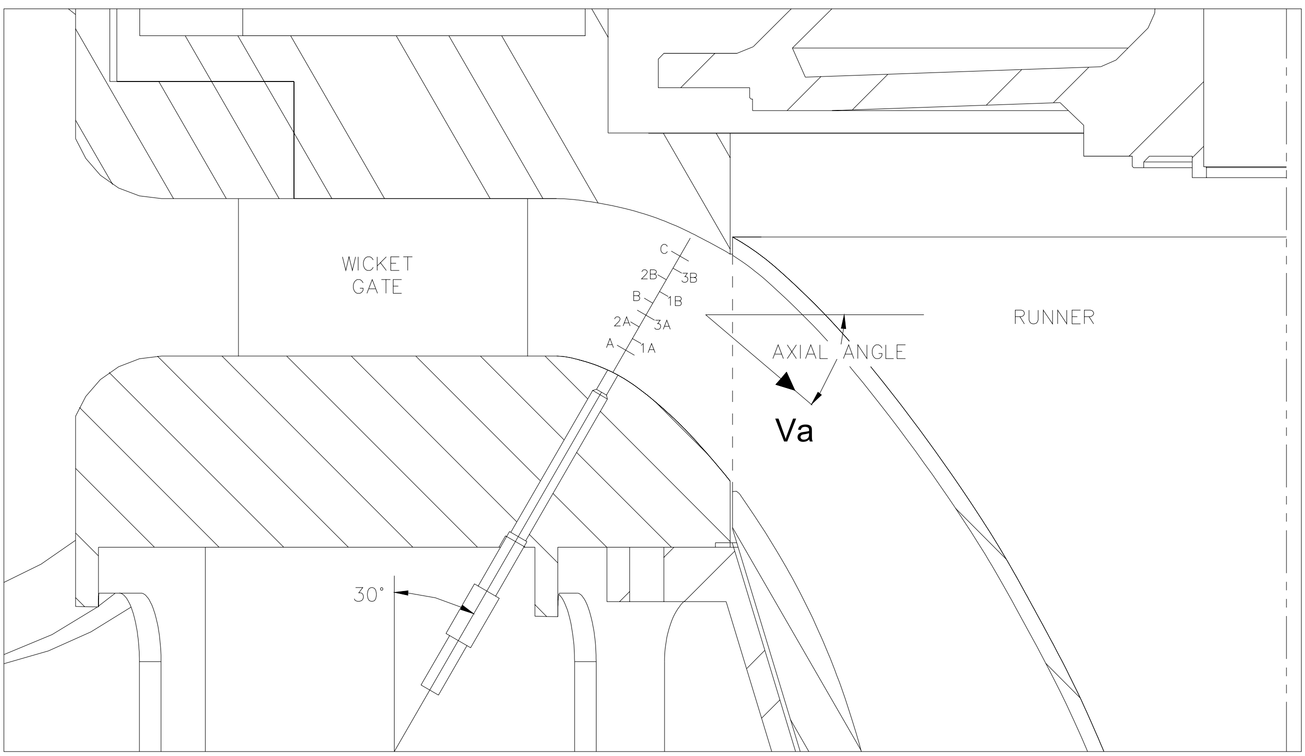
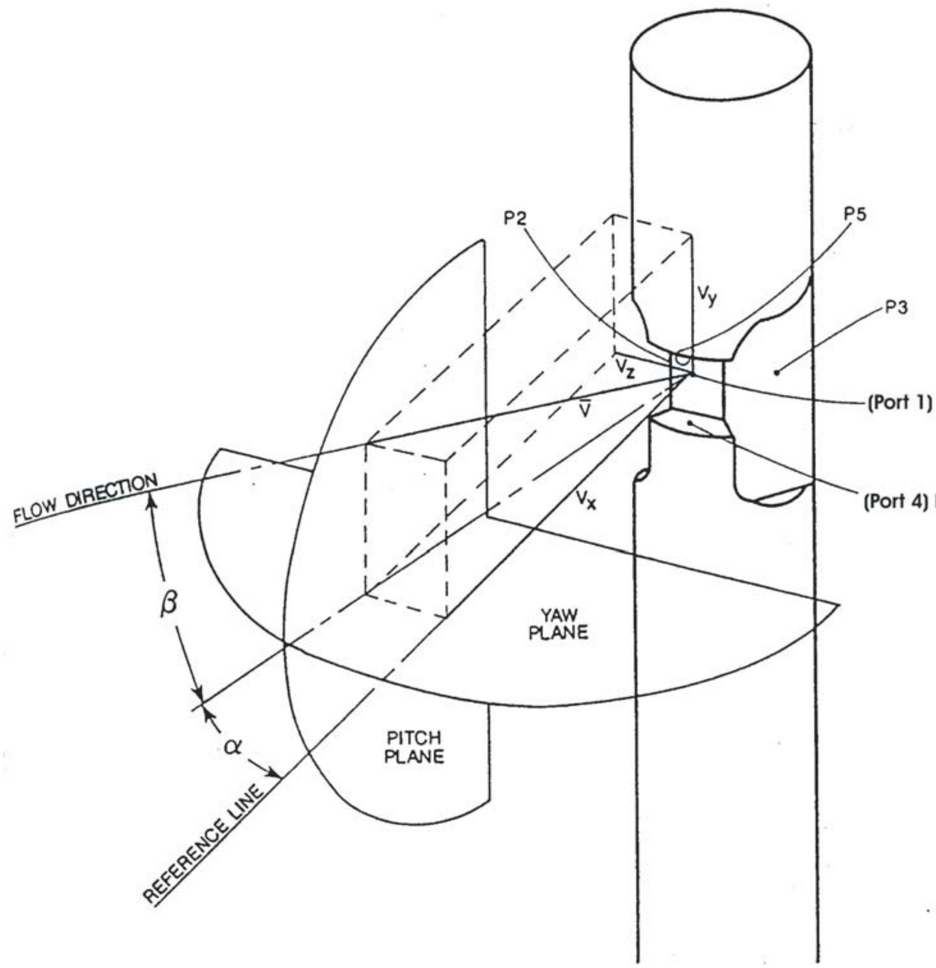


FIGURE F-18   RUNNER INLET VELOCITY MEASUREMENT INSERTION DEPTHS



NOTE: VELOCITY VECTOR COMPONENTS Vx, Vy, Vz APPLY ONLY WHEN PROBE IS HORIZONTALLY ORIENTATED.

Vx = V cos cos

Vy = V cos cos

Vz = V cos cos

FIGURE F-19 VELOCITY PROBE REFERENCE ANGLES AND VECTORS

TABLE F-11
TURBINE RUNNER INLET VELOCITY MEASUREMENTS

Description	Location	Depth	Axial Angle (deg)	Radial Angle (deg)	Velocity Magnitude (ft/sec)
22 degree wicket gate position, 40 ft head, 61 cfs, 240 rpm, phi 0.990	1	A	17.6	64.2	19.9
	2	A	20.1	65.2	20.6
	3	A	19.4	65.1	20.6
		Avg.A	**19.0**	**64.8**	**20.4**
	1	B	14.8	68.9	20.3
	2	B	13.6	73.7	19.3
	3	B	15.5	69.3	20.6
		Avg.B	**14.6**	**70.6**	**20.1**
	1	C	15.3	69.4	21.8
	2	C	17.9	70.6	21.7
	3	C	17.2	70.2	22.4
		Avg.C	**16.8**	**70.1**	**22.0**
18.2 degree wicket gate position, 40 ft head, 61 cfs, 240 rpm, phi 0.990	1	A	14.2	62.7	23.0
	2	A	13.3	71.1	22.5
	3	A	12.7	73.5	20.3
		Avg.A	**13.4**	**69.1**	**21.9**
	1	B	15.7	66.9	24.4
	2	B	14.4	69.2	24.6
	3	B	12.6	72.5	21.6
		Avg.B	**14.2**	**69.5**	**23.5**
	1	C	19.6	68.6	25.3
	2	C	15.2	69.5	24.7
	3	C	13.3	70.9	22.7
		Avg.C	**16.0**	**69.7**	**24.2**
18.2 degree wicket gate position, 40 ft head, 61 cfs, 240 rpm, phi 0.990	1	A	12.6	72.7	20.7
		1A	12.4	71.5	21.9
		2A	13.0	71.5	21.8
		3A	13.1	70.9	22.5
		B	12.9	70.5	22.9
		1B	12.9	70.2	23.1
		2B	12.9	70.1	23.2
		3B	12.9	69.9	23.3
		C	13.2	70.0	23.4

TABLE F-11 (CONTINUED)

Description	Location	Depth	Axial Angle (deg)	Radial Angle (deg)	Velocity Magnitude (ft/sec)
18.2 degree wicket gate position, 80 ft head, 92.7 cfs, 345 rpm, phi 1.005	1	A	17.1	70.2	29.9
	2	A	16.0	68.3	28.0
	3	A	15.9	69.5	31.5
		Avg.A	**16.3**	**69.3**	**29.8**
	1	B	12.9	71.5	32.5
	2	B	13.5	70.6	31.5
	3	B	14.0	72.1	31.5
		Avg.B	**13.5**	**71.4**	**31.8**
	1	C	11.3	73.0	32.4
		Avg.C	**11.3**	**73.0**	**32.4**

The runner inlet velocity measurements indicate that the original CFD analysis predicted flow angles at the leading edge of the runner with good accuracy, but overestimated the turbine flow for the design head.

APPENDIX G

ENGINEERING TEST DATA

APPENDIX G
ENGINEERING TEST DATA

TABLE G-1
ENGINEERING TEST DATA WITHOUT WICKET GATES

Test No.	Flow (cfs)	Turbine Head (ft)	Turbine Speed (rpm)	Turbine Power (HP)	Turbine Efficiency (%)	Runner Efficiency (%)	Runner Head (ft)	Phi (φ)	Unit Power
1a	94.78	82.08	332.5	755.0	85.57	95	75.01	0.958	0.0635
2a	93.70	81.14	337.2	740.5	85.90	94	75.2	0.977	0.0633
3a	92.21	79.62	343.1	716.2	86.01	93	75.3	1.004	0.0630
4a	89.55	77.23	352.1	673.3	85.85	90	75.05	1.046	0.0620
5a	88.01	75.93	358.1	648.0	85.47	88	75.01	1.073	0.0612
6a	91.53	79.51	349.6	711.2	86.17	92	76.16	1.023	0.0627
7a	90.68	79.71	361.3	703.3	85.79	89	77.98	1.056	0.0618
8a	68.57	41.98	225.3	273.4	83.76	97	36.77	0.908	0.0628
9a	66.27	40.11	232.8	256.8	85.17	95	36.73	0.959	0.0632
10a	64.41	39.02	241.1	243.2	85.33	92	36.96	1.007	0.0624
10b	64.46	39.00	240.2	243.4	85.38	92	36.85	1.004	0.0625
11a	62.27	37.65	244.6	225.2	84.71	90	36.25	1.041	0.0609
12a	59.61	36.06	257.6	202.5	83.09	84	36.55	1.120	0.0584
13a	81.54	60.16	280.2	474.0	85.23	96	54.38	0.943	0.0635
14a	80.68	60.07	290.7	472.0	85.90	94	55.83	0.979	0.0634
15a	79.72	60.13	302.3	467.4	86.00	92	57.35	1.018	0.0626
16a	78.72	60.14	313.8	459.6	85.63	89	58.79	1.056	0.0616
17a	77.60	60.07	325.6	448.4	84.85	86	60.13	1.097	0.0602
18a	97.10	85.31	332.2	802.4	85.41	97	76.78	0.939	0.0636
19a	96.10	85.29	341.4	801.1	86.18	96	78.11	0.965	0.0636
20a	94.90	85.41	362	790.0	85.96	91	81.76	1.022	0.0626
21a	93.75	85.27	374.3	776.3	85.65	89	83.52	1.058	0.0616
22a	93.00	85.80	387.3	769.1	84.99	87	85.73	1.091	0.0605
23a	74.52	50.02	253.2	357.7	84.62	96	44.9	0.934	0.0632
24a	73.85	50.09	263.4	358.0	85.38	94	46.29	0.971	0.0631
25a	72.57	50.03	277.6	351.8	85.47	91	47.95	1.024	0.0621
26a	71.52	50.05	290	344.3	84.83	88	49.36	1.070	0.0608
27a	70.95	50.23	298.2	340.5	84.23	86	50.35	1.098	0.0598
28a	88.13	70.25	302.4	597.1	85.04	96	63.44	0.942	0.0634
29a	87.24	70.25	313.9	596.1	85.79	94	65.19	0.978	0.0633
30a	86.19	70.34	327.5	591.7	86.05	92	67.19	1.019	0.0627
31a	84.88	69.89	338.8	576.1	85.63	89	68.45	1.058	0.0616
32a	83.86	70.31	354.5	566.5	84.72	86	70.75	1.103	0.0601

TABLE G-2
APRIL PRELIMINARY TURBINE TEST DATA WITH WICKET GATES

Date	Gate Position (degree)	Flow Rate (cfs)	Turbine Head (ft)	Turbine (rpm)	Turbine (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
12-Apr-02	22	97.55	80.28	346.30	764.96	86.08	1.009	0.066
12-Apr-02	22	98.35	80.38	338.44	771.90	86.05	0.985	0.067
12-Apr-02	22	99.00	80.37	331.25	775.07	85.85	0.964	0.067
12-Apr-02	22	99.61	80.40	324.78	777.08	85.50	0.945	0.067
12-Apr-02	22	100.18	80.45	317.59	778.05	85.08	0.924	0.067
12-Apr-02	22	97.15	80.42	353.18	766.61	86.46	1.028	0.066
12-Apr-02	22	96.58	80.29	359.01	761.33	86.52	1.046	0.066
12-Apr-02	22	95.96	80.30	367.04	755.29	86.38	1.069	0.066
12-Apr-02	22	95.70	80.47	372.90	754.18	86.29	1.085	0.065
12-Apr-02	22	95.20	80.54	379.69	748.59	86.05	1.104	0.065
15-Apr-02	22	97.89	80.66	345.88	773.52	86.34	1.005	0.067
Ave			**80.41**					
15-Apr-02	22	69.83	40.93	244.20	276.78	85.34	0.996	0.066
15-Apr-02	22	67.29	38.41	240.40	249.84	85.19	1.013	0.066
15-Apr-02	22	68.15	38.54	232.93	253.64	85.11	0.979	0.066
15-Apr-02	22	68.40	38.27	226.76	251.92	84.82	0.957	0.067
15-Apr-02	22	69.45	38.62	218.01	255.27	83.87	0.916	0.066
15-Apr-02	22	69.65	38.42	212.15	253.01	83.32	0.893	0.066
15-Apr-02	22	66.47	38.43	249.91	246.64	85.07	1.052	0.065
15-Apr-02	22	66.10	38.34	254.13	244.28	84.95	1.071	0.064
15-Apr-02	22	65.60	38.50	262.22	242.24	84.52	1.103	0.063
15-Apr-02	22	65.34	38.61	268.26	241.35	84.30	1.127	0.063
15-Apr-02	22	64.82	38.56	274.29	237.46	83.71	1.153	0.062
Ave			**38.69**					
16-Apr-02	20	62.53	38.28	241.21	233.41	85.93	1.018	0.062
16-Apr-02	20	63.23	38.34	233.22	236.46	85.95	0.983	0.062
16-Apr-02	20	64.07	38.54	225.04	239.37	85.43	0.946	0.063
16-Apr-02	20	64.21	38.30	219.83	237.37	85.05	0.927	0.063
16-Apr-02	20	64.61	38.19	212.37	235.79	84.22	0.897	0.062
16-Apr-02	20	62.10	38.31	246.92	232.17	85.99	1.041	0.061
16-Apr-02	20	61.54	38.30	254.17	229.01	85.59	1.072	0.060
Ave			**38.32**					
17-Apr-02	20	91.11	80.38	345.28	720.86	86.75	1.005	0.063
17-Apr-02	20	91.67	80.37	338.41	724.44	86.64	0.985	0.063
17-Apr-02	20	92.09	80.26	330.90	723.60	86.34	0.964	0.063
17-Apr-02	20	92.53	80.23	325.03	724.77	86.09	0.947	0.063
17-Apr-02	20	93.12	80.27	316.86	725.29	85.58	0.923	0.063
17-Apr-02	20	90.56	80.48	353.46	719.85	87.09	1.028	0.062
17-Apr-02	20	89.99	80.44	360.63	714.26	87.00	1.050	0.062
17-Apr-02	20	89.65	80.46	365.36	711.03	86.93	1.063	0.062

Date	Gate Position (degree)	Flow Rate (cfs)	Turbine Head (ft)	Turbine (rpm)	Turbine (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
17-Apr-02	20	88.87	80.19	372.25	700.28	86.65	1.085	0.061
17-Apr-02	20	88.35	80.45	380.46	693.87	86.09	1.107	0.060
Ave	20		**80.35**					
17-Apr-02	18	84.80	80.10	345.17	672.11	87.36	1.007	0.059
17-Apr-02	18	85.47	80.29	338.20	678.47	87.29	0.985	0.059
17-Apr-02	18	85.98	80.26	331.47	681.53	87.19	0.966	0.059
17-Apr-02	18	86.36	80.18	324.41	680.34	86.75	0.946	0.059
17-Apr-02	18	87.02	80.41	316.98	683.43	86.22	0.923	0.059
17-Apr-02	18	84.31	80.20	352.15	669.57	87.42	1.026	0.058
17-Apr-02	18	83.74	80.38	359.52	663.57	87.03	1.047	0.058
17-Apr-02	18	82.82	80.14	366.71	649.17	86.34	1.069	0.057
18-Apr-02	18	82.16	80.27	372.45	636.19	85.17	1.085	0.055
18-Apr-02	18	81.46	80.38	380.13	625.83	84.40	1.107	0.054
Ave			**80.26**					
18-Apr-02	18	58.25	38.27	240.16	217.66	86.20	1.013	0.057
18-Apr-02	18	58.77	38.19	233.16	219.51	86.33	0.985	0.058
18-Apr-02	18	59.45	38.31	225.44	221.66	85.93	0.951	0.058
18-Apr-02	18	59.72	38.16	218.76	219.95	85.20	0.924	0.058
18-Apr-02	18	60.11	38.14	210.19	218.37	84.11	0.888	0.058
18-Apr-02	18	57.57	38.37	247.83	214.07	85.59	1.044	0.056
18-Apr-02	18	57.15	38.45	253.15	211.25	84.87	1.066	0.055
Ave			**38.27**					
18-Apr-02	16	53.51	38.30	240.10	197.13	84.91	1.013	0.052
18-Apr-02	16	54.39	38.59	234.27	204.20	85.88	0.984	0.053
18-Apr-02	16	54.85	38.46	226.64	205.20	85.85	0.954	0.054
18-Apr-02	16	55.06	38.31	220.75	204.02	85.38	0.931	0.054
19-Apr-02	16	52.98	38.39	246.28	191.83	83.27	1.037	0.050
Ave			**38.41**					
19-Apr-02	16	77.82	80.36	345.98	607.57	85.77	1.007	0.053
19-Apr-02	16	78.49	80.36	338.04	617.10	86.38	0.984	0.054
19-Apr-02	16	79.01	80.40	331.98	621.32	86.34	0.966	0.054
19-Apr-02	16	79.55	80.39	324.24	623.63	86.08	0.944	0.054
19-Apr-02	16	79.72	80.28	319.19	621.73	85.77	0.930	0.054
19-Apr-02	16	77.29	80.50	351.96	601.50	85.37	1.024	0.052
19-Apr-02	16	76.74	80.65	359.11	593.58	84.66	1.044	0.051
19-Apr-02	16	75.95	80.61	367.01	581.50	83.85	1.067	0.050
19-Apr-02	16	75.23	80.42	374.46	568.48	82.95	1.090	0.049
19-Apr-02	16	74.55	80.45	381.74	556.94	81.98	1.111	0.048
22-Apr-02	16	74.67	80.41	378.76	557.70	82.02	1.102	0.048
22-Apr-02	16	75.47	79.87	365.50	570.19	83.52	1.067	0.050
Ave			**80.39**					
23-Apr-02	24	103.79	80.29	344.79	809.84	85.67	1.004	0.070
23-Apr-02	24	104.54	80.54	338.83	817.29	85.56	0.985	0.071

Date	Gate Position (degree)	Flow Rate (cfs)	Turbine Head (ft)	Turbine (rpm)	Turbine (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
23-Apr-02	24	104.83	80.11	331.54	811.95	85.20	0.967	0.071
23-Apr-02	24	105.67	80.45	324.78	817.22	84.73	0.945	0.071
23-Apr-02	24	106.34	80.45	316.84	817.51	84.24	0.922	0.071
23-Apr-02	24	104.46	81.91	351.40	832.14	85.74	1.013	0.070
23-Apr-02	24	102.35	80.42	359.78	800.28	85.69	1.047	0.069
23-Apr-02	24	101.92	80.74	367.78	798.37	85.52	1.068	0.069
23-Apr-02	24	101.13	80.29	373.57	785.52	85.28	1.088	0.068
23-Apr-02	24	100.71	80.46	380.52	782.00	85.08	1.107	0.068
Ave			**80.57**					
23-Apr-02	24	71.34	38.17	239.21	262.03	84.80	1.011	0.069
23-Apr-02	24	72.00	38.25	233.12	264.59	84.70	0.984	0.070
23-Apr-02	24	72.61	38.32	227.42	266.16	84.35	0.959	0.070
23-Apr-02	24	73.25	38.28	218.93	265.80	83.54	0.924	0.070
23-Apr-02	24	73.61	38.21	212.76	264.35	82.86	0.898	0.070
23-Apr-02	24	70.67	38.39	247.64	260.43	84.62	1.043	0.068
23-Apr-02	24	70.11	38.35	253.49	257.33	84.36	1.068	0.068
23-Apr-02	24	69.45	38.27	261.16	253.36	84.03	1.102	0.067
23-Apr-02	24	69.00	38.39	268.94	251.34	83.65	1.133	0.066
23-Apr-02	24	68.48	38.30	275.01	247.04	83.02	1.160	0.065
Ave			**38.29**					
SET POINTS								
25-Apr-02	18.2	83.96	78.62	344.51	644.34	86.02	1.014	0.058
25-Apr-02	18.2	84.15	79.02	345.44	649.45	86.09	1.014	0.058
26-Apr-02	18.2	85.01	80.35	346.49	666.31	85.98	1.009	0.058
26-Apr-02	18.2	85.74	81.13	344.19	678.36	85.98	0.997	0.058
26-Apr-02	18.2	82.76	77.02	344.67	621.19	85.90	1.025	0.057
26-Apr-02	18.2	83.48	78.16	345.80	636.64	86.00	1.021	0.058
25-Apr-02	18.2	60.72	40.58	241.43	238.34	85.26	0.989	0.058
25-Apr-02	18.2	60.85	40.65	240.78	230.27	85.25	0.986	0.056
25-Apr-02	18.2	61.67	41.40	239.71	246.70	86.17	0.972	0.058

TABLE G-3
RECORDED DATA FOR SPRING 2002 BIOLOGICAL BEP TESTS AT 240 RPM

Date	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
25-Apr-02	60.72	40.58	241.43	239.61	85.71	0.989	0.058
26-Apr-02	60.40	40.21	241.32	235.69	85.54	0.993	0.058
26-Apr-02	60.41	40.19	240.59	235.71	85.59	0.991	0.058
29-Apr-02	60.74	40.56	240.79	238.71	85.40	0.987	0.058
30-Apr-02	60.69	40.42	239.99	236.81	85.11	0.985	0.058
1-May-02	60.86	40.62	240.16	239.91	85.56	0.983	0.058
2-May-02	60.52	40.34	240.90	235.94	85.20	0.990	0.058
2-May-02	60.63	40.41	240.52	236.96	85.26	0.988	0.058
3-May-02	60.54	40.38	241.56	236.30	85.23	0.992	0.058
8-May-02	61.01	40.75	241.03	242.40	85.95	0.985	0.058
9-May-02	60.44	40.08	239.78	234.72	85.40	0.989	0.058
9-May-02	60.27	39.97	240.64	233.59	85.47	0.993	0.058
9-May-02	60.93	40.61	240.55	240.10	85.53	0.985	0.058
10-May-02	61.03	40.52	239.29	240.79	85.80	0.981	0.058
13-May-02	60.55	40.28	240.58	235.66	85.17	0.989	0.058
13-May-02	60.29	39.94	239.84	233.00	85.29	0.991	0.058
13-May-02	60.50	40.29	241.80	236.09	85.37	0.994	0.058
17-May-02	60.61	40.33	239.42	238.15	85.91	0.984	0.058
17-May-02	60.63	40.42	240.97	238.84	85.95	0.989	0.058
17-May-02	60.59	40.35	240.32	238.56	86.05	0.987	0.058
20-May-02	60.67	40.51	239.60	237.52	85.20	0.983	0.058
20-May-02	60.65	40.39	238.85	237.43	85.48	0.981	0.058
20-May-02	61.04	40.69	239.64	242.47	86.09	0.981	0.058
21-May-02	60.61	40.40	239.48	237.02	85.38	0.983	0.058
21-May-02	60.46	40.34	240.27	236.65	85.56	0.987	0.058
21-May-02	61.02	40.86	239.72	242.50	85.75	0.979	0.058
22-May-02	60.79	40.56	240.64	241.01	86.19	0.986	0.058
24-May-02	60.99	40.61	238.18	239.74	85.36	0.976	0.058
24-May-02	60.74	40.39	239.68	237.55	85.40	0.984	0.058
28-May-02	60.60	40.37	240.35	235.88	85.03	0.987	0.057
30-May-02	61.27	40.95	239.43	242.33	85.17	0.977	0.058
31-May-02	60.56	40.43	240.59	235.62	84.89	0.988	0.057
Average	**60.68**	**40.43**	**240.25**	**237.91**	**85.50**	**0.986**	**0.058**
Median	**60.63**	**40.41**	**240.34**	**237.48**	**85.43**	**0.987**	**0.058**
Minimum	**60.27**	**39.94**	**238.18**	**233.00**	**84.89**	**0.976**	**0.057**
Maximum	**61.27**	**40.95**	**241.80**	**242.50**	**86.19**	**0.994**	**0.058**
Std. Dev.	**0.24**	**0.22**	**0.81**	**2.59**	**0.33**	**0.005**	**0.000**

TABLE G-4
RECORDED DATA FOR SPRING 2002 BIOLOGICAL BEP TESTS AT 345 RPM

Date	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
25-Apr-02	84.15	79.02	345.44	653.03	86.58	1.014	0.058
26-Apr-02	83.48	78.16	345.80	640.15	86.47	1.021	0.058
29-Apr-02	83.94	78.79	345.72	648.82	86.48	1.017	0.058
29-Apr-02	84.13	78.91	344.80	651.74	86.55	1.013	0.058
1-May-02	84.02	78.98	346.36	650.67	86.44	1.017	0.058
1-May-02	84.33	79.18	344.37	655.35	86.52	1.010	0.058
2-May-02	84.29	79.29	346.07	656.25	86.56	1.014	0.058
2-May-02	84.65	79.76	345.25	662.89	86.56	1.009	0.058
8-May-02	84.62	79.48	346.71	661.39	86.69	1.015	0.058
8-May-02	84.59	79.58	345.93	663.78	86.90	1.012	0.058
8-May-02	84.66	79.46	346.09	664.36	87.06	1.013	0.059
10-May-02	84.81	79.42	343.74	663.70	86.86	1.007	0.059
14-May-02	84.12	79.09	346.71	654.42	86.72	1.018	0.058
14-May-02	84.82	79.68	343.46	666.48	86.93	1.004	0.059
15-May-02	84.72	79.67	345.38	664.24	86.73	1.010	0.058
15-May-02	84.69	79.80	345.38	666.31	86.91	1.009	0.058
15-May-02	84.53	79.45	344.77	662.40	86.94	1.010	0.058
16-May-02	84.10	79.33	346.81	658.35	87.03	1.016	0.058
16-May-02	84.31	79.48	346.24	662.41	87.17	1.014	0.058
22-May-02	84.57	79.17	342.83	658.83	86.77	1.006	0.058
22-May-02	84.50	79.20	343.64	661.28	87.14	1.008	0.059
24-May-02	84.14	79.07	345.34	650.79	86.27	1.014	0.058
28-May-02	84.52	79.22	344.25	657.25	86.55	1.010	0.058
28-May-02	84.71	79.31	343.71	659.70	86.59	1.007	0.058
29-May-02	84.50	79.24	344.41	656.26	86.42	1.010	0.058
30-May-02	84.39	79.33	344.93	654.65	86.23	1.011	0.058
30-May-02	84.53	79.52	345.52	657.88	86.31	1.011	0.058
31-May-02	84.51	79.45	346.36	658.00	86.42	1.014	0.058
Average	**84.40**	**79.29**	**345.22**	**657.91**	**86.67**	**1.012**	**0.058**
Median	**84.51**	**79.32**	**345.38**	**658.18**	**86.58**	**1.012**	**0.058**
Minimum	**83.48**	**78.16**	**342.83**	**640.15**	**86.23**	**1.004**	**0.058**
Maximum	**84.82**	**79.80**	**346.81**	**666.48**	**87.17**	**1.021**	**0.059**
Std. Dev.	**0.31**	**0.34**	**1.09**	**6.04**	**0.26**	**0.004**	**0.000**

TABLE G-5
RECORDED DATA FOR FALL 2002 BIOLOGICAL BEP TESTS AT 240 RPM

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
17-Sep-02	18.2	61.48	40.54	240.89	237.76	84.15	0.987	0.058
17-Sep-02	18.2	61.29	40.52	240.97	237.62	84.40	0.988	0.058
17-Sep-02	18.2	60.92	40.28	242.18	235.29	84.58	0.996	0.058
17-Sep-02	18.2	61.27	40.40	239.00	237.56	84.64	0.981	0.058
17-Sep-02	18.2	61.10	40.39	240.62	237.54	84.91	0.988	0.058
18-Sep-02	18.2	60.99	40.36	240.31	235.60	84.40	0.987	0.057
18-Sep-02	18.2	61.05	40.39	239.91	236.72	84.65	0.985	0.058
18-Sep-02	18.2	60.96	40.42	242.07	236.74	84.72	0.994	0.058
18-Sep-02	18.2	61.18	40.35	238.07	237.14	84.69	0.978	0.058
18-Sep-02	18.2	61.04	40.39	240.53	237.06	84.80	0.988	0.058
18-Sep-02	18.2	61.08	40.39	240.00	237.59	84.93	0.986	0.058
19-Sep-02	18.2	61.13	40.48	240.26	237.13	84.51	0.986	0.058
19-Sep-02	18.2	61.64	40.41	239.46	236.76	83.85	0.983	0.058
19-Sep-02	18.2	61.08	40.42	240.33	236.95	84.64	0.987	0.058
19-Sep-02	18.2	61.03	40.41	241.28	237.34	84.86	0.991	0.058
20-Sep-02	18.2	61.21	40.42	238.77	237.17	84.53	0.980	0.058
20-Sep-02	18.2	60.90	40.22	240.16	235.31	84.72	0.988	0.058
20-Sep-02	18.2	61.11	40.37	240.16	237.34	84.85	0.987	0.058
20-Sep-02	18.2	61.06	40.41	241.05	237.55	84.91	0.990	0.058
23-Sep-02	18.2	60.98	40.29	238.84	236.22	84.78	0.982	0.058
23-Sep-02	18.2	60.83	40.25	240.53	235.74	84.91	0.990	0.058
23-Sep-02	18.2	61.66	41.40	241.71	246.63	85.21	0.981	0.058
24-Sep-02	18.2	60.94	40.40	239.96	235.31	84.28	0.985	0.057
24-Sep-02	18.2	60.84	40.38	241.17	235.92	84.68	0.991	0.057
24-Sep-02	18.2	60.75	40.34	239.37	236.61	85.13	0.984	0.058
25-Sep-02	18.2	60.73	40.48	242.13	236.50	84.84	0.993	0.057
25-Sep-02	18.2	60.65	40.26	240.46	235.26	84.97	0.989	0.058
25-Sep-02	18.2	60.61	40.28	241.49	235.24	84.98	0.993	0.058
25-Sep-02	18.2	60.74	40.26	240.12	235.84	85.02	0.988	0.058
25-Sep-02	18.2	60.68	40.20	240.32	235.19	84.99	0.989	0.058
26-Sep-02	18.2	60.83	40.57	242.27	237.25	84.73	0.993	0.057
26-Sep-02	18.2	60.84	40.36	240.18	236.18	84.78	0.987	0.058
26-Sep-02	18.2	60.94	40.52	241.03	237.40	84.73	0.988	0.058
27-Sep-02	18.2	60.94	40.53	240.27	237.36	84.74	0.985	0.057
27-Sep-02	18.2	60.73	40.37	240.99	235.84	84.81	0.990	0.057

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
27-Sep-02	18.2	60.83	40.41	240.52	236.44	84.82	0.988	0.058
27-Sep-02	18.2	60.55	40.10	239.95	233.62	84.83	0.989	0.057
27-Sep-02	18.2	60.64	40.27	241.20	235.17	84.92	0.992	0.058
30-Sep-02	18.2	60.66	40.49	242.63	235.57	84.58	0.995	0.057
30-Sep-02	18.2	60.68	40.36	240.39	234.85	84.57	0.988	0.057
30-Sep-02	18.2	60.77	40.46	240.62	542.00	84.70	0.987	0.132
30-Sep-02	18.2	60.78	40.44	240.59	542.00	84.72	0.987	0.132
30-Sep-02	18.2	60.78	40.44	240.39	541.61	84.70	0.987	0.132
30-Sep-02	18.2	60.68	40.42	241.95	236.38	84.97	0.993	0.057
1-Oct-02	18.2	60.66	40.38	240.18	235.75	84.86	0.986	0.057
1-Oct-02	18.2	60.39	40.20	240.99	234.13	85.05	0.992	0.057
1-Oct-02	18.2	60.47	40.28	241.15	235.20	85.17	0.992	0.057
1-Oct-02	18.2	60.46	40.26	240.36	235.39	85.27	0.989	0.058
1-Oct-02	18.2	60.61	40.36	238.86	236.73	85.35	0.981	0.058
2-Oct-02	18.2	60.93	40.54	240.83	237.45	84.77	0.987	0.057
2-Oct-02	18.2	60.72	40.24	239.55	235.01	84.81	0.986	0.058
2-Oct-02	18.2	60.68	40.25	240.72	235.19	84.91	0.990	0.058
2-Oct-02	18.2	60.68	40.17	240.01	234.77	84.94	0.988	0.058
2-Oct-02	18.2	60.67	40.19	240.36	235.25	85.06	0.990	0.058
7-Oct-02	18.2	61.47	40.50	235.06	237.44	84.13	0.964	0.058
7-Oct-02	18.2	60.96	40.45	240.59	235.84	84.33	0.987	0.057
7-Oct-02	18.2	60.78	40.25	240.27	233.93	84.30	0.988	0.057
7-Oct-02	18.2	60.65	40.10	239.95	232.61	84.34	0.989	0.057
7-Oct-02	18.2	61.01	40.64	242.52	237.84	84.58	0.993	0.057
7-Oct-02	18.2	61.19	40.57	240.16	238.41	84.68	0.984	0.058
8-Oct-02	18.2	61.07	40.61	241.07	236.81	84.20	0.987	0.057
8-Oct-02	18.2	60.90	40.44	240.48	235.40	84.28	0.987	0.057
8-Oct-02	18.2	60.82	40.37	240.71	235.02	84.41	0.989	0.057
8-Oct-02	18.2	60.96	40.36	241.25	236.52	84.78	0.991	0.058
8-Oct-02	18.2	61.07	40.32	239.52	236.86	84.83	0.985	0.058
9-Oct-02	18.2	61.11	40.47	239.42	236.36	84.27	0.982	0.057
9-Oct-02	18.2	60.86	40.30	240.10	234.37	84.26	0.987	0.057
9-Oct-02	18.2	60.82	40.24	239.67	234.11	84.36	0.986	0.057
9-Oct-02	18.2	60.85	40.18	239.52	234.21	84.46	0.986	0.057
9-Oct-02	18.2	61.08	40.37	238.89	236.22	84.49	0.981	0.058
9-Oct-02	18.2	60.97	40.41	240.88	236.33	84.60	0.989	0.057
10-Oct-02	18.2	61.16	40.62	239.56	236.95	84.11	0.981	0.057
10-Oct-02	18.2	60.89	40.50	241.42	235.65	84.26	0.990	0.057
10-Oct-02	18.2	60.88	40.38	240.62	235.25	84.38	0.988	0.057

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
14-Oct-02	18.2	61.07	40.59	240.69	236.77	84.22	0.986	0.057
14-Oct-02	18.2	60.83	40.28	240.07	234.17	84.27	0.987	0.057
14-Oct-02	18.2	60.77	40.30	240.87	234.11	84.29	0.990	0.057
14-Oct-02	18.2	60.77	40.27	240.69	234.37	84.45	0.990	0.057
14-Oct-02	18.2	60.81	40.26	240.12	234.35	84.40	0.988	0.057
14-Oct-02	18.2	60.81	40.28	240.73	234.48	84.41	0.990	0.057
15-Oct-02	18.2	61.00	40.66	240.98	235.65	83.78	0.986	0.057
15-Oct-02	18.2	60.59	40.34	242.14	232.62	83.93	0.995	0.057
16-Oct-02	18.2	60.82	40.46	241.44	234.79	84.14	0.991	0.057
16-Oct-02	18.2	60.83	40.35	239.96	234.10	84.11	0.986	0.057
16-Oct-02	18.2	60.63	40.22	241.13	232.73	84.17	0.992	0.057
16-Oct-02	18.2	60.57	40.13	240.71	232.15	84.20	0.992	0.057
16-Oct-02	18.2	60.68	40.19	240.17	233.22	84.33	0.989	0.057
18-Oct-02	20.0	64.58	40.55	239.66	249.29	83.95	0.982	0.060
18-Oct-02	20.0	63.78	39.89	240.64	242.17	83.94	0.994	0.060
18-Oct-02	20.0	63.90	39.78	237.98	242.42	84.08	0.985	0.060
21-Oct-02	18.2	60.77	40.44	240.72	234.29	84.06	0.988	0.057
21-Oct-02	18.2	60.80	40.37	239.69	234.07	84.09	0.985	0.057
21-Oct-02	18.2	60.84	40.40	239.01	234.45	84.11	0.981	0.057
22-Oct-02	24.0	71.67	38.85	240.22	261.59	82.85	1.006	0.068
22-Oct-02	24.0	71.86	38.90	239.24	262.86	82.92	1.001	0.068
22-Oct-02	24.0	72.03	39.05	238.98	264.68	82.98	0.998	0.068
22-Oct-02	24.0	72.00	39.08	239.69	265.14	83.11	1.001	0.068
23-Oct-02	22.0	68.41	39.81	242.42	257.36	83.36	1.003	0.064
23-Oct-02	22.0	68.15	39.50	241.47	254.84	83.50	1.003	0.064
23-Oct-02	22.0	68.00	39.37	240.91	253.27	83.45	1.002	0.064
23-Oct-02	22.0	68.09	39.40	240.44	254.11	83.55	1.000	0.064
24-Oct-02	16.0	57.24	42.22	240.26	230.06	83.95	0.965	0.052
24-Oct-02	16.0	56.24	40.99	237.70	219.58	83.98	0.969	0.052
24-Oct-02	16.0	56.02	41.01	240.65	218.53	83.89	0.981	0.052
24-Oct-02	16.0	56.11	41.10	240.35	219.63	83.98	0.979	0.052
25-Oct-02	26.0	75.21	38.26	239.14	268.63	82.28	1.009	0.071
25-Oct-02	26.0	75.57	38.35	236.51	270.38	82.25	0.997	0.071
25-Oct-02	26.0	75.20	38.47	241.97	270.22	82.35	1.018	0.071
25-Oct-02	26.0	75.16	38.36	240.59	269.23	82.34	1.014	0.071
25-Oct-02	26.0	75.55	38.53	239.10	272.09	82.42	1.005	0.071
25-Oct-02	26.0	75.76	38.56	237.75	273.26	82.49	0.999	0.071
25-Oct-02	26.0	75.33	38.45	240.83	271.28	82.57	1.014	0.071

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
28-Oct-02	22.0	68.50	39.63	240.03	256.58	83.33	0.995	0.064
28-Oct-02	22.0	68.12	39.39	241.43	253.74	83.38	1.004	0.064
28-Oct-02	22.0	68.04	39.34	241.58	253.43	83.46	1.005	0.064
28-Oct-02	22.0	68.30	39.38	239.29	254.74	83.50	0.995	0.064
28-Oct-02	22.0	68.31	39.38	239.28	254.83	83.53	0.995	0.064
28-Oct-02	22.0	68.20	39.39	240.75	254.62	83.57	1.001	0.064
28-Oct-02	22.0	68.72	39.65	238.53	258.42	83.60	0.989	0.065
28-Oct-02	22.0	68.44	39.38	238.96	255.18	83.48	0.994	0.065
28-Oct-02	22.0	68.18	39.39	241.01	254.78	83.64	1.002	0.064
29-Oct-02	16.0	56.37	41.47	240.87	222.80	84.02	0.976	0.052
29-Oct-02	16.0	56.57	41.39	239.29	223.65	84.22	0.971	0.053
29-Oct-02	16.0	56.36	41.21	239.85	221.73	84.15	0.975	0.052
29-Oct-02	16.0	56.23	41.19	240.86	220.93	84.11	0.980	0.052
29-Oct-02	16.0	56.22	41.13	240.63	220.71	84.14	0.979	0.052
30-Oct-02	18.2	61.33	40.91	239.00	238.92	83.94	0.975	0.057
30-Oct-02	18.2	60.74	40.47	241.38	234.13	83.97	0.990	0.057
30-Oct-02	18.2	60.77	40.34	239.41	233.50	83.96	0.984	0.057
30-Oct-02	18.2	60.72	40.33	239.66	233.36	83.98	0.985	0.057
30-Oct-02	18.2	60.56	40.22	240.36	232.16	84.00	0.989	0.057
30-Oct-02	18.2	60.58	40.18	239.81	232.25	84.10	0.987	0.057
30-Oct-02	18.2	61.04	40.63	239.32	236.78	84.16	0.980	0.057
30-Oct-02	18.2	60.65	40.32	241.06	233.67	84.22	0.991	0.057
31-Oct-02	20.0	64.56	40.10	240.54	245.46	83.57	0.991	0.060
31-Oct-02	20.0	64.49	40.01	240.14	244.90	83.66	0.991	0.060
31-Oct-02	20.0	64.64	39.93	237.37	245.09	83.71	0.980	0.061
31-Oct-02	20.0	64.22	39.90	241.66	243.52	83.77	0.999	0.060
31-Oct-02	20.0	64.29	39.82	239.92	243.37	83.80	0.992	0.061
31-Oct-02	20.0	64.25	39.83	240.68	243.32	83.81	0.995	0.060
31-Oct-02	20.0	64.35	39.83	239.57	243.91	83.87	0.991	0.061
31-Oct-02	20.0	64.73	40.21	240.02	247.87	83.95	0.988	0.061
31-Oct-02	20.0	64.53	40.03	239.91	245.78	83.94	0.990	0.061
1-Nov-02	24.0	72.24	39.17	239.25	266.02	82.88	0.998	0.068
1-Nov-02	24.0	71.87	39.11	242.29	264.53	82.95	1.011	0.068
1-Nov-02	24.0	72.10	38.97	238.30	264.63	83.04	0.996	0.068
1-Nov-02	24.0	71.89	38.96	240.60	263.87	83.03	1.006	0.068
1-Nov-02	24.0	71.93	38.97	240.12	264.13	83.04	1.004	0.068
1-Nov-02	24.0	71.84	39.00	241.50	264.24	83.12	1.009	0.068
1-Nov-02	24.0	72.38	39.37	240.05	268.80	83.18	0.999	0.068
1-Nov-02	24.0	72.19	39.25	240.77	267.78	83.32	1.003	0.068
4-Nov-02	26.0	75.52	38.73	241.48	271.74	81.86	1.013	0.070
4-Nov-02	26.0	75.42	38.62	241.20	270.79	81.92	1.013	0.071
4-Nov-02	26.0	75.43	38.53	239.77	270.21	81.92	1.008	0.071

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
4-Nov-02	26.0	75.44	38.52	239.89	270.61	82.06	1.009	0.071
4-Nov-02	26.0	75.60	38.80	241.53	273.36	82.11	1.012	0.071
4-Nov-02	26.0	75.52	38.56	239.35	271.38	82.14	1.006	0.071
4-Nov-02	26.0	75.76	38.83	240.60	274.24	82.16	1.008	0.071
11-Nov-02	16.0	56.57	41.49	240.44	220.74	82.90	0.974	0.052
11-Nov-02	16.0	56.04	40.88	240.41	215.28	82.84	0.981	0.051
11-Nov-02	16.0	56.01	40.84	240.43	214.94	82.84	0.982	0.051
11-Nov-02	16.0	56.28	41.16	240.55	217.82	82.91	0.979	0.052
11-Nov-02	16.0	56.32	41.06	239.56	217.96	83.10	0.976	0.052
11-Nov-02	16.0	56.31	41.13	240.66	218.02	83.01	0.980	0.052
11-Nov-02	16.0	56.21	41.03	240.31	217.42	83.11	0.979	0.052
12-Nov-02	20.0	64.00	39.71	240.15	238.28	82.64	0.995	0.060
12-Nov-02	20.0	63.92	39.52	238.80	237.01	82.71	0.991	0.060
12-Nov-02	20.0	63.96	39.77	241.10	238.94	82.80	0.998	0.060
12-Nov-02	20.0	64.24	39.79	238.27	239.87	82.76	0.986	0.060
13-Nov-02	18.2	60.85	40.67	242.55	233.15	83.07	0.993	0.056
13-Nov-02	18.2	60.81	40.50	240.77	232.04	83.06	0.987	0.056
13-Nov-02	18.2	60.74	40.47	241.37	231.62	83.08	0.990	0.056
13-Nov-02	18.2	60.67	40.33	240.15	230.47	83.06	0.987	0.056
13-Nov-02	18.2	60.64	40.30	240.56	230.46	83.15	0.989	0.056
13-Nov-02	18.2	60.51	40.23	240.89	229.40	83.10	0.991	0.056
14-Nov-02	24.0	72.69	39.89	241.89	269.37	81.94	1.000	0.067
14-Nov-02	24.0	72.77	39.90	241.44	269.76	81.92	0.998	0.067
14-Nov-02	24.0	72.69	39.77	240.33	268.67	81.96	0.995	0.067
14-Nov-02	24.0	72.89	39.99	240.89	270.98	81.99	0.994	0.067
15-Nov-02	22.0	68.44	40.06	245.76	256.36	82.43	1.014	0.063
15-Nov-02	22.0	68.90	39.88	238.32	256.98	82.45	0.985	0.064
15-Nov-02	22.0	68.70	39.96	241.66	257.00	82.52	0.998	0.064
15-Nov-02	22.0	68.66	39.84	240.43	255.95	82.48	0.994	0.064
15-Nov-02	22.0	68.56	39.81	241.31	255.54	82.54	0.998	0.064
15-Nov-02	22.0	68.77	39.78	238.52	256.27	82.61	0.987	0.064
18-Nov-02	26.0	75.39	38.62	239.08	281.23	85.13	1.004	0.073
18-Nov-02	26.0	75.19	38.54	240.37	280.43	85.31	1.011	0.073
18-Nov-02	26.0	74.95	38.36	240.82	278.67	85.45	1.015	0.073

TABLE G-6
JUNE PRELIMINARY ENGINEERING TEST DATA WITH WICKET GATES

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
3-Jun-02	18.2	58.02	37.82	239.57	209.21	84.08	1.017	0.056
3-Jun-02	18.2	58.93	40.67	261.32	226.15	83.22	1.070	0.054
3-Jun-02	18.2	59.43	41.70	266.86	233.57	83.10	1.079	0.054
3-Jun-02	18.2	59.96	43.25	279.18	242.37	82.63	1.108	0.053
3-Jun-02	18.2	59.18	43.58	289.77	235.35	80.46	1.146	0.051
3-Jun-02	18.2	59.47	44.63	297.96	240.15	79.78	1.164	0.050
3-Jun-02	18.2	64.50	42.73	209.61	253.93	81.27	0.837	0.057
3-Jun-02	18.2	64.75	42.56	198.33	248.37	79.49	0.793	0.056
3-Jun-02	18.2	64.73	42.57	199.63	248.97	79.69	0.799	0.056
4-Jun-02	18.2	84.52	79.15	343.42	654.90	86.34	1.008	0.058
4-Jun-02	18.2	81.11	80.43	390.08	612.59	82.81	1.135	0.053
4-Jun-02	18.2	80.51	80.82	399.50	603.85	81.82	1.160	0.052
4-Jun-02	18.2	81.89	80.21	380.19	625.52	84.01	1.108	0.054
4-Jun-02	18.2	86.68	80.11	323.82	676.80	85.95	0.944	0.059
4-Jun-02	18.2	86.82	78.09	299.39	647.64	84.23	0.884	0.059
4-Jun-02	18.2	87.19	77.81	288.30	639.80	83.16	0.853	0.058
4-Jun-02	24	73.93	40.27	239.87	285.70	84.60	0.987	0.070
4-Jun-02	24	71.73	41.09	275.24	279.47	83.61	1.121	0.066
4-Jun-02	24	70.98	41.36	291.92	274.93	82.56	1.185	0.065
4-Jun-02	24	70.15	41.58	305.31	266.43	80.55	1.236	0.062
5-Jun-02	24	73.96	40.46	241.56	286.07	84.30	0.991	0.069
5-Jun-02	24	75.21	39.49	210.66	274.93	81.62	0.875	0.069
5-Jun-02	24	75.07	39.10	202.27	267.09	80.23	0.844	0.068
5-Jun-02	24	75.04	38.95	190.56	258.42	77.95	0.797	0.066
5-Jun-02	24	103.83	80.19	344.28	807.57	85.54	1.004	0.070
5-Jun-02	24	101.74	81.34	380.24	800.38	85.27	1.100	0.068
5-Jun-02	24	101.47	81.80	388.47	800.50	85.05	1.121	0.068
5-Jun-02	24	99.08	78.97	390.83	750.85	84.62	1.148	0.067
5-Jun-02	24	97.19	76.57	389.71	711.58	84.32	1.162	0.066
5-Jun-02	24	92.50	71.05	391.02	617.33	82.84	1.211	0.064
5-Jun-02	24	89.15	67.74	390.66	552.25	80.65	1.239	0.062
5-Jun-02	24	99.82	70.96	299.89	676.48	84.23	0.929	0.071
5-Jun-02	24	99.97	70.31	290.38	665.93	83.54	0.904	0.071
5-Jun-02	24	101.85	72.63	290.81	697.47	83.15	0.891	0.070
5-Jun-02	24	106.77	78.68	290.40	780.79	81.97	0.855	0.070
6-Jun-02	16	53.93	38.52	240.33	197.03	83.63	1.011	0.052
6-Jun-02	16	55.64	37.75	201.23	193.57	81.27	0.855	0.052
6-Jun-02	16	56.23	37.55	180.84	187.13	78.19	0.770	0.051

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
6-Jun-02	16	56.48	37.29	161.31	177.56	74.35	0.690	0.049
6-Jun-02	16	55.78	37.36	141.46	161.63	68.42	0.604	0.044
6-Jun-02	16	58.86	42.51	137.53	183.58	64.70	0.551	0.041
6-Jun-02	16	54.59	40.21	250.59	206.73	83.05	1.031	0.051
6-Jun-02	16	54.62	41.40	262.22	209.81	81.84	1.064	0.049
6-Jun-02	16	55.69	43.37	270.79	223.67	81.66	1.073	0.049
6-Jun-02	16	55.34	43.96	280.88	221.16	80.17	1.106	0.047
6-Jun-02	16	56.98	47.63	299.69	243.56	79.17	1.133	0.046
6-Jun-02	16	57.52	49.28	310.44	251.23	78.15	1.154	0.045
7-Jun-02	16	77.83	80.14	346.55	602.29	85.16	1.010	0.052
7-Jun-02	16	75.24	76.24	345.07	549.48	84.47	1.032	0.052
7-Jun-02	16	64.75	67.69	379.82	363.09	73.06	1.205	0.041
7-Jun-02	16	64.59	68.48	387.00	349.15	69.64	1.221	0.039
7-Jun-02	16	79.14	78.72	317.35	603.15	85.38	0.934	0.054
7-Jun-02	16	80.16	78.43	290.16	589.19	82.63	0.855	0.053
10-Jun-02	18.2	60.82	40.32	240.52	235.29	84.60	0.989	0.057
10-Jun-02	18.2	59.91	38.27	225.44	219.43	84.39	0.951	0.058
10-Jun-02	18.2	59.64	39.61	246.85	226.85	84.67	1.024	0.057
10-Jun-02	18.2	60.93	40.40	241.16	237.13	84.95	0.990	0.058
10-Jun-02	18.2	60.95	40.24	238.84	236.37	84.99	0.983	0.058
10-Jun-02	18.2	60.81	40.32	241.57	236.36	85.00	0.993	0.058
10-Jun-02	18.2	60.69	40.17	240.83	235.07	85.04	0.992	0.058
13-Jun-02	18.2	60.89	40.47	240.47	236.23	84.55	0.987	0.057
13-Jun-02	18.2	60.86	40.44	240.34	236.01	84.56	0.986	0.057
13-Jun-02	18.2	60.90	40.47	240.16	236.23	84.53	0.985	0.057
13-Jun-02	18.2	60.87	40.41	239.71	235.87	84.56	0.984	0.057
13-Jun-02	18.2	60.88	40.38	239.41	235.82	84.57	0.983	0.057
13-Jun-02	18.2	60.76	40.35	240.93	234.92	84.51	0.990	0.057
13-Jun-02	18.2	60.87	40.30	239.03	235.13	84.54	0.983	0.057
13-Jun-02	18.2	60.57	40.40	242.40	235.10	84.72	0.995	0.057
13-Jun-02	18.2	60.57	40.37	242.22	234.90	84.57	0.995	0.057
13-Jun-02	18.2	60.80	40.26	239.00	234.81	84.59	0.983	0.057
13-Jun-02	18.2	60.71	40.22	239.15	234.51	84.68	0.984	0.057
13-Jun-02	18.2	60.81	40.25	239.14	234.68	84.54	0.984	0.057
13-Jun-02	18.2	60.64	40.30	240.60	234.76	84.69	0.989	0.057
13-Jun-02	18.2	85.13	80.15	346.85	665.51	86.02	1.011	0.058
13-Jun-02	18.2	85.37	80.22	345.61	666.43	85.83	1.007	0.058
13-Jun-02	18.2	85.31	80.35	347.26	667.70	85.91	1.011	0.058
13-Jun-02	18.2	85.48	80.38	345.32	669.51	85.92	1.005	0.058
13-Jun-02	18.2	85.48	80.32	342.99	669.96	86.06	0.999	0.058
13-Jun-02	18.2	85.43	80.35	345.58	669.38	86.00	1.006	0.058
13-Jun-02	18.2	85.46	80.45	346.36	669.94	85.94	1.008	0.058

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
13-Jun-02	18.2	85.47	80.39	346.23	669.21	85.90	1.008	0.058
13-Jun-02	18.2	85.63	80.42	344.08	670.75	85.90	1.001	0.058
13-Jun-02	18.2	83.05	76.77	322.54	626.75	82.86	0.961	0.058
13-Jun-02	18.2	61.50	41.14	242.25	243.37	84.82	0.986	0.058
13-Jun-02	18.2	61.69	41.02	239.03	243.07	84.74	0.974	0.058
13-Jun-02	18.2	61.54	40.97	239.29	242.56	84.84	0.976	0.058
13-Jun-02	18.2	61.55	40.90	239.12	242.07	84.79	0.976	0.058
13-Jun-02	18.2	61.43	40.92	240.16	242.01	84.89	0.980	0.058
13-Jun-02	18.2	60.99	40.64	242.13	238.44	84.83	0.991	0.058
13-Jun-02	18.2	61.00	40.54	240.51	237.88	84.82	0.986	0.058
13-Jun-02	18.2	60.97	40.45	238.75	237.67	84.97	0.980	0.058
13-Jun-02	18.2	61.00	40.46	239.91	237.52	84.84	0.984	0.058
13-Jun-02	18.2	61.01	40.46	240.99	236.95	84.66	0.989	0.058
13-Jun-02	18.2	84.16	78.64	346.46	646.37	86.13	1.020	0.058
13-Jun-02	18.2	84.21	78.63	346.91	645.95	86.03	1.021	0.058
13-Jun-02	18.2	84.52	78.60	344.72	647.32	85.94	1.015	0.058
13-Jun-02	18.2	84.62	78.84	344.83	650.13	85.95	1.014	0.058
13-Jun-02	18.2	84.38	78.90	347.17	649.50	86.03	1.020	0.058
13-Jun-02	18.2	84.51	78.89	344.90	650.98	86.11	1.014	0.058
18-Jun-02	18.2	61.29	40.88	239.95	239.96	84.44	0.979	0.057
18-Jun-02	18.2	61.32	40.88	240.12	240.08	84.45	0.980	0.057
18-Jun-02	18.2	61.30	40.84	240.21	239.50	84.36	0.981	0.057
18-Jun-02	18.2	61.20	40.83	240.49	239.24	84.43	0.982	0.057
18-Jun-02	18.2	84.63	79.25	345.19	652.45	85.78	1.012	0.058
18-Jun-02	18.2	84.68	79.29	346.00	652.44	85.70	1.014	0.058
18-Jun-02	18.2	84.68	79.29	346.00	652.44	85.70	1.014	0.058
18-Jun-02	18.2	84.75	79.44	344.29	656.18	85.95	1.008	0.058
18-Jun-02	18.2	84.82	79.56	345.82	656.70	85.82	1.012	0.058
18-Jun-02	18.2	61.18	40.76	239.57	239.80	84.81	0.979	0.058
18-Jun-02	18.2	61.30	40.70	238.55	239.52	84.63	0.976	0.058
18-Jun-02	18.2	61.07	40.63	240.28	238.34	84.70	0.984	0.058
18-Jun-02	18.2	61.11	40.64	240.56	238.18	84.59	0.985	0.057
18-Jun-02	18.2	84.63	79.29	345.78	653.62	85.91	1.014	0.058
18-Jun-02	18.2	84.57	79.35	345.98	654.75	86.04	1.014	0.058
26-Jun-02	18.2	62.51	42.23	240.88	252.26	84.27	0.968	0.057
26-Jun-02	18.2	62.32	42.01	240.56	250.85	84.44	0.969	0.058
26-Jun-02	18.2	62.43	42.09	239.69	250.79	84.38	0.964	0.057
26-Jun-02	18.2	85.17	79.99	345.35	664.29	86.00	1.008	0.058
26-Jun-02	18.2	85.27	79.92	343.54	665.45	86.04	1.003	0.058
27-Jun-02	26	77.60	40.35	241.46	296.02	83.37	0.992	0.072
27-Jun-02	26	76.88	40.52	250.89	294.58	83.41	1.029	0.071

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
27-Jun-02	26	76.24	40.74	259.64	292.86	83.15	1.062	0.070
27-Jun-02	26	75.27	40.70	269.16	286.84	82.55	1.101	0.069
27-Jun-02	26	74.53	40.72	279.78	282.18	82.01	1.144	0.068
27-Jun-02	26	74.21	40.94	289.21	280.30	81.36	1.180	0.067
27-Jun-02	26	79.89	40.40	198.64	284.21	77.65	0.816	0.069
27-Jun-02	26	79.87	40.36	200.24	285.38	78.06	0.823	0.070
27-Jun-02	26	79.80	40.38	210.00	292.70	80.10	0.863	0.071
27-Jun-02	26	79.59	40.47	218.90	298.11	81.61	0.898	0.072
27-Jun-02	26	79.05	40.65	230.30	302.45	83.00	0.943	0.073
27-Jun-02	26	109.03	80.02	344.95	836.52	84.55	1.006	0.073
28-Jun-02	26	102.52	70.90	326.85	694.64	84.27	1.013	0.073
28-Jun-02	26	109.35	79.30	335.31	827.53	84.16	0.983	0.073
28-Jun-02	26	108.56	79.37	344.05	824.39	84.38	1.008	0.073
28-Jun-02	26	107.53	79.37	355.08	818.50	84.55	1.040	0.072
28-Jun-02	26	106.85	79.68	364.81	815.08	84.41	1.067	0.072
1-Jul-02	28	82.86	40.43	229.38	310.82	81.83	0.942	0.076
1-Jul-02	28	82.14	40.60	240.30	312.76	82.71	0.984	0.076
1-Jul-02	28	81.75	41.01	249.16	315.21	82.90	1.016	0.075
1-Jul-02	28	81.03	41.24	258.90	313.90	82.85	1.052	0.074
1-Jul-02	28	115.09	78.36	325.09	849.17	83.03	0.959	0.077
1-Jul-02	28	114.87	79.11	335.89	861.01	83.55	0.986	0.076
1-Jul-02	28	114.75	80.08	346.25	872.34	83.71	1.010	0.076
1-Jul-02	28	114.26	80.66	356.37	877.15	83.93	1.036	0.076
1-Jul-02	28	113.93	81.09	363.57	879.09	83.93	1.054	0.075

TABLE G-7
FINAL ENGINEERING TEST DATA

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
12-Dec-02	16	79.74	81.13	324.81	620.97	84.58	0.941	0.053
12-Dec-02	16	79.33	81.56	334.82	622.90	84.85	0.968	0.053
12-Dec-02	16	78.72	81.80	344.82	616.98	84.43	0.995	0.052
12-Dec-02	16	77.92	81.88	352.15	607.63	83.95	1.016	0.051
12-Dec-02	16	77.74	82.10	356.21	604.79	83.50	1.026	0.051
12-Dec-02	16	76.94	82.47	366.37	594.21	82.55	1.053	0.050
12-Dec-02	16	76.31	82.71	373.71	585.36	81.71	1.073	0.049
13-Dec-02	20	91.32	78.60	321.37	682.56	83.83	0.946	0.061
12-Dec-02	20	90.96	78.69	325.85	683.87	84.22	0.959	0.061
12-Dec-02	20	90.22	78.65	334.77	679.24	84.38	0.985	0.061
12-Dec-02	20	90.22	78.65	334.77	679.24	84.38	0.985	0.061
12-Dec-02	20	89.86	79.18	344.66	681.61	84.45	1.011	0.060
12-Dec-02	20	89.17	78.33	345.48	668.97	84.43	1.019	0.060
12-Dec-02	20	89.12	79.27	355.25	675.91	84.32	1.041	0.060
12-Dec-02	20	88.57	79.43	365.18	671.61	84.14	1.069	0.059
13-Dec-02	22	97.41	77.90	314.77	717.16	83.31	0.931	0.065
13-Dec-02	22	97.41	77.83	314.15	716.06	83.28	0.929	0.065
13-Dec-02	22	96.86	78.23	324.57	719.68	83.73	0.958	0.065
13-Dec-02	22	96.15	78.65	336.27	720.31	83.97	0.990	0.065
13-Dec-02	22	95.91	79.43	345.80	724.50	83.83	1.013	0.064
13-Dec-02	22	95.01	79.26	355.28	715.68	83.78	1.042	0.063
13-Dec-02	22	94.33	79.48	366.43	710.33	83.52	1.073	0.063
16-Dec-02	24	103.76	78.39	315.67	760.93	82.43	0.931	0.069
13-Dec-02	24	102.87	78.30	324.99	760.16	83.22	0.959	0.069
13-Dec-02	24	102.33	78.73	334.70	762.83	83.50	0.985	0.068
13-Dec-02	24	102.06	79.64	345.26	769.75	83.49	1.010	0.068
13-Dec-02	24	100.76	78.16	346.42	745.48	83.39	1.023	0.067
13-Dec-02	24	101.08	79.79	357.27	762.36	83.36	1.044	0.067
13-Dec-02	24	100.45	79.87	364.98	756.95	83.17	1.066	0.066
13-Dec-02	24	100.11	79.90	369.36	753.39	83.05	1.079	0.066
16-Dec-02	26	109.47	78.70	316.08	801.26	81.95	0.930	0.072
16-Dec-02	26	109.02	79.27	326.60	808.21	82.39	0.957	0.072
16-Dec-02	26	108.58	79.66	334.68	811.49	82.66	0.979	0.071
16-Dec-02	26	107.63	79.49	342.65	803.72	82.77	1.003	0.071
16-Dec-02	26	107.67	80.31	349.91	814.44	82.99	1.019	0.071
16-Dec-02	26	106.73	80.00	356.54	802.15	82.77	1.040	0.070
16-Dec-02	26	106.14	80.34	365.40	798.59	82.50	1.064	0.069
16-Dec-02	26	105.90	80.45	368.81	797.12	82.43	1.073	0.069
16-Dec-02	26	111.53	80.88	374.74	837.99	81.84	1.088	0.072

Date	Gate Position (degree)	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power
16-Dec-02	28	113.38	78.14	314.73	824.70	82.01	0.929	0.075
16-Dec-02	28	113.38	78.63	326.28	834.38	82.47	0.960	0.075
16-Dec-02	28	113.38	79.06	334.24	839.33	82.51	0.981	0.075
16-Dec-02	28	113.38	80.10	344.86	849.06	82.38	1.006	0.074
16-Dec-02	28	112.79	80.22	355.41	844.33	82.21	1.036	0.073
16-Dec-02	28	112.15	80.58	365.64	842.31	82.11	1.063	0.073
16-Dec-02	28	111.53	80.88	374.74	837.99	81.84	1.088	0.072
19-Dec-02	18.2	86.33	79.06	316.64	650.53	83.98	0.930	0.058
19-Dec-02	18.2	85.81	79.29	326.72	652.12	84.45	0.958	0.058
21-Dec-02	18.2	85.37	79.57	335.44	652.97	84.70	0.982	0.058
21-Dec-02	18.2	84.84	79.82	346.40	651.15	84.72	1.012	0.057
21-Dec-02	18.2	84.24	80.04	355.44	646.26	84.44	1.037	0.056
21-Dec-02	18.2	83.48	80.37	365.56	637.03	83.65	1.064	0.055
21-Dec-02	18.2	82.64	80.66	375.71	625.05	82.62	1.092	0.054

APPENDIX H

TEST LOOP INSTRUMENTATION TESTS

APPENDIX H
TEST LOOP INSTRUMENTATION TESTS

DYNAMOMETER OIL HOSE CHARACTERISTICS

Due to a hose failure and changes in the hose connections, three different oil hoses had to be used during the spring 2002 engineering and biological tests. The oil hose configuration, as show on Figures H-1 and H-2, was designed such that the oil hose entered the dynamometer radially through the center of the turbine shaft to eliminate external forces that would affect the turbine torque measurements.

The original 150 psi oil hose, which was used during the fall 2001 tests without wicket gates, was used during the April engineering tests with wicket gates and the spring 2002 biological tests until a failure of a hose connection occurred on May 2. A new 150 psi replacement hose was temporarily installed to allow biological tests to continue until a higher pressure hose could be delivered. On May 23, a 200 psi hose was installed for the remainder of the spring 2002 biological tests and the June engineering tests.

For the preliminary engineering tests with wicket gates, one of Alden's Calibration Department's temperature gauges was installed in the oil pipe between the oil system heat exchanger and the oil pipe inlet to the dynamometer. The gauge was used to visually monitor oil temperature in the hose feeding the dynamometer and to manually control operation of the oil cooling fan. The accuracy of the gauge was ± 2º F.

During the preliminary engineering tests, oil temperature in the dynamometer varied from about 70° F to 150°F. As the oil temperature warmed up, the dynamometer control system would start the oil cooling fan. When the oil temperature dropped, the controls would stop the fan. This cycling did not allow accurate control of the turbine speed due to the oil viscosity changes with temperature. Therefore, the oil cooling fan was manually controlled to maintain a more consistent oil temperature which allowed the dynamometer to hold a more constant turbine speed.

Even though the oil hose system was designed to prevent the transfer of forces in the oil hose to the torque load cell, test data was reviewed to determine if thermal expansion over the range of oil temperatures for these three oil hoses could have affected on the torque (load cell) measurements. The biological tests, which were conducted with all three hoses, did not indicate any obvious trends in the turbine efficiency for the three hose configurations. As shown on Tables H-3 and H-4, the average turbine efficiency was 85.5% for the 40 ft/240 rpm condition with a standard deviation of 0.33% and 86.7% for the 80 ft/345 rpm condition with a standard deviation of 0.26% for the BEP tests with wicket gates. Measured turbine efficiency for tests with the original 150 psi hose, the second temporary 150 psi hose, and the final 200 psi hose are summarized in Table H-1. Efficiency versus time for the two head conditions are plotted on Figures H-3 and H-4. This data did not show any obvious trends in the torque measurements (efficiency) at the 40 ft/240 rpm condition. This data indicated that characteristics of the three different oil hoses had negligible effects on the measured torque at the lower head/speed condition. At the 80 ft/345 rpm condition, the average measured efficiency with the second 150 psi temporary hose was greater than the average efficiency with the original 150 psi and the 200 psi hose. However, the average BEP efficiency for each hose was within 0.3% of the average BEP efficiencies for all of the hoses indicating that the different oil hoses did not explain the lower efficiencies after April 25th.

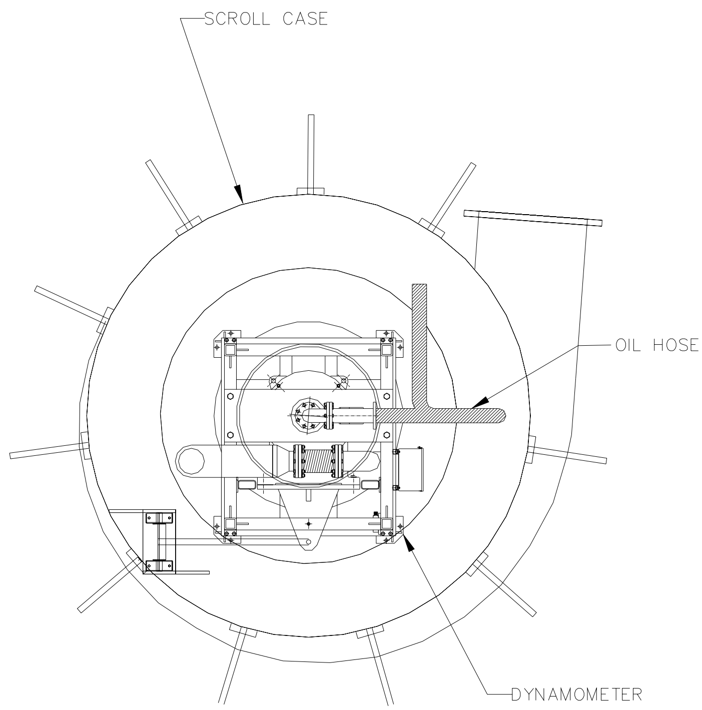


FIGURE H-1 DYNAMOMETER OIL HOSE CONFIGURATION – PLAN

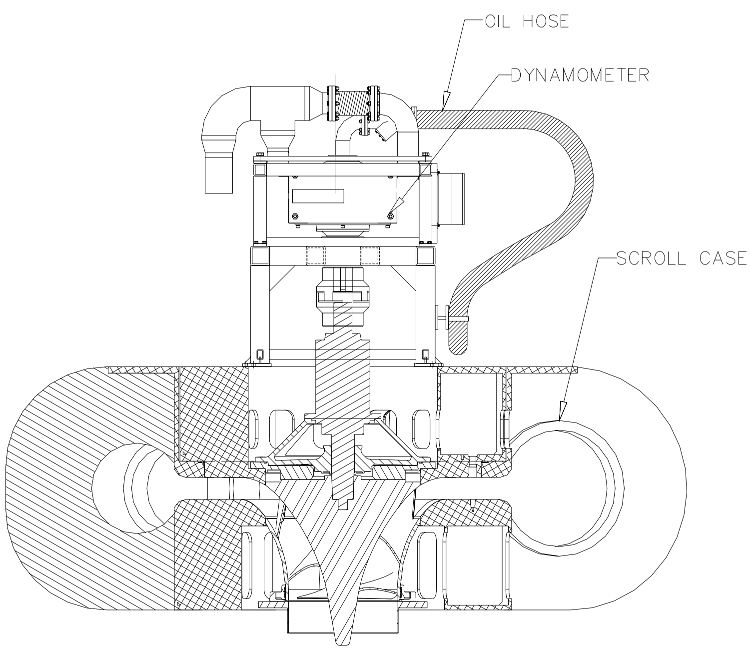


FIGURE H-2 DYNAMOMETER OIL HOSE CONFIGURATION – SECTION

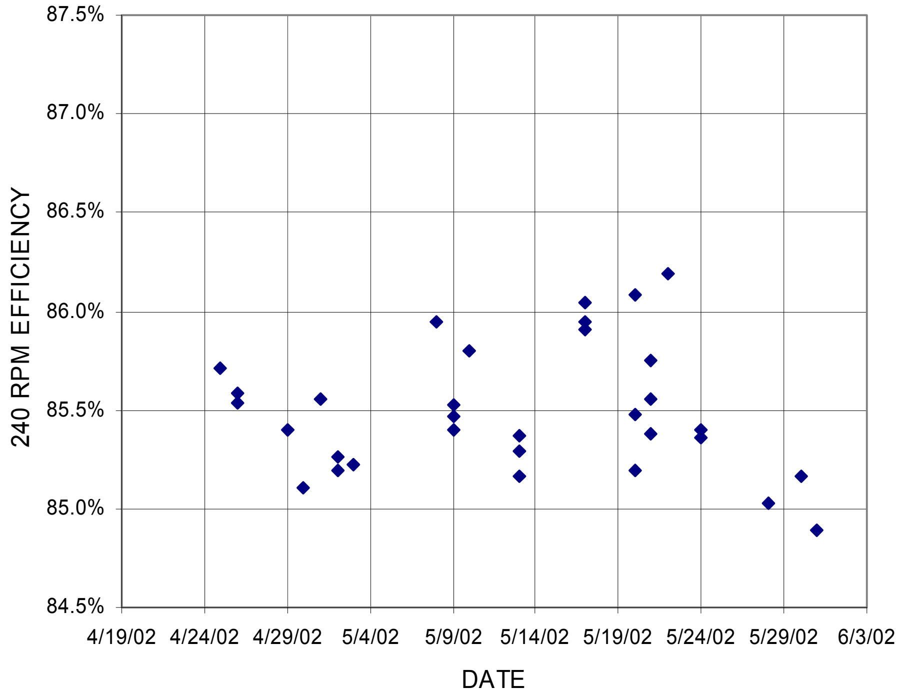


FIGURE H-3 240 RPM (40 FT HEAD) EFFICIENCY VERSUS TIME

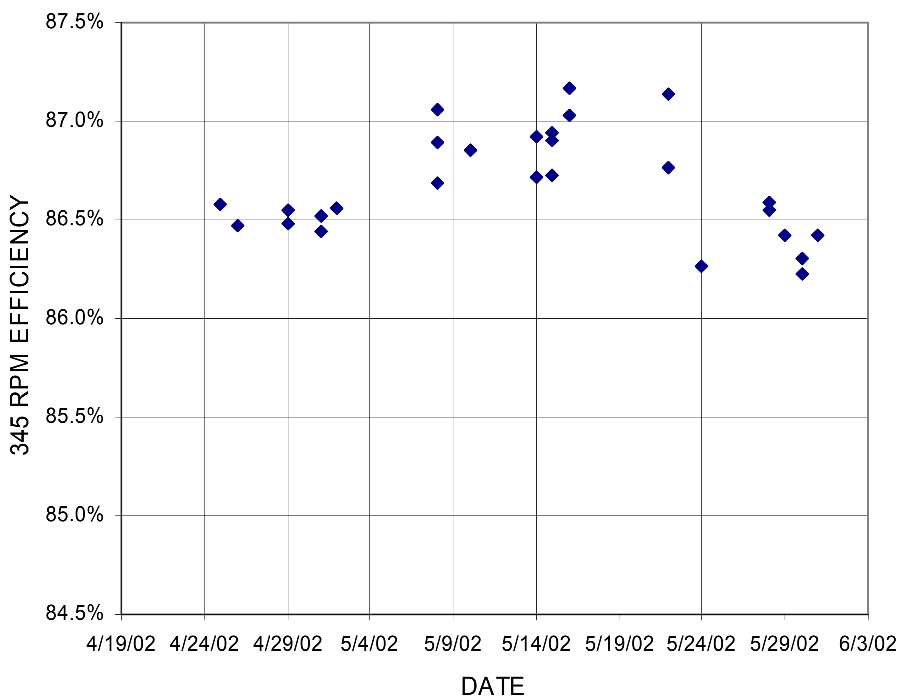


FIGURE H-4 345 RPM (80 FT HEAD) EFFICIENCY VERSUS TIME

TABLE H-1
TURBINE EFFICIENCY VARIATIONS
FOR THE THREE DYNAMOMETER OIL HOSE CONFIGURATIONS

Oil Hose Configuration	Head/Speed (ft/rpm)	Average Turbine Efficiency (%)	Standard Deviation of Average Turbine Efficiency (%)
Original 150 psi	40/240	85.4	0.21
	80/345	86.5	0.05
Temporary 150 psi	40/240	85.6	0.33
	80/345	86.9	0.16
200 psi	40/240	85.2	0.22
	80/345	86.4	0.13
Average for All Three Hoses	40/240	85.5	0.27
	80/345	86.7	0.26

In October 2002, additional engineering tests were conducted to verify that oil temperature did not affect the dynamometer torque measurements. For these tests, the dynamometer was operated at oil temperatures ranging between 90º F and 150º F. The measured turbine torques and efficiencies for oil temperatures tested, which are summarized in Table H-2, conclusively proved that oil temperature did not affect the dynamometer torque measurements.

TABLE H-2
DYNAMOMETER OIL HOSE TEMPERATURE EFFECT MEASUREMENTS

	Flow (cfs)	Head (ft)	Speed (rpm)	Power (HP)	Turbine Efficiency (%)	Phi (φ)	Unit Power	Oil Temperature
40 ft data	60.93	40.40	241.16	237.13	84.95	0.990	0.058	92
	60.95	40.24	238.84	236.37	84.99	0.983	0.058	93
	60.81	40.32	241.57	236.36	84.99	0.993	0.058	99
	60.69	40.17	240.83	235.07	85.04	0.992	0.058	105
	60.12	39.40	237.6	227.19	84.55	0.988	0.057	115
	61.24	40.73	239.06	239.66	84.72	0.978	0.058	118
	61.08	40.63	240.42	238.26	84.65	0.984	0.057	120
	61.2	40.83	240.49	239.24	84.43	0.982	0.057	128
	61.01	40.54	240.21	237.5	84.67	0.985	0.057	129
	61.32	40.88	240.12	240.08	84.44	0.980	0.057	130
	61.29	40.88	239.95	239.96	84.44	0.979	0.057	131
Average	60.97	40.46	240.02	236.98	84.71	0.98	0.06	
Standard Deviation	0.35	0.43	1.14	3.65	0.24	0.01	0.00	
80 ft data	84.45	78.89	346.04	650.24	86.07	1.017	0.058	125
	84.61	78.84	344.83	650.13	85.95	1.014	0.058	130
	84.62	79.29	345.78	653.62	85.91	1.014	0.058	139
	84.69	79.36	345.55	654.16	85.83	1.012	0.058	140
	84.5	79.00	346.24	651.29	86.03	1.017	0.058	143
	85.37	80.22	345.61	666.43	85.83	1.007	0.058	144
	85.31	80.35	347.26	667.7	85.91	1.011	0.058	145
	85.48	80.38	345.32	669.51	85.92	1.005	0.058	146
	85.46	80.34	344.29	669.67	86.03	1.003	0.058	147
	84.9	79.50	339.8	659.16	85.15	0.995	0.058	148
Average	84.94	79.62	345.07	659.19	85.86	1.01	0.06	
Standard Deviation	0.42	0.64	2.02	8.31	0.26	0.01	0.00	

DYNAMOMETER OIL HOSE PRESSURE

Tests were conducted on June 10 and 11, 2002 to determine if pressure in the dynamometer oil hose could affect the torque load cell. Load cell readings were obtained with no rotation on the turbine and with and without the oil pump operating at various oil temperatures. These test results, which are summarized in Table H-3, indicated that there is less than 1 ft-lb torque difference between the zero load cell reading with and without oil pressure. A 5 ft-lb difference in the load cell zero point would have amounted to a difference in turbine efficiency of about 0.1% at the 40 ft/240 rpm and about 0.05% at the 79 ft/345 rpm setpoints. These test results indicated that the oil pressure had negligible affects on the torque measurement.

TABLE H-3
DYNAMOMETER OIL PRESSURE EFFECTS
ON LOAD CELL TORQUE MEASUREMENTS

Date	Load Cell (Volts)	Load Cell (ft lb)	Operating Condition	Oil Temperature (°F)
10-Jun-02	0.2753	1.28	Oil pump on, no turbine rpm	115
10-Jun-02	0.5367	1.87	Oil pump off, no turbine rpm	115
10-Jun-02	0.2911	1.20	Oil pump off, no turbine rpm	95
10-Jun-02	0.2331	0.95	Oil pump on, no turbine rpm	95
10-Jun-02	2.2386	6.72	Oil pump on, no turbine rpm	105
10-Jun-02	1.9688	5.91	Oil pump off, no turbine rpm	105
11-Jun-02	-1.2144	0.01	Oil pump off, no turbine rpm	68
11-Jun-02	-1.2788	0.00	Oil pump on, no turbine rpm	74-82

TORQUE LOAD CELL POWER SUPPLY AND RAW SIGNAL TEMPERATURE EFFECTS

Tests were conducted on September 5 and 6, 2002 to investigate air temperature effects on the load cell power supply and raw signal. In addition to normally recorded data, the following measurements were recorded during typical load cell calibrations and during tests at 40 ft and 80 ft operating conditions:

- load cell body temperature
- electronics temperature

- raw signal voltage
- supply voltage (critical to the signal produced by the cell)

Temperature measurements were obtained with Alden's resistance thermal detectors (RTDs). Voltage measurements were obtained with a Hewlett Packard 6.5 Digit Multimeter.

Test data were recorded with the turbine operating at the 40 ft/240 rpm and 80 ft/345 rpm setpoint and with the power supply at various air temperatures. As shown in Table H-4, the supply voltage was found to be constant at all ambient temperatures. The last three sets of data for the 40 ft condition shown in Table H-4 are with a preload on the dynamometer calibration arm. Since the stability of the load cell is directly related to the stability of the power supply, the constant supply voltage at different air temperatures for all of the test conditions indicates that temperature did not affect the power supply and the load cell (torque) measurements.

The raw (un-amplified) signal from the load cell was also recorded for several calibrations and was found to correlate well with the (amplified) voltage used in the loop data acquisition system, as shown in Table H-5. These data indicated that the amplifier system was stable and consistent with the raw voltage produced by the load cell.

Attempts to raise or lower the load cell temperature during a calibration were unsuccessful because a means to heat or cool the load cell as mounted on the dynamometer could not be found. Overall load cell stability versus temperature was re-examined with other tests as discussed below

TABLE H-4

TORQUE LOAD CELL POWER SUPPLY TEMPERATURE EFFECTS TEST DATA

Date	Power Supply Voltage (volts)	Load Cell Body Temp (°F)	Load Cell Air Temp (°F)	Load Cell Electronics (°F)	Flow Rate (cfs)	Turbine Head (ft)	Turbine Speed (rpm)	Turbine Power (hp)	Turbine Efficiency (%)	Phi (φ)
Sep. 06 2002	9.908865	87.5	66.1	85.5	85.6	80.41	345.2	665.4	85.27	1.00
Sep. 06 2002	9.908784	88.1	66.7	86.4	85.7	80.41	344.3	666.6	85.39	1.00
Sep. 06 2002	9.908643	89.2	68.0	88.0	85.7	80.51	344.9	668.7	85.46	1.00
Average	9.908764									
Standard Deviation	0.00011									
Sep. 06 2002	9.908467	90.2	71.6	90.5	60.9	40.35	241.1	237.3	85.19	0.99
Sep. 06 2002	9.908363	90.6	72.2	91.3	61.0	40.55	240.7	452.8	84.09	0.99
Sep. 06 2002	9.908291	91.1	73.4	91.9	61.1	40.45	239.6	451.7	84.20	0.98
Sep. 06 2002	9.908229	91.1	74.0	92.7	60.9	40.35	240.6	451.5	84.10	0.99
Average	9.908338									
Standard Deviation	0.0001									

TABLE H-5
TORQUE LOAD CELL RAW SIGNAL AND AMPLIFIED SIGNAL CALIBRATION DATA

Force at Load Cell (lbs)	Raw Signal (millivolts)	Percent Different from Predicted	Amplified Signal (volts)	Percent Different from Predicted
-1.909	2.23676		2.9053	
174.317	2.75316	-0.10%	3.1130	-2.21%
349.356	3.27212	0.23%	3.3193	-1.09%
701.299	4.30836	0.04%	3.7341	-0.27%
1051.037	5.34303	0.14%	4.1463	-0.20%
1403.404	6.37826	0.02%	4.5616	0.02%
1752.548	7.40947	0.05%	4.9731	-0.04%
2110.770	8.46452	0.02%	5.3953	0.00%
2458.047	9.49148	0.06%	5.8046	-0.06%
2804.730	10.51635	0.09%	6.2132	-0.17%
3155.910	11.54364	-0.01%	6.6271	-0.11%
3503.950	12.56902	-0.02%	7.0373	-0.13%
3506.411	12.57177	-0.06%	7.0402	-0.06%
3160.491	11.55340	-0.05%	6.6325	0.03%
2811.008	10.53013	0.03%	6.2206	0.06%
2463.053	9.50446	0.04%	5.8105	0.15%
2117.558	8.47725	-0.09%	5.4033	0.33%
1759.590	7.41962	-0.16%	4.9814	0.37%
1409.089	6.38948	-0.12%	4.5683	0.42%
1057.315	5.35454	-0.08%	4.1537	0.39%
706.814	4.31842	-0.25%	3.7406	0.52%
354.956	3.28058	-0.55%	3.3259	0.51%
1.909	2.24270		2.9098	

PRELOAD TESTS

Preload tests were conducted to determine if the operating point on the original load cell affected the measured turbine efficiency at the 40 ft and 80 ft test conditions. The calibration arm system was used to apply a preload to the load cell such that the signal magnitude at the lower torque (40 ft head) condition would be similar (or higher) to that normally produced by the 80 ft operation condition. Applying preload also shifted the load cell operating point into a region of lower hysteresis (friction in load cell linkage and calibration arm), which was found to be present in the system at the lower loadings by the calibrations.

The addition of the preload to the 40 ft operating condition shifted the load cell signal to approximately 1 volt above that produced by the 80 ft condition. The measured efficiency at the 40 ft head remained approximately 1% below that of the 80 ft head condition, as shown by the September 11th preload test data in Table H-6. This difference was consistent with the efficiency measurements without the preload at the 40 ft operating condition.

Although the difference in efficiency between the 80 ft and 40 ft conditions was consistent, both the 80 ft and 40 ft values were lower than typically measured by approximately 1.5% to 2.0%. All preload data collected on September 11th had this shift, and because of this shift, the tests were repeated September 30th. Efficiency data were first collected without the preload and then, while the turbine was operating, the calibration arm and preload was installed and measurements were repeated. The arm was removed and installed again that day and was left in place when the system was shut down. When the test loop flow stopped, a tare of the additional load (preload) was taken and the data collected with the preload installed was post-processed to calculate efficiency.

The results (Table H-6) were identical to the earlier preload tests, in that the turbine efficiency was independent of the load cell operating point; with and without the preload, the 40 ft operating point produced an average efficiency of 84.0%. These results indicate that the operating point of the load cell, in terms of voltage, did not produce a shift in the measured turbine efficiency at the 40 ft and 80 ft test conditions.

TABLE H-6
TORQUE LOAD CELL PRELOAD TEST DATA

Date	Preload Condition	Load Cell Signal (volts)	Torque (ft lbs)	Flow (cfs)	Head (ft)	Speed (rpm)	Efficiency (%)	Phi (φ)
11-Sep-02	None	4	5,185	61.5	40.75	240.3	83.59	0.98
11-Sep-02	Calibration arm and Preload	6.7	11,922	61.7	40.86	239.7	82.89	0.98
30-Sep-02	None	5	5,148	60.8	40.45	240.9	84.79	0.99
30-Sep-02	Calibration arm and Preload	8.9	11,824	60.7	40.35	240.5	84.69	0.99

STABILITY OF TORQUE ZERO WITH NO TURBINE LOAD

Measurements of indicated torque (torque used to calculate turbine power and efficiency) were made in the morning before starting the test loop between September 17 and October 1. Each day, one record was made with the oil system off, and then a second record was obtained after the oil was turned on, as shown in Table H-7. At the end of each test day, torque was again recorded after the flow loop had been off for ½ hour.

Daily posttest torque measurements showed residual drag of 40 ft-lbs to 60 ft-lbs. When the dynamometer brake system was manually shaken, or the oil system was turned back on, the residual torque dropped to less than 12 ft-lbs. If the brake was not shaken at the end of a test day, the residual torque was found to diminish somewhat overnight and return to within 12 ft-lbs of zero when the oil system was turned on the next morning. These posttest torque values show that when the test loop was shutdown at the end of the day, there was a substantial residual drag on the load cell. However, these high posttest torques were easily reduced to a negligible value (less than 12 lb-ft) either by shaking the brake system, or turning on the oil pump. This "offset" torque (less than 12 ft-lbs), which amounts to about 0.1% of the torque at the 80 ft turbine head condition, was not considered significant enough to correct measurements, but was included in the uncertainty analysis for the final engineering performance test data.

TABLE H-7
STABILITY OF TORQUE LOAD CELL ZERO WITH NO TURBINE LOAD

Date	Torque[1] w/o oil flow (pretest)	Torque[1] w/ oil flow (pretest)	Torque[1] (posttest)	Torque[1] after shake hose
9/16 pm calibration & tare in acquisition program				
9/17	-6.4	-12.0	59.8	8.4
9/18	10.5	-5.3	50.9	-
9/19	1.5	-11.2	52	-
9/19 pm calibration & tare in acquisition program				
9/20	-3.9	-7.5	46.0	-
9/23	29.9	-1.3	-	-
9/24	29.0	-4.2	43.9	-
9/24 pm calibration (no change in program values)				
9/25	-13.4	-8.3	28.4	-
9/26	22.9	2.9	13.5	-
9/27	10.2	-9.7	-	-
9/27 pm calibration (no change in program values)				
9/30	8.8	-11.7	-4.0	-
10/1	3.7	-9.8	31.7	-

[1] Torque in ft-lbs

LOAD CELL STABILITY DURING OPERATION

The stability of the original torque load cell during operation was evaluated by monitoring turbine performance at various temperatures that were experienced in the test facility. Temperature sensors were installed to document:

- The load cell body temperature
- The air temperature near the load cell
- The temperature of the load cell electronics module
- Oil temperature (dynamometer lube flow)
- Outside air temperature.

TABLE H-8
STABILITY OF TORQUE LOAD CELL DURING OPERATION

Date	Torque (ft lbs)	Flow (cfs)	Head (ft)	Speed (rpm)	Phi (φ)	Turbine Efficiency (%)	Oil Temp (°F)	Outside Temp (°F)	Load Cell Body Temp (°F)	Load Cell Air Temp (°F)	Load Cell Electronics (°F)
9/17/2003	5,186	61.5	40.6	240.9	0.99	84.15	101.6	60.5	89.6	65.3	84.7
9/17/2003	5,220	61.3	40.5	239.0	0.98	84.64	99.7	68	91	71.8	89.4
9/17/2003	5,185	61.1	40.4	240.6	0.99	84.91	103.2	71.5	89.2	75.4	92.8
9/18/2003	5,164	61.1	40.5	240.3	0.99	84.45	97.7	55	86.5	60.8	80.1
9/18/2003	5,150	61.0	40.4	240.3	0.99	84.40	96.3	56	86.6	61.1	80.6
9/18/2003	5,197	61.1	40.4	240.0	0.99	84.93	110.3	73	93.2	75.2	92.8
9/19/2003	5,193	61.2	40.6	240.7	0.99	84.49	98.5	62.5	88.3	63.8	82.2
9/19/2003	5,184	61.1	40.5	240.3	0.99	84.51	98.4	62.5	89.1	64.4	83
9/19/2003	5,142	61.0	40.5	241.9	0.99	84.68	98.7	64	89.3	66.5	85.5
9/19/2003	5,179	61.1	40.5	240.3	0.99	84.64	100	64	89.8	67.6	86.1
9/19/2003	5,196	61.1	40.4	239.6	0.98	84.76	97	64	90.6	72.3	88.9
9/19/2003	5,166	61.0	40.5	241.3	0.99	84.86	98.9	64	88.5	74.1	90.7
9/20/2003	5,169	61.0	40.4	240.1	0.99	84.62	95.9	65	90.2	66.8	85.9
9/20/2003	5,147	60.9	40.3	240.2	0.99	84.72	97.3	65	89.5	69	87.9
9/20/2003	9,732	84.2	77.7	342.6	1.01	85.51	117.1	71.5	94.5	78	95
9/20/2003	9,618	84.0	77.9	346.3	1.02	85.46	117.9	71.5	94.5	78	95
9/20/2003	9,584	84.0	78.0	347.6	1.03	85.42	117.9	71.5	94.5	78	95
9/23/2003	5,132	60.8	40.3	241.4	0.99	84.87	97.5	68.5	89.2	70.4	89.7
9/23/2003	5,169	60.8	40.2	239.4	0.99	84.91	96.1	68	86.6	72	90.9
9/23/2003	5,181	60.8	40.5	241.1	0.99	85.19	96.5	72.5	87.5	74.4	93.1
9/23/2003	9,895	84.9	79.0	345.7	1.02	85.61	117	71.5	90	76	94
9/23/2003	10,034	85.3	79.5	344.9	1.01	85.64	117	71.5	92.2	76.3	95
9/24/2003	5,138	60.8	40.4	241.2	0.99	84.68	89.5	56	86.9	63.1	82.5
9/24/2003	5,161	60.7	40.4	240.6	0.99	85.16	89.5	60.5	87.2	63.9	84.1
9/25/2003	5,127	60.7	40.5	242.1	0.99	84.84	88	50	83.2	58.1	77.6
9/25/2003	5,094	60.5	40.3	241.7	0.99	84.94	93.2	57	84	60.9	80.3
9/25/2003	5,139	60.7	40.3	240.5	0.99	84.97	88.8	57	85.4	64.6	82.6
9/25/2003	5,117	60.6	40.3	241.5	0.99	84.98	90.3	67	86.3	66.1	84.1
9/25/2003	5,197	61.0	40.5	239.9	0.98	84.91	90.9	66	88.6	69.5	87
9/25/2003	5,158	60.7	40.3	240.1	0.99	85.02	91.5	66	89	69.6	87.8
9/25/2003	5,140	60.7	40.2	240.3	0.99	84.99	91.8	67	89.4	69.8	88.5

Date	Torque (ft lbs)	Flow (cfs)	Head (ft)	Speed (rpm)	Phi (φ)	Turbine Efficiency (%)	Oil Temp (°F)	Outside Temp (°F)	Load Cell Body Temp (°F)	Load Cell Air Temp (°F)	Load Cell Electronics (°F)
9/25/2003	5,145	60.8	40.6	242.3	0.99	84.73	88.7	53.5	84.7	59.1	78.6
9/25/2003	5,165	60.8	40.4	240.2	0.99	84.78	88.3	58	84.6	60.7	80.9
9/25/2003	5,173	60.9	40.6	241.0	0.99	84.73	88.1	59	86.8	61.9	81.7
9/27/2003	5,188	60.9	40.6	240.3	0.98	84.74	86.3	57	82	59.4	79.6
9/27/2003	5,140	60.7	40.4	241.0	0.99	84.81	87.7	55	84	59.6	79.9
9/27/2003	5,165	60.8	40.5	240.5	0.99	84.82	86.8	57	84.1	60.4	79.1
9/27/2003	5,113	60.5	40.2	240.0	0.99	84.83	87.4	58	85	60.7	80
9/27/2003	5,120	60.6	40.3	241.2	0.99	84.92	88.7	58	89.1	61.7	81.4
9/30/2003	5,157	60.8	40.6	240.9	0.99	84.52	85.5	54.5	81.4	57.2	77.4
9/30/2003	5,100	60.7	40.5	242.6	1.00	84.58	86.4	55	81.5	57.4	77.6
9/30/2003	5,132	60.7	40.4	240.4	0.99	84.57	89.3	56	82	58.7	78.5
9/30/2003	5,190	60.8	40.5	239.6	0.98	84.83	87	56	84.9	62	82.3
9/30/2003	5,183	60.8	40.5	239.8	0.98	84.90	87.1	56	84.9	62.4	82.4
9/30/2003	5,162	60.8	40.5	240.7	0.99	84.91	87.8	56	84.6	62.7	82.6
9/30/2003	5,131	60.7	40.5	241.9	0.99	84.97	89.3	56	85	63.8	83.1
10/1/2003	5,155	60.7	40.4	240.2	0.99	84.86	89.6	56	84.9	60.9	80.1
10/1/2003	5,103	60.4	40.3	241.0	0.99	85.05	91.1	56	86.2	62.9	82
10/1/2003	5,123	60.5	40.3	241.1	0.99	85.17	94.1	65	89	67.7	85.5
10/1/2003	5,142	60.5	40.3	240.4	0.99	85.27	88.9	66	90	69.7	87
10/1/2003	5,205	60.6	40.4	238.9	0.98	85.35	90.3	66	91	72.1	88.9
10/1/2003	9,978	84.8	79.3	344.5	1.01	85.88	116.7	70.5	92.8	75	92.5
10/1/2003	10,003	85.1	79.8	346.5	1.01	85.69	118.1	71.5	92	74	93
10/1/2003	10,109	85.3	79.9	344.5	1.01	85.75	118.1	71.5	91	74.8	94
10/1/2003	5,205	61.0	40.6	241.4	0.99	85.34	94.1	72.5	91	73.7	93.6
10/1/2003	5,182	60.9	40.6	242.1	0.99	85.25	93.9	72.5	91	73.9	93.3
10/2/2003	5,178	60.9	40.6	240.8	0.99	84.77	91.9	63.5	88.8	63.8	83.1
10/2/2003	5,153	60.7	40.3	239.6	0.99	84.81	95.4	68.5	90.8	67.7	85.8
10/2/2003	5,131	60.7	40.3	240.7	0.99	84.91	92.7	71.5	91.3	70.8	88.1
10/2/2003	5,137	60.7	40.2	240.0	0.99	84.94	93.8	73	92.7	72.7	89
10/2/2003	5,140	60.7	40.2	240.4	0.99	85.06	94.7	73	92.7	75	91.5
10/4/2003	9,908	84.9	79.3	345.6	1.01	85.32	104.2	54.5	86.4	62.3	82.2
10/4/2003	9,887	84.9	79.3	345.8	1.01	85.34	104.6	54.5	86.8	62.2	82.2
10/4/2003	9,893	84.9	79.3	345.8	1.01	85.37	104.2	56	87.3	61.8	82.1
10/4/2003	9,916	84.9	79.2	345.0	1.01	85.40	104.8	54.5	88.5	62.1	82.4
10/4/2003	9,899	84.9	79.3	345.8	1.01	85.38	104.3	55	90.2	62.4	82.5
10/4/2003	9,930	85.0	79.4	345.5	1.01	85.38	134	55	89.3	63.3	82.8
10/4/2003	9,913	84.9	79.4	346.1	1.01	85.39	135.4	55	89.9	63.1	83.1
10/4/2003	9,939	85.0	79.4	345.4	1.01	85.40	135.5	55	90.4	63	83.3

Date	Torque (ft lbs)	Flow (cfs)	Head (ft)	Speed (rpm)	Phi (φ)	Turbine Efficiency (%)	Oil Temp (°F)	Outside Temp (°F)	Load Cell Body Temp (°F)	Load Cell Air Temp (°F)	Load Cell Electronics (°F)
10/4/2003	5,197	61.0	40.4	239.0	0.98	84.68	90.7	55	92.8	61.2	82.3
10/4/2003	5,108	60.8	40.4	241.8	0.99	84.64	89.9	55	93.3	61	82.1
10/4/2003	5,154	60.9	40.2	239.1	0.98	84.63	88.5	53.5	91.9	61.3	81.7
10/4/2003	5,128	60.7	40.1	238.9	0.99	84.60	87.9	53.5	90.9	60.9	81.4
10/4/2003	5,102	60.6	40.1	240.1	0.99	84.65	87.9	53.5	90.9	60.4	84.3
10/4/2003	5,112	60.6	40.0	239.5	0.99	84.75	86.7	52.5	91	60.6	88.4
10/4/2003	5,073	60.5	40.1	241.4	1.00	84.79	86.7	51.5	91	60.4	90.3
10/4/2003	5,116	60.6	40.1	239.8	0.99	84.75	87.6	52.5	91	60.5	92.9
10/4/2003	5,089	60.6	40.0	240.2	0.99	84.79	89	52.5	91	60.3	95.1
10/4/2003	5,085	60.5	40.1	240.6	0.99	84.83	89.3	51.5	91	60.2	95.8
10/10/2003	5,195	61.2	40.7	239.6	0.98	84.11	86.2	51.5	86.7	56.1	76.3
10/10/2003	5,126	60.9	40.5	241.4	0.99	84.26	85.5	53.5	90.2	57.8	77.6
10/10/2003	5,134	60.9	40.4	240.6	0.99	84.38	88	53.5	89.8	59.8	79.1
10/10/2003	5,159	60.9	40.4	239.6	0.98	84.39	87.8	53.5	89.7	60.4	79.3
10/10/2003	5,128	60.8	40.4	240.7	0.99	84.47	87.3	53.5	89.4	60.4	79.4
10/10/2003	5,134	60.8	40.4	240.4	0.99	84.43	87.1	53.5	89.6	60.7	79.8
10/10/2003	5,123	60.8	40.4	240.6	0.99	84.47	87.2	53.5	89.2	61.1	80
10/10/2003	5,208	61.0	40.3	236.2	0.97	84.38	93.3	57	88.6	61.5	80.1
10/10/2003	5,239	61.1	40.3	236.0	0.97	84.47	118.1	57	88.7	62.1	80.4
10/10/2003	5,074	60.7	40.5	244.4	1.00	84.57	123.1	58	88.8	62.4	80.5
10/10/2003	5,303	61.3	40.3	234.1	0.96	84.46	130.2	58	89	62.4	80.6
10/10/2003	5,071	60.7	40.5	244.4	1.00	84.61	137	58	89.1	62.5	80.7

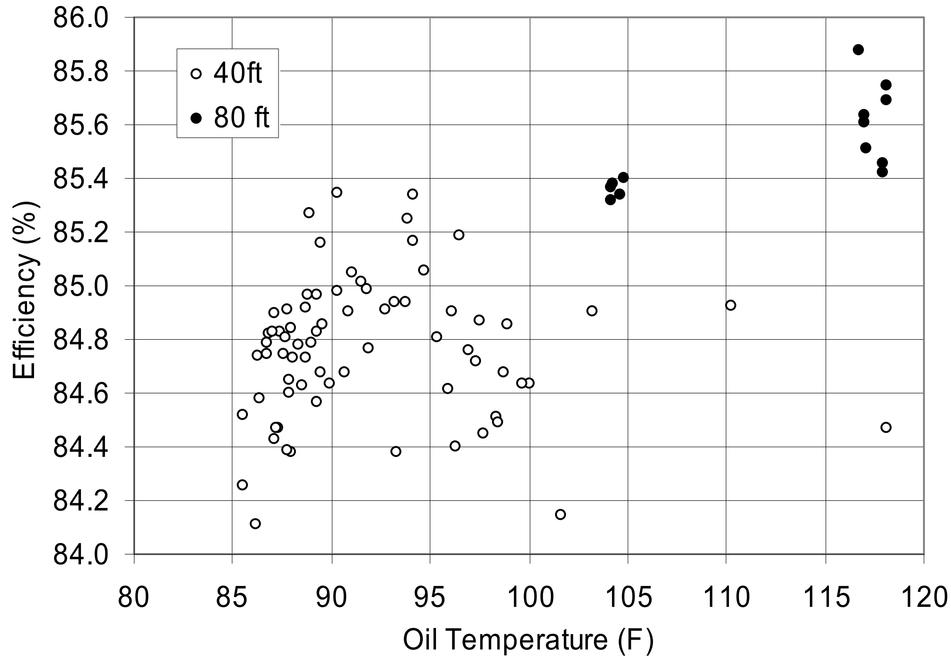


FIGURE H-5   OIL TEMPERATURE VERSUS TURBINE EFFICIENCY

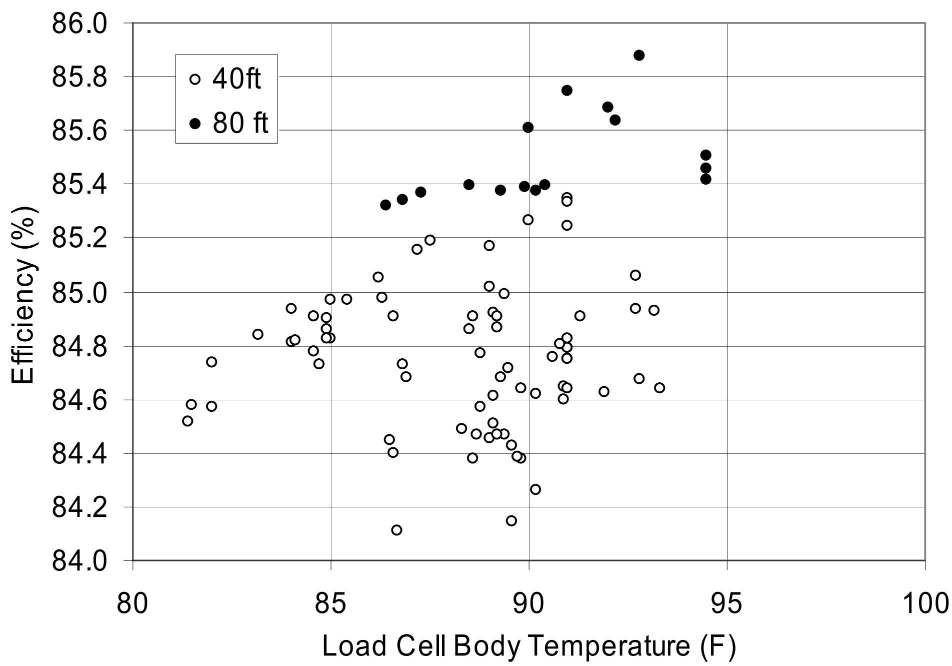


FIGURE H-6   LOAD CELL BODY TEMPERATURE VERSUS TURBINE EFFICIENCY

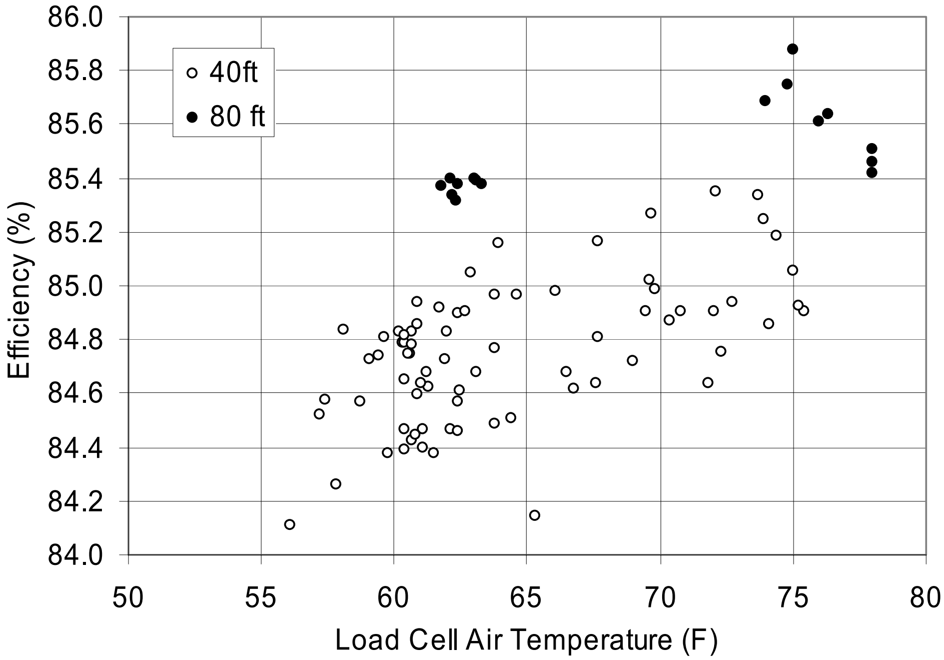


FIGURE H-7 LOAD CELL AIR TEMPERATURE VERSUS TURBINE EFFICIENCY

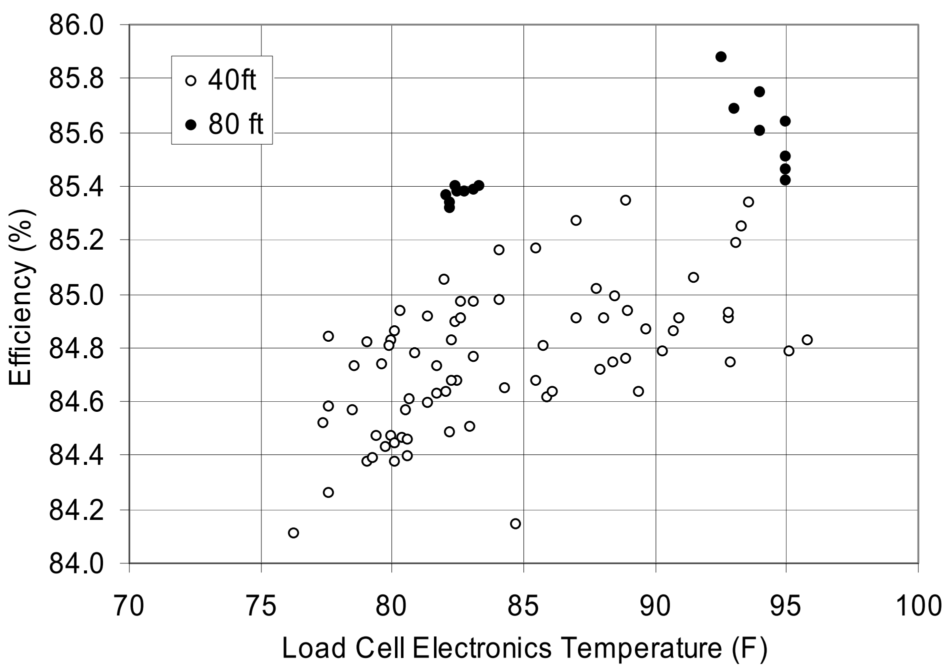


FIGURE H-8 LOAD CELL ELECTRONICS TEMPERATURE VERSUS TURBINE EFFICIENCY

During all of the biological testing in September, these temperature measurements were recorded throughout each test day and are summarized in Table H-8. Plotting these temperatures versus turbine efficiency, as shown on Figures H-5 through H-8 for the 240 rpm/40 ft condition, did not indicate any trends associated with oil temperature and load cell body and air temperatures changes. Turbine efficiency increased about 0.5% over the course of a day with load cell electronics temperature increases of 10° F (Figure H-8).

Tests were conducted on October 4 to isolate the temperature effects of the oil and the load cell electronics. While at the 80 ft operating point and maintaining a constant electronics temperature, the dynamometer oil temperature was allowed to increase from 105° F to 135° F. Standard performance measurements were made at both operating temperatures, as shown in Table H-8. The results of this test showed clearly that the oil temperature did not affect the recorded efficiency and that the oil temperature did not affect the characteristics of the oil hose connected to the dynamometer as discussed above.

During tests at the 40 ft operating point while maintaining constant oil temperature, an electric heater was used to raise the temperature of the panel containing the load cell electronics module. The load cell electronics were heated from 80° F to 95° F over the course of one hour. Performance measurements, which are presented in Table H-8, were recorded periodically throughout the hour. All other temperatures (air, oil, load cell body) remained constant within 2° to 3° F. The results indicate that efficiency increased steadily by 0.25% with the increasing load cell electronics temperature.

These results/observations indicated that the load cell system supplied with the dynamometer was not stable at the two operating points. The calibration stability discussed in the following section verified the need to replace the load cell for the final engineering tests.

VARIATIONS IN TORQUE LOAD CELL CALIBRATIONS

The first four torque load calibrations, which were conducted during the fall 2002 tests without wicket gates and the spring 2002 tests with wicket gates, produced cell coefficients that were within 0.75% of each other. These initial calibrations indicated that the uncertainty of the torque measurements was about 0.75%. In order to obtain additional data about the stability of torque measurement load cell which was supplied with the dynamometer, eleven additional load cell calibrations were conducted between September 5 and October 10, 2002. As shown in Table H-9, the September 5 calibration yielded a slope (lbs/volt) that was within 0.23% of the previous calibration (conducted July 15 at the end of the wicket gate tests). Two subsequent calibrations produced slopes within 0.1% of the September 5 result.

On September 12, the load cell span (electronics) was changed to allow readings up to 300 ft-lbs negative torque while checking for shifts in the zero when oil pressure was applied to the dynamometer hose. The cell was not calibrated until September 16. Data collected on the September 12th and 13th were post-processed using the later calibration.

TABLE H-9
TORQUE LOAD CELL CALIBRATION HISTORY

Calibration Date	Cell Coefficient (lb-ft/volt)	% Change from previous calibration
8/28/01	854.96	
10/3/01	848.539	0.75%
3/4/02	850.829	0.27%
4/5/02	852.997	0.25%
5/7/02	856.047	0.36%
5/24/02	851.165	-0.57%
7/15/2002-A	851.165	-0.52%
7/15/2002-B	846.495	-0.03%
9/5/02	848.465	0.23%
9/6/02	848.915	0.05%
9/10/02	848.592	-0.04%
9/16/02	860.211	(span change)
9/18/02	863.683	0.40%
9/19/02	577.249	(span change)
9/24/02	577.418	0.03%
9/27/02	577.67	0.04%
10/2/02	576.317	-0.23%
10/9/02	581.081	0.83%
10/10/02	577.883	-0.55%
11/6/02	626.964	NEW CELL
11/7/02	627.292	0.052
11/8/02	639.032	(span change)
11/14/02	637.517	-0.24%
11/22/02	637.318	-0.03%
12/5/02	637.492	-0.03%
12/12/02	639.962	-0.39%
1/14/03	638.23	-0.27%

A calibration on September 18 showed a 0.4% shift in the slope compared to the September 16 calibration. No cause for the shift could be identified. At the end of the day on September 19, the load cell span was changed (2nd time) to maximize the voltage output over cell's working range. Although this produced a significant (30%) change in the cell output slope (lb/volt), the turbine efficiency measured after this change agreed well with previous data. The following calibration on September 24 agreed within +0.03% of the September 19 calibration.

The second calibration after the September 19 re-spanning of the cell, which was performed on September 27, showed good agreement (+.04%) to the previous September 24 calibration, but meant an overall change of 0.07% from the second re-ranging on September 19. The calibration performed on October 2 produced a coefficient which was 0.23% lower than the previous calibration (September 27). Two additional calibrations, which were completed on October 9 and October 10, were more than 0.5% different than the previous calibration.

Using the September 19 calibration as a baseline, the five subsequent calibrations indicated that the cell coefficient drifted approximately ± 0.70%. Turbine performance data collected during biological testing between September 19 and October 10 utilized the September 19 calibration; the later calibration coefficients were not used in the acquisition program. This means that the data collected over the September 19 to October 10 period has a ±0.7% uncertainty in torque values.

Although the load cell calibrations were fairly stable throughout these calibrations, the cell produced a 0.4% shift on the September 18 calibrations and a 0.8% shift on the October 9 calibrations for no apparent reason. In general, over the September test period, the stability of the load cell was less than desired (i.e., drifted greater than 0.2%). For these reasons, the load cell which was supplied with the dynamometer was replaced with one sized for the actual torques generated by the turbine. The original load cell was sized for testing turbine power on the order of 1,000 hp with capacity for up to 1,800 HP for off-BEP testing, while the replacement load cell was sized for the 400-800 HP measured torques at the 40 ft and 80 ft head conditions.

LOOP HEAD AND FLOW PRESSURE TRANSDUCERS

During the fall 2002 biological testing, "end of the day" recordings of the test loop flow and the turbine head measurement transducers were obtained with flow in the system completely stopped. These measurements were obtained to verify that the difference in measured turbine efficiency at the two test heads was not due to measurement errors, including possible air accumulation in the manometer lines during tests. As shown in Table H-10, the measurements yielded deflections of less than 0.002 ft and 0.083 ft for the flow and turbine head transducers, respectively. The zero offsets for flow and head were deemed to be negligible relative to turbine efficiency. A 0.002 ft correction in the flow measurement deflection would have amounted to less than 0.01% in overall turbine efficiency. Correction of the data for the 0.08 ft head offset would have produced a 0.1% increase in overall turbine efficiency at the 40 ft condition and 0.05% at the 80 ft condition. Therefore, the turbine flow and head transducers were considered adequate for the final engineering tests.

TABLE H-10
TURBINE HEAD AND TEST LOOP FLOW END OF DAY DIFFERENTIAL PRESSURE CELL ZERO MEASUREMENTS

Date	Flow (ft)	Head (ft)
9/11/2002	-	0.085
9/13/2003	0.003	0.073
9/17/2003	0.002	0.033
9/17/2003	0.001	0.035
9/18/2003	0.002	0.029
9/18/2003	0.008	0.052
9/19/2003	0.002	0.089
9/24/2003	0.009	0.080
9/25/2003	0.004	0.070
9/26/2003	0.003	0.070
9/30/2003	0.003	0.084
10/1/2003	0.002	0.061
10/2/2003	0.003	0.070
10/4/2003	0.002	0.098
10/10/2003	0.001	0.115

UNIFORMITY OF PIEZOMETRIC TAP MEASUREMENTS FOR TURBINE HEAD

The ASME PTC-18-1992 guidelines require that the pressure readings from individual taps at each turbine head location not vary from the reading of any other tap in the section of measurement by more than 1% of the net head or 20% of the velocity head. The 20% velocity head limits are 0.27 ft and 0.17 ft for the scroll case inlet and the draft tube exit pressure measurement locations, respectively, at the 40 ft operating condition. At 80 ft, the 20% limits are 0.54 ft at the inlet and 0.24 ft at the draft tube. These are conservative (stricter) requirements than the 1% of net head rule, the latter yielding larger allowed limits of 0.8 ft at 80 ft head and 0.4 ft at the 40 ft operating head.

A survey of the pressure taps at the 40 ft operating point was completed on September 18, 2002. As shown on Table H-11, the maximum deviation within the four inlet pressure taps was 0.066 ft and 0.05 ft within the four draft tube pressure taps, which was well below the 20% velocity head limits at both locations and the 1% net head limit (0.4 ft). These results indicate that there was no significant tap effect influencing the reliability of the turbine head measurement.

TABLE H-11
UNIFORMITY OF PIEZOMETER READINGS
AT TURBINE HEAD MEASUREMENT TAPS

Inlet Tap Survey

Inlet Tap Location	Recorded Flow (cfs)	Head (ft)	Deviation from Average of all Head Readings (ft)
All before	59.9	40.4	
1	60.0	40.4	-0.066
2	59.9	40.4	0.025
3	60.0	40.4	-0.007
4	59.9	40.4	-0.012
All after	59.8	40.5	

20% velocity head limit at 40 ft head condition = 0.27ft

Draft Tube Tap Survey

Draft Tube Tap Location	Recorded Flow (cfs)	Head (ft)	Deviation from Average of all Head Readings (ft)
All before	60.1	40.4	
1	59.9	40.5	0.0492
2	60.0	40.4	-0.022
3	60.0	40.4	-0.0071
4	60.0	40.4	-0.0134
All after	59.9	40.4	

20% velocity head limit at 40 ft head condition = 0.17ft

UNIFORMITY OF TEST LOOP FLOW MEASUREMENTS

Measured turbine efficiency during the spring 2002 biological tests with wicket gates was lower than the measured efficiency during preliminary testing. Because of these variations in efficiency, surveys of the flow meter pressure taps were conducted in September 2002 during the scheduled biological tests. The piezometer readings in each of the venturi taps (inlet and throat) were individually measured using the same methodology used to survey the turbine head taps as discussed in the previous section. Each throat tap pressure was measured, in turn, with respect to the manifolded inlet taps, and then each inlet tap was measured against the manifolded throat tap set.

Table H-12 presents the results of these surveys at the 40 ft and 80 ft BEP operating setpoints. The surveys on September 20, 23, and 24 identified lower differential pressures using the top inlet and throat taps than the differential pressure measured using the manifolded taps, corresponding to lower indicated flows. Additional surveys were completed on September 26 and October 1 to verify the results of the previous surveys and to fully document the pressure measurements on the flow meter. Although the effect on flow could not be determined from these measurements, the difference in indicated flow between the upper and lower taps was on the order of 1%.

The test loop was opened and the flow meter was inspected on October 3, 2002 prior to final engineering tests. This inspection focused on the flow meter pressure taps and the meter throat for any deposit or organic growth that could have affected the indicated flow. Although nothing was found within the meter itself, the inspection revealed that the rubber gasket used in the pipe flanges immediately upstream of the meter had been installed such that the gasket material projected into the flow a maximum of approximately 1.5 inches at the top of the pipe. The lower pressure readings on the upper taps in the meter inlet and throat which were obtained during the tap surveys conducted on September 26 and October 1 (with the gasket protruding) were consistent with pressures that would be expected with the upper taps being in the wake of the protruding gasket.

Construction records indicated that this flange had been loosened by the general contractor to adjust a minor misalignment of the test loop pipe during installation of the turbine scroll case. This pipe adjustment was made after the test loop had been inspected by Alden personnel, but prior to initial operation in fall of 2001. Therefore, the gasket was protruding in the pipe prior to the initial engineering tests without wicket gates and was in the flow for the engineering and biological testing with the wicket gates up to the October 3 inspection.

TABLE H-12
UNIFORMITY OF PIEZOMETER READINGS
AT TEST LOOP FLOW METER TAPS

9/20/2002

Throat Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	60.1	5.84	40.4		
A	60.2	5.87	40.3	0.60%	0.30%
B	60	5.83	40.4	-0.10%	-0.10%
C	59.9	5.82	40.4	-0.30%	-0.20%
D	60	5.83	40.5	-0.10%	-0.10%
All after	59.9	5.82	40.5		

9/20/2002

Pipe Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	60	5.83	40.4		
1	59.3	5.71	40.4	-1.10%	-0.50%
2	58.9	5.61	40.4	-2.70%	-1.40%
3	60.2	5.87	40.4	1.90%	0.90%
4	60.2	5.88	40.4	1.90%	1.00%
All after	59.9	5.82	40.5		

9/23/2002

Throat Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	83.3	11.24	79.0		
A	82.7	11.07	79.2	-2.20%	-1.10%
B	83.6	11.31	79.3	0.00%	0.00%
C	84.1	11.46	79.3	1.30%	0.60%
D	84	11.42	79.5	0.90%	0.40%
All after	na	na	na		

TABLE H-12 (continued)

9/23/2002

Pipe Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	na	na	na		
1	84.4	11.53	79.4	1.10%	0.60%
2	84.1	11.43	79.5	0.30%	0.20%
3	83.5	11.28	79.5	-1.10%	-0.60%
4	83.8	11.36	79.5	-0.40%	-0.20%
All after	83.7	11.35	79.5		

9/24/2002

Throat Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	59.8	5.78	40.4		
A	59.7	5.77	40.4	-0.20%	-0.10%
B	59.7	5.78	40.4	0.00%	0.00%
C	59.8	5.78	40.4	0.20%	0.10%
D	59.7	5.77	40.4	0.00%	0.00%
All after	59.9	5.8	40.4		

9/24/2002

Pipe Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	59.6	5.75	40.5		
1	59.1	5.66	40.4	-1.90%	-1.00%
2	59.6	5.75	40.4	-0.50%	-0.20%
3	60.1	5.85	40.4	1.30%	0.60%
4	60	5.84	40.4	1.10%	0.60%
All after	59.7	5.77	40.4		

TABLE H-12 (continued)

9/26/2002

Throat Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	59.8	5.8	40.6		
A	59.6	5.76	40.5	-0.30%	-0.10%
B	59.5	5.73	40.5	-0.70%	-0.30%
C	59.8	5.8	40.4	0.40%	0.20%
D	59.9	5.81	40.4	0.60%	0.30%
All after	59.8	5.78	40.4		

9/26/2002

Pipe Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	59.8	5.79	40.4		
1	59.2	5.68	40.4	-1.80%	-0.90%
2	59.7	5.77	40.4	-0.30%	-0.10%
3	60.1	5.85	40.4	1.00%	0.50%
4	60.1	5.85	40.4	1.10%	0.50%
All after	59.7	5.77	40.4		

10/1/2002

Throat Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	83.3	11.22	79.3		
A	83.4	11.26	79.5	-0.30%	-0.20%
B	83.1	11.19	79.5	-0.90%	-0.50%
C	83.8	11.37	79.5	0.70%	0.30%
D	83.8	11.36	79.7	0.50%	0.30%
All after	83.5	11.3	79.8		

TABLE H-12 (continued)

10/1/2002

Pipe Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	83.5	11.3	79.8		
1	83	11.15	79.7	-1.70%	-0.90%
2	83.6	11.31	79.8	-0.40%	-0.20%
3	84.1	11.46	79.8	1.00%	0.50%
4	84.2	11.48	79.9	1.10%	0.60%
All after	83.8	11.37	79.9		

10/4/2002 After Gasket Fix

Throat Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	84.9	11.66	79.3		
A	85	11.7	79.3	0.20%	0.10%
B	84.8	11.67	79.2	0.00%	0.00%
C	84.8	11.65	79.2	-0.10%	0.00%
D	84.8	11.65	79.2	-0.20%	-0.10%
All after	84.9	11.67	79.2		

10/4/2002 After Gasket Fix

Pipe Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	84.9	11.67	79.2		
1	84.9	11.67	79.2	0.10%	0.00%
2	84.9	11.68	79.2	0.10%	0.00%
3	84.8	11.65	79.3	-0.10%	-0.10%
4	84.9	11.67	79.3	0.00%	0.00%
All after	84.9	11.67	79.3		

TABLE H-12 (continued)

10/4/2002 After Gasket Fix

Throat Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	60.8	5.99	40.4		
A	60.9	6.01	40.3	0.30%	0.20%
B	60.8	5.99	40.3	-0.10%	0.00%
C	60.8	6	40.3	0.10%	0.00%
D	60.8	5.98	40.3	-0.20%	-0.10%
All after	60.9	6	40.2		

10/4/2002 After Gasket Fix

Pipe Tap Location	Recorded Flow (cfs)	Flow Differential (ft)	Head (ft)	Deviation from Average of all Flow Differential Readings (ft)	Deviation from Average of all Flow (cfs)
All before	60.9	6	40.2		
1	60.9	6	40.2	0.50%	0.20%
2	60.8	5.99	40.3	0.30%	0.20%
3	60.7	5.97	40.2	-0.10%	0.00%
4	60.5	5.93	40.2	-0.70%	-0.40%
All after	60.7	5.97	40.1		

The protruding gasket was trimmed and surveys of the flow meter tap pressures were repeated on October 4 at the 40 ft and 80 ft operating setpoints. The survey data without the protruding gasket, which is presented on Table H-12, showed very uniform pressures at both taps sets and at both operating points. These data with the gasket corrected indicated there was no reason to suspect the meter was not performing as it did during its calibration in October 2000.

Tests with the corrected gasket determined that the previous test loop flows, with the protruding gasket, were 1.81% low at the 80 ft operating point and 1.91% low at the 40 ft point. An average correction factor of 1.0186 was applied to all flow measurements obtained before October 3, 2002. The effect of this increase in flow after correcting the gasket was to reduce the calculated turbine efficiencies by 1.86%.

IN SITU DIFFERENTIAL PRESSURE CELL CALIBRATIONS

Prior to final engineering tests, the turbine head and the test loop flow meter differential pressure cells were calibrated *in situ* on October 29, 2002. The *in situ* calibrations, which are provided in Appendix D, used the same dead weight tester that was used for all previous calibrations of pressure cells conducted for this project in the Calibration Department at Alden. A comparison of the original calibration results (Table 4-1) to the *in situ* calibration results is presented in Table H-13. The *in situ* calibrations were all essentially the same as the previous calibrations (± 0.1%).

As part of this *in situ* calibration, all piezometer lines were reinstalled to slope continuously upward to minimize low points and potential air traps. Comparing turbine operating data before and after the *in situ* calibrations (Appendix D) indicates that there were no measurable differences in head and flow with the new lines and the original lines. This comparison verifies that the procedures used to bleed the DP cells were adequate.

TABLE H-13
IN SITU DIFFERENTIAL PRESSURE CELL CALIBRATION DATA

Pressure Measurement	Calibration Range (psi)	Slope (m)	Intercept (b in psi)	In Situ Slope (m)	In Situ Intercept (b in psi)
Test Loop Flow Meter	0-8	1.12687	-2.2439	1.127118	-2.2443
Turbine Head	0-50	6.2513	-12.488	6.255504	-12.5257

SCROLL EXPANSION MEASUREMENTS

In order to investigate the effects of potential geometry, and therefore, velocity changes in the scroll case between the 40 ft and 80 ft test conditions, Lindskog Balancing obtained laser measurements of the scroll at both operating conditions and without the turbine and test loop on. The laser measuring system was mounted to a fixed point on the floor in the test facility and a detector was mounted on top of the scroll case in the vertical direction to measure the vertical expansion. The measuring devices were leveled and the reading zeroed with the turbine offline. The turbine was then brought online and the measurements were made at the two operating points. The process was repeated to measure the vertical down and horizontal expansions.

No vertical downward expansion was measured from 0 to 80 ft head. Vertical upward expansion was 0.0045” at 40 ft and 0.011” at 80 ft heads. Horizontal expansion was 0.008” at 40 ft and

0.014" at 80 ft. These expansions are consistent with the values predicted with the computer model used to design the scroll case. These measurements verify that there was no significant geometry change which could affect flow patterns or velocity head at the runner inlet. Therefore, differences in turbine efficiency at the 40 ft and 80 ft conditions can not be attributed to scroll case expansion.

TURBINE BEARING FRICTION ANALYSIS

Prior to final assembly of the pilot scale turbine, tests on the turbine bearing were conducted to investigate the amount of friction at speeds up to 400 rpm. The tests included two configurations: 1) bearing shaft only and 2) bearing shaft with runner top cover. A small motor with a belt drive was connected to the top of the bearing shaft coupling. The bearing shaft was brought up to an initial speed and the belt drive instantaneously released. A data acquisition system from Alden's Calibration Department was used to record the shaft decceleration (speed versus time). Bearing friction was calculated from the slope of the deceleration and the inertia of the rotating components.

The results of the preliminary bearing friction tests are presented on Figure H-9. Test data indicated that the bearing friction without any downthrust was 1.0-1.5 HP at 240 rpm and 1.7-2.1 HP at 345 rpm, depending on the seal water pressure. These friction losses are about 0.5% and 0.2% of the turbine output measured during the preliminary tests with wicket gates at the 240 rpm and 345 rpm speeds, respectively. These preliminary friction tests indicate that some of the difference in turbine efficiency measured at the two heads could be attributed to bearing friction.

Tests with downthrust on the bearing shaft could not be conducted prior to turbine assembly or after the turbine installation in the test loop. However, partial runaway tests were contemplated during the final engineering tests to estimate the total mechanical and viscous friction with downthrust. Knowing the mass of runner and acceleration during first few seconds of load rejection, the total friction under load could have been determined if the residual friction on the dynamometer was known. Because the test loop pump speed could not be reduced low enough to determine the relationship between residual friction in the dynamometer and speed, and operating the turbine at speeds approaching 400 rpm would have damage the runner, partial load rejection tests were not conducted and bearing/viscous friction with downthrust could not be measured in the pilot scale turbine.

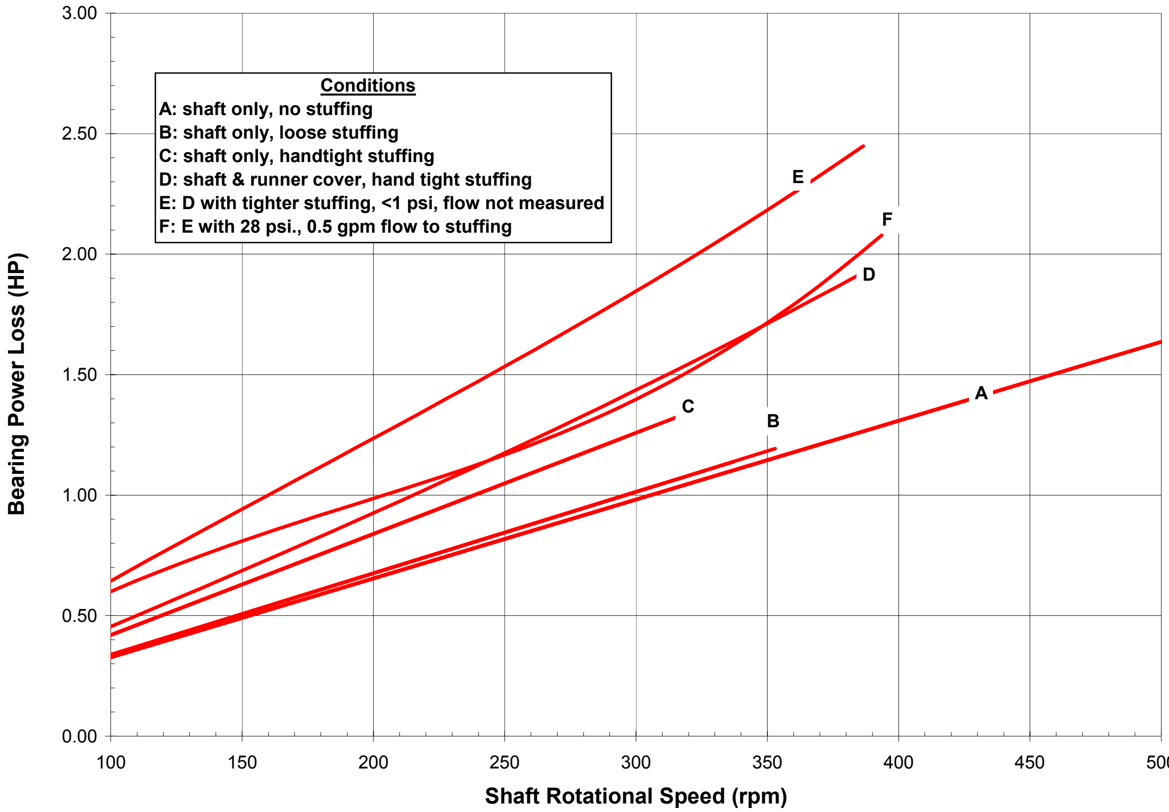


FIGURE H-9 PRELIMINARY BEARING FRICTION TEST RESULTS

Therefore, power consumption for the rolling elements in the bearing was calculated based on formulas for friction due to the applied load (downthrust) and fluid viscosity. Frictional torque (M_1) created by the applied load was determined using (Harris 1984):

$$M_1 = Z\,(F_s/C_s)^y\,F_B\,d_m \qquad \text{H-1}$$

where: $Z = 0.001$ for roller bearing

F_s = static equivalent load (8,000 lbs downthrust)

C_s= Basic static load rating (32,500 lbs)

$y = 0.33$ for roller bearings

F_B = Effective load = $1 / (0.9 \tan \alpha)$ H-2

α = Bearing contact angle (20°)

d_m = Bearing pitch circle diameter (7.68 in.)

Frictional torque (M_v) caused by the bearing lubricant was determined using (Harris 1984):

$$M_v = 0.0000142\ f_o\ (\nu^2\ n)^{0.6667}\ d_m^{\ 3} \qquad \text{H-3}$$

where: f_o = 2 for oil bath, deep grove bearings
ν = kinematic viscosity of oil (18 cSt)
n = rotational speed (rpm)

Addition of the frictional torques (M_1 plus M_v) provided an estimate of the pilot scale turbine bearing friction of about 0.75 HP and 1.1 HP at 240 rpm and 345 rpm speeds, respectively, with downthrust. These calculated bearing friction losses are about 50% of the losses measured for the bearing and seal packing without any downthrust on the runner at both test conditions (1.5 HP at 240 rpm and 2.1 HP at 345 rpm). The calculated bearing friction was about 0.3% of the pilot scale turbine power at 240 rpm and 0.1% at 345 rpm. The measured bearing and shaft seal friction was about 0.5% of the pilot turbine power at 240 rpm and 0.2% at 345 rpm. Both the measured bearing and seal packing friction measurements without downthrust and the calculated bearing friction with downthrust for the pilot turbine were consistent with bearing and seal friction expected for similar components. Therefore, bearing and shaft seal friction were considered a scalable loss. Bearing and shaft seal friction accounted for about 0.3% of the difference in measured efficiency between the 240 rpm and 345 rpm conditions

TURBINE RUNNER DOWNTHRUST EFFECTS

Prior to final engineering tests for operation at different wicket positions, tests with the runner head cover vent valve throttled were conducted to evaluate any possible effects of downthrust on turbine efficiency. During normal operation, the head cover vent valve was fully opened to drain top seal leakage away from the head cover. Top cover leakage was measured to be about 25 gpm at 40 ft head and 40 gpm at 80 ft head with the vent valve open. Draining the leakage in this manner was intended to minimize pressure on the top cover, which would minimize downthrust transferred to the shaft bearing.

The data presented in Table H-14 shows that there was no difference in the turbine efficiency with the head cover vent valve completely closed and full open. With the vent valve closed, the additional downthrust on the runner bearing was estimated to be 31,000 lbs assuming the full turbine head (40 ft) was acting on the top cover. With the vent valve open, all bearing downthrust was due to water flowing through the runner, approximately 14,000 lbs assuming the top cover seal has minimal leakage. These test results indicated that bearing friction loss was not affected by downthrust on the top cover. If bearing friction was a major contributor to the turbine losses, the measured efficiency should have decreased with the higher downthrust.

TABLE H-14
TURBINE RUNNER DOWNTHRUST TEST DATA

Date	Head Cover Vent Position	Flow (cfs)	Head (ft)	Speed (rpm)	Turbine Efficiency (%)
10-Oct-02	open	61.2	40.7	239.6	84.11
10-Oct-02	open	60.9	40.5	241.4	84.26
10-Oct-02	open	60.9	40.4	240.6	84.38
Average		61.0	40.5	240.5	84.2
10-Oct-02	closed	60.9	40.4	239.6	84.39
10-Oct-02	closed	60.8	40.4	240.7	84.47
10-Oct-02	closed	60.8	40.4	240.4	84.43
10-Oct-02	closed	60.8	40.4	240.6	84.47
Average		60.8	40.4	240.3	84.4

TURBINE SHAFT SEAL FLOW

Measurements of flow to the runner shaft stuffing (seal) box were attempted to evaluate effects on turbine efficiency with different seal flow rates. During operation of the turbine, a small amount of water was delivered to the seal box from the scroll case inlet pipe (high pressure). During initial operational testing without wicket gates, the runner shaft seal was tightened to assure a small drip out of the packing. The packing was never adjusted at any time after this initial tightening, but always had a small drip indicating that the packing was properly adjusted.

During normal operation, small air bubbles in the seal water plastic tubing indicated that there was flow into the seal box. However, this flow was too small to be accurately measured. Even with a booster pump, which has a design point of 1.5 gpm at 30 ft head and a shutoff head of 48 ft, flow measurements in the line were not possible. This low flow at both heads indicated that shaft seal flow did not affect turbine efficiency measurement at the high and low head test conditions.

BOTTOM SEAL LEAKAGE MEASUREMENTS

In early December 2001, the turbine bearing/runner assembly was pulled out of the scroll case for installation of the wicket gates. During reassembly of the turbine, the runner was manually turned to check for binding. During this check, and for the remainder of the winter, all water was drained from the test loop.

The test loop was prepared for engineering tests with wicket gates in February 2002. During initial operation, the runner would not rotate. Inspection of the runner indicated that the runner had dropped down about ¾ of an inch and was seized in the scroll case. The displacement was the result of water filling and freezing in the hollow portion of the runner hub sometime in the mid-December 2001 to mid-February 2002 period. Apparently, water had leaked into the runner casting during the first operational period and was not detected during the turbine disassembly and reassembly for installation of the wicket gates.

The turbine bearing and adaptor plate and the runner top plate were shipped as a unit to a machine shop for further investigation of the damage. In the shop, the bearing shims were removed to lower the shaft to see the top seal teeth. The top seal appeared to be undamaged and the shaft and runner top plate rotated freely without any obvious friction points.

The bottom seal, which remained in place at the top of the draft tube when the runner was removed, was inspected and found damaged. A fracture was found in the bottom seal backing plate at one location. The inside of the backing plate was slightly lower than the design elevation indicating that the facture extended around about ¼ of the perimeter along the thin portion of the backing plate. The remainder of the backing plate was at the proper elevation and appeared to be undamaged. The seal showed considerable wear. Measurements of the inside diameter of the seal indicated that the clearance had increased to 0.055 inches from the 0.010 inch design clearance.

The bottom seal backing ring was repaired *in situ* in order to limit the repair time to several days rather than several months to remove the scroll case. Wedges were inserted between the backing ring and the top of the draft tube flange. One wedge was placed under the fracture and one wedge was placed adjacent to the fracture (looking down) under that portion of the backing ring that appeared to be undamaged. Three other wedges were placed equidistance around the damaged portion of the backing ring. All of the wedges were tack welded in place.

The runner and bearing assembly was rebalanced and installed back in the test loop for the spring tests. During the preliminary tests in April 2002 to determine the BEP wicket gate position, the turbine operation near BEP for the each gate position indicating that the runner repairs were adequate. In fact, the April preliminary engineering tests indicated that the BEP turbine efficiency with wicket gates was actually higher than the turbine efficiency without wicket gates. However, off-BEP tests produced unacceptable turbine vibrations at φ values less than 0.95 and unacceptable pump vibrations at φ values greater than 1.05. Off-BEP tests at the 16°, 18°, and 24° gate positions produced very rough operating conditions, which may have created additional wear on the bottom seal leading to increased leakage.

On April 17 and 18, peak efficiencies were measured at the 38 ft and 80 ft heads with an 18° wicket gate angle. On April 25 and 26, the wicket gates were set at the selected BEP position (18.2°) and tests were conducted to verify turbine operation at BEP for spring testing with wicket gates. The high efficiencies measured on April 17 and 18 could not be replicated on April 25 and 26. This indicated a mechanical change in the turbine such as increased bottom seal leakage. The only way to determine the condition of the bottom seal was to disassemble the turbine and inspect the seal, which was not possible without jeopardizing the schedule for biological testing. However, measurements of the seal leakage were obtained at the 40 ft and 80 ft operating conditions, and the final engineering test data was adjusted for what was found to be abnormally high bottom seal leakage that would not exist in a prototype turbine.

On January 8, 2003, dye dilution measurements of bottom seal leakage were obtained with the turbine operating at the 40 ft/240rpm and the 80 ft/345 rpm BEP wicket gate positions. Dye injection ports were drilled and tapped in the runner housing, one near the runner inlet and one just above the bottom seal, as shown on Figure H-10. The flow measurement techniques consisted of injecting a known flow and concentration of dye into the annular cavity around the runner shroud near the runner inlet and measuring the mixed concentration of the dye in the leakage flow near the bottom seal. A CFD analysis was conducted to verify that the dye would be fully mixed at the sampling port near the bottom seal. A complete description of the flow measurement techniques and the test data are provided in Appendix I.

Results of the bottom seal leakage tests are summarized on Figure H-11. Bottom seal leakage was 928 gpm (2.07 cfs) at 40 ft and 1,292 gpm (2.88 cfs) at 80 ft heads. This leakage is about 3% of the turbine flow at both conditions. Head loss coefficients (K_L) were determined for leakage (Q_L in cfs) at these two turbine heads (H in ft) were calculated using:

$$H = K_L \, Q_L^2 \qquad \text{H-4}$$

The head loss coefficients for these two measured conditions were 9.33 at 40 ft and 9.65 at 80 ft. The bottom seal leakage at the final engineering test turbine heads were estimated using Equation H-2 and the average of the head loss coefficient (9.49) for the two leakage measurements. As discussed in Appendix I, the accuracy of the leakage flow measurements was about 5%, which amounts to about 0.15% of the turbine flow. Since measured leakage was proportional to the square root of the turbine head, these measurements also indicate that bottom seal leakage did not contribute to the difference in turbine efficiency at the 40 ft and 80 ft heads.

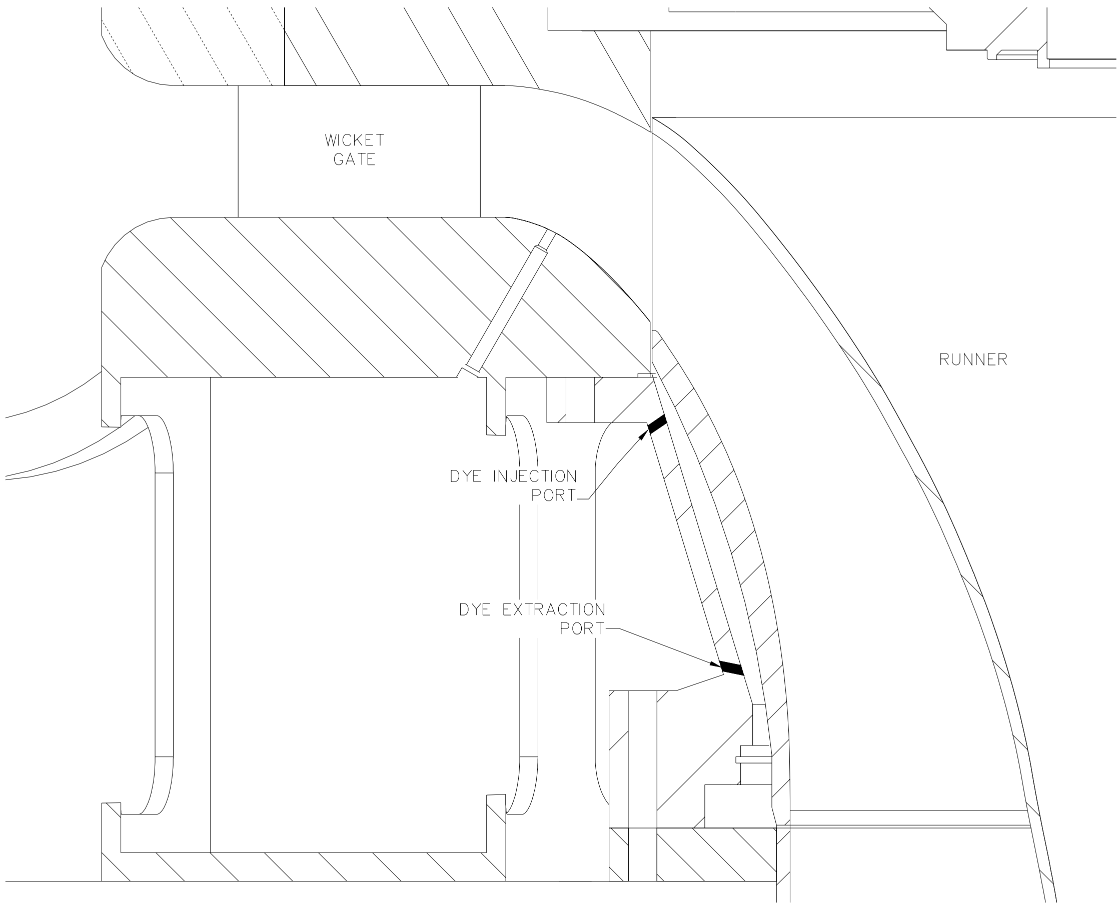


FIGURE H-10 DYE INJECTION PORTS TO MEASURE RUNNER BOTTOM SEAL LEAKAGE

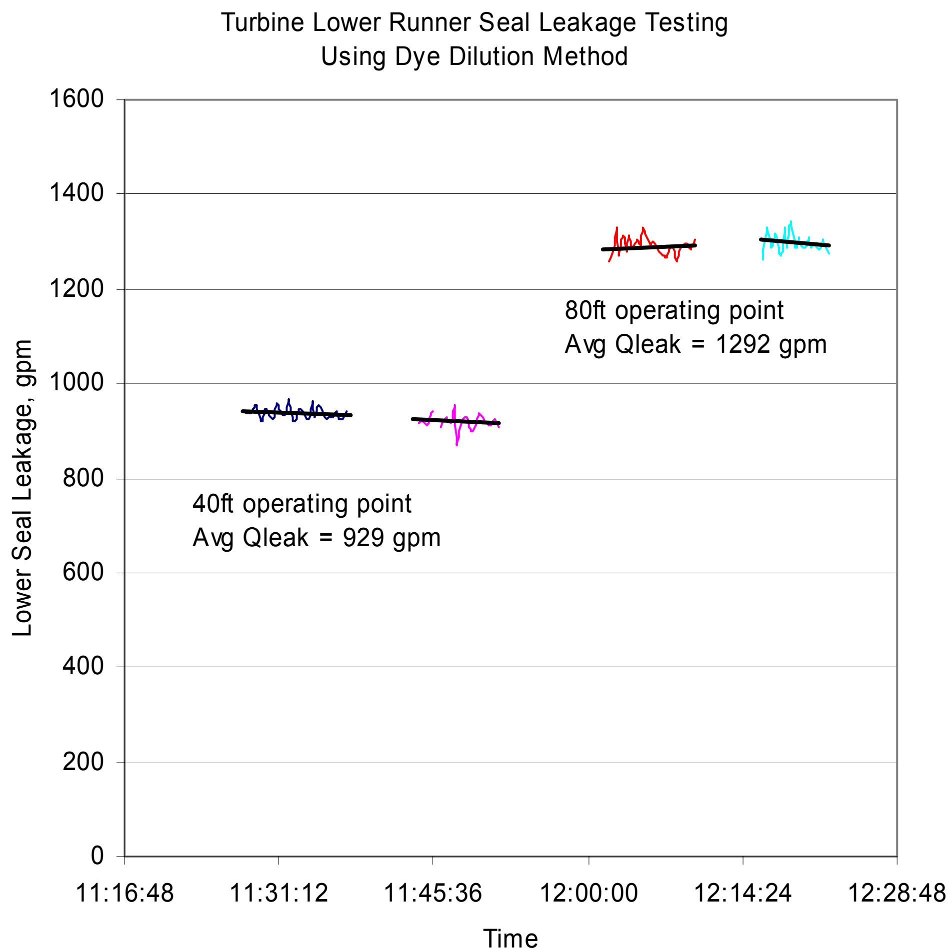


FIGURE H-11 RUNNER BOTTOM SEAL LEAKAGE MEASUREMENTS

APPENDIX I

TRACER DILUTION FLOW MEASUREMENT
OF PILOT SCALE TURBINE LOWER SEAL LEAKAGE

APPENDIX I
TRACER DILUTION FLOW MEASUREMENT OF PILOT SCALE TURBINE LOWER SEAL LEAKAGE

INTRODUCTION

Measurements of lower seal clearance around the runner shroud were taken in spring of 2002 when the runner was removed for installation of the wicket gates. The measurements indicated that the seal had worn and the gap was greater than designed. Since additional leakage through this bottom seal clearance reduced the flow available for power generation, measurement of the flow through the worn bottom seal was necessary to accurately determine the turbine efficiency with the bottom seal design clearance.

Because the leakage path was internal to the turbine structure, conventional flow measurement techniques using pitot tubes and velocity meters could not be used. The flow path between the runner shroud and housing was very narrow with the leakage bypassing the runner at the leading edge of the blades, following along the outside of the shroud in the limited space inside the housing, passing through the seal, and reentering the draft tube at the trailing edge of the runner.

The dye dilution method, using the fluorescent dye Rhodamine WT, was chosen as the most suitable flow measurement method. Dye concentrations were measured by a fluorometer capable of detecting concentrations of about 0.001 ppb, such that mixed concentrations below 3 ppb provide sufficient measurement accuracy while producing a concentration undetectable by eye.

The leakage tests were performed by Alden while typical performance measurements were recorded with the turbine operating at the two operating test conditions (40 ft and 80 ft heads). The tracer was injected through an injection port installed in the turbine housing near the runner inlet. The sample location was through a second port installed in the housing above the bottom seal near the runner trailing edge. Leakage calculations and an assessment of the flow swirl in the cavity between the runner and shroud generated by the turning runner indicated that there would be adequate mixing of the tracer with these injection and sampling port locations.

A Turner Designs Model 10 fluorometer was used in the through-flow mode to record tracer concentration. The tracer was introduced at the pump discharge flanges, and dye injection flow was measured by the volumetric method. The fluorometer was calibrated using loop water. Flow was calculated based on conservation of the tracer dye; using the tracer flow multiplies by the injected concentration, divided by the final concentration minus any initial background concentration. Because of the closed loop, the tracer eventually re-circulated and the background concentration increased throughout the testing. Records of the background concentration before and after each test were used to correct the results for the changing background concentration.

The following describes the test measurement procedures and instrumentation, the calculation of flows and heads, and lists the test results.

FLOW MEASUREMENT

Principles of the Dye Dilution Method

The dye dilution method is based on a mass balance calculation. A small quantity of fluorescent dye at high concentration is continuously injected at a measured, constant rate into the test flow. Concentration of the fully mixed flow is determined by fluorescence intensity measurement. The ratio of the injected concentration to the final concentration, minus any background concentration in the incoming flow, multiplied by the injection flow equals the fully mixed test flow.

$$Qt = \frac{q_i C_i}{(C_t - C_B)} \qquad \text{I-1}$$

where:

q_i	=	injected flow (ft^3/sec)
C_i	=	injected concentration (ppb)
C_t	=	mixed concentration (ppb)
C_B	=	background concentration (ppb)
Q_t	=	flow to be measured (ft^3/sec)

The tracer may be any conservative substance detectable in small concentrations. A convenient tracer is a fluorescent dye, Rhodamine WT, which is detectable in concentrations as low as 0.001 ppb using standard techniques. Rhodamine WT has low adsorption characteristics and is supplied at nominal 20% concentration by weight. A stock injection solution was prepared at a concentration of 1.7×10^6 ppb from the supplied solution with distilled water. Calibrations are conducted with the stock solution reduced to measured concentration by serial dilution with site water. Therefore, the fluorometer concentration measurements are comparative measurements and the true stock solution concentration need not be known to a high accuracy to attain a high measurement accuracy. The mixed concentration at the sampling location, on the order of 0.3 ppb, assured sufficient measurement accuracy while remaining undetectable by eye.

Fluorescence is a function of water temperature, and temperature variations from the calibration temperature are accounted for by:

$$C = C_r e^{k(T_r - T_c)} \qquad \text{I-2}$$

where:

C	=	concentration (ppb)
C_r	=	apparent concentration at temperature T_r (ppb)
T_c	=	calibration temperature (°F)
k	=	temperature correction coefficient (1/°F)

The temperature coefficient, k, used was 0.0144/°F, which is a standard value (Smart et al) for Rhodamine WT and has been verified at Alden.

Instrumentation Description

The Turner Designs Model 10 fluorometer, used to measure dye concentration, has multiple ranges to increase the range of measurable concentrations. Two range settings are available, X1 and X100 having a 100 to 1 effect on sensitivity. Sensitivity can also be changed within each range from X1 to X31.6 in four equal steps, having maximum 30-fold effect on sensitivity. The instrument span and zero offset are also adjustable to match the output to the measured concentration. The fluorometer was set up to read in the upper one third of the output for the maximum sensitivity scale on the X100 range to ensure good resolution for a wide concentration range. The fluorometer may be operated in either the through-flow mode or the grab sample mode by making a minor change.

Fluorometer voltage output and two RTD thermometers measuring water and instrument temperatures were recorded by a portable computer with a 12 bit A to D converter. Transmission characteristics of the primary light filter in the fluorometer change slightly with temperature, affecting the instrument sensitivity. Therefore, a platinum resistance temperature sensor was mounted on the filter to monitor the temperature and assure instrument drift was within acceptable limits. No corrections to the calibrations were included for filter temperature drift. A similar temperature sensor, mounted in a 1/8" diameter rod, measured through flow sample temperature. The thermometer used to determine the water temperature at the fluorometer and the dye injection temperature were calibrated versus an NIST traceable thermometer standard prior to testing, and were found to be accurate within 2°F. Resolution of the digital temperature readout was 0.1°F.

Primary dye injection was by a constant displacement pump, whose variable stroke controlled the dye release to achieve a mixed concentration of about 3 ppb above background concentration. Dye injection flow was constant for each test and was measured periodically by the volumetric method. The injection pump and a 100 ml pipette with reduced area measuring stations were supplied from a 20 liter Mariotte vessel, which maintains a constant inlet pressure on the injection pump. When the Mariotte vessel was shut off via a valve, dye was supplied to the pump from the pipette, which is a Class A vessel having a volume uncertainty of 0.1%. A timer was started and stopped as the meniscus of the dye passed the measuring locations on the pipette. As the measuring locations were at small diameter tubes, the meniscus moved rapidly, which reduced the uncertainty of the time measurement.

A transport flow, taken from the pump intake sump in this case, transported the dye rapidly into the main flow. The time to inject 100 ml ranged from about 55 to 150 seconds, and several injection flow measurements were averaged for each test.

Injection and Sampling Locations

Dye was injected near the top of the shroud through a ½ inch pipe installed through the housing. Primary dye injection flow was low, about one ml/sec, so that a secondary transport flow of about 4 gpm was provided to rapidly carry the dye from the injection pump into the pump line. The secondary transport flow was withdrawn from the flow loop from a port upstream of the turbine.

Sampling of the mixed flow was performed through a ½ inch pipe installed in the runner housing near the runner trailing edge. Flexible tubing was plumbed from the port and to the fluorometer. The sample flow was not returned to turbine loop.

After flowing through the fluorometer, the sample flow, of approximately 2 to 3 gpm, was discharged to a building drain.

INSTRUMENT CALIBRATION

A 12.5 ppb initial calibration solution was prepared, using loop water, from the 1.0 x 10^4 injection solution for the in-situ calibration of the fluorometer. The 12.5 ppb solution was used to construct calibration samples with site water. The calibration samples were constructed by serial dilutions of the initial calibration solution with site water to obtain three concentrations covering the range of concentrations measured; the three point calibration was fit to a linear least squares curve for conversion of the fluorometer output to concentration.

Concentration data were recorded by a personal computer data acquisition system. Fluorometer output and water and filter temperatures were read at about 11 Hz and, after about 10 seconds (90 readings), the average and standard deviation were calculated, stored, and printed. Three such averaging periods were recorded and averaged for each of the six calibration solutions.

During data acquisition, individual temperature and fluorometer readings were displayed for visual evaluation. Average fluorometer output, corrected to the calibration temperature, was also displayed versus time. Variation of the corrected output from the previous test point was displayed as a percent to show trends on a magnified scale. Approximately 8 minutes of steady state fluorometer readings were averaged for each measured pump flow.

TEST PROCEDURE

For concentration measurements, the flow-through fluorometer continually monitored the tracer level in the leakage flow from prior to dye injection until after dye injection was completed. Tracer concentration was monitored and once the concentration had stabilized, the concentration was averaged over approximately 8 minutes at each of turbine operating points.

Dye injection flow was monitored during the test by measuring the time required to inject 100 ml of dye, and dye temperature was recorded periodically. Three injection flow measurements were recorded during each test.

At the completion of each flow test, the tracer was turned off and the fluorometer continued to record in order to establish the background concentrations.

TEST RESULTS

An example of a fluorometer calibration is plotted on Figure I-1 as concentration versus voltage and the deviation of the concentration calculated with a linear regression line from the actual concentration (as a percent of the maximum concentration) versus concentration. A typical standard error estimate of the calibration data set from the best fit line was 0.02%, indicating a precise calibration.

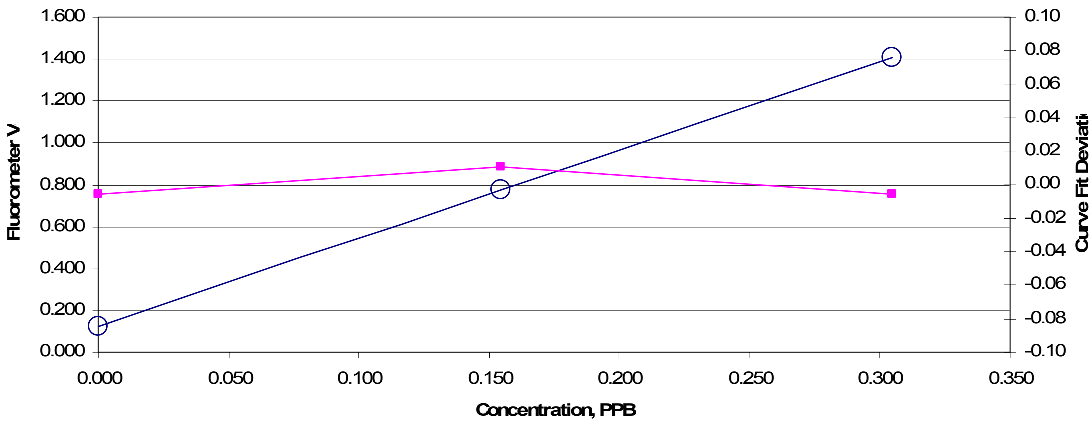


FIGURE I-1 TYPICAL FLUOROMETER CALIBRATION

During each test, fluorometer voltage was defined as the average voltage measured over approximately an 8 minute period, for each flow setting. A plot of the fluorometer trace for the four consecutive test points is shown in Figure I-2 below.

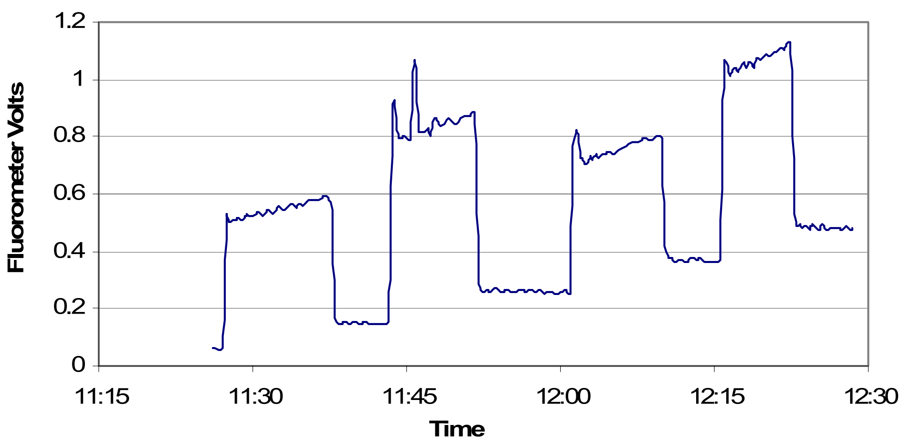


FIGURE I-2 FLUOROMETER RECORD

Fluorometer data indicated sufficient mixing, as shown by the consistent signal voltage in Figure I-2. The fluorometer signal was stable, which indicated that there was no fluctuating "plume" of partially mixed dye. The “spikes” shown in the second and third periods of Figure I-2 were caused by momentary interruptions in secondary transport flow as power to the pump was lost due to a loose wall socket plug.

The mixed tracer concentration through the fluorometer was defined as:

$$\text{Concentration} = m * (V_o - B) \qquad \text{I-3}$$

where:

V_o	=	average fluorometer output, volts
m	=	slope of calibration, ppb/volt
B	=	background concentration, volts

Figure I-3 shows the resulting calculated flows four the four tests after correcting for the increasing background concentrations.

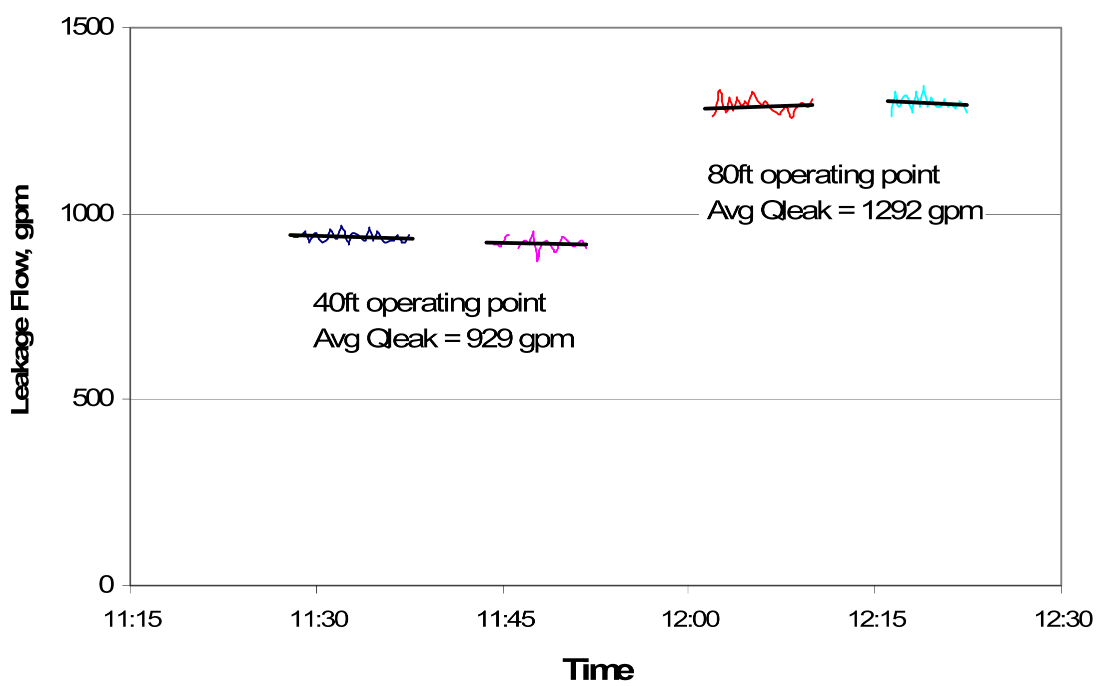


FIGURE I-3 CALCULATED LEAKAGE FLOWS

The average leakage flow at the 40 ft operating point was 929 gpm. The average leakage flow at the 80 ft operating point was 1,292 gpm.

REFERENCES

Smart, P.L. and Laidlaw, I. M. S. 1977. An Evaluation of Some Fluorescent Dyes for Water Tracing. Water Resources Research.

APPENDIX J

PROTOTYPE TURBINE OPERATING CHARACTERISTICS

APPENDIX J
PROTOTYPE TURBINE OPERATING CHARACTERISTICS

TABLE J-1
PROTOTYPE TURBINE OPERATING CHARACTERISTICS

Date	Gate Position (°)	φ	η_m (%)	Q_L (cfs)	$\Delta\eta_L$ (%)	$\Delta\eta_{sf}$ (%)	η_p (%)	p_{11}
12-Dec-02	16	0.941	84.6	2.90	3.1	2.7	90.4	0.053
12-Dec-02	16	0.968	84.8	2.91	3.1	2.7	90.7	0.053
12-Dec-02	16	0.995	84.4	2.91	3.1	2.8	90.3	0.052
12-Dec-02	16	1.016	83.9	2.91	3.1	2.9	89.9	0.051
12-Dec-02	16	1.026	83.5	2.92	3.1	2.9	89.6	0.051
12-Dec-02	16	1.053	82.6	2.92	3.1	3.1	88.8	0.050
12-Dec-02	16	1.073	81.7	2.93	3.1	3.2	88.1	0.049
13-Dec-02	20	0.946	83.8	2.85	2.6	2.9	89.3	0.061
12-Dec-02	20	0.959	84.2	2.86	2.6	2.8	89.7	0.061
12-Dec-02	20	0.985	84.4	2.85	2.7	2.8	89.8	0.061
12-Dec-02	20	0.985	84.4	2.85	2.7	2.8	89.8	0.061
12-Dec-02	20	1.011	84.4	2.86	2.7	2.8	89.9	0.060
12-Dec-02	20	1.019	84.4	2.85	2.7	2.8	89.9	0.060
12-Dec-02	20	1.041	84.3	2.87	2.7	2.8	89.8	0.060
12-Dec-02	20	1.069	84.1	2.87	2.7	2.8	89.7	0.059
13-Dec-02	22	0.931	83.3	2.84	2.4	3.0	88.7	0.065
13-Dec-02	22	0.929	83.3	2.84	2.4	3.0	88.7	0.065
13-Dec-02	22	0.958	83.7	2.85	2.5	2.9	89.1	0.065
13-Dec-02	22	0.990	84.0	2.85	2.5	2.9	89.3	0.065
13-Dec-02	22	1.013	83.8	2.87	2.5	2.9	89.2	0.064
13-Dec-02	22	1.042	83.8	2.87	2.5	2.9	89.2	0.063
13-Dec-02	22	1.073	83.5	2.87	2.5	2.9	89.0	0.063
16-Dec-02	24	0.931	82.4	2.85	2.3	3.1	87.8	0.069
13-Dec-02	24	0.959	83.2	2.85	2.3	3.0	88.5	0.069
13-Dec-02	24	0.985	83.5	2.86	2.3	3.0	88.8	0.068
13-Dec-02	24	1.010	83.5	2.87	2.4	2.9	88.8	0.068
13-Dec-02	24	1.023	83.4	2.85	2.4	3.0	88.7	0.067
13-Dec-02	24	1.044	83.4	2.88	2.4	3.0	88.7	0.067
13-Dec-02	24	1.066	83.2	2.88	2.4	3.0	88.6	0.066
13-Dec-02	24	1.079	83.0	2.88	2.4	3.0	88.5	0.066
16-Dec-02	26	0.930	81.9	2.86	2.1	3.2	87.3	0.072
16-Dec-02	26	0.957	82.4	2.87	2.2	3.1	87.7	0.072
16-Dec-02	26	0.979	82.7	2.87	2.2	3.1	87.9	0.071

Date	Gate Position (°)	φ	η_m (%)	Q_L (cfs)	$\Delta\eta_L$ (%)	$\Delta\eta_{sf}$ (%)	η_p (%)	p_{11}
16-Dec-02	26	1.003	82.8	2.87	2.2	3.1	88.1	0.071
16-Dec-02	26	1.019	83.0	2.88	2.2	3.0	88.2	0.071
16-Dec-02	26	1.040	82.8	2.88	2.2	3.1	88.1	0.070
16-Dec-02	26	1.064	82.5	2.89	2.2	3.1	87.9	0.069
16-Dec-02	26	1.073	82.4	2.89	2.2	3.1	87.8	0.069
16-Dec-02	26	1.088	81.8	2.90	2.1	3.2	87.2	0.072
16-Dec-02	28	0.929	82.0	2.85	2.1	3.2	87.3	0.075
16-Dec-02	28	0.960	82.5	2.85	2.1	3.1	87.7	0.075
16-Dec-02	28	0.981	82.5	2.86	2.1	3.1	87.7	0.075
16-Dec-02	28	1.006	82.4	2.88	2.1	3.1	87.6	0.074
16-Dec-02	28	1.036	82.2	2.88	2.1	3.2	87.5	0.073
16-Dec-02	28	1.063	82.1	2.89	2.1	3.2	87.4	0.073
16-Dec-02	28	1.088	81.8	2.90	2.1	3.2	87.2	0.072
19-Dec-02	18.2	0.930	84.0	2.86	2.8	2.9	89.6	0.058
19-Dec-02	18.2	0.958	84.4	2.87	2.8	2.8	90.0	0.058
21-Dec-02	18.2	0.982	84.7	2.87	2.8	2.7	90.3	0.058
21-Dec-02	18.2	1.012	84.7	2.88	2.9	2.7	90.3	0.057
21-Dec-02	18.2	1.037	84.4	2.88	2.9	2.8	90.1	0.056
21-Dec-02	18.2	1.064	83.7	2.89	2.9	2.9	89.5	0.055
21-Dec-02	18.2	1.092	82.6	2.89	2.9	3.1	88.6	0.054

APPENDIX K

EXPERIMENTAL UNCERTAINTY IN PILOT SCALE TURBINE MEASUREMENTS

APPENDIX K
EXPERIMENTAL UNCERTAINTY IN PILOT SCALE TURBINE MEASUREMENTS

INTRODUCTION

In order to determine the accuracy of the turbine performance based on the pilot scale test data, an experimental uncertainty analysis was performed to reflect the accuracy of the measurements. Engineering performance of the pilot scale turbine was calculated using the following fundamental measurements:

- turbine head
- turbine flow
- shaft speed
- shaft torque

All turbine pressures (head) and differential pressures for the test loop venture meter (flow) were measured using calibrated pressure transducers. Each transducer, or differential pressure (DP) cell, was calibrated prior to and at the completion of testing. The calibration was conducted using one of Alden's dead weight testers with an accuracy that is traceable to NIST (Section 4.3 in Appendix D). In addition, these calibrations were performed using the hardware, including acquisition boards and the computer system that were used during actual testing. The result of such "end-to-end" calibration significantly reduces the uncertainty of the measurement system.

Shaft speed (rpm) was measured using a proximity trigger, which sensed each tooth on a 60 tooth sprocket that was attached to the turbine output shaft. The sensor signal was interpreted using a counter/timer tachometer module, which produced an rpm value that was sent to the data acquisition computer to record the test data.

Shaft torque was measured using a load cell connected to the output arm of the dynamometer. The torque measuring load cell was calibrated *in situ* by using a system of levers and hanging weights to apply a (known) load to the cell. The lever arm lengths were accurately measured and the hanging weights were from Alden's stock of NIST traceable calibration weights.

ELEMENTARY ERROR SOURCES

Each of the turbine measurements has elementary error sources, which contribute to the overall experimental uncertainty. These include systematic (bias) uncertainty, and random (precision) uncertainty, and the values, or indices, of each were used to estimate the overall uncertainty in the turbine performance.

Estimates of precision indices were made from measurement standard deviations, while bias uncertainties were estimated from comparative tests and experience. Bias and precision components were propagated separately from the individual measurements to the final result. Elementary error source uncertainties for each component were combined by the root sum square (RSS) method. Precision uncertainty was estimated as the precision index (estimated by the standard deviation of the test data) multiplied by the Student t factor. The Student t factor corrects the standard deviation calculated using the limited number of measurements in the sample to estimate the standard deviation of a population having an infinite number of points. The overall uncertainty of the result is reported as the sum of the bias and precision uncertainties at a 95% confidence level. Details of this method are described in Measurement Uncertainty, ANSI/ASME PTC 19.1 -1998.

ESTIMATING OVERALL UNCERTAINTY

Using the characteristic Equation for a given parameter (m), as shown in eq. K-1, comprised of constituents (Xi), each with known uncertainty values (w_{Xi}), the following method may be utilized to calculate the overall uncertainty in the calculated parameter (from ANSI/ASME PTC 19.5 Draft VII – May 2000). The process involves taking partial derivative of the characteristic eq. K-1 with respect to each constituent and multiplying these by the uncertainty of the respective constituent, as shown in eq. K-2. These values are squared and added together and the square root of the sum, referred to as the root sum squared (RSS), is the resulting uncertainty, w_m, in units of the characteristic equation. Dividing the uncertainty value (w_m) in eq. K-2 by the nominal value of the characteristic equation (eq. K-1) produces a non-dimensional expression shown in eq. K-3, which yields the measurement uncertainty in percent (eq. K-4).

$$m = m(X_1, X_2, ..., X_j) \qquad \text{K-1}$$

$$w_m = \left[\left(\frac{\delta m}{X_1}\right)^2 (w_{X_1})^2 + \left(\frac{\delta m}{X_2}\right)^2 (w_{X_2})^2 + \left(\frac{\delta m}{X_3}\right)^2 (w_{X_3})^2 + ... + \left(\frac{\delta m}{X_j}\right)^2 (w_{X_j})^2\right]^{1/2} \qquad \text{K-2}$$

$$\frac{w_m}{m} = \left[\left(\frac{X_1}{m}\frac{\delta m}{X_1}\right)^2 \left(\frac{w_{X_1}}{X_1}\right)^2 + \left(\frac{X_2}{m}\frac{\delta m}{X_2}\right)^2 \left(\frac{w_{X_2}}{X_2}\right)^2 + ... \left(\frac{X_j}{m}\frac{\delta m}{X_j}\right)^2 \left(\frac{w_{X_j}}{X_j}\right)^2\right]^{1/2} \qquad \text{K-3}$$

$$\left({w_m}/{m}\right)100 = \%\ \text{Uncertainty} \qquad \text{K-4}$$

The square root of the coefficient of each $(w_x/X)^2$ term in eq. K-3 is the sensitivity coefficient (S) of the particular variable X. An S greater than 1 indicates that the uncertainty in that X is magnified as it propagates into w_m ; less than 1 indicates that the uncertainty in X is diminished as it propagates into w_m. The resulting uncertainty is:

$$w_m = \left[\left(\frac{w_{X1}}{X_1} S_1 \right)^2 + \left(\frac{w_{X2}}{X_2} S_2 \right)^2 + \ldots + \left(\frac{w_{Xj}}{X_j} S_j \right)^2 \right]^{1/2} \qquad \text{K-5}$$

Head - The elementary error sources for measurement of head include the calibration equipment, the "fit" of the equation used to convert volts to pressure and the calculation of head (feet of water column) based on the density of the test fluid. Estimates of the dead weight tester precision and bias indices (-0.005% each) were based on the manufacturers specification and Alden's experience with the instrument. Calibration data were fit to a linear equation to convert voltage to pressure (psi) and the quality of the fit of the curve was used to estimate the precision index for the conversion of volts to pressure (psi). The maximum deviation of the calibration data from the linear regression curves fit to each DP cell was within 0.05%. Head, in units of feet of water, was calculated from psi by using the density of the test fluid. Density was calculated based on the temperature of the test water and a 3rd order equation fit to a table of published standard water density versus temperature. Water temperature within the test loop was measured using an un-calibrated sensor located within the chiller loop system. Applying a conservative (i.e., high) ±5 deg F accuracy to this temperature results in a bias index of 0.05%. The elementary error sources include a precision index calculated from a representative average of the 2 minute test data. This index (S_i) was calculated using:

$$S_i = \frac{\sigma_i}{\bar{u}\sqrt{M}} \qquad \text{K-6}$$

where,

σ_i = the standard deviation of the two minute data

$\bar{u}$ = average value

M = the number of data points recorded over the 2 minute period

The two minute test point precision indices for all DP cells, including turbine head and Venturi pressure signals, were similar and averaged 0.03%. Table K-1 summarizes the DP cell uncertainty indices. The resulting RSS estimate of bias and precision were combined by assigning a Student t factor to the precision index to attain an estimate at the 95% confidence level. A Student t value of 2.0 was used based on the number of calibration data points (or population), which was well above 20. The resulting overall measurement uncertainty in head was 0.11% at the 95% confidence level.

TABLE K-1
PRESSURE MEASUREMENT UNCERTAINTY ESTIMATE (%)

Elementary Error Source	Bias	Precision
Calibration Dead weight tester	0.005	0.005
calibration curve fit	0.050	
Water column calculation (density)[1]	0.050	0.050
Typical 2 minute test point variation		0.030
Root Sum Square (RSS)	0.071	0.059

[1] 5 deg F variation in water temperature.

$[\text{Bias}^2 + 2 \times \text{Precision}^2]^{1/2} =$ **0.11%**

Test Loop Flow - The turbine test loop flow was measured using a Venturi meter calibrated at Alden's flow meter calibration facility. The characteristic flow equation is:

$$Q = C\sqrt{H} \tag{K-7}$$

where,

Q = test loop flow in ft^3/sec
C = meter discharge coefficient
H = the pressure differential signal produced by the meter, in ft of water.

From eq. F-3, the non-dimensional expression for the uncertainty in test loop flow is:

$$\frac{wQ}{Q} = \left[\left(\frac{w_C}{C}\right)^2 + \left(\frac{w_H}{2H}\right)^2\right]^{1/2} \tag{K-8}$$

The sensitivity coefficients and uncertainty values for each term used in eq. K-8 are summarized in Table K-2 below. This calibration includes a 0.25% overall bias index in the coefficient term "C" and includes both the measured physical characteristics and the hydraulic values determined by calibration. The total uncertainty estimate for flow is 0.26%.

TABLE K-2
TEST LOOP FLOW MEASUREMENT UNCERTAINTY ESTIMATE (%)

Term	Total Uncertainty (%) $\left(\frac{w_X}{X}\right)$	Sensitivity Coefficient (S)	$\left(\frac{w_X}{X}\right)S$ (%)
C	0.25	1.00	0.25
H	0.11	0.5	0.05

Total Uncertainty in Flow Eq. K-32 = **0.26%**

Turbine Flow

Turbine flow (Q_T) for the final engineering tests was calculated as the test loop flow (Q) minus the bottom seal leakage (Q_L). The characteristics flow equation is:

$$Q_T = Q - Q_L \qquad \text{K-9}$$

The non-dimensional expression for turbine flow is:

$$\frac{wQ_T}{Q_T} = \left[\left(\frac{w_Q}{Q}\right)^2 + \left(\frac{w_{QL}}{Q_L}\right)^2\right]^{1/2} \qquad \text{K-10}$$

As discussed in Appendix E, the accuracy of the bottom seal leakage measurements were less than 5%. However, since the bottom seal leakage is only 3% of the test loop flow, the uncertainty in the turbine flow was adjusted to account for the fact that leakage flow is a small portion of the test loop flow. This adjustment was treated as a relative sensitivity coefficient (S_2). The resulting overall uncertainty in the turbine flow is 0.29% as shown in Table K-3.

TABLE K-3
TURBINE FLOW MEASUREMENT UNCERTAINTY ESTIMATE (%)

Term	Total Uncertainty (%) $\left(\frac{w_X}{X}\right)$	Relative Sensitivity Coefficient (S)	Relative Sensitivity Coefficient (S_2)	$\left(\frac{w_X}{X}\right)S$ (%)
Q	0.26	1.00	0.97	0.25
Q_L	5.00	1.00	0.03	0.15

Total Uncertainty in Flow Eq. K-10 = **0.29%**

Torque - The torque applied by the dynamometer to maintain the turbine speed was measured using a load cell connected to an arm on the dynamometer. The load cell was calibrated *in situ* by installing a lever system to which weights were hung to apply a known force to the load cell. The computer acquisition system used to collect test data was also used during the calibration of the load cell in order to maintain continuity in the equipment and reduce equipment uncertainty. Elementary error sources in the torque measurement system include the calibration weights, temperature effects on the calibration and dynamometer arm lengths, measurement accuracy of all lengths, and the performance of the load cell.

The weights used to apply torque during calibration are NIST traceable and have minor bias and precision indices. A bias index of 0.060% was applied to the lengths of calibration and dynamometer arms based upon the ability to measure the pivot-to-pivot centerline distances to within 1/16 inch in 9 ft. Using a “worst case” 60° F change in temperature (from the time of the arm’s measurement), thermal expansion would produce a random (precision) index of 0.04%.

Bias and precision indices for the load cell were derived from the *in situ* calibrations of the cell. Calibrations were performed before and after each preliminary engineering/fish test series and from these data, the “stability” of the original load cell supplied with the dynamometer was assessed and determined to be insufficient for conducting the final engineering tests with wicket gates (Section 4.8). The duration of testing introduced a variety of environmental changes, including temperature, humidity, and “aging“ of the equipment, that affected the torque measurements. Therefore, turbine performance with wicket gates has been evaluated using a higher quality load cell that was less sensitive to environmental factors.

Using calibrations of the original load cell during the preliminary engineering and biological test series without and with wicket gates, the stability of the torque measurement load cell was evaluated by comparing the output signal slope, or volts per applied force (pounds mass). The worst case change in the original load cell slope from pre and post-test calibrations was 0.50%. The change in slope of the load cell was attributed to differences in the ambient temperatures during the two calibrations; the pretest calibration was at a low temperature and the post test calibration was at a higher temperature. Because daily temperatures varied over the course of the testing period, the *true* slope probably lies between the two calibrations. For this reason, the effect of temperature on the load cell was treated as an instrumentation bias. Because an equal number of tests were conducted under warm and cool conditions, the bias index due to load cell stability was taken to be ½ of the worst case change found in the pre and post-test calibrations (i.e., 0.25%).

Inherent in the torque measuring system was the use of linkages and bearings to transmit the shaft torque, and calibration load, to the load cell. Friction in these connections introduced hysteresis, which was evident in the calibration of the load cell. A typical load cell calibration conducted during final engineering tests is presented in Figure K-1.

The wedge-shape curve shows the deviation in the calibration data from the best-fit linear equation used to describe the cell's voltage signal at the applied load. Greater deviations from the linear curve at the lower loading indicate friction within the system. The hysteresis varied slightly from calibration to calibration, which was attributed to how the calibration weights were applied to the loading arm; a slight jolt as the individual weights were loaded would help overcome friction in the linkages. In the same way, vibration of the operating turbine may allow the links to "settle-in" and be less affected by friction. To explore whether hysteresis could be exaggerated during the calibration procedure without the system vibration, a motor vibrator was attached to the calibration arm and a calibration was performed during the preliminary engineering tests with the original load cell. The results indicated that the system vibrations did reduce the width of the hysteresis "wedge".

Using the results with the motor vibrator, two hysteresis precision indices were used to estimate the uncertainty in the torque measurement with the original load cell. These were chosen based on the two operating ranges of the turbine; the 40 ft head and 80 ft head conditions. At the low head (power) condition, the original load cell operated around 4.7 volts where the average hysteresis was about 0.4 %. The 80 ft head condition produced higher torque and the load cell signal was about 6.7 volts, where the hysteresis was significantly lower; near 0.10%.

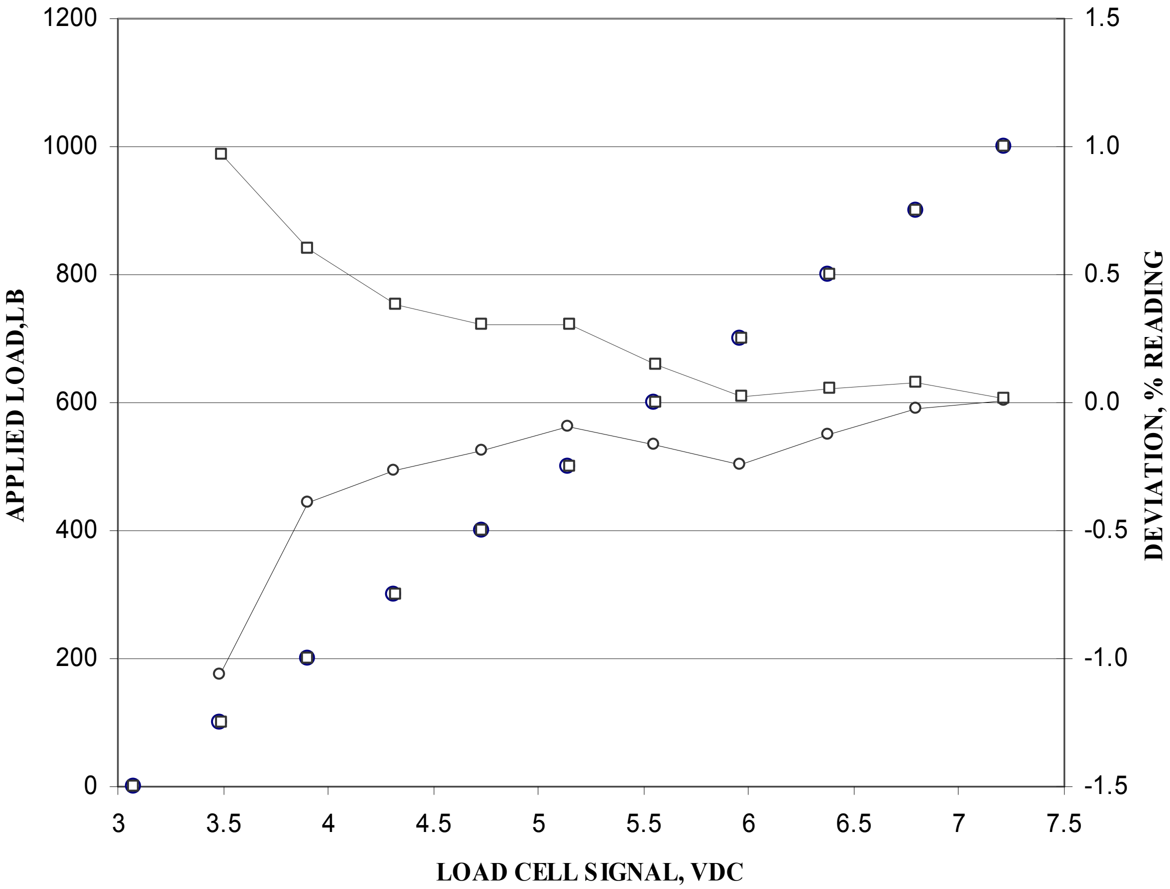


FIGURE K-1 TYPICAL DYNAMOMETER LOAD CELL CALIBRATION

The two values of hysteresis associated with the two operating points were used to generate different uncertainty estimates in the torque measurements with the original load cell, and therefore, power and efficiency, for the 40 ft and 80 test conditions. The elementary error sources for torque measurements with the original load cell are summarized in Table K-4 at the low (40 ft) head and Table K-5 at the high (80 ft) head conditions.

The resulting RSS estimates of bias and precision were combined by assigning a Student t factor to the precision index to attain an estimate at the 95% confidence level. A Student t value of 2.0 was used based on the number of calibration data points (or population), which was well above 20. The resulting overall measurement uncertainty in torque with the original load cell at the low head operating condition was 0.46% at the 95% confidence level. Due to the lower hysteresis at the high head operating condition, the uncertainty in torque at the 80 ft head operating condition was 0.29% with the original load cell.

TABLE K-4
UNCERTAINTY ESTIMATE (%) FOR LOW HEAD TORQUE MEASUREMENTS
WITH ORIGINAL LOAD CELL

Elementary Error Source	Bias	Precision
Calibration weights	0.001	0.001
Thermal expansion of torque arm[1]		0.040
Measured lever arm lengths[2]	0.060	
Load Cell "stability"[3]	0.400	
System hysteresis[4]	0.380	
Typical 2 minute test point variation		0.010
Root Sum Square (RSS)	0.555	0.041

$[\text{bias}^2+2 \times \text{precision}^2]^{1/2} =$ **0.56%**

(student-t = 2, from >20 point calibration)

[1] Change in length due to 60 deg F temp change.
[2] Measurement accuracy of 1/16 in 9 feet.
[3] From Pre & Post Test Calibration (lbm/volt) history.
[4] From torque arm calibration.

TABLE K-5
UNCERTAINTY ESTIMATE (%) FOR HIGH HEAD TORQUE MEASUREMENTS
WITH ORIGINAL LOAD CELL

Elementary Error Source	Bias	Precision
Calibration weights	0.001	0.001
Thermal expansion of torque arm[1]		0.040
Measured lever arm lengths[2]	0.060	
Load Cell "stability"[3]	0.400	
System hysteresis[4]	.100	
Typical 2 minute test point variation		0.010
Root Sum Square (RSS)	0.417	0.041

$[\text{bias}^2+2 \times \text{precision}^2]^{1/2} =$ **0.43%**

(student-t = 2, from >20 point calibration)

[1] Change in length due to 60 deg temp change.
[2] Measurement accuracy of 1/16 in 9 feet.
[3] From Pre & Post Test Calibration (lbm/volt) history.
[4] From torque arm calibration.

Stability of the calibrations of the new load cell before and after the final engineering test series with wicket gates was also evaluated by comparing the output signal slope, or volts per applied force (lbm). The worst case change in the new load cell slope was 0.22%. The final engineering tests were conducted at 80 ft and the new load cell hysteresis associated with the final engineering tests was 0.20% at the 80 ft test condition. The elementary error sources for torque measurements during final engineering tests with the new load cell are summarized in Table K-6.

The resulting RSS estimates of bias and precision were combined by assigning a Student t factor of 2.0 to the precision index to attain an estimate at the 95% confidence level. A Student t value was selected based on the number of calibration data points (or population), which was well above 20. The resulting overall measurement uncertainty in torque with the new load cell at the high head (80 ft) operating condition was 0.31% at the 95% confidence level.

TABLE K-6
UNCERTAINTY ESTIMATE (%) FOR FINAL ENGINEERING TESTS
TORQUE MEASUREMENTS (NEW LOAD CELL)

Elementary Error Source	**Bias**	**Precision**
Calibration weights	0.001	0.001
Thermal expansion of torque arm[1]		0.040
Measured lever arm lengths[2]	0.060	
Load Cell "stability"[3]	0.220	
System hysteresis[4]	0.200	
Typical 2 minute test point variation		0.010
Root Sum Square (RSS)	0.303	0.041

$[\text{bias}^2 + 2 \times \text{precision}^2]^{1/2}$ = **0.31%**

(student-t = 2, from >20 point calibration)

[1] Change in length due to 60 deg temp change.
[2] Measurement accuracy of 1/16 in 9 feet.
[3] From Pre & Post Test Calibration (lbm/volt) history.
[4] From torque arm calibration.

Turbine RPM - The elementary errors of measuring the turbine shaft speed were estimated from a) the precision of the proximity sensor triggering on the shaft sprocket and b) the resolution of the tachometer readout. The proximity sensor was checked at low (hand turned) shaft speeds and found to trigger at each tooth on the sprocket. As there was no reasonable method to check the triggering of the sensor when the turbine was operating at test speeds, a random precision index was estimated based on the sensor missing one out of every 10,000 teeth passing (approximately 2-4 missed teeth per 2 minute recording period). The tachometer readout precision uncertainty was based on the manufacturer's resolution. The two minute precision index was based on an average standard deviation of 1 rpm over the period of measurement. Because the signal from the tachometer readout was in digital form, and involved no further calculation within the acquisition computer, no additional elementary error sources were attributed to the speed measurement. Table K-7 lists the elementary error sources and the resulting RSS uncertainty estimate of 0.05%.

TABLE K-7
SHAFT SPEED (RPM) MEASUREMENT UNCERTAINTY ESTIMATE %

Elementary Error Source	Bias	Precision
Proximity sensor signal		0.010
Tachometer readout		0.010
Typical 2 minute test point variation		0.030
Root Sum Square (RSS)		0.033

$[\text{Bias}^2 + 2 \times \text{Precision}^2]^{1/2} =$ **0.05%**

Turbine Power - Turbine power (P) was calculated using eq. K-3, which can also be written as:

$$P = \frac{T\omega}{550} \qquad \text{K-11}$$

where:

T = shaft torque in lbm-ft,
ω = shaft speed in radians/second

From eq. K-3, the non-dimensional expression for the uncertainty in turbine power (P) is:

$$\frac{wP}{P} = \left[\left(\frac{w_T}{T}\right)^2 + \left(\frac{w_\omega}{\omega}\right)^2\right]^{1/2} \qquad \text{K-12}$$

Three estimates of the uncertainty in turbine power were generated for the uncertainty of the torque measurements with the two load cells. Two estimates were made for torque measurements with the original load cell at each operating head (40 ft and 80 ft) and one estimate was for the torque measurements with the new load cell used during final engineering tests. Uncertainty estimates of the power measurements with the original load cell are summarized in Table K-8 for low power (40 ft head) and Table K-9 for the high power (80 ft head) conditions. Table F-10 summarizes the uncertainty estimate of power measurements with the new load cell used during final engineering tests. Sensitivity coefficients and total term uncertainty values for the torque and speed that were used in eq. K-12 are summarized in the tables for the two load cells.

The total uncertainty estimate for turbine power (P) with the original load cell was 0.46% and 0.29% at the low head and high head conditions, and was 0.25% for the final engineering tests with the new load cell.

TABLE K-8
TURBINE POWER UNCERTAINTY ESTIMATE (%) FOR MEASUREMENTS WITH ORIGINAL LOAD CELL AT LOW HEAD

Term	Term Total Uncertainty (%) $\left(\frac{w_X}{X}\right)$	Sensitivity Coefficient (S)	$\left(\frac{w_X}{X}\right)$S (%)
T	0.460	1.00	0.46
ω	0.033	1.00	0.033

Total Uncertainty in P = **0.46%**

TABLE K-9
TURBINE POWER UNCERTAINTY ESTIMATE (%) FOR MEASUREMENTS WITH ORIGINAL LOAD CELL AT HIGH HEAD

Term	Term Total Uncertainty (%) $\left(\frac{w_X}{X}\right)$	Sensitivity Coefficient (S)	$\left(\frac{w_X}{X}\right)$S (%)
T	0.290	1.00	0.29
ω	0.033	1.00	0.033
Total Uncertainty in P = **0.29%**			

TABLE K-10
FINAL ENGINEERING TEST TURBINE POWER MEASUREMENT UNCERTAINTY ESTIMATE (%) (NEW LOAD CELL)

Term	Term Total Uncertainty (%) $\left(\frac{w_X}{X}\right)$	Sensitivity Coefficient (S)	$\left(\frac{w_X}{X}\right)$S (%)
T	0.250	1.00	0.25
ω	0.033	1.00	0.033
Total Uncertainty in P = **0.25%**			

Turbine Efficiency - The uncertainty values for flow, head, and turbine power were combined to produce an estimate of the overall uncertainty in the calculated turbine efficiency using the following characteristic equation:

$$\eta = \frac{HP_{shaft}}{HP_{hydraulic}} = \frac{T\omega}{\gamma\, Q\, H} \qquad \text{K-13}$$

where:

T = shaft torque
ω = shaft speed
γ = water density
Q = turbine flow
H = turbine head

From eq. K-3, the non-dimensional expression for the uncertainty in efficiency is:

$$\frac{w\eta}{\eta} = \left[\left(\frac{w_T}{T}\right)^2 + \left(\frac{w\omega}{\omega}\right)^2 + \left(\frac{w\gamma}{\gamma}\right)^2 + \left(\frac{wQ}{Q}\right)^2 + \left(\frac{wH}{H}\right)^2\right]^{1/2} \qquad \text{K-14}$$

Three estimates of the uncertainty in turbine efficiency were generated, similar to the turbine power estimates. Uncertainty estimates are summarized in Tables K-11 and K-12 for the low power (40 ft head) and high power (80 ft head) measurements, respectively, which were obtained with the original load cell used during preliminary engineering and biological tests. Uncertainty estimates for the high power (80 ft head) final engineering tests with the new load cell are presented in Table K-13. The sensitivity coefficients and total uncertainty values for the terms used in eq. K-14 are summarized in the tables.

The RSS uncertainty estimate for turbine efficiency using the original load cell was 0.56% for the low head tests and 0.43% at the high head test conditions. The lower value at the high head conditions is directly related to hysteresis in the torque measurement system that was found to produce lower random errors in torque when the system was used at the higher power condition. The RSS uncertainty estimate for the turbine efficiency measured during the final engineering tests (high head with new load cell) was 0.41%.

TABLE K-11
TURBINE EFFICIENCY UNCERTAINTY ESTIMATE (%) FOR MEASUREMENTS WITH ORIGINAL LOAD CELL AT LOW HEAD

Term	Term Total Uncertainty (%) $\left(\frac{w_X}{X}\right)$	Sensitivity Coefficient (S)	$\left(\frac{w_X}{X}\right)$S (%)
T	0.460	1.00	0.460
ω	0.033	1.00	0.033
γ^1	0.087	1.00	0.087
Q	0.290	1.00	0.290
H	0.100	1.00	0.100
Total Uncertainty in Efficiency = **0.56%**			

[1]Term uncertainty calculated using constituents from Table K-2: $[0.050^2+2 \times 0.050^2]^{1/2} = 0.087$

TABLE K-12
TURBINE EFFICIENCY UNCERTAINTY ESTIMATE (%) FOR MEASUREMENTS WITH ORIGINAL LOAD CELL AT HIGH HEAD

Term	Term Total Uncertainty (%) $\left(\frac{w_X}{X}\right)$	Sensitivity Coefficient (S)	$\left(\frac{w_X}{X}\right)$S (%)
T	0.290	1.00	0.290
ω	0.033	1.00	0.033
γ[1]	0.087	1.00	0.087
Q	0.290	1.00	0.290
H	0.100	1.00	0.100
Total Uncertainty in Efficiency = **0.43%**			

[1]Term uncertainty calculated using constituents from Table K-2: $[0.050^2+2 \times 0.050^2]^{1/2} = 0.087$

TABLE K-13
FINAL ENGINEERING TEST TURBINE EFFICIENCY MEASUREMENT UNCERTAINTY ESTIMATE (%) (NEW LOAD CELL)

Term	Term Total Uncertainty $\left(\frac{w_X}{X}\right)$ (%)	Sensitivity Coefficient (S)	$\left(\frac{w_X}{X}\right)$S (%)
T	0.250	1.00	0.250
ω	0.033	1.00	0.033
γ[1]	0.087	1.00	0.087
Q	0.290	1.00	0.290
H	0.100	1.00	0.100
Total Uncertainty in Efficiency = **0.41%**			

[1]Term uncertainty calculated using constituents from Table K-2: $[0.050^2+2 \times 0.050^2]^{1/2} = 0.087$

APPENDIX L

WATER QUALITY DATA

TABLE L-1

FALL 2001 WATER QUALITY DATA FOR THE FISH HOLDING FACILITY AND THE TURBINE TEST LOOP

Week Beginning	Location	Water Temperature (^oC) Min	Max	Salinity (ppt) Min	Max	Dissolved Oxygen (ppm) Min	Max	pH Min	Max	Ammonia (Total; ppm) Min	Max	Ammonia (NH^3; ppm) Min	Max	Alkalinity (ppm) Min	Max	Hardness (ppm) Min	Max
30-Sep	Holding Facility	14.3	14.6	0.8	1.7	3.9	7.7	7.0	7.6	0.6	2.0	0.005	0.021	86.0	128.0	124.0	152.0
	Test Facility																
7-Oct	Holding Facility	12.3	14.5	1.7	2.9	4.8	9.3	7.1	7.4	0.7	1.2	0.002	0.008	76.0	86.0	130.0	160.0
	Test Facility																
14-Oct	Holding Facility	12.1	14.5	2.0	7.0	6.8	8.8	6.9	7.0	0.4	0.8	0.001	0.003	36.0	36.0	112.0	154.0
	Test Facility	12.9	12.9	0.1	0.1	9.3	9.3	7.6	7.6	0.2	0.2	0.003	0.003	38.0	38.0	36.0	36.0
21-Oct	Holding Facility	12.4	13.1	1.8	3.3	6.2	9.3	6.8	7.8	0.3	1.2	0.001	0.006	24.0	40.0	98.0	142.0
	Test Facility	13.1	13.1	0.1	0.1	8.8	8.8	7.4	7.4	0.2	0.2	0.002	0.002	43.0	43.0	42.0	42.0
28-Oct	Holding Facility	11.3	13.3	2.4	3.3	6.5	8.9	6.6	7.5	0.8	2.0	0.003	0.020	18.0	92.0	116.0	168.0
	Test Facility	11.0	13.4	0.1	0.1	9.3	9.5	7.6	7.6	0.2	0.2	0.003	0.003	24.0	24.0	56.0	56.0
4-Nov	Holding Facility	12.7	13.7	2.4	2.9	7.7	8.9	6.8	7.8	0.4	1.2	0.002	0.010	34.2	239.4	102.6	478.8
	Test Facility	12.9	12.9	0.1	0.1	8.7	8.7	7.0	7.0	0.2	0.2	0.001	0.001	22.2	22.2	34.2	34.2

TABLE L-2

SPRING 2002 WATER QUALITY DATA FOR THE FISH HOLDING FACILITY AND THE TURBINE TEST LOOP

		Water Temperature (°C)		Salinity (ppt)		Dissolved Oxygen (ppm)		pH		Ammonia (Total; ppm)		Ammonia (NH^3; ppm)		Alkalinity (ppm)		Hardness (ppm)	
Week Beginning	Location	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
14-Apr	Holding Facility	11.2	13.3	0.0	2.4	9.5	16.4	7.7	8.0	1.0	105.0	0.005	0.025	85.5	119.7	85.5	119.7
	Test Facility	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
21-Apr	Holding Facility	10.7	13.1	0.0	2.8	9.3	12.8	7.4	8.0	1.0	1.7	0.018	0.040	85.5	136.8	85.5	119.7
	Test Facility	12.9	12.9	0.1	0.1	10.1	10.1	7.2	7.2	0.4	0.4	0.002	0.002	34.2	34.2	34.2	34.2
28-Apr	Holding Facility	13.0	13.8	2.9	3.4	8.1	9.4	7.7	8.0	2.0	2.3	0.027	0.051	80.0	119.7	85.5	136.8
	Test Facility	10.4	12.5	0.1	0.1	10.2	11.0	7.0	7.3	0.2	0.2	0.001	0.001	34.2	34.2	34.2	34.2
5-May	Holding Facility	13.1	13.5	2.7	3.2	8.6	10.5	7.6	7.7	1.0	2.3	0.009	0.031	64.0	98.0	85.5	102.6
	Test Facility	13.0	13.3	0.1	0.1	10.0	11.5	7.1	7.2	0.0	0.0	0.000	0.000	40.0	40.0	83.0	83.0
12-May	Holding Facility	12.6	15.7	2.8	3.2	9.1	10.9	7.6	8.0	0.3	1.0	0.008	0.011	64.0	100.0	85.5	132.0
	Test Facility	12.7	15.4	0.1	0.1	10.1	11.7	7.1	7.3	0.0	0.0	0.000	0.000	30.0	30.0	41.0	41.0
19-May	Holding Facility	14.9	17.2	2.9	3.2	8.9	9.6	8.0	8.1	0.2	0.3	0.007	0.014	82.0	94.0	100.0	128.0
	Test Facility	12.2	14.2	0.1	0.1	9.6	10.0	7.2	7.4	0.0	0.0	0.000	0.000	20.0	20.0	64.0	64.0
26-May	Holding Facility	14.9	19.7	2.8	3.2	8.5	10.0	8.0	8.2	0.1	0.2	0.003	0.012	63.0	113.0	48.0	128.0
	Test Facility	15.6	16.3	0.1	0.1	9.3	9.8	6.7	7.5	0.0	0.0	0.000	0.000	20.0	20.0	60.0	60.0
2-Jun	Holding Facility	12.7	16.6	2.9	3.1	9.2	10.5	8.1	8.3	0.2	0.2	0.006	0.012	96.0	120.0	110.0	128.0
	Test Facility	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

TABLE L-2 (CONTINUED)

Week Beginning	Location	Water Temperature (°C) Min	Max	Salinity (ppt) Min	Max	Dissolved Oxygen (ppm) Min	Max	pH Min	Max	Ammonia (Total; ppm) Min	Max	Ammonia (NH^3; ppm) Min	Max	Alkalinity (ppm) Min	Max	Hardness (ppm) Min	Max
9-Jun	Holding Facility	12.5	14.3	2.8	3.1	9.8	10.5	8.1	8.2	0.1	0.2	0.003	0.007	81.0	104.0	96.0	108.0
	Test Facility	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

TABLE L-3

FALL 2002 WATER QUALITY DATA FOR THE FISH HOLDING FACILITY AND THE TURBINE TEST LOOP

Week Beginning	Location	Water Temperature (°C)		Salinity (ppt)		Dissolved Oxygen (ppm)		pH		Ammonia (Total; ppm)		Ammonia (NH^3; ppm)		Alkalinity (ppm)		Hardness (ppm)	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
1-Sep	Holding Facility	16.9	20.7	2.5	3.9	8.0	8.8	7.1	7.9	0.0	0.0	0.000	0.000	24.0	44.0	48.0	86.0
	Test Facility	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
8-Sep	Holding Facility	16.8	17.9	3.2	3.8	7.4	9.0	7.5	8.1	0.0	0.6	0.000	0.006	45.0	72.0	130.0	200.0
	Test Facility	17.4	18.9	0.1	0.1	6.7	7.7	7.5	7.7	0.4	0.4	0.002	0.002	34.2	34.2	34.2	34.2
15-Sep	Holding Facility	13.8	17.0	3.1	4.0	7.9	9.9	7.6	8.0	0.4	1.0	0.004	0.021	60.0	130.0	160.0	300.0
	Test Facility	17.0	19.8	0.1	0.1	6.0	7.4	7.6	7.8	0.2	0.2	0.001	0.001	34.2	34.2	34.2	34.2
22-Sep	Holding Facility	12.3	15.7	3.5	3.9	8.5	10.3	7.8	8.1	0.2	0.4	0.002	0.011	112.0	160.0	180.0	350.0
	Test Facility	13.4	17.7	0.1	0.1	7.0	9.0	7.4	7.8	0.0	0.0	0.000	0.000	32.0	32.0	68.0	68.0
29-Sep	Holding Facility	13.7	16.6	3.5	3.9	8.9	9.9	8.0	8.3	0.0	0.2	0.000	0.008	122.0	162.0	184.0	336.0
	Test Facility	14.7	16.1	0.1	0.1	6.7	8.4	7.2	7.6	0.0	0.0	0.000	0.000	30.0	30.0	41.0	41.0
6-Oct	Holding Facility	15.6	17.0	3.8	4.7	5.3	9.4	7.6	8.3	0.2	0.6	0.005	0.011	130.0	168.0	265.0	320.0
	Test Facility	13.7	16.0	0.1	0.1	7.5	8.5	7.1	7.9	0.0	0.0	0.000	0.000	28.0	28.0	34.0	34.0
13-Oct	Holding Facility	13.1	17.2	3.6	4.7	5.3	9.4	7.7	8.0	0.4	1.7	0.006	0.032	126.0	157.0	250.0	299.0
	Test Facility	11.2	15.2	0.1	0.1	7.5	8.3	7.0	7.9	0.0	0.0	0.000	0.000	20.0	20.0	60.0	60.0
20-Oct	Holding Facility	13.4	16.9	3.9	4.7	6.2	9.5	7.6	8.2	0.2	0.4	0.003	0.011	130.0	183.0	246.0	318.0
	Test Facility	11.5	14.2	0.1	0.1	7.5	9.1	7.0	7.5	0.0	0.0	0.000	0.000	36.0	36.0	52.0	52.0

TABLE L-3 (CONTINUED)

Week Beginning	Location	Water Temperature (°C) Min	Max	Salinity (ppt) Min	Max	Dissolved Oxygen (ppm) Min	Max	pH Min	Max	Ammonia (Total; ppm) Min	Max	Ammonia (NH^3; ppm) Min	Max	Alkalinity (ppm) Min	Max	Hardness (ppm) Min	Max
27-Oct	Holding Facility	12.7	14.8	3.2	4.0	6.9	9.4	7.7	8.1	0.2	0.2	0.002	0.005	120.0	196.0	210.0	280.0
	Test Facility	11.2	14.0	0.1	0.1	8.6	9.6	7.3	7.8	--	--	--	--	--	--	--	--
3-Nov	Holding Facility	10.5	14.5	3.4	5.0	7.9	10.7	7.8	8.4	0.0	0.2	0.000	0.010	82.0	190.0	168.0	290.0
	Test Facility	9.0	10.6	0.1	0.1	8.7	9.8	7.4	7.5	--	--	--	--	--	--	--	--
10-Nov	Holding Facility	14.2	16.1	4.0	5.0	8.3	9.4	7.7	8.1	0.2	0.2	0.003	0.005	68.0	128.0	132.0	173.0
	Test Facility	11.4	14.5	0.1	0.1	7.6	9.7	7.3	7.6	0.0	0.0	0.000	0.000	40.0	40.0	40.0	40.0
17-Nov	Holding Facility	11.4	13.2	5.0	5.3	9.4	10.3	7.8	8.1	0.2	0.2	0.002	0.004	78.0	110.0	115.0	130.0
	Test Facility	9.4	11.6	0.1	0.1	8.8	9.6	7.3	7.7	--	--	--	--	--	--	--	--

APPENDIX M

STATISTICAL INPUT TO THE DESIGN AND ANALYSIS OF THE ALDEN/CONCEPTS NREC TURBINE

Statistical Input to the Design and Analysis

of the ARL/NREC Pilot Scale Fish-Friendly Turbine

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13 October 1999

1.0 Recommendations on Study Design

The overall design and proposed conduct of the study seems fine. Adequacy of sample sizes for the various studies will be addressed at the end of the report. Below are some suggestions that may be helpful, given my experience in conducting smolt survival studies:

1. Recommend holding fish 48 hrs rather than 24 hrs after marking and before release.

2. Hold the two marked groups of fish in the same pool after marking and before release. Sort the two mark types as the fish are transferred to the 5-gallon pools. Additional handing will likely be offset by the identical holding conditions that if violated would have a larger affect on precision and accuracy.

3. Assure all fish in a release group go through the release pipe with a full complement of water. No fish should contact dry pipe walls when released.

4. To validly compare different test conditions, the replicate releases for the various treatments need to be randomly intermixed in the time. Otherwise, the treatment comparisons will be totally confounded with time, invalidating comparisons

The last recommendation emphasizes the importance of prioritizing which treatment comparisons are essential to the investigators. These treatment comparisons should be designed as a formal experiment with proper attention to replication and randomization. Other test conditions may be of lesser importance and should be designed strictly for purposes of estimating turbine survival.

2.0 Statistical Analysis

The data generated by the turbine trials will be binomially distributed alive and dead counts. Therefore, the most appropriate analysis would be based on that probability distribution. Estimates of turbine survival (and its complement mortality) will be based on maximum likelihood estimation (MLE). Likelihood ratio tests could be used to compare survival rates between test conditions, fish species, and sizes of fish. The exact form of the analysis will depend on the comparisons and tests performed.

2.1 Analysis of a Single Test Release

Define the following quantities:

N_C = number of control fish released,

c = number of control fish surviving the trial,

N_T = number of test fish released,

t = number of treatment (i.e., turbine exposed) fish surviving the trial.

The likelihood describing the test data can then be written as

$$L(S_c, S_T | N_C, N_T, c, t) = \binom{N_C}{c} S_C^c (1 - S_C)^{N_C - c} \binom{N_T}{t} (S_C S_T)^t (1 - S_C S_T)^{N_T - t} \tag{1}$$

where S_C = survival probability from the control release location to recovery,

S_T = survival probability through the turbine.

Based on the likelihood (1), the maximum likelihood estimates of the parameters are:

$$\hat{S}_C = \frac{c}{N_C} \tag{2}$$

$$\hat{S}_T = \frac{tN_C}{N_T c}. \tag{3}$$

The above likelihood has the following assumptions:

1. All treatment fish have equal and identical probabilities of survival.
2. All control fish have equal and identical probabilities of survival.
3. All fish (control and treatment) have equal survival from the control release location to recovery.

4. Survival from the control release location to recovery is conditionally independent of turbine survival.

The estimate of the control survival probability has a variance of

$$Var(\hat{S}_C) = \frac{S_C(1-S_C)}{N_C}$$

and estimated by

$$V\hat{a}r(\hat{S}_C) = \frac{\left(\frac{c}{N_C}\right)\left(1-\frac{c}{N_C}\right)}{N_C} \tag{4}$$

The estimate of turbine survival has an approximate variance of

$$Var(\hat{S}_T) \doteq S_T^2\left[\frac{(1-S_C S_T)}{N_T S_C S_T} + \frac{(1-S_C)}{N_C S_C}\right] \tag{5}$$

which can be estimated by

$$V\hat{a}r(\hat{S}_T) = \hat{S}_T^2\left[\frac{(1-\hat{S}_C\hat{S}_T)}{N_T\hat{S}_C\hat{S}_T} + \frac{(1-\hat{S}_C)}{N_C\hat{S}_C}\right] \tag{6}$$

A $(1-\alpha)$ 100% confidence interval estimate for $\hat{S}_T$ can be computed as

$$\hat{S}_T \pm Z_{1-\frac{\alpha}{2}}\sqrt{V\hat{a}r(\hat{S})}$$

However, profile likelihood confidence intervals are recommended rather than the normal approximations. This is particularly important when the estimate of S_T will be near a boundary value (i.e., 1.0).

2.2 Analysis of Replicate Releases

Each control-treatment release can be described by likelihood (1). The joint likelihood describing the K multiple release trials can then be written as

$$L\left(\underset{\sim}{S_C}, S_T \middle| \underset{\sim}{N_C}, \underset{\sim}{N_t}, \underset{\sim}{c}, \underset{\sim}{t}\right)=\prod_{i=1}^{K}\left[\binom{N_{C_i}}{c_i}S_{C_i}^{c_i}\left(1-S_{C_i}\right)^{N_{C_i}-c_i}\binom{N_{T_i}}{t_i}\left(S_{C_i}S_T\right)^{t_i}\left(1-S_{C_i}S_T\right)^{N_{T_i}-t_i}\right] \tag{7}$$

Likelihood (7) assumes the control survival rate varies between trials, the result of differences in fish groups, marking, handling, and release procedures between replicates. A common turbine survival rate (S_T) is estimated across the replicates, taking into account fluctuations in control survival rates. Alternatively, the likelihood could be written with a common control survival rate where

$$L\left(S_C, S_T \middle| \underset{\sim}{N_C}, \underset{\sim}{N_T}, \underset{\sim}{c}, \underset{\sim}{t}\right)=\prod_{i=1}^{K}\left[\binom{N_{C_i}}{c_i}S_C^{c_i}\left(1-S_C\right)^{N_{C_i}-c_i}\cdot\binom{N_{T_i}}{t_i}\left(S_C S_T\right)^{t_i}\left(1-S_C S_T\right)^{N_{T_i}-t_i}\right] \tag{8}$$

in which case

$$\hat{S}_T=\frac{\sum_{i=1}^{K}t_i\cdot\sum_{i=1}^{K}N_{C_i}}{\sum_{i=1}^{K}N_{T_i}\cdot\sum_{i=1}^{K}c_i} \tag{9}$$

$$\hat{S}_C=\frac{\sum_{i=1}^{K}c_i}{\sum_{i=1}^{K}N_{C_i}} \tag{10}$$

with variance estimates analogous to Equations (4, 6). If the control survival rate is constant (i.e., $S_{C_1}=S_{C_2}=\ldots=S_{C_K}$), then the precision of the estimate of $\hat{S}_T$ will be improved using likelihood (8). A test of equal control survival can be performed using a likelihood ratio test between likelihoods (7) and (8) or using an R x C chi-square contingency table test of homogeneity of the form

	Release				
	1	2	3		K
Alive				...	
Dead				...	

based on the results of the control release groups. Both tests are chi-square distributed with $K-1$ degrees of freedom.

For both single and replicated release trials, a test of the hypotheses

$$H_o: \quad S_T = 1$$

vs.

$$H_a: \quad S_T < 1$$

can be performed using a likelihood ratio test based on likelihood functions (1, 7, 8). However, hypotheses testing of $S_T = 1$ should be considered superfluous to the goal of precise parameter estimation.

A third nonparametric approach to estimating an overall turbine survival estimate can be used. This approach would be most applicable if S_T varied significantly between replicates. In this scenario, each replicate trial would produce an estimate $\hat{S}_{T_i}(i = 1, \ldots, K)$. The overall average would be computed as a weighted average

$$\hat{\hat{S}}_T = \frac{\sum_{i=1}^{K} w_i \hat{S}_{T_i}}{\sum_{i=1}^{K} w_i}$$

where $w_i = 1/\hat{Var}\left(\hat{S}_{T_i}\right)$. The variance of $\hat{\hat{S}}_T$ would be computed as

$$\hat{Var}\left(\hat{\bar{S}}_T\right) = \frac{\sum_{i=1}^{K} w_i \left(\hat{S}_{T_i} - \hat{\bar{S}}_T\right)^2}{(K-1)\cdot \sum_{i=1}^{K} w_i}$$

A $(1-\alpha)$ 100% CI would be computed as

$$\hat{\bar{S}}_T \pm Z_{1-\frac{\alpha}{2}} \sqrt{\hat{Var}\left(\hat{\bar{S}}_T\right)}$$

This third approach would be the most imprecise approach if the turbine survival was homogeneous across trials. In which case, likelihood analysis based on Equations (7) or (8) would be preferred.

2.3 Comparison of Different Test Conditions

There are two alternative approaches for comparing the turbine survival rates across test conditions. The traditional approach would be to use the transformation

$$x_i = arcsin\sqrt{\hat{S}_{T_i}}$$

for each of the replicate release trials. Then using the transformed observations (i.e., x_i's), perform a two-sample t-test if comparing two different conditions. A one-way ANOVA would be used if multiple treatments are to be compared.

It should be remembered that if treatments are to be compared, the replicate releases should be randomly intermixed between test conditions. Otherwise, the tests of comparison will be totally confounded with differences in time, perceived or not.

The more modern approach to the analysis of treatment comparisons would be to perform an analysis of deviance (ANODEV) based on the likelihood (7-8). An ANODEV table to compare the different treatment conditions would be constructed of the form illustrated below:

Source	df	Change in Deviance	DEV/df	F-test
$\text{Total}_{\text{Cor}}$	$TK-1$	$\text{DEV}_{\text{TOT}} = 2\left(ln\,L\left(S_{T_{ij}}\right) - ln(S)\right)$		
Treatments	$T-1$	$\text{DEV}_{\text{TR}} = 2\left(ln\,L\left(S_{T_i}\right) - ln\,L\left(S_T\right)\right)$	$\text{MDEV} = \dfrac{\text{DEV}_{\text{TR}}}{T-1}$	$\text{F} = \dfrac{\text{MDEV}_{\text{TR}}}{\text{MDEV}_{\text{ERR}}}$
Residual	$T(K-1)$	$\text{DEV}_{\text{ERR}} = 2\left(ln\,L\left(S_{T_{ij}}\right) - ln\,L\left(S_{T_i}\right)\right)$	$\text{MDEV}_{\text{ERR}} = \dfrac{\text{DEV}_{\text{ERR}}}{T(K-1)}$	

In the above ANODEV table, T refers to the number of treatment conditions, K refers to the number of replicate trials per treatment. In addition, $L\left(S_{T_{ij}}\right)$ denotes a likelihood where each replicate release in each treatment is modeled with a unique turbine survival. The likelihood $L(S)$ denotes a joint likelihood where all replicates and all treatments are modeled with a common turbine survival. The likelihood $L\left(S_{T_i}\right)$ denotes a function where each treatment is modeled with a unique turbine survival ($i = 1, \ldots, T$) parameter, but all replicates within a treatment ($j = 1, \ldots, K$) are modeled with the common turbine survival parameter for that treatment. An asymptotic F-test of treatment differences (e.g., fish species, size, turbine operation) would be calculated analogous to a one-way ANOVA with $T-1$ and $T(K-1)$ degrees of freedom. The nature of the control survival parameters used in the ANODEV would be determined prior to the analysis using R x C contingency table tests of homogeneity.

3.0 Sample Size Calculations

The variance formula (5) for $\hat{S}_T$ can be used to determine adequate sample sizes assuming replicate releases are homogeneous. Define the precision of $\hat{S}_T$ as

$$P\left(\left|\hat{S}_T - S_T\right| < \varepsilon\right) = 1 - \alpha \tag{11}$$

which specifies that the absolute error in estimation (i.e., $|\hat{S}_T - S_T|$) should be less than ε, $(1-\alpha)$ 100% of the time. For example, to be within ±2% of the true value of S_T, 95% of the time, precision should be expressed as

$$P\left(\left|\hat{S}_T - S_T\right| < 0.02\right) = 0.95$$

Hence, precision is defined by the dual quantitative objectives of ε and α. Using the objective function (11) along with variance expression (5), sample size formulas can be constructed as follows:

$$P\left(\left|\hat{S}_T - S_T\right| < \varepsilon\right) = 1-\alpha$$

$$P\left(-\varepsilon < \hat{S}_T - S_T < \varepsilon\right) = 1-\alpha$$

$$P\left(\frac{-\varepsilon}{\sqrt{Var\left(\hat{S}_T\right)}} < \frac{\hat{S}_T - S_T}{\sqrt{Var\left(\hat{S}_T\right)}} < \frac{\varepsilon}{\sqrt{Var\left(\hat{S}_T\right)}}\right) = 1-\alpha$$

$$P\left(\frac{-\varepsilon}{\sqrt{Var\left(\hat{S}_T\right)}} < Z < \frac{\varepsilon}{\sqrt{Var\left(\hat{S}_T\right)}}\right) = 1-\alpha$$

$$P\left(Z < \frac{-\varepsilon}{\sqrt{Var\left(\hat{S}_T\right)}}\right) = \frac{\alpha}{2}$$

$$\Phi\left(\frac{-\varepsilon}{\sqrt{Var\left(\hat{S}_T\right)}}\right) = \frac{\alpha}{2}$$

$$\frac{-\varepsilon}{\sqrt{Var\left(\hat{S}_T\right)}} = I^{-1}\left(\frac{\alpha}{2}\right) = Z_{\frac{\alpha}{2}}$$

$$\frac{\varepsilon}{\sqrt{Var\left(\hat{S}_T\right)}} = Z_{1-\frac{\alpha}{2}}$$

$$\frac{\varepsilon^2}{Z^2_{1-\frac{\alpha}{2}}} = Var\left(\hat{S}_T\right) \qquad (12)$$

Assuming a common release size $(N_c = N_T)$, substituting Equation (5) into Equation (12) yields

$$\frac{\varepsilon^2}{Z^2_{1-\frac{\alpha}{2}}} = \frac{S_T^2}{N}\left[\frac{(1-S_cS_T)}{S_cS_T} + \frac{(1-S_c)}{S_c}\right]$$

or

$$N = \frac{Z^2_{1-\frac{\alpha}{2}} S_T^2}{\varepsilon^2}\left[\frac{(1-S_cS_T)}{S_cS_T} + \frac{(1-S_c)}{S_c}\right] \quad (13)$$

Equation (13) can then be used to determine the required release sizes $(N = N_c = N_T)$ to have a precision of ε and $(1-\alpha)$ 100% when control survival is S_c and turbine survival is S_T.

Table 1 summarizes some sample size calculations for various trial and precision scenarios. Sample size per release group (i.e., control or treatment) pooled across replicates were determined for precision defined by $\varepsilon = 0.01, 0.02, 0.03$ at $1-\alpha = 0.90, 0.95$ or 0.99. Data supplied from trials conducted at Elwha Dam estimated an overall control survival probability of $1-\frac{34}{3149} = 0.989$. The subsequent sample size calculations used the average control survival rate and turbine survival probabilities of 0.98, 0.99, or 1.0. Inspection of Table 1 suggests turbine survival can be estimated within ±0.01, 90% of the time with release sizes of $N_C = N_T = 1161$ when the true survival rate is $S_T = 0.98$. The value of ε can be interpreted as the half-width of a $(1-\alpha)$ 100% confidence interval about $\hat{S}_T$. As turbine survival increases, the sample size generally declines. Of course, as the quantitative criteria ε and α become more stringent, sample sizes also increase.

Table 1. Projected sample sizes for a turbine survival study where $S_c = 0.989$, $S_T = 0.98, 0.99$ or 1.0 for a precision defined by $\varepsilon = 0.01, 0.02$, or 0.03 and $1-\alpha = 0.90, 0.95$, or 0.99.

S_c	S_T	ε	$1-\alpha$	$N = N_c = N_T$
0.989	0.98	0.01	0.90	1161
		0.02	0.90	210
		0.03	0.90	129
		0.01	0.95	1648
		0.02	0.95	412
		0.03	0.95	183
		0.01	0.99	2846
		0.02	0.99	712
		0.03	0.99	317
0.989	0.99	0.01	0.90	879
		0.02	0.90	220
		0.03	0.90	98
		0.01	0.95	1247
		0.02	0.95	312
		0.03	0.95	139
		0.01	0.99	2154
		0.02	0.99	539
		0.03	0.99	240
0.989	1.0	0.01	0.90	602
		0.02	0.90	151
		0.03	0.90	67
		0.01	0.95	855
		0.02	0.95	214
		0.03	0.95	95
		0.01	0.99	1477
		0.02	0.99	369
		0.03	0.99	164

Equation (13) can be rearranged to the form

$$\varepsilon = Z_{1-\frac{\alpha}{2}}\sqrt{\frac{S_T^2}{N}\left(\frac{1-S_C S_T}{S_C S_T}+\frac{1-S_C}{S_C}\right)}$$

Now the expected ε for a given sample size N can be computed. For example, at $N_C = N_T = N$ = 1200, $S_T = 0.98$, $S_C = 0.989$, a 95% CI (i.e., $Z_{1-\frac{\alpha}{2}} = 1.96$) has an expected half-width of ε = 0.0115. For a sample size of $N_C = N_T = N = 600$ under the same conditions, $\varepsilon \approx 0.0162$.

APPENDIX N

USER MANUAL FOR THE PASSAGE ANALYSIS OF TURBINE SURVIVAL STUDIES (PATSS) PROGRAM

User Manual for the
Passage Analysis of Turbine Survival Studies
(PATSS) Program

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1.0 Preface

This manual provides a cursory explanation of Program PATSS used to analyze control-treatment, paired-release studies to estimate turbine passage survival. Program installation is explained below along with data input and interpretation of the analysis output. Program PATSS is written in a noninteractive batch mode. All available data analyses are performed regardless of their applicability to a particular dataset. Tests of assumptions are provided, and the user must judiciously select the most appropriate output to interpret. No attempt was made to incorporate a branching process that would lead users to only the most relevant output. In subsequent sections, an example output will be used to illustrate the analyses and the selection of the most appropriate data interpretations.

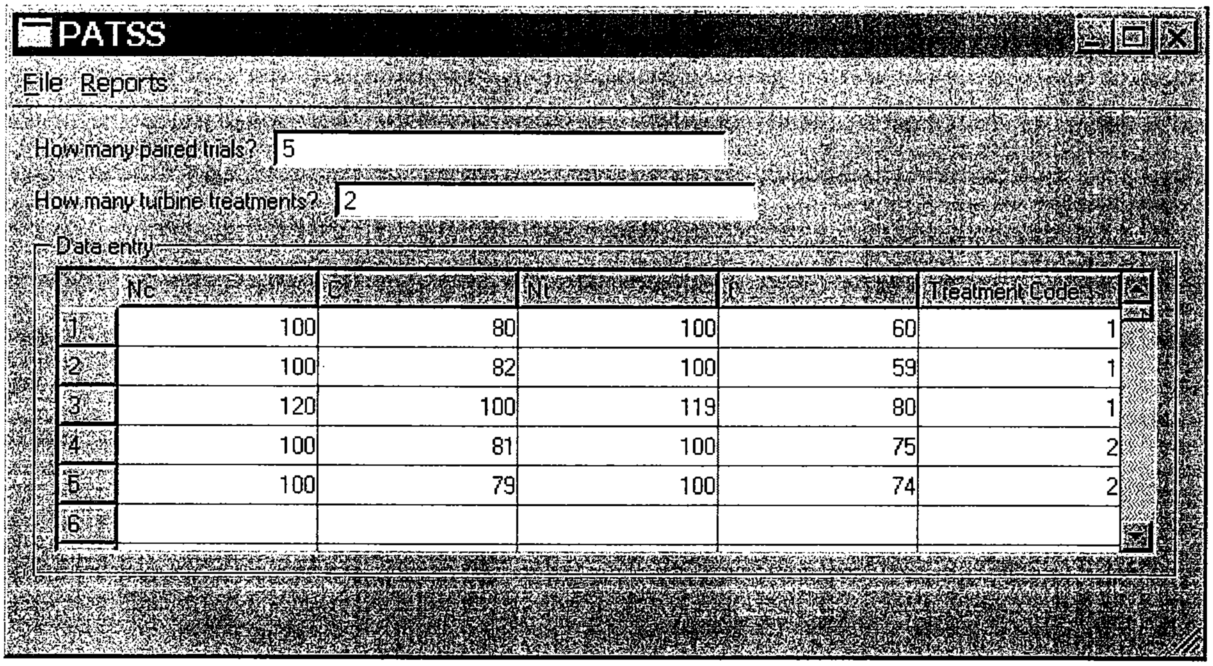
2.0 Program Installation

The program is a single file and once downloaded to a local computer, can be executed without any additional setup.

3.0 Data Input

The input for Program PATSS consists of the total number of trials, the number of different turbine treatments, and rows of data that represent the data specification for a particular paired release-recapture control-treatment trial. A trial consists of a group of control and treatment fish released concurrently to estimate turbine survival. The number of treatments is the number of different turbine conditions to be compared.

Below is an example of an input file for a study consisting of five trials split among two different treatment conditions. The first three rows of fish counts correspond to three replicate trials for treatment condition 1. The last two rows correspond to the fish counts for the two replicate trials for treatment condition 2. There must be at least two replicate trials in each treatment condition to perform a valid test of treatment effects.



The first row of the input file consists of a single number, the number of total trials. The second row of the file consists of a single number, the number of treatment conditions to be compared. If there is only one condition, this input should be "1". Each subsequent row of the input file corresponds to the data specification for a particular paired release-recapture control-treatment trial.

Each row of the data has the following columns:

N_C = number of control fish released,

c = number of control fish recovered alive,

N_T = number of treatment fish released,

t = number of treatment fish recovered alive,

Treatment Code = treatment designation (1, 2, 3, etc., must be a whole number).

Note: Treatment replicates must be grouped together (all 1's, then all 2's, etc.).

Below is an example data file that corresponds to the input in the previous example.

```
5
2
100    80     100    60    1
100    82     100    59    1
120    100    119    80    1
100    81     100    75    2
100    79     199    74    2
```

4.0 Interpretation of Output

4.1 Preliminary Summary of Control-treatment Release Trials

The initial output of Program PATSS is a summary of the survival analyses on a trial-by-trial basis. For each control-treatment paired-release, the program estimates the survival and recovery probability of the controls and the turbine passage survival (S_T) along with associated standard errors. In addition, 95% profile likelihood confidence intervals are calculated for each of the turbine passage survival estimates (e.g., CI ($S_L < S_T < S_U$) = 0.95).

No association is assumed among the replicate release trials in providing the parameter estimates. Each trial is analyzed independent of the others.

In the example below, two treatment conditions are illustrated; one with three replicate trials, the other with two replicate trials.

RESULTS FOR FULL MODEL (Individual Trials)

Trial	Treatment	Control Recovery (se)	Treatment Survival (se)	95 Per CI. (St)
1	1	0.8000 (0.0400)	0.7500 (0.0718)	(0.6151, 0.8996)
2	1	0.8200 (0.0384)	0.7195 (0.0688)	(0.5896, 0.8617)
3	1	0.8333 (0.0340)	0.8067 (0.0612)	(0.6897, 0.9325)
4	2	0.8100 (0.0392)	0.9259 (0.0698)	(0.7942, 1.0000)
5	2	0.7900 (0.0407)	0.9367 (0.0736)	(0.7989, 1.0000)

Subsequent sections of the analysis will be used to identify the best parsimonious description of the treatment conditions and their comparisons.

4.2 R x C Contingency Table Tests of Homogeneity

These contingency table tests examine whether the control recovery rates and turbine survival rates are homogeneous (e.g., equal) among replicate trials within a treatment category. Within a treatment category, separate R x C contingency table tests are performed to assess whether the control releases and/or test releases are homogeneous among replicates.

In particular, the nature of the homogeneity among the control releases must be determined in selecting the most appropriate analysis of deviance (ANODEV) table in latter sections of this program. To this end, an R x C table test of homogeneity is also performed to compare control recovery rates between treatment conditions.

Chi-square values and associated degrees of freedom are produced by Program PATSS. The user must enter a standard chi-square table to determine the P-values associated with each test of homogeneity.

In the example below, none of the tests of homogeneity are statistically significant at P = 0.10.

R x C Contingency Table Tests of Homogeneity

Group	Treatment	Chi-Sqr	df	Group	Treatment	Chi-Sqr	df
Control	1	0.4099	2	Test	1	1.9195	2
Control	2	0.1250	1	Test	2	0.0263	1

Contingency Table Test of Homogeneity of Control Groups across Treatments

Chi-Sqr	df
0.2829	1

Based on these test results, it would be appropriate to compare and estimate turbine survival rates assuming equal control recovery rates across replicates and treatments as well.

4.3 Tests of Homogeneity Using Likelihood Ratio Tests

These likelihood ratio tests (LRTs) provide an alternative means of tests for homogeneity among replicate trials within treatment conditions. Again, the purpose of the tests is to identify the most parsimonious description of the test data. The LRT compares nested models to assess whether the more parameterized model improves the description of the data. Should the chi-square statistic be significant, one would conclude the more parameterized model better describes the recovery data.

To characterize the various models, symbols were used to identify alternative formulations. For example, model

$$C_{ij}T_{ij}$$

identifies a formulation where both the control and test releases have unique recovery and survival parameters for every replicate trials. Omission of the subscript j signifies the replicate trials within a treatment condition are homogeneous. Omission of the i subscript signifies that the trials are also homogeneous across treatment conditions. For example, model

$$C_iT_i$$

identifies a formulation where control recovery rates are assumed equal among the replicate trials within a treatment as well as homogeneity among the turbine survival probabilities among the replicate trials within a treatment.

The LRT are used to assess alternative model formulations *within* treatment conditions. The user must enter a standard chi-square table to determine the P-value associated with each LRT. The results of the LRT are used to select the most parsimonious description of the data among replicate trials within a treatment condition.

In the example below, one would conclude the recovery rates for controls and the turbine survival rates were homogeneous among replicate trials within each treatment condition, specifically:

Treatment 1

$$C_{ij}T_{ij} \text{ vs. } C_iT_i \quad P\left(\chi_4^2 \geq 2.3429\right) = 0.6730$$

Treatment 2

$$C_{ij}T_{ij} \text{ vs. } C_iT_i \quad P\left(\chi_2^2 \geq 0.1514\right) = 0.9271$$

The output file for this example is illustrated below.

```
Tests of Homogeneity using Likelihood Ratio Tests
      =================================================

Subscripts are defined as
      i = 1 to number of treatments
      j = 1 to number of replicates within treatment


Within Treatment 1
-------------------------------

  Models Tested     Chi-Sqr   df
-----------------   -------   --
CijTij vs. Ci Ti :   2.3429   4
CijTij vs. CijTi :   0.9409   2
CijTij vs. Ci Tij:   0.4077   2
CijTi  vs. Ci Ti :   1.4020   2
Ci Tij vs. Ci Ti :   1.9352   2
-------------------------------


Within Treatment 2
-------------------------------

  Models Tested     Chi-Sqr   df
-----------------   -------   --
CijTij vs. Ci Ti :   0.1514   2
CijTij vs. CijTi :   0.0113   1
CijTij vs. Ci Tij:   0.1250   1
CijTi  vs. Ci Ti :   0.1401   1
Ci Tij vs. Ci Ti :   0.0263   1

-------------------------------
```

Hence, the most precise estimates of turbine survival rates might be expected to be calculated under model C_iT_i. The R x C contingency table test (Section 4.2) of homogeneity for control releases between treatments was nonsignificant $\left(P\left(\chi_1^2 \geq 0.2829\right) = 0.5948\right)$, suggesting further simplification to model CT_i.

4.4 Alternative Estimates of Turbine Passage Survival Under Different Recovery Models

In Section 4.1, model parameters were provided under the most general case of $C_{ij}T_{ij}$. Based on the LRTs, more parsimonious models may adequately describe the release-recovery data. The user must interpret the LRT results of Section 4.3 in selecting the best model for the turbine survival estimates within treatments.

In the example below, estimates of turbine survival and associated standard errors are calculated for models C_iT_i, $C_{ij}T_i$, and C_iT_{ij}. Note the estimated standard errors generally decrease the more parsimonious the model selected.

```
Within Treatment Summaries
=================================================

Subscripts are defined as
      i = 1 to number of treatments
      j = 1 to number of replicates within treatment

Treatment 1
-------------------------------

under Model CiTi

0.7619   (0.0387)


under Model CijTi

0.7641   (0.0388)


under Model CiTij

0.7328   (0.0629)
0.7206   (0.0630)
0.8211   (0.0568)
```

```
Treatment 2
-------------------------------

under Model CiTi

0.9313   (0.0507)


under Model CijTi

0.9311   (0.0506)


under Model CiTij

0.9375   (0.0635)
0.9250   (0.0638)
```

Based on the LRT results of Section 4.3, model C_iT_i would be selected as appropriate in the above example. For treatment 1, turbine passage survival would be estimated to be $\hat{S}_T = 0.7619$ ($\widehat{SE} = 0.0387$); for treatment 2, $\hat{S}_T = 0.9312$ ($\widehat{SE} = 0.0507$).

4.5 Across Treatment Comparisons (ANODEV)

Output for this sections occurs only if there are two or more treatment conditions specified during data input. Separate analysis of deviance (ANODEV) tables are computed for this test of treatment effects under alternative specifications for the degree of homogeneity around controls, e.g., models C_{ij}, C_i, or C. The user must select the most appropriate ANODEV table, depending on the outcome of the tests of homogeneity in Section 4.2 and 4.3.

The test of equal turbine survival under different treatment conditions is based on the asymptotic F-test reported in the appropriate ANODEV tables. Illustrated below is the ANODEV table output for the example used throughout this manual.

```
            Across Treatment Comparisons (ANODEV)
            =====================================
Subscripts are defined as
      i = 1 to number of treatments
      j = 1 to number of replicates within treatment
```

ANALYSIS OF DEVIANCE TABLE, unique controls (CijTi Model)

Source	df	Change in deviance	DEV/df	F-test
Total(cor)	4	7.9583		
Treatments	1	7.0061	7.0061	22.0742
Residual	3	0.9522	0.3174	

Survival estimates under CijTi Model

Treatment	Survival (standard error)
1	0.7641 (0.0388)
2	0.9311 (0.0506)

ANALYSIS OF DEVIANCE TABLE, pooled controls within treatment(CiTi Model)

Source	df	Change in deviance	DEV/df	F-test
Total(cor)	4	9.1791		
Treatments	1	7.2176	7.2176	11.0387
Residual	3	1.9615	0.6538	

Survival estimates under CiTi Model

Treatment	Survival (standard error)
1	0.7619 (0.0387)
2	0.9312 (0.0507)

ANALYSIS OF DEVIANCE TABLE, pooled controls across treatment (CTi Model)

Source	df	Change in deviance	DEV/df	F-test
Total(cor)	4	10.2926		
Treatments	1	8.3311	8.3311	12.7416
Residual	3	1.9615	0.6538	

Survival estimates under CTi Model

Treatment	Survival (standard error)
1	0.7687 (0.0372)
2	0.9180 (0.0426)

For this example, model C would be the best choice based on the R x C results in Section 4.2. The user must enter a standard F-table with the appropriate degrees of freedom to determine the P-value for the test of no treatment effects. In the case of the example,

$$P\left(F_{1,3} \geq 12.7416\right) = 0.0376,$$

and one would conclude there was a significant treatment effect on turbine passage survival.

The value of the residual mean deviance (i.e., DEV/df) under ideal conditions of binomial sampling error has the expected value of 1.0. Values greater than 1 suggest overdispersion or extra-likelihood variability due to changes in handling or test conditions over the course of the study. The quotient is known as the "scale parameter," and will be used later in power calculations.

APPENDIX O

BIOLOGICAL TEST DATA

TABLE O-1
POST-TEST RECOVERY DATA (I.E., FISH RECOVERED DURING TESTS CONDUCTED AFTER THE ONE IN WHICH THEY WERE RELEASED) FOR TEST CONDITIONS EVALUATED DURING THE FALL 2001 PRELIMINARY TEST SERIES

Test Conditions	Test Group	Total Number of Fish Released	Post-Test Recovery Data: Number Recovered Live	Number Recovered Dead	Percent of Fish Released
38 ft head off-BEP 226 rpm	T	150	1	0	0.7
	C	156	4	0	2.6
38 ft head BEP 240 rpm	T	151	9	0	6.0
	C	148	17	1	12.2
80 ft head Off-BEP 322 rpm	T	150	1	3	2.7
	C	150	0	0	0
80 ft head BEP 345 rpm	T	150	1	0	0.7
	C	153	2	1	2.0

TABLE O-2
POST-TEST RECOVERY DATA (I.E., FISH RECOVERED DURING TESTS CONDUCTED AFTER THE ONE IN WHICH THEY WERE RELEASED) FOR THE TEST CONDITIONS EVALUATED DURING TEST SERIES 1 (WITHOUT WICKET GATES)

Treatment Fish Release Location	Test Group	Total Number of Fish Released	Post-Test Recovery Data		
			Number Recovered Live	Number Recovered Dead	Percent of Fish Released
top	T	871	17	1	2.1
	C	873	12	0	1.4
middle	T	889	20	2	2.5
	C	897	12	2	1.6
bottom	T	900	8	2	1.0
	C	898	6	1	0.8

TABLE O-3
DELAYED MORTALITY FOR TEST SERIES 1 (WITHOUT WICKET GATES)

Test Group codes are: T, treatment; C, control

Treatment Fish Release Location	Test Group	Number Recovered Live	Delayed Mortality (number of fish)			
			24 hr	48 hr	72 hr	96 hr
top	T	788	9	6	4	2
	C	861	0	0	0	0
middle	T	791	11	2	0	3
	C	879	1	0	2	3
bottom	T	820	8	4	1	2
	C	885	0	0	0	5

TABLE O-4
PERCENT OF RAINBOW TROUT WITH VARIOUS LEVELS OF DESCALING AT THREE LOCATIONS ALONG THE BODY
TEST SERIES 1 - WITHOUT WICKET GATES

Data for live fish and immediate mortalities are combined.

Treatment Release Location	Percent Scale Loss	Location 1		Location 2		Location 3	
		Treatment	Control	Treatment	Control	Treatment	Control
top	< 3	81.0	87.4	82.5	90.1	90.1	95.0
	3 – 20	17.1	12.4	15.3	9.5	8.8	4.7
	20 – 40	1.7	0.2	1.7	0.3	1.0	0.3
	> 40	0.2	0.0	0.5	0.0	0.1	0.0
middle	< 3	80.0	84.8	80.7	83.5	83.1	85.4
	3 – 20	17.5	14.8	18.1	16.3	15.6	14.3
	20 – 40	2.4	0.3	1.1	0.2	1.1	0.3
	> 40	0.1	0.0	0.0	0.0	0.1	0.0
bottom	< 3	78.5	82.6	77.2	82.4	88.5	91.7
	3 – 20	18.2	16.3	20.3	16.3	10.2	7.8
	20 – 40	2.9	1.1	2.2	1.3	1.2	0.4
	> 40	0.3	0.0	0.2	0.0	0.1	0.0

TABLE O-5
POST-TEST RECOVERY DATA (I.E., FISH RECOVERED DURING TESTS CONDUCTED AFTER THE ONE IN WHICH THEY WERE RELEASED) FOR THE TEST CONDITIONS EVALUATED DURING TEST SERIES 2/3 (WITHOUT WICKET GATES)

Test group codes are: T, treatment; C, control; and NM, no identifiable mark.

Head (ft)	Mean Fish Length (mm)	Test Group	Total Number of Fish Released	Post-Test Recovery Data		
				Number Recovered Live	Number Recovered Dead	Percent of Fish Released
38	93.7	T	882	12	1	1.5
		C	883	22	0	2.5
80	93.1	T	851	8	0	0.9
		C	862	6	0	0.7
38	173.8	T	890	35	1	4.0
		C	885	28	5	3.7
80	173.0	T	897	2	2	0.5
		C	897	5	0	0.6

TABLE O-6
DELAYED MORTALITY FOR TEST SERIES 2/3 (WITHOUT WICKET GATES)

Test group codes are: T, treatment; C, control; and NM, no identifiable mark.

Head (ft)	Mean Fish Length (mm)	Test Group	Number Recovered Live	Delayed Mortality (number of fish)			
				24 hr	48 hr	72 hr	96 hr
38	93.7	T	827	14	2	1	2
		C	852	0	0	0	0
80	93.1	T	771	9	0	1	2
		C	856	0	0	0	0
38	173.8	T	714	14	3	0	1
		C	823	7	0	1	1
80	173.0	T	746	14	1	0	0
		C	869	7	1	0	0

TABLE O-7
PERCENT OF RAINBOW TROUT WITH VARIOUS LEVELS OF DESCALING AT THREE LOCATIONS ALONG THE BODY

TEST SERIES 2/3 - WITHOUT WICKET GATES

Live fish and immediate mortalities combined.

Head (ft)	Mean Fish Length (mm)	Percent Scale Loss	Location 1		Location 2		Location 3	
			Treatment	Control	Treatment	Control	Treatment	Control
38	93.7	< 3	39.5	46.0	62.6	70.4	87.1	91.1
		3 – 20	50.7	48.6	30.7	27.2	11.2	8.1
		20 – 40	8.4	5.3	5.3	2.3	1.4	0.8
		> 40	1.4	0.1	1.4	0.1	0.3	0.0
38	173.8	< 3	56.5	61.5	60.1	64.8	86.9	88.8
		3 – 20	35.3	34.7	31.2	31.0	9.7	9.4
		20 – 40	5.3	3.4	6.5	3.5	2.4	1.7
		> 40	2.9	0.3	2.1	0.7	1.0	0.1
80	93.1	< 3	54.3	56.8	73.0	79.0	81.2	87.5
		3 – 20	39.2	39.7	21.0	20.2	14.5	11.9
		20 – 40	5.8	3.4	4.4	0.7	3.7	0.6
		> 40	0.7	0.1	1.5	0.1	0.6	0.0
80	173.0	< 3	59.6	67.2	58.2	66.1	81.4	90.4
		3 – 20	30.3	28.7	29.7	28.4	11.8	7.8
		20 – 40	6.5	3.9	7.3	4.8	4.3	1.7
		> 40	3.5	0.2	4.8	0.7	2.5	0.1

TABLE O-8
POST-TEST RECOVERY DATA (I.E., FISH RECOVERED DURING TESTS CONDUCTED AFTER THE ONE IN WHICH THEY WERE RELEASED) FOR THE TEST CONDITIONS EVALUATED DURING TEST SERIES 5/6 (WICKET GATES INSTALLED)

Test group codes are: T, treatment; C, control

Test Conditions (head and mean FL)	Test Group	Total Number of Fish Released	Post-Test Recovery Data: Number Recovered Live	Number Recovered Dead	Percent of Fish Released
40 ft 38.0 mm	T	890	8	1	1.0
	C	884	9	1	1.1
80 ft 38.4 mm	T	891	10	1	1.2
	C	890	7	2	1.0
40 ft 85.0 mm	T	876	7	0	0.8
	C	874	10	0	1.1
80 ft 84.9 mm	T	859	9	0	1.0
	C	858	14	0	1.6
40 ft 169.8 mm	T	899	16	1	1.9
	C	877	19	1	2.3
80 ft 174.7 mm	T	898	2	8	1.1
	C	864	0	0	0.0

TABLE O-9
DELAYED MORTALITY FOR TEST SERIES 5/6 (WICKET GATES INSTALLED)

Test group codes are: T, treatment; C, control; and NM, no identifiable mark.

Head (ft)	Mean Length (mm)	Test Group	Number Recovered Live	Delayed Mortality (number of fish)			
				24 hr	48 hr	72 hr	96 hr
40	38.0	T	836	10	22	28	11
		C	863	11	20	32	18
80	38.4	T	825	10	23	32	23
		C	867	5	24	32	20
40	85.0	T	829	6	1	0	0
		C	866	0	1	0	1
80	84.9	T	775	4	0	1	3
		C	843	0	0	0	1
40	169.8	T	803	13	1	3	1
		C	856	3	1	0	0
80	174.7	T	724	21	2	0	2
		C	853	4	0	0	2

TABLE O-10
SUMMARY OF PERCENT DESCALING AT THREE LOCATIONS ALONG THE BODY FOR SPRING 2002 RAINBOW TROUT TESTS (TEST SERIES 5/6, WICKET GATES INSTALLED)

Data for live fish and immediate mortalities combined.

Head (ft)	Mean Fish Length (mm)	Percent Scale Loss	Location 1		Location 2		Location 3	
			Treatment	Control	Treatment	Control	Treatment	Control
40	38.0	< 3	99.7	99.9	99.8	99.9	100.0	0.0
		3 – 20	0.3	0.1	0.2	0.1	0.0	0.0
		20 – 40	0.0	0.0	0.0	0.0	0.0	0.0
		> 40	0.0	0.0	0.0	0.0	0.0	0.0
80	38.4	< 3	98.2	100.0	98.6	100.0	99.2	100.0
		3 – 20	1.6	0.0	1.1	0.0	0.7	0.0
		20 – 40	0.0	0.0	0.0	0.0	0.0	0.0
		> 40	0.0	0.0	0.0	0.0	0.0	0.0
40	85.0	< 3	85.9	91.7	85.9	92.5	88.8	93.9
		3 – 20	13.5	8.1	13.1	7.3	10.6	5.9
		20 – 40	0.6	0.2	0.9	0.2	0.5	0.1
		> 40	0.1	0.0	0.1	0.0	0.1	0.0
80	84.9	< 3	83.1	91.4	83.9	92.2	87.4	93.5
		3 – 20	16.2	8.5	15.5	7.8	12.0	6.4
		20 – 40	0.7	0.1	0.6	0.0	0.6	0.1
		> 40	0.0	0.0	0.0	0.0	0.0	0.0
40	169.8	< 3	86.5	86.3	80.8	81.2	79.6	78.6
		3 – 20	12.0	13.5	16.9	17.5	19.7	20.6
		20 – 40	1.2	0.2	2.1	1.2	0.4	0.3
		> 40	0.2	0.0	0.0	0.0	0.2	0.4
80	174.7	< 3	76.6	82.8	73.0	82.5	72.5	77.6
		3 – 20	20.0	16.6	23.1	16.7	24.4	20.9
		20 – 40	1.9	0.4	2.5	0.7	2.1	1.4
		> 40	1.1	0.1	1.2	0.0	1.2	0.1

TABLE O-11
POST-TEST RECOVERY DATA (I.E., FISH RECOVERED DURING TESTS CONDUCTED AFTER THE ONE IN WHICH THEY WERE RELEASED) FOR TEST SERIES 7

Test Group codes are: T, treatment; C, control

Species	Test Group	Total Number of Fish Released	Post-Test Recovery Data: Number Recovered Live	Number Recovered Dead	Percent of Fish Released
alewife	T	891	3	6	1.0
	C	887	0	0	0
coho salmon	T	902	54	3	6.3
	C	905	60	1	6.7
white sturgeon	T	888	4	1	0.6
	C	892	1	1	0.2

TABLE O-12
DELAYED MORTALITY FOR TEST SERIES 7 (WITH WICKET GATES)

Test Group codes are: T, treatment; C, control

Species	Test Group	Number Recovered Live	Delayed Mortality (number of fish): 24 hr	48 hr	72 hr	96 hr
alewife	T	843	11	4	4	2
	C	886	0	0	2	0
coho salmon	T	801	12	0	1	1
	C	835	0	0	0	0
white sturgeon	T	864	9	4	1	2
	C	879	2	2	1	0

TABLE O-13
PERCENT OF FISH WITH VARIOUS LEVELS OF DESCALING AT THREE LOCATIONS ALONG THE BODY
TEST SERIES 7 - WITH WICKET GATES

Data for live fish and immediate mortalities are combined.

Species	Percent Scale Loss	Location 1 Treatment	Location 1 Control	Location 2 Treatment	Location 2 Control	Location 3 Treatment	Location 3 Control
alewife	< 3	25.5	28.2	22.0	18.5	39.6	42.3
	3 – 20	41.9	46.6	40.8	50.2	44.3	47.3
	20 – 40	27.0	24.0	30.6	29.3	13.0	9.9
	> 40	5.7	1.2	6.7	2.0	3.1	0.5
coho salmon	< 3	3.2	4.2	3.0	4.6	8.8	8.0
	3 – 20	82.7	82.9	78.6	80.1	83.6	84.8
	20 – 40	11.7	12.1	15.7	13.8	6.4	6.8
	> 40	2.4	0.8	2.7	1.6	1.2	0.4

TABLE O-14
POST-TEST RECOVERY DATA (I.E., FISH RECOVERED DURING TESTS CONDUCTED AFTER THE ONE IN WHICH THEY WERE RELEASED) FOR AMERICAN EEL TESTS

TEST SERIES 8 - WICKET GATES INSTALLED

All tests were conducted at a head of 40 ft and at the best efficiency point (BEP).

Test Group codes are: T, treatment; C, control.

Fish Size Group	Test Group	Total Number of Fish Released	Post-Test Recovery Data		
			Number Recovered Live	Number Recovered Dead	Percent of Fish Released
small	T	901	18	0	1.9
	C	902	17	2	2.1
large	T	894	76	0	8.5
	C	891	123	0	13.8

TABLE O-15
DELAYED MORTALITY FOR AMERICAN EEL TESTS
TEST SERIES 8 - WICKET GATES INSTALLED

All tests were conducted at a head of 40 ft and at the best efficiency point (BEP).
Test Group codes are: T, treatment; C, control.

Fish Size Group	Test Group	Number Recovered Live	Delayed Mortality (number of fish)			
			24 hr	48 hr	72 hr	96 hr
small	T	892	3	2	0	1
	C	866	1	0	1	0
large	T	804	5	4	4	7
	C	765	2	1	1	1

TABLE O-16
POST-TEST RECOVERY DATA (I.E., FISH RECOVERED DURING TESTS CONDUCTED AFTER THE ONE IN WHICH THEY WERE RELEASED) FOR TESTS WITH SMALLMOUTH BASS (TEST SERIES 8; WITH WICKET GATES)

Fish Size Group	Test Group	Total Number of Fish Released	Post-Test Recovery Data		
			Number Recovered Live	Number Recovered Dead	Percent of Fish Released
small	T	902	10	0	1.2
	C	894	7	1	0.9
large	T	901	9	0	1.1
	C	898	24	0	2.8

TABLE O-17
DELAYED MORTALITY FOR TESTS WITH SMALLMOUTH BASS (TEST SERIES 8; WITH WICKET GATES)

Fish Size Group	Test Group	Number Recovered Live	Delayed Mortality (number of fish)			
			24 hr	48 hr	72 hr	96 hr
small	T	852	7	0	1	1
	C	874	0	0	1	1
large	T	827	15	11	2	1
	C	864	0	0	1	0

TABLE O-18
PERCENT OF SMALLMOUTH BASS WITH VARIOUS LEVELS OF DESCALING AT THREE LOCATIONS ALONG THE BODY (TEST SERIES 8; WITH WICKET GATES)

Live fish and immediate mortalities combined.

Fish Size Group	Percent Scale Loss	Location 1		Location 2		Location 3	
		Treatment	Control	Treatment	Control	Treatment	Control
small	< 3	96.3	98.4	93.6	97.3	94.7	98.2
	3 – 20	1.8	0.9	4.3	1.6	3.7	1.1
	20 – 40	0.7	0.5	1.7	0.9	1.5	0.7
	> 40	1.2	0.2	0.5	0.2	0.1	0.0
large	< 3	85.2	94.3	73.6	87.4	83.4	94.3
	3 – 20	10.2	4.4	18.0	11.0	11.3	5.3
	20 – 40	3.5	1.3	7.5	1.6	4.3	0.3
	> 40	1.1	0.0	0.9	0.0	1.0	0.0

TABLE O-19
POST-TEST RECOVERY DATA (I.E., FISH RECOVERED DURING TESTS CONDUCTED AFTER THE ONE IN WHICH THEY WERE RELEASED) FOR THE TEST CONDITIONS EVALUATED DURING TEST SERIES 9/10

Test group codes are: T, treatment; C, control

Wicket Gate Position	Test Group	Total Number of Fish Released	Post-Test Recovery Data: Number Recovered Live	Post-Test Recovery Data: Number Recovered Dead	Post-Test Recovery Data: Percent of Fish Released
18.2° (BEP)	T	892	19	0	2.1
	C	907	23	0	2.5
16°	T	896	11	0	1.2
	C	901	24	0	2.6
20°	T	902	23	0	2.5
	C	902	21	0	2.3
22°	T	906	12	1	1.4
	C	902	15	0	1.7
24°	T	910	13	1	1.5
	C	906	24	1	2.8
26°	T	900	10	0	1.1
	C	898	5	0	0.5

TABLE O-20
DELAYED MORTALITY FOR TEST SERIES 9/10 (WICKET GATES INSTALLED)

Test group codes are: T, treatment; C, control

Wicket Gate Position	Test Group	Number Recovered Live	Delayed Mortality (number of fish)			
			24 hr	48 hr	72 hr	96 hr
18.2° (BEP)	T	838	14	26	21	29
	C	880	4	10	26	17
16°	T	845	11	28	51	37
	C	874	9	15	31	34
20°	T	837	12	2	3	7
	C	869	1	1	2	1
22°	T	863	11	20	42	46
	C	890	3	15	27	51
24°	T	870	5	7	12	21
	C	878	0	3	4	11
26°	T	853	20	35	41	44
	C	891	8	21	39	53

TABLE O-21
SUMMARY OF PERCENT DESCALING AT THREE LOCATIONS ALONG THE BODY FOR RAINBOW TROUT TESTS EVALUATED DURING TEST SERIES 9/10 (WICKET GATES INSTALLED)

Data for live fish and immediate mortalities combined.

Wicket Gate Position	Percent Scale Loss	Location 1		Location 2		Location 3	
		Treatment	Control	Treatment	Control	Treatment	Control
18° (BEP)	< 3	50.2	56.5	45.4	56.6	53.0	61.9
	3 – 20	47.5	42.2	52.0	41.9	46.1	37.3
	20 – 40	1.7	1.2	2.3	1.4	0.9	0.7
	> 40	0.6	0.0	0.3	0.1	0.0	0.1
16°	< 3	54.4	65.6	48.4	58.2	52.9	66.2
	3 – 20	43.0	33.1	48.5	40.0	45.6	33.1
	20 – 40	2.3	1.3	2.9	1.4	1.4	0.6
	> 40	0.3	0.1	0.2	0.3	0.1	0.1
20°	< 3	60.1	63.1	53.6	55.2	58.2	62.8
	3 – 20	37.6	36.0	43.3	43.3	40.0	36.4
	20 – 40	2.0	0.9	3.0	1.5	1.7	0.8
	> 40	0.3	0.0	0.1	0.0	0.0	0.0
22°	< 3	57.6	63.4	54.9	60.5	59.6	66.6
	3 – 20	40.5	35.4	42.5	37.5	39.6	33.0
	20 – 40	1.9	1.2	2.6	2.0	0.8	0.4
	> 40	0.0	0.0	0.0	0.0	0.0	0.0
24°	< 3	51.0	57.9	47.4	52.5	52.3	59.8
	3 – 20	46.8	41.1	50.0	45.6	46.8	39.4
	20 – 40	1.9	1.0	2.3	1.9	0.9	0.8
	> 40	0.3	0.0	0.2	0.0	0.0	0.0
26°	< 3	52.1	58.9	50.2	55.2	53.8	61.2
	3 – 20	45.7	39.8	47.4	43.8	44.4	37.8
	20 – 40	2.3	1.0	2.5	0.8	1.8	0.8
	> 40	0.0	0.2	0.0	0.2	0.0	0.2

APPENDIX P

COMPUTER ANALYSIS OF BEP AND OFF-BEP OPERATION

APPENDIX P
COMPUTER ANALYSIS OF BEP AND OFF-BEP OPERATION

OBJECTIVES OF CFD ANALYSIS

Computation Fluid Dynamic (CFD) analysis was performed to simulate the complex flow conditions through the whole turbine, including the scroll case, wicket gates, runner, and draft tube, operating at different wicket gate positions. The objectives of this analysis were to:

1) Investigate why the actual best efficiency point (BEP) wicket gate setting (18.2^o) and runner speed measured in the pilot scale turbine were not identical to the gate setting (22^o) and runner speed originally derived as the BEP.

2) Study the flow fields for different off-BEP operating conditions to help understand why similar fish survival was observed during pilot scale testing regardless of the turbine operation conditions.

3) Relate observed fish injury for BEP and off-BEP tests to internal runner flow characteristics, such as strain rates and pressure change rates. Correlation of survival or injury to certain values of such parameters increases the knowledge of flow conditions that are acceptable to fish passing through the turbine.

4) Evaluate if the turbine design could be further improved for fish passage and power efficiency.

A total of five turbine operation scenarios were simulated, as shown in Table P-1. Two high head cases (Case Nos. 1 and 2) were studied to better understand the differences in turbine performance between the "theoretical" BEP (22^o gate setting, 325 rpm, and 95 cfs) and the actual measured BEP (18.2^o gate setting, 345 rpm, and 84.1 cfs), and to identify any turbine features that could be further improved. Three low head cases (Case Nos. 3, 4 and 5) were simulated to cover the whole range of turbine operation tested with fish at the 240 rpm rotational speed and the pilot scale turbine at different gate positions, from the most wide open wicket gate position (26^o) to the most closed wicket gate position (16^o). The results of these simulations were used to correlate flow characteristics with fish survival.

TABLE P-1
CFD CASES ANALYZED

Case No.	High Head		Low Head		
	1	2*	3	4*	5
Wicket Gate Setting (^{o} from fully closed)	22	18.2	26	18.2	16
Speed, n (rpm)	325	345	240	240	240
Flow, Q (cfs)	95.0	84.1	76.9	60.7	54.7

*Actual BEP wicket gate position

METHODOLOGY FOR FLOW SIMULATIONS

Software

A widely used commercial computer software program, FLUENT (version 6), was used to perform the CFD simulations. This CFD package solves the Navier-Stokes equations and turbulence closure equations in both stationary and rotating reference frames to simulate three-dimensional flows. The standard κ-epsilon turbulence model was used with a wall function for the boundary layer. Computational meshes for this study were generated using Gambit (Version 2.0) and the CFD results were post-processed using visualization software FieldView (Version 8.0).

Solution Approach

Flows through a hydraulic turbine are complex and difficult to simulate accurately because the upstream and downstream components (scroll case and draft tube) of the turbine are in a stationary reference frame, while the runner is rotating. There are important interactions between flow in the scroll case and runner inlet as well as between flow in the runner exit and the draft tube. For the final CFD analysis, two methods were used by Alden and Concepts/NREC to simulate the interaction between flows in stationary and rotating parts of the turbine: 1) a mixing plane method and 2) a multiple frame of reference (MFR) method. The mixing plane and MFR methods both assumed the flow field was steady-state, with the stator-rotor interactions being accounted for by different approximations.

To simplify the flow analysis, flow through the turbine runner was simulated using the mixing plane method. This method, which is typically used for rotating machinery, modeled a single rotating reference frame with only one-blade passage, similar to the model used for the original analysis to design the runner. Flow was assumed to be periodical (repetitive) for each blade passage. Separate simulations for the flow through the scroll case were required to prescribe the inlet boundary conditions for the runner domain by averaging the scroll outlet boundary profiles of the flow variables. A pressure-outlet type of boundary condition was applied at the runner outlet and separate simulations were used to define flow conditions in the draft tube. The mixing plane method treats each fluid zone as a steady-state problem. Flow-field data from adjacent zones are passed as boundary conditions that are spatially averaged at the mixing plane interfaces. This averaging process removes circumferential variations in the passage-to-passage flow field. Therefore, interactions between the scroll and the runner, as well as between the runner and the draft tube, are accounted for on a circumferential average basis in the mixing plane model.

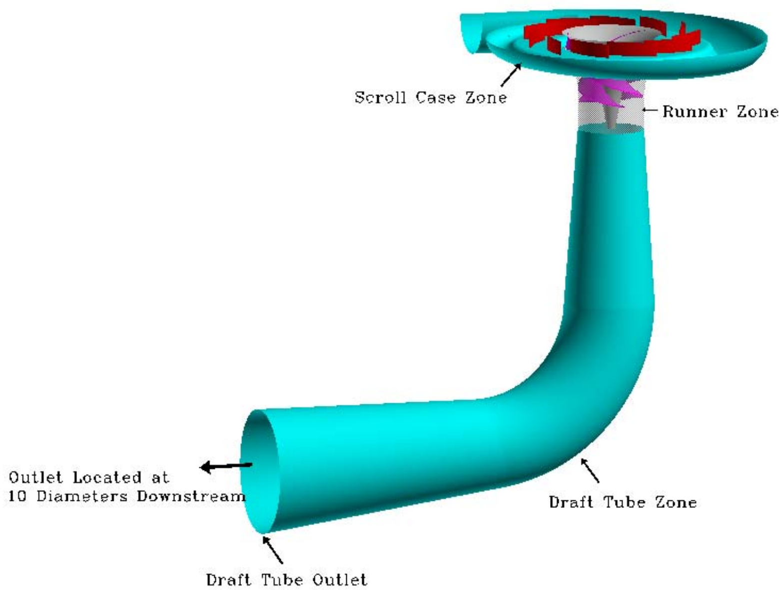
In the MFR method, individual fluid zones can move at different rotation speeds or can be stationary. Non-conformal interfaces between these zones are created and simulated by directly passing the flow information across these interfaces. All three blade passages were simulated in the MFR model of the Alden/Concepts NREC turbine, which provided a reasonable approximation of the time-averaged flow field in the turbine. The time average values reported herein do not fully represent the extreme values that turbulent, unsteady local flows may produce.

Even though only one blade passage was simulated in the mixing plane model, the mixing plane approach required much more computational effort to get a fully converged solution. In addition, a jump in total pressure across the mixing planes was found in the simulation results. Therefore, only the results of the MFR model are presented in this report.

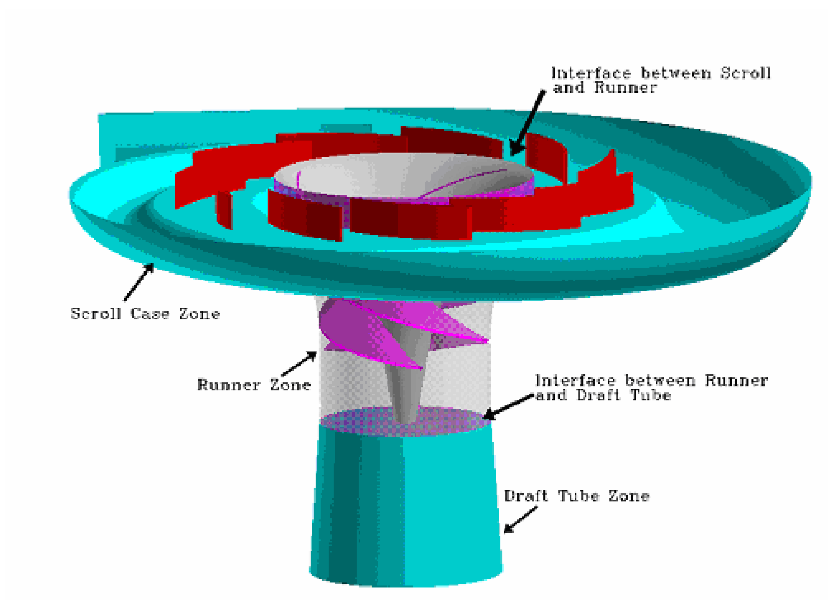
<u>Model Setup</u>

As shown in Figure P-1(a), the MFR method simulated the whole turbine, including all three runner blade passages, in a single model. The scroll fluid zone and the draft tube fluid zone were stationary and the turbine runner fluid zone was rotating. The computational domain had meshes clustered closely around the solid walls with a total of about 2.7 million computational elements used for each CFD simulation. Near solid walls, the mesh spacing was 0.2 inches and the maximum mesh size was one inch for the runner and two inches for other regions, all relative to a 4 ft diameter runner.

As show in Figure P-1(b), there were two grid interfaces. One interface was located between the end of the scroll case zone and the beginning of the runner zone and the other interface was located between the end of the runner zone and the beginning of the draft tube zone. At these interfaces, the flow-field variables are directly transferred from the upstream zone to the downstream zone for each calculation iteration. Therefore, mass flow and momentum are strictly conserved between the zones. A uniform velocity inlet



(a) Whole Computational Domain



(b) Detailed View

FIGURE P-1 COMPUTATIONAL DOMAIN AND TURBINE GEOMETRY
(TOP OF SCROLL NOT SHOWN FOR CLARITY

boundary condition was imposed at the scroll case inlet and an outflow pressure boundary condition was applied at the model outlet, which extended 10 pipe diameters downstream from the draft tube exit. The outflow pressure boundary was set to produce an average static pressure at the runner outlet slightly below atmospheric pressure, which is typical for runner settings and the pilot scale tests. A non-slip wall boundary condition was applied on all walls and the rotational speed was specified for each wall (zero for fixed surfaces and turbine speed (rpm) for the runner surfaces).

CFD PREDICTED TURBINE OPERATING CHARACTERISTICS

Turbine performance predicted with CFD was summarized in terms of runner torque (T), turbine power (P), turbine head (H), runner head (Hr), actual turbine head (Ha), turbine efficiency ($\eta=Ha/H$), runner efficiency ($\eta_r=Ha/Hr$), hydraulic losses in the scroll case and draft tube (ΔHs and ΔHd), and the averaged velocity angle from the radial direction at the downturn entrance in the plan view (β). The turbine head (H) is defined as the difference in total head (static plus kinetic) between the scroll inlet and draft tube outlet. The runner head (Hr) is defined as the difference in total head between runner inlet and runner outlet. The actual turbine head (Ha) is the actual power head of the turbine and is defined as $P/(Q\gamma)$, where Q is the flow rate and γ is the specific weight of the water.

BEP Performance

The predicted turbine performance based on the MFR CFD model at the high head condition is compared to the measured pilot scale turbine performance in Table P-2. The predicted turbine efficiency at a 325 rpm rotational speed with the wicket gates set at 22°, Case No. 1 ("theoretical" BEP), was 83.5%. At 345 rpm with the gates at the 18.2° angle, Case No. 2 (actual BEP), the predicted efficiency was 84.8%. These CFD results are consistent with the pilot scale measurements which indicated that the wicket gates had to be closed 3.8° from the "theoretical" setting to operate the turbine at BEP. The turbine efficiency at the actual BEP was predicted to be 1.3% higher than the "theoretical" BEP, similar to the measured turbine efficiencies for these two cases. The CFD analysis also predicted reasonably well the measured efficiencies at the higher head (83.5% vs 83.7% for Case No. 1 and 84.8% vs. 84.7%, for Case No. 2). Some differences between turbine head (77.1ft vs 78.2 ft and 81.5 ft vs 79.8 ft) were observed, as indicted in Table P-2, partially because flow rates were specified in the CFD analysis while the pilot scale testing was conducted at specified turbine heads. The CFD analysis did not include leakage, viscous losses external to the runner flow path, and mechanical losses. Although CFD predicted efficiencies are close to the measured efficiencies, the

CFD values are meaningful in showing trends between operating conditions. The CFD simulations confirmed that the turbine runner has a higher efficiency at the operating condition for Case No. 2, the actual BEP gate position measured during the pilot scale tests.

TABLE P-2
COMPARISON OF HIGH HEAD CFD RESULTS TO
PILOT SCALE TURBINE MEASUREMENTS

	Case No. 1		Case No. 2	
	CFD*	Measured**	CFD*	Measured**
Wicket Gate Setting (° from fully closed)	22	22	18.2	18.2
Speed, *n* (rpm)	325	325	345	345
Flow, *Q* (cfs)	95.0	96.9	84.1	84.8
Runner Torque, *T* (N-m)	15194		13605	
Power, *P* (hp)	693	720	659	651
Turbine Head, *H* (ft)	77.1	78.2	81.5	79.8
Runner Head, *Hr* (ft)	74.5		79.5	
Actual Head, *Ha* (ft)	64.4		69.2	
Turbine Efficiency, η (%)	83.5	83.7	84.8	84.7
Runner Efficiency, η_r (%)	86.5		87.0	
Loss at Scroll, ΔHs (ft)	1.11		1.26	
Loss at Draft Tube, ΔHd (ft)	1.56		0.74	
Average Velocity Angle at Down Turn Entrance, β (°)	67.5	69.4	71.4	71.2

* CFD input parameters identified above double line.

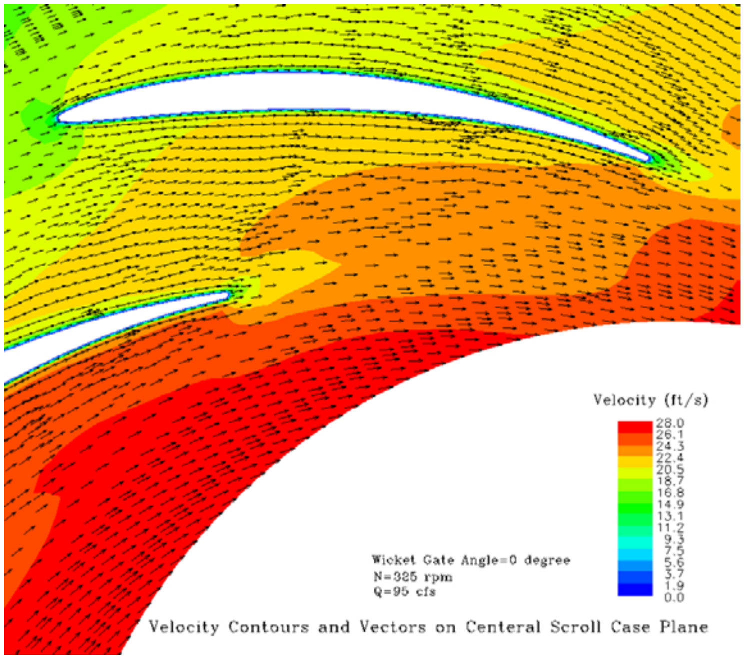
** Measured in pilot scale turbine final engineering tests (Table G-7, Appendix G). Turbine efficiency has not been adjusted for runner bottom seal leakage and other mechanical/viscous losses.

To help understand why the actual measured BEP was at a wicket gate position more closed than the gate position for the "theoretical" BEP, the average velocity angle (in plan view) from the radial direction at the downturn entrance was calculated using the CFD model for the two gate positions. The computer results were also compared to the velocity angles measured in the pilot scale turbine. As shown in Table P-2, the average velocity angle predicted with CFD for the "theoretical" BEP (Case No. 1) wicket gate position was 67.5° at the downturn entrance, about 2° less than the original design value of about 69.5° (Cook et al. 2002). The CFD results showed that for the actual BEP gate position (Case No. 2), the average velocity angle at the down turn entrance was 71.4°, about 2° more than the original design angle. The CFD analysis indicated that the measured BEP gate position (18.2° from full closed) has a higher head at a lower flow than the "theoretical" BEP gate position (22°). Therefore, Case No. 2 with the more closed wicket gates should have a better efficiency than Case No. 1 wicket gate setting.

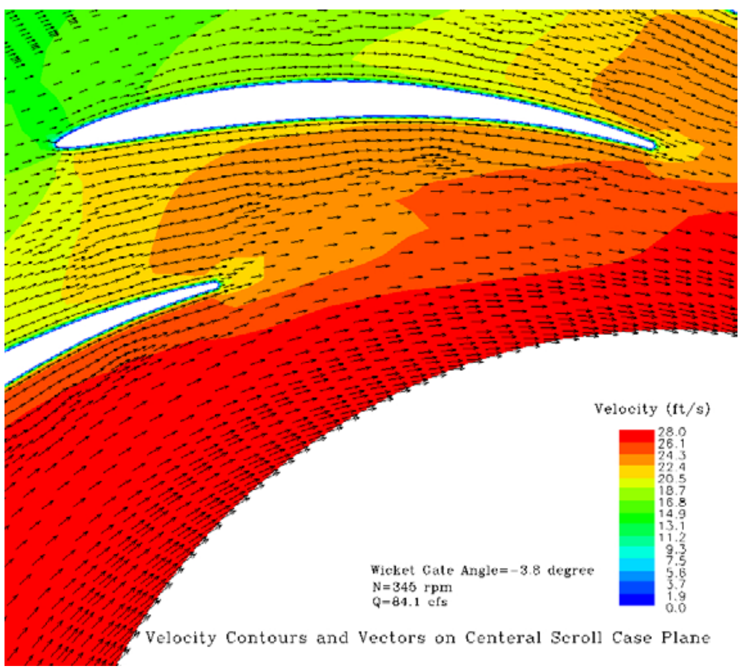
Detailed velocity vectors/contours, pressure contours within the runner, and pressure loading on the turbine blades were plotted to identify differences in the values for these two wicket gate positions. Figures P-2(a) and (b) show velocity contours and vectors on the central scroll plane for Case Nos. 1 and 2, respectively. No obvious flow separation or visual differences in the velocity contours were found between the two gate positions, indicating that flow patterns were not significantly altered with the wicket gates closed 3.8°. However, as shown in Table P-2, the flow angle entering the runner is actually more tangential (by about 3.8°) for Case No. 2 with the gates at 18.2° than for Case No. 1 with the gates at 22°. As shown in Figure 4-16, a gate opening of 18° would produce a more tangential runner inflow than an opening of 22°, and this is confirmed by the CFD analysis.

Figure P-3 shows the pressure contours on the mid-span plane for the two high head cases. Although difficult to see in Figure P-3(a) for the "theoretical" BEP wicket gate angle of 22°, there is an area near the trailing edge where the pressure on the pressure side of the blade is less than the pressure on the suction side of the blade. Figure P-3(b) for the actual BEP wicket gate angle of 18.2° also shows a small area of pressure reversal, which is smaller than the one observed for the "theoretical" BEP case. This trend is more obvious on Figures P-4 through P-6. These figures show the pressure loading on planes near the hub, the mid-span plane and near the shroud, and confirm the pressure reversal on the trailing edge of the runner blades at the two gate positions. Changes to the blade shape would eliminate this pressure reversal and would produce higher turbine efficiencies than the current design.

In addition, Figures P-4 through P-6 show that pressures on the suction side of the blade around the leading edge for the actual BEP case is higher than those for the "theoretical" BEP case. This higher pressure is related to a lower potential for flow separation near the leading edge at the actual BEP gate position, resulting in a higher turbine efficiency at the actual BEP gate position than at the theoretical BEP gate position. Pressures around the leading edge on the pressure side of the blades are similar for both gate positions.

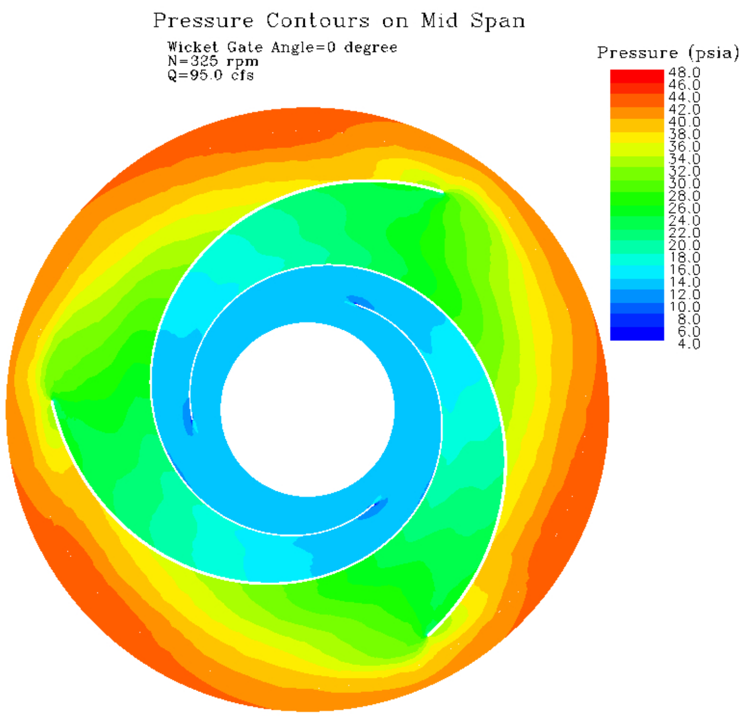


(a) Case No. 1 (22° Wicket Gate Angle from Full Closed)

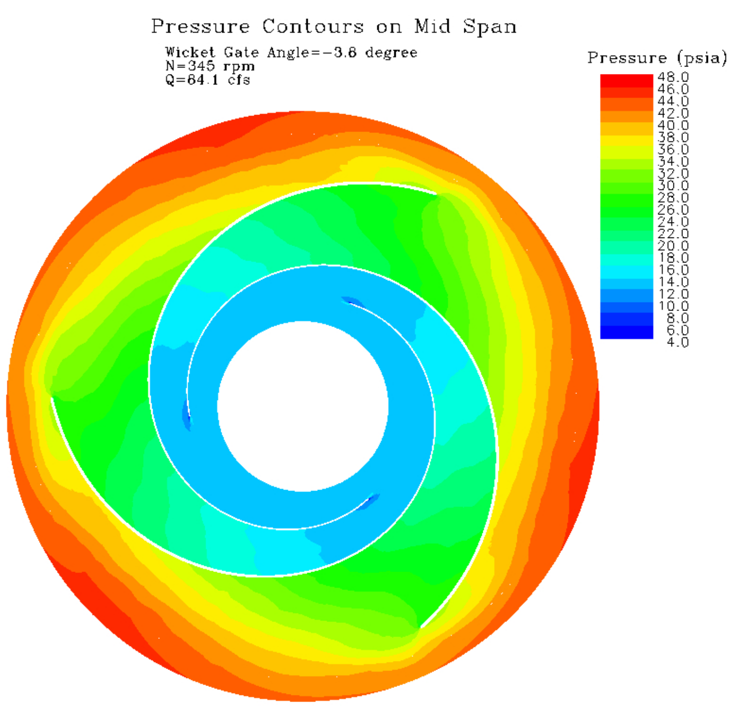


(b) Case No. 2 (18.2° Wicket Gate Angle from Full Closed)

FIGURE P-2 VELOCITY CONTOURS AND VECTORS ON MID-SPAN SCROLL PLANE

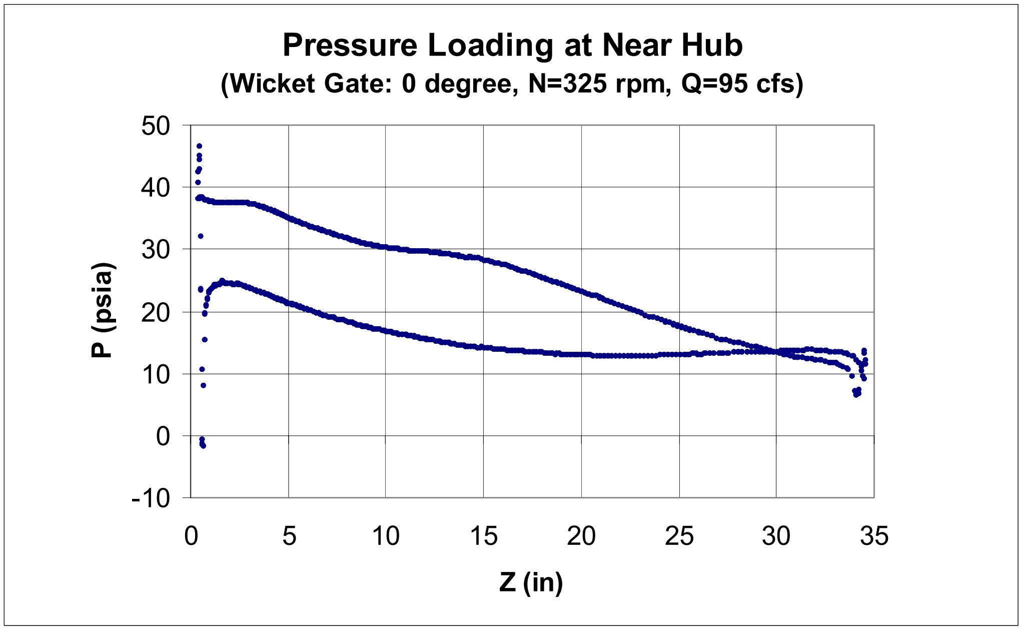


(a) 22° Wicket Gate Angle from Full Closed

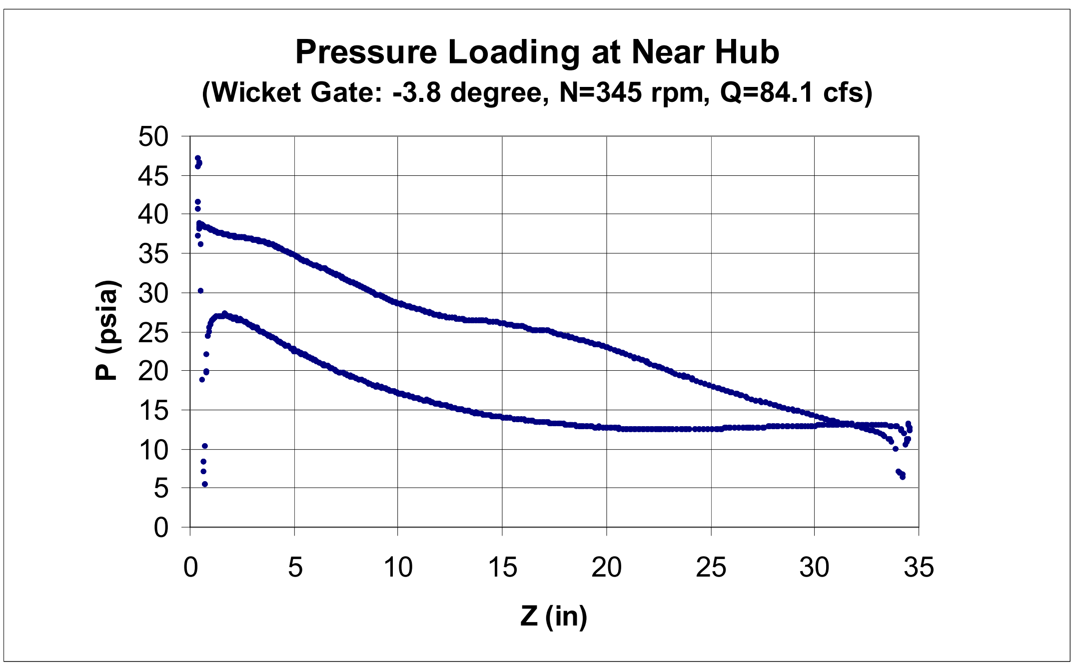


(b) 18.2° Wicket Gate Angle from Full Closed

FIGURE P-3 PRESSURE CONTOURS ON MID-SPAN PLANE

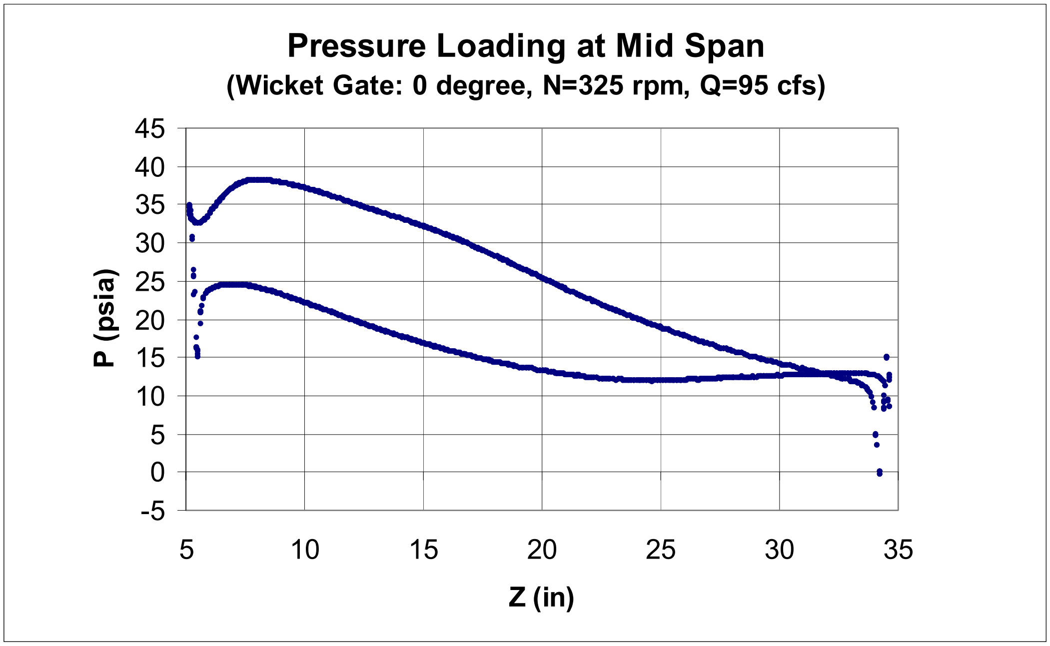


(a) 22° Wicket Gate Angle from Full Closed

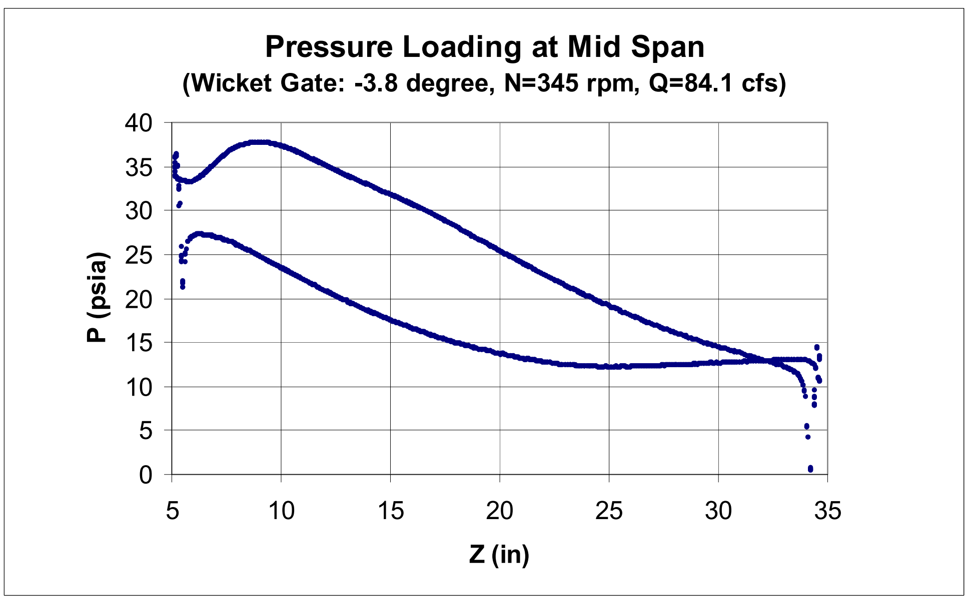


(b) 18.2° Wicket Gate Angle from Full Closed

FIGURE P-4 PRESSURE LOADING AT A NEAR HUB SURFACE

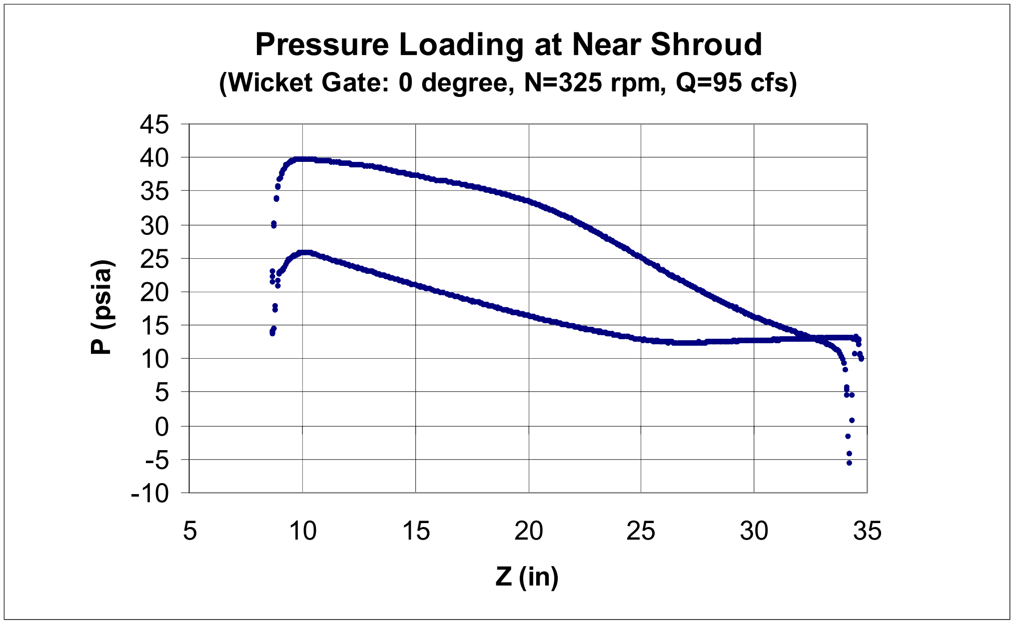


(a) 22° Wicket Gate Angle from Full Closed

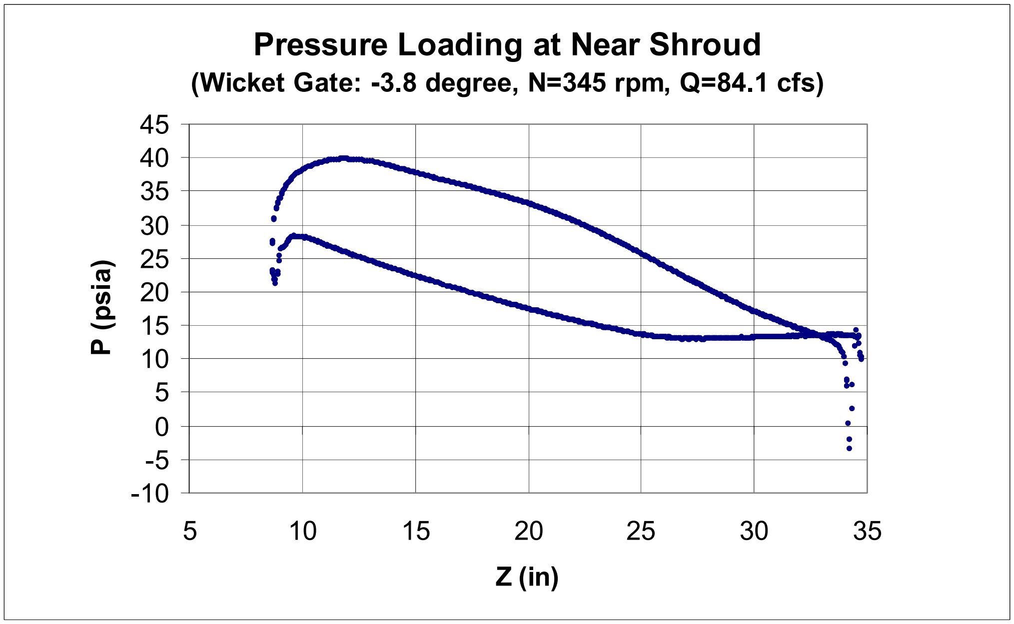


(b) 18.2° Wicket Gate Angle from Full Closed

FIGURE P-5 PRESSURE LOADING AT MID-SPAN SURFACE



(a) 22° Wicket Gate Angle from Full Closed)



(b) 18.2° Wicket Gate Angle from Full Closed

FIGURE P-6 PRESSURE LOADING AT A NEAR SHROUD SURFACE

An important point to remember when viewing Figures P-4 through P-6 is that the same amount of change of z-coordinate (vertical distance) through the runner does not equate to the same camberline distance change at the shroud and the hub. Figure P-7 shows the change of normalized camberline distance (m') starting from the leading edge of the blade, with respect to the axial coordinate (Z). This figure shows that a given amount of z-coordinate change will translate to a larger amount of camberline distance change at the shroud than at the hub near the trailing edge.

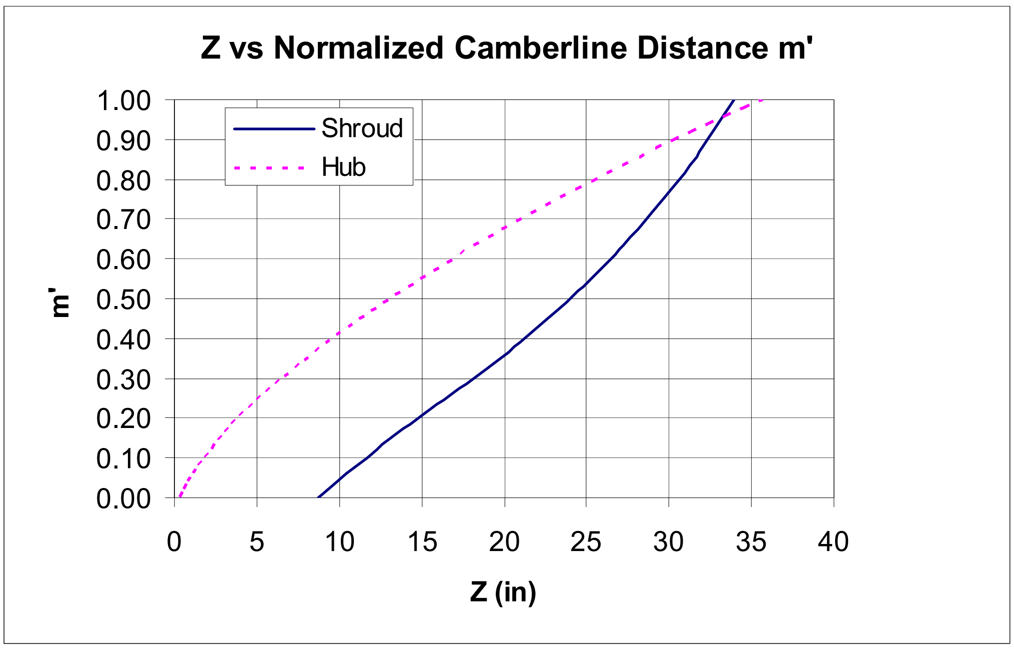
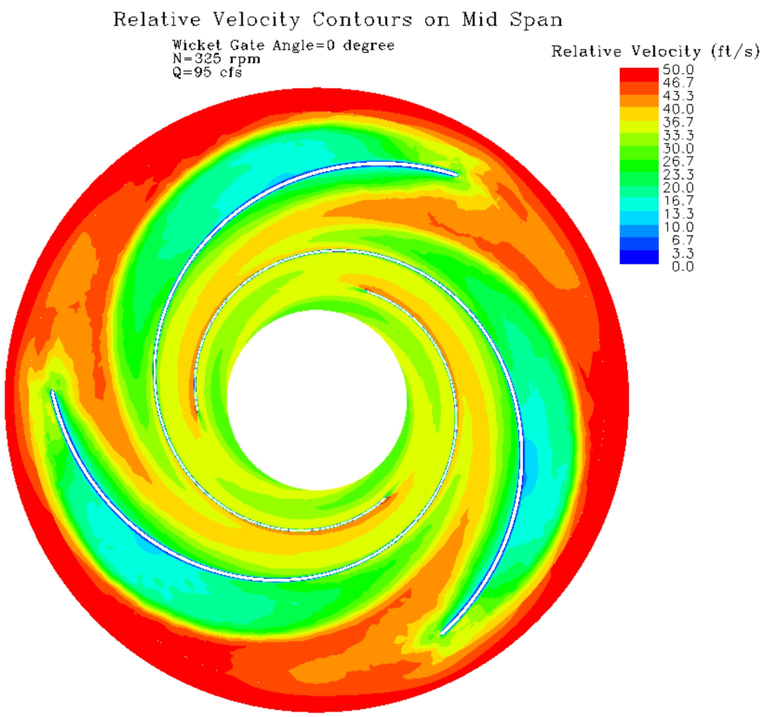
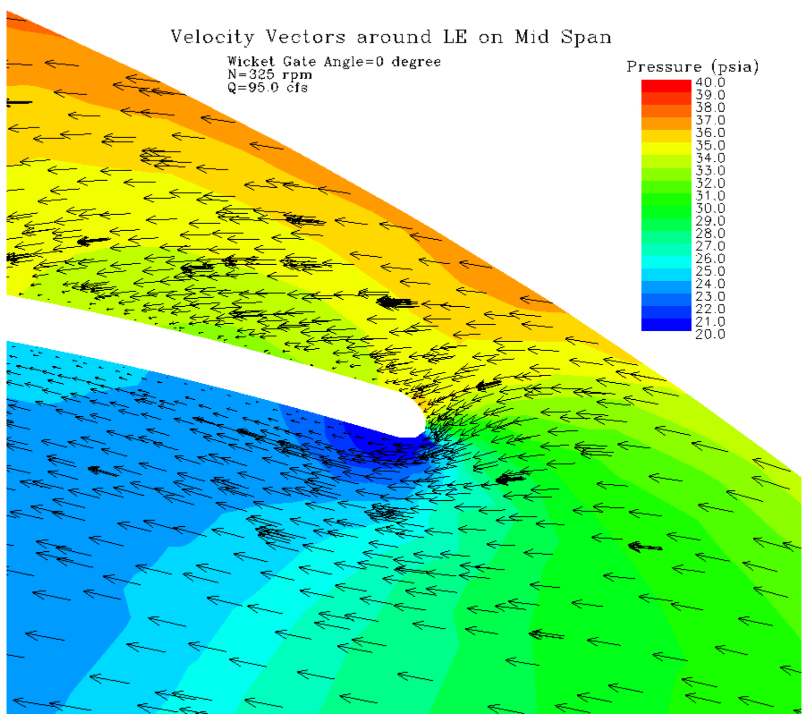


FIGURE P-7 AXIAL COORDINATE (Z) VS. NORMALIZED CAMBERLINE DISTANCE (m' = 0.00 IS LEADING EDGE)

Figure P-8(a) for the “theoretical” BEP gate position (22°) shows that the flow deceleration zone extends a considerable distance from the blade leading edge towards the trailing edge. Figure P-9(a) shows a smaller flow deceleration zone for the actual BEP gate position (18.2°). This longer deceleration zone is related to the pressure reversal near the trailing edge. Figures P-8(b) and P-9(b) show that the tendency for flow separation on the suction side near the leading edges is less for the actual BEP gate position (18.2°) than for the “theoretical” BEP gate position (22°). These figures also show that the stagnation point locations for both the actual BEP and the “theoretical” BEP are similar.

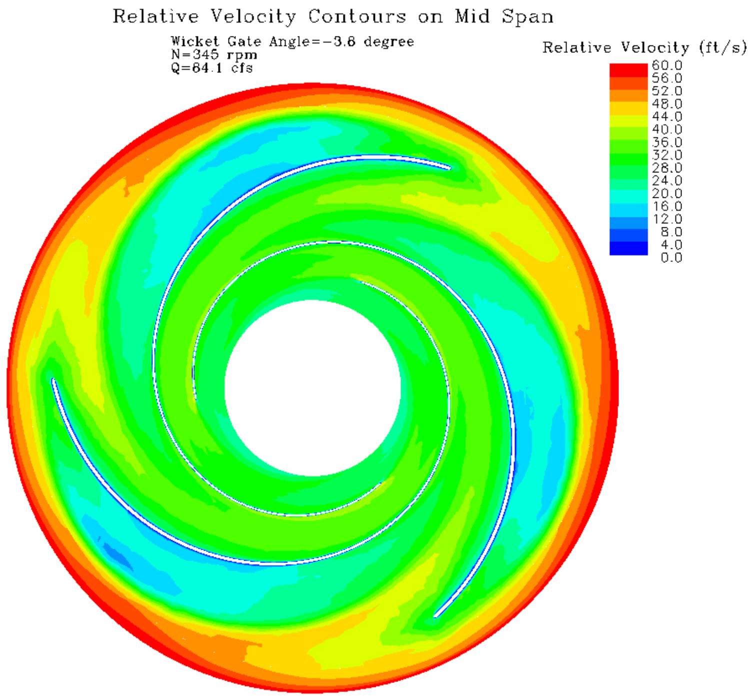


(a)

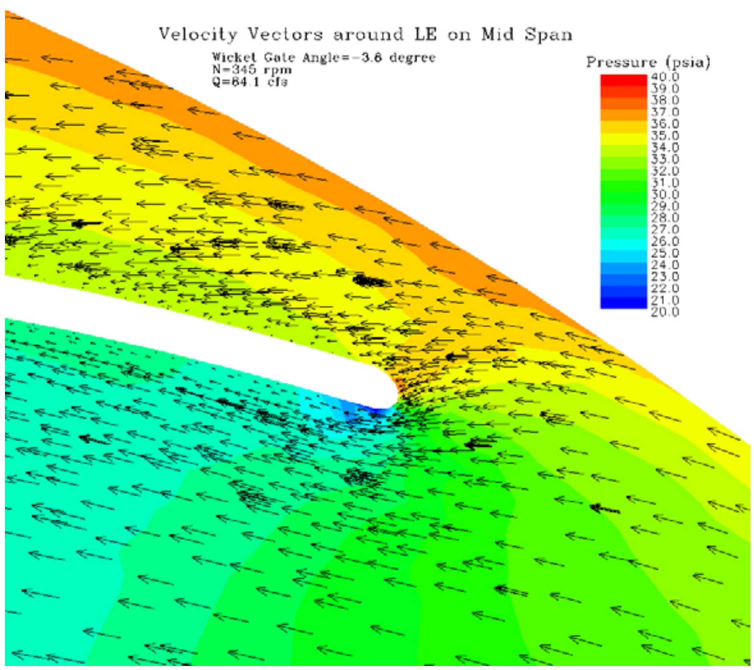


(b)

FIGURE P-8 RELATIVE VELOCITY CONTOURS AND VECTORS ON MID-SPAN (CASE NO. 1, 22° WICKET GATE ANGLE FROM FULL CLOSED)



(a)



(b)

FIGURE P-9 RELATIVE VELOCITY CONTOURS AND VECTORS ON MID-SPAN (CASE NO. 2, 22° WICKET GATE ANGLE FROM FULL CLOSED)

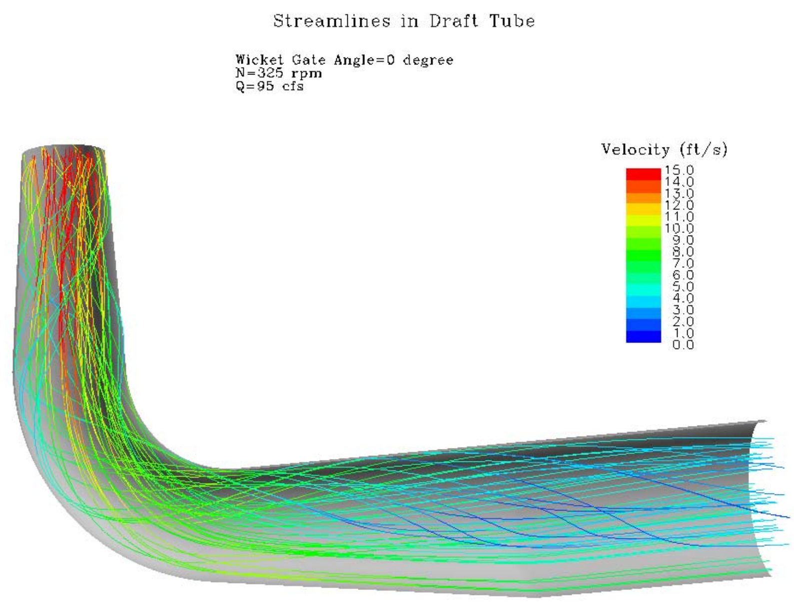
Figures P-10 to P-12 show the flow streamlines' velocity contours and vectors in the draft tube. Figure P-10 indicates that Case No. 2 (actual BEP gate) has stronger swirl in the draft tube than Case No. 1 ("theoretical" BEP gate). The swirl angle at the draft tube exit for the "theoretical" BEP gate (Figure P-11) is relatively small (about 5-10^o) because the magnitude of the velocity perpendicular to the axis (i.e., the resultant of the tangential Vxz) is relatively small compared to the axial velocity component (Vy). However, the swirl angle at the draft tube exit for the actual BEP gate (Case No. 2) is about 40-45^o because the velocity perpendicular to the axis is relatively high compared to the axial velocity component (Figure P-12). This indicates that improvements to the blade shape should be made and these changes would decrease the residual swirl and increase the turbine efficiency.

The CFD analysis confirmed the flow patterns and efficiency trends that were observed the pilot scale turbine test facility. The results demonstrate that the flow patterns at the leading and trailing edges and within the runner for the actual BEP gate position result in a higher turbine efficiency than for the "theoretical" BEP gate position. The higher residual swirl at the actual BEP gate position does not appear to be a major contributor to turbine power losses, probably because losses in the draft tube are small and some swirl helps flow from separating in the expanding area of the draft tube.

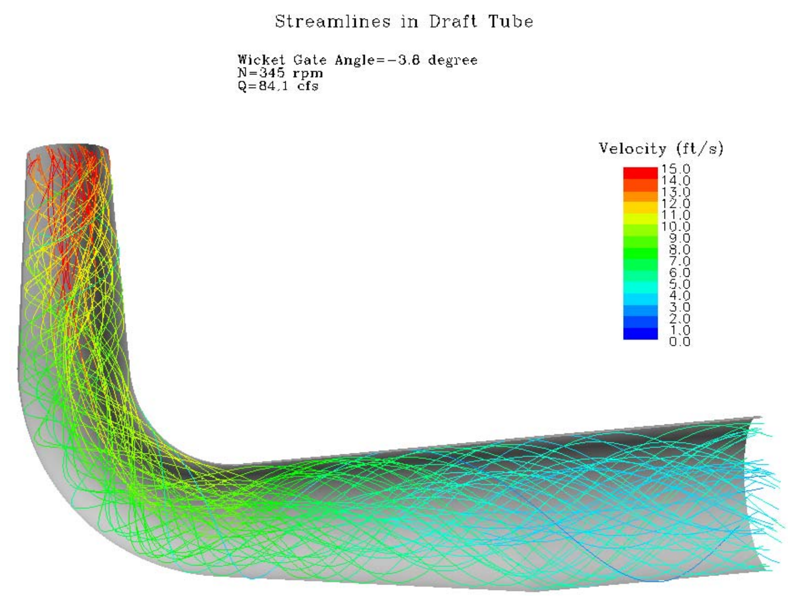
Turbine Performance at Off-BEP Conditions

Three off-BEP conditions were simulated with CFD for comparison to the fish survival test results. The simulations were completed with the lower head at three wicket gate positions (26°, 18.2°, and 16°) to cover the full range of conditions tested with fish. Turbine performance parameters under these conditions are summarized in Table P-3. The main objective for this off-BEP analysis was to evaluate differences in flow characteristics that the fish were exposed to at the different gate positions.

As shown in Table P-3, CFD simulation of the actual BEP test condition (Case No. 4) had higher turbine efficiency (84.2%) than the other two cases with the wicket gates at the 26° gate setting (82.3% for Case No. 3) and at the 16° gate position (83.4% for Case No. 5). These results confirm the ability of CFD model of the entire turbine to predict the best efficiency operating point.

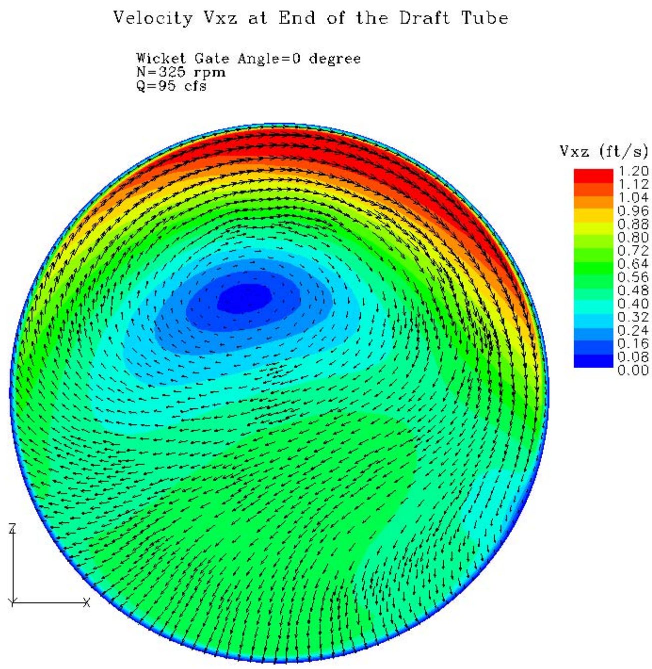


(a) 22° Wicket Gate Angle from Full Closed

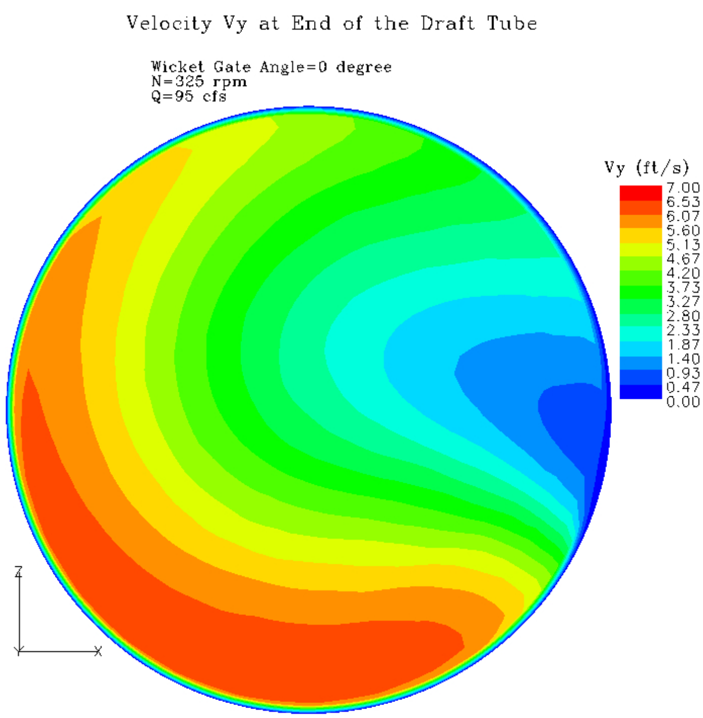


(b) 18.2° Wicket Gate Angle from Full Closed

FIGURE P-10 STREAMLINES IN DRAFT TUBE (CASE NOS. 1 AND 2)

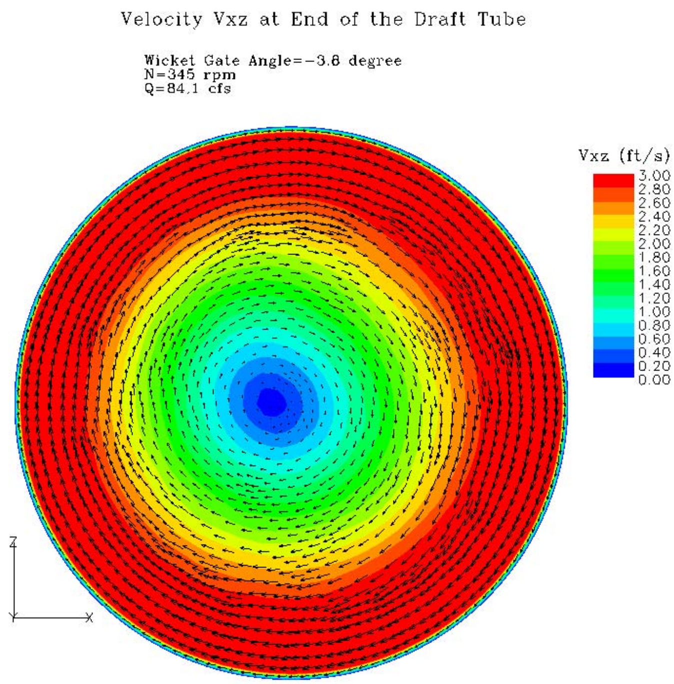


(a) Velocity Perpendicular to Axis

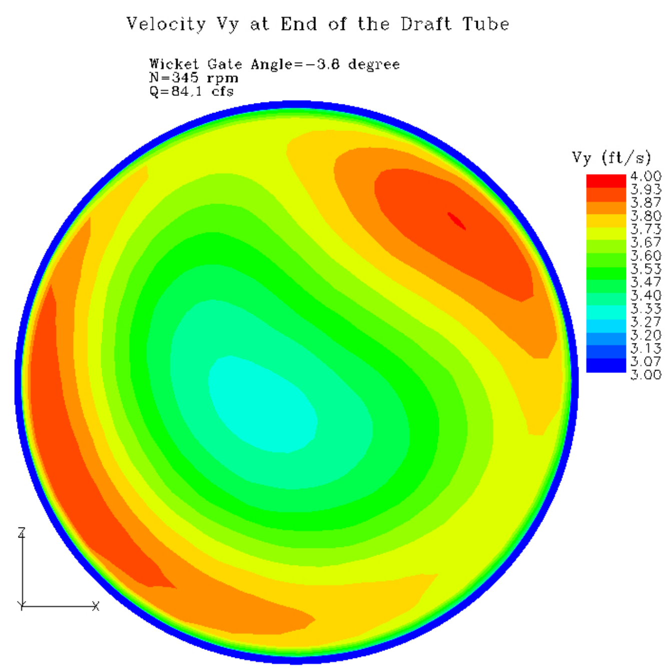


(b) Axial Velocity Component

FIGURE P-11 VELOCITY CONTOURS AND VECTORS AT DRAFT TUBE END (CASE NO. 1, 22° WICKET GATE ANGLE FROM FULL CLOSED)



(a) Velocity Perpendicular to Axis



(b) Axial Velocity Component

FIGURE P-12 VELOCITY CONTOURS AND VECTORS AT DRAFT TUBE END (CASE NO. 2, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)

TABLE P-3
COMPARISON OF LOW HEAD CFD RESULTS TO
PILOT SCALE TURBINE MEASUREMENTS

	Case No. 3		Case No. 4		Case No. 5	
	CFD*	Measured**	CFD*	Measured**	CFD*	Measured**
Wicket Gate Setting (° from fully closed)	26	26	18.2	18.2	16	16
Speed, n (rpm)	240	240	240	240	240	240
Flow, Q (cfs)	76.9	77.6	60.7	60.8	54.7	53.9
Runner Torque, T (N-m)	8696		7184		6440	
Power, P (hp)	293	296	242	236	217	197
Turbine Head, H (ft)	40.9	40.4	41.8	40.3	42.0	38.5
Runner Head, Hr (ft)	39.1		40.8		40.9	
Actual Head, Ha (ft)	33.6		35.2		35.0	
Turbine Efficiency, η (%)	82.3	83.4	84.2	84.1	83.4	83.6
Runner Efficiency, η_r (%)	86.0		86.4		85.6	
Loss at Scroll, ΔHs (ft)	0.65		0.68		0.74	
Loss at Draft Tube, ΔHd (ft)	1.13		0.39		0.34	
Average Velocity Angle at Down Turn Entrance, β (°)	63.3		71.4		73.7	

* CFD input parameters identified above double line.

** Actual BEP from pilot scale turbine preliminary engineering test in June 2002 (Table G-6, Appendix G). Turbine efficiency has not been adjusted for runner bottom seal leakage and other mechanical losses.

Pressure contours at mid-span and plots of pressure along the pressure and suction sides of the blade are shown on Figures P-13 through P-18. A discussion of the effects of the differences in these pressures distributions in the runner at the various wicket gate positions is presented below under Factors Related to Fish Survival.

Potential Turbine Improvements

The CFD analysis predicted that flow patterns and pressures at the leading/trailing edges and within the runner are more favorable at the actual BEP wicket gate position than at the "theoretical" BEP gate position (determined from the original CFD design). The results show that there is a pressure reversal on the runner blade trailing edges that decreases the overall turbine efficiency. The turbine blade shaping could be refined to solve the pressure reversal problem. Also, the residual swirl leaving the runner could be reduced by refining the blade shape. Such changes in blade geometry would increase the turbine efficiency.

Other areas for potential improvement in the turbine design would be to minimize the length of the downturn, increase the thickness of the blade leading edge shape, and increase the power density, i.e., power output per turbine size. Reducing the downturn in the scroll case at the runner inlet would decrease the overall diameter of the scroll case. Thicker leading edges on the runner blades could improve fish survival. Increasing the flow and the height of the radial space at the runner inlet (i.e., the wicket gates) would increase the power density, but would require additional and shorter wicket gates. These refinements could decrease the size of the turbine for a given power output, or increase the power output for a given size.

FACTORS RELATED TO FISH SURVIVAL

Biological Design Criteria

The CFD computed flow field characteristics were compared to available fish survival criteria and to actual fish survival in the pilot scale test facility. The results presented herein are intended to define flow parameters in the runner and to identify regions in the runner where the values of these parameters approach or exceed the critical values that have been defined by experiments by others in the industry and used as biological criteria for safe fish passage through turbines. The flow parameters that have discrete values that can be used to evaluate fish survival are: minimum pressures, pressure change rates, and flow shear stress (strain rate).

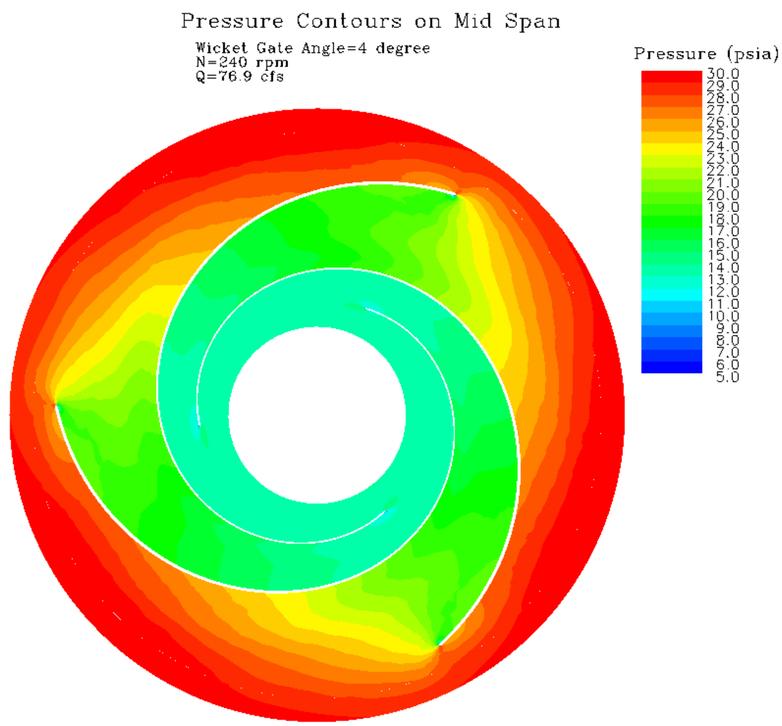


FIGURE P-13 PRESSURE CONTOURS ON MID SPAN (CASE NO. 3, 26° WICKET GATE ANGLE FROM FULL CLOSED)

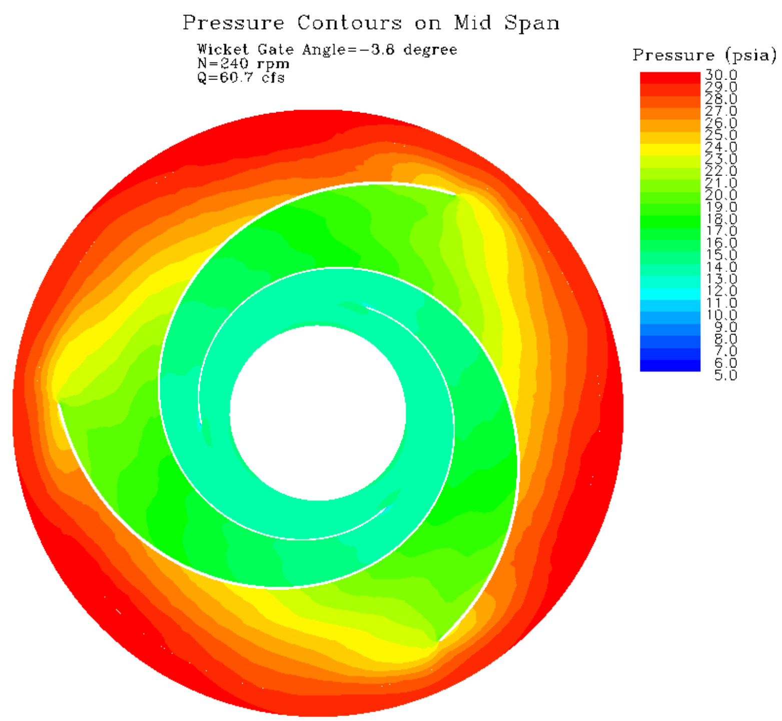


FIGURE P-14 PRESSURE CONTOURS ON MID SPAN (CASE NO. 4, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)

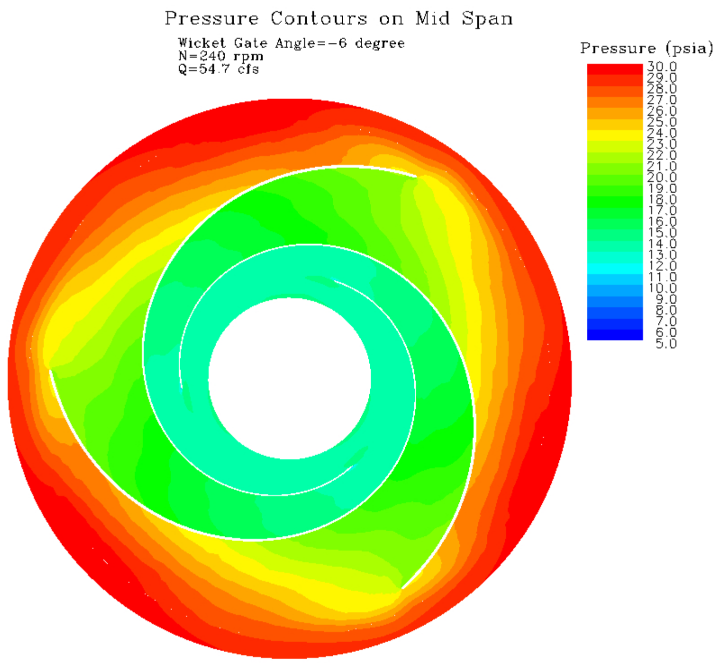


FIGURE P-15 PRESSURE CONTOURS ON MID SPAN (CASE NO. 5, 16° WICKET GATE ANGLE FROM FULL CLOSED)

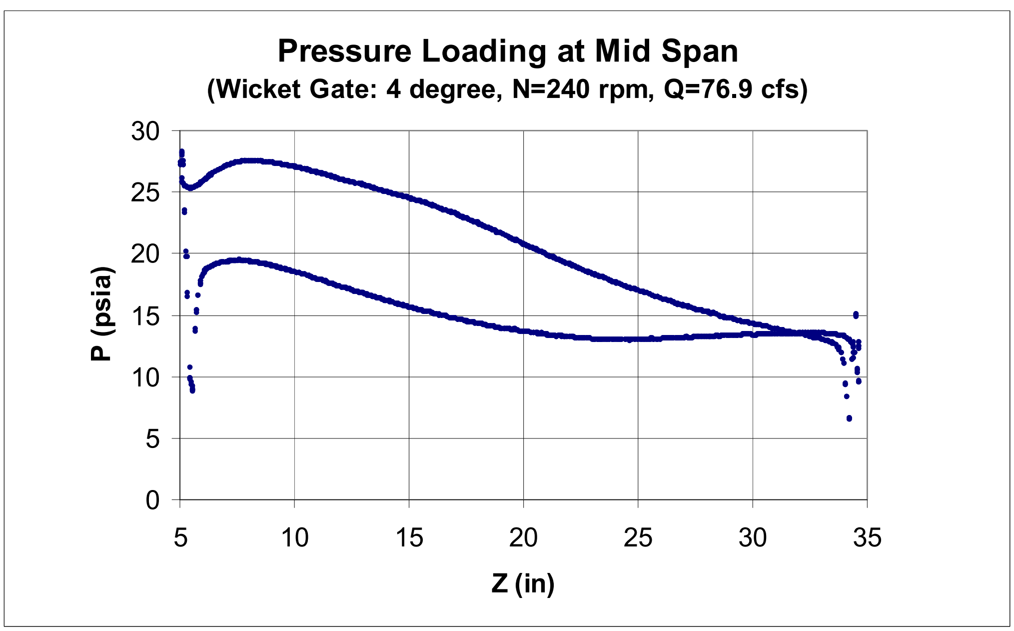


FIGURE P-16 PRESSURE LOADING AT MID SPAN (CASE NO. 3, 26° WICKET GATE ANGLE FROM FULL CLOSED)

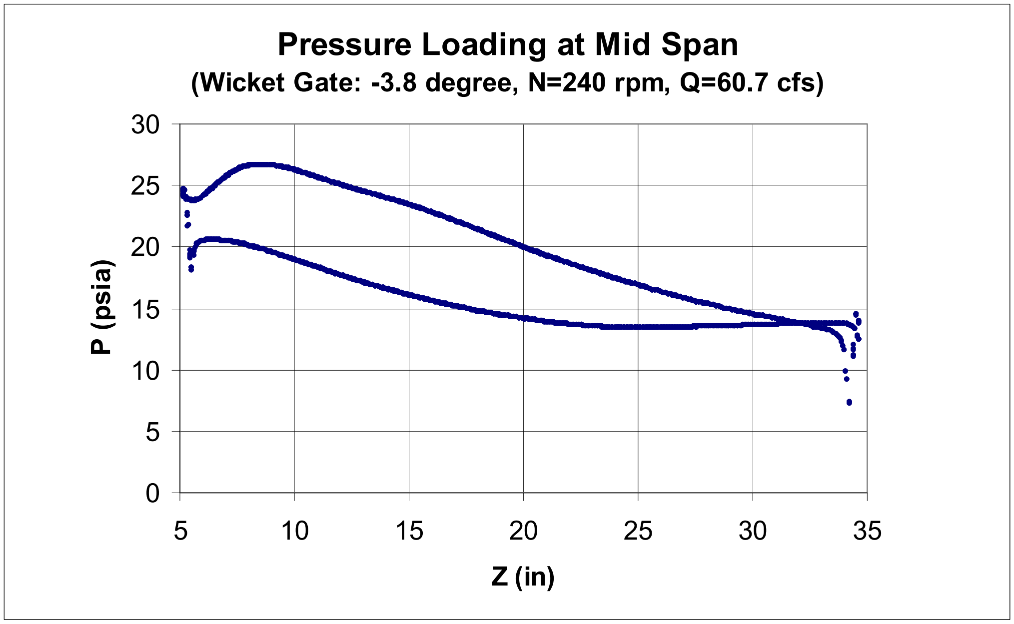


FIGURE P-17 PRESSURE LOADING AT MID SPAN (CASE NO. 4, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)

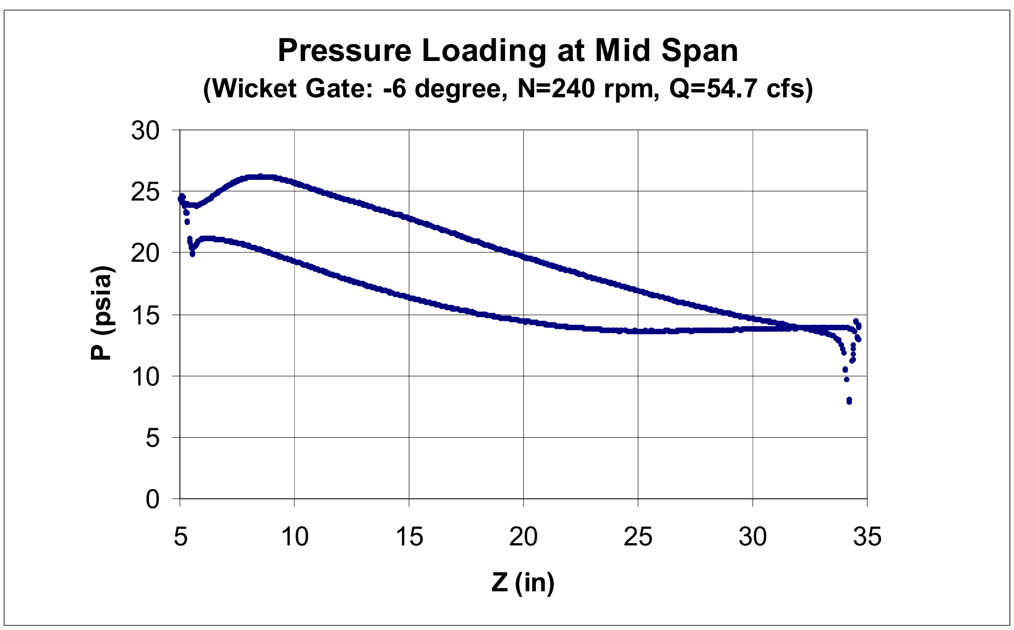


FIGURE P-18 PRESSURE LOADING AT MID SPAN (CASE NO. 5, 16° WICKET GATE ANGLE FROM FULL CLOSED)

Minimum Pressures

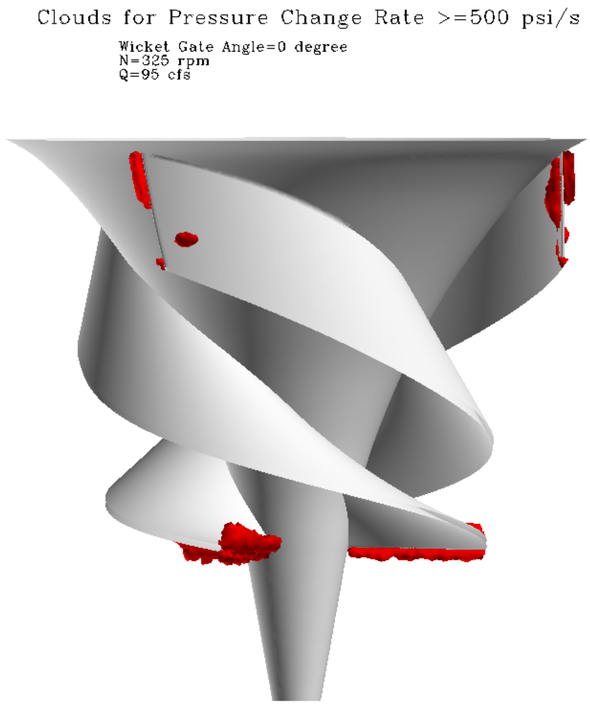
The CFD analysis indicates that the minimum local pressure in the runner is about 10 psia (the minimum pressure that was selected for the original design of the turbine) for all of the wicket gate positions evaluated and the high and low turbine head conditions. Static pressure distributions on the mid-span plane for Case Nos. 1 and 2 (high head "theoretical" and actual BEP) are shown in Figure P-3. Figure P-5 shows the pressure distribution along the mid-span of the runner blade surface for these cases. For low head Case Nos. 3-5, the pressure distributions on the mid-span plane are shown on Figures P-13 to P-15. Figures P-16 to P-18 show the pressure distribution along the mid-span of the runner blade. All of these figures show that the lowest pressure zones are located near the trailing edge and that the minimum local static pressure is about 10 psia for most of the trailing area. Local pressures less than 10 psia only occur in limited spots near the trailing edge, as shown in Figures P-4 to P-6 and Figures P-16 to P-18. Therefore, the CFD results indicate that the minimum local pressure in the turbine runner is consistent with the selected minimum local pressure criteria of about 10 psia. The limited spots of lower pressures are consistent with the minimum recommended value for safe fish passage (Abernethy et al. 2002) of 0.5 atm or 7.4 psia, even for the off-design conditions.

Pressure Change Rate

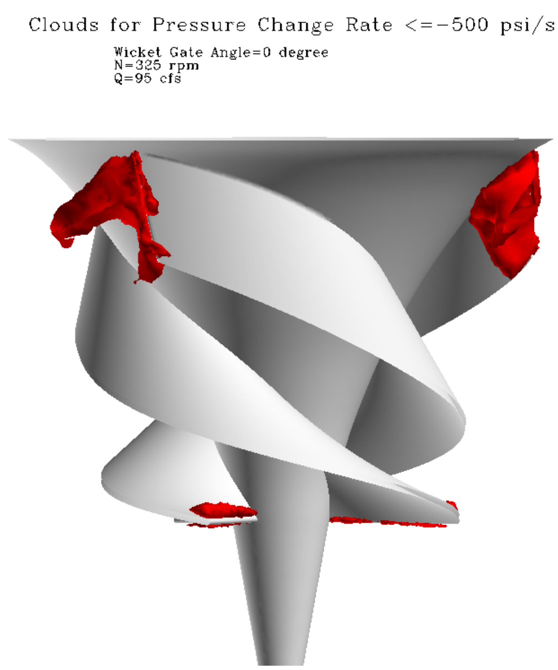
For steady flow, the pressure change rate ($\Delta p/\Delta t$) can be calculated based on the product of the pressure gradient ($\Delta p/\Delta s$) and the velocity vector ($\Delta s/\Delta t$). The pressure change rate is a measurement of the time rate of change of pressure experienced by a fish moving along a streamline. Tests reported by Abernethy et al. (2002) indicted that fish survived a pressure reduction of 3.5 atm over 0.1 second, or slightly greater than 500 psi/sec.

Pressure change rates determined with the CFD simulations have been plotted as three-dimensional volumes ("clouds") within which the pressure rate of change is more than 500 psi/sec. Because positive pressure changes are known not to harm fish, the emphasis for evaluating the CFD results has been placed on negative pressure rate changes.

The pressure change rate clouds are shown on Figures P-19 through P-23 for Case Nos. 1 to 5, respectively. In these plots, the volumes where the pressure change rate exceeds 500 psi/sec and less than -500 psi/sec are shown in red. All of these figures show that high negative pressure change rates occur mainly near the leading edge, with smaller volumes near the trailing edge. The high head cases (Case Nos. 1 and 2) have larger volumes where the pressure change rate exceeds -500 psi/second than low head cases (Case Nos. 3 to 5).

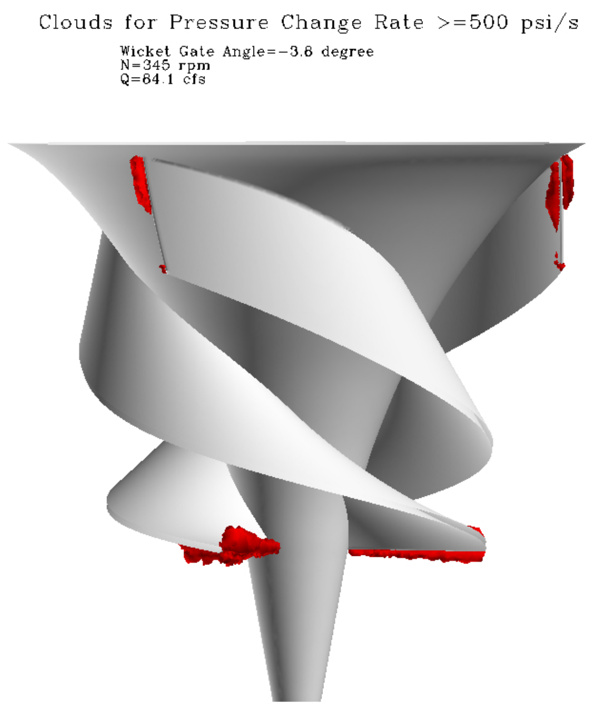


(a)

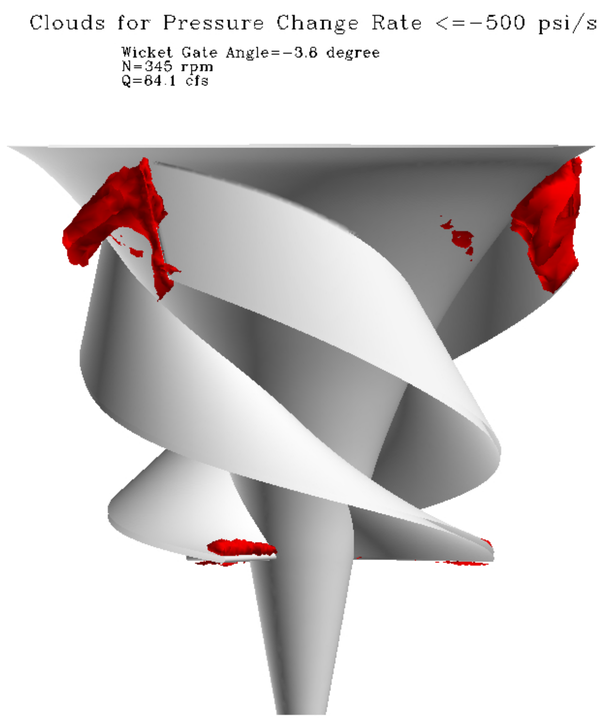


(b)

FIGURE P-19 CLOUDS FOR POSITIVE AND NEGATIVE PRESSURE CHANGE RATE EXCEEDING 500 PSI/SEC (CASE NO. 1, 22° WICKET GATE ANGLE FROM FULL CLOSED)

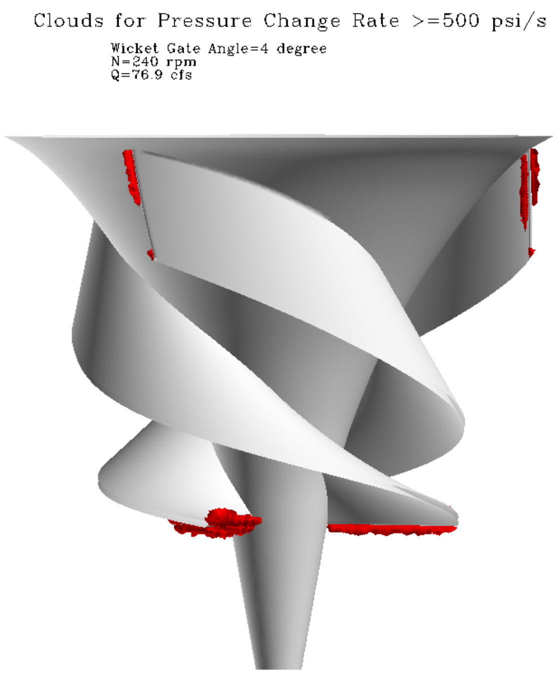


(a)

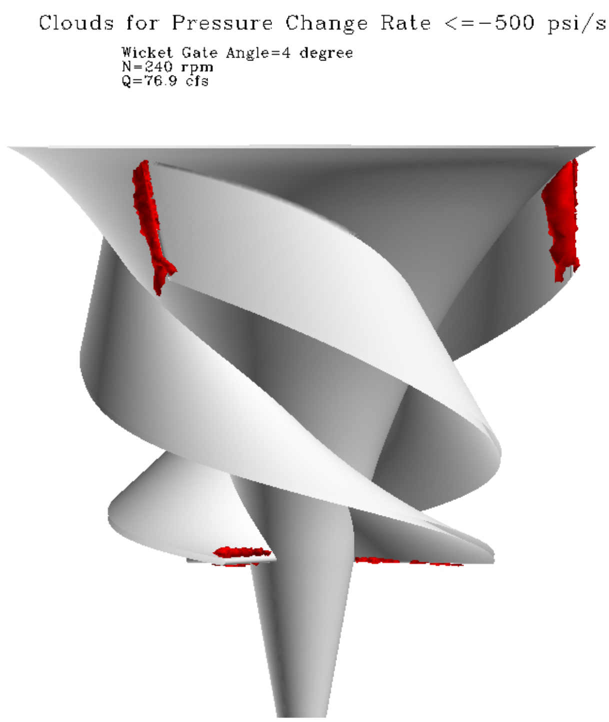


(b)

FIGURE P-20 CLOUDS FOR POSITIVE AND NEGATIVE PRESSURE CHANGE RATE EXCEEDING 500 PSI/SEC (CASE NO. 2, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)

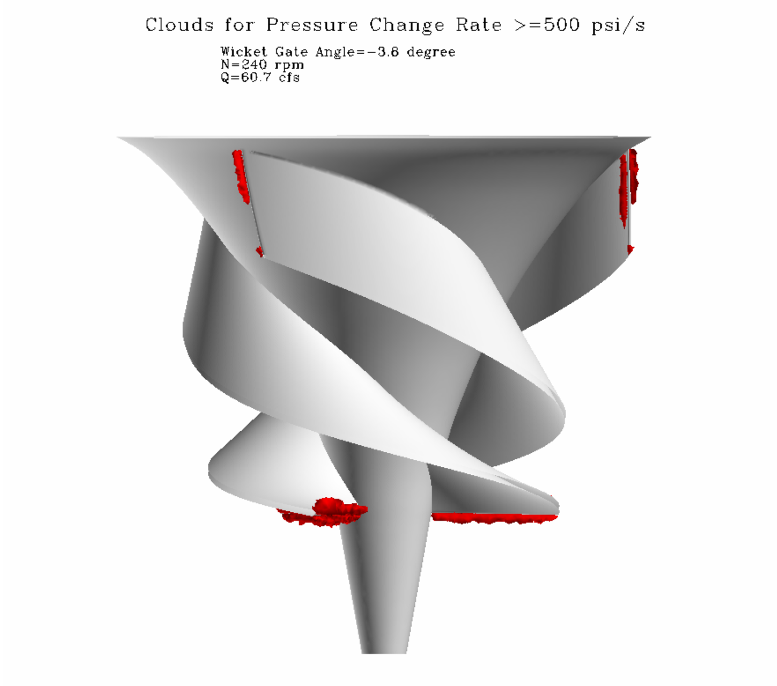


(a)

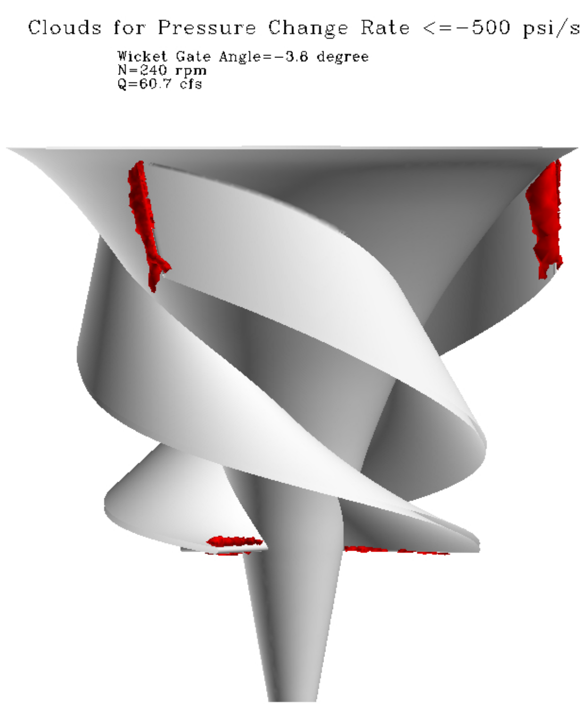


(b)

FIGURE P-21 CLOUDS FOR POSITIVE AND NEGATIVE PRESSURE CHANGE RATE EXCEEDING 500 PSI/SEC (CASE NO. 3, 26° WICKET GATE ANGLE FROM FULL CLOSED)

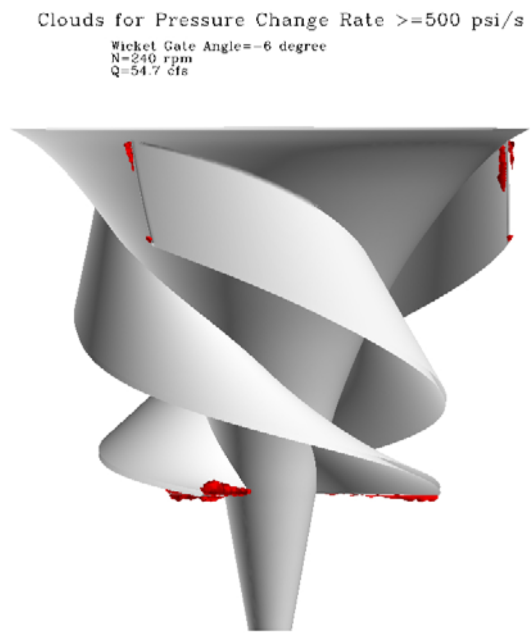


(a)

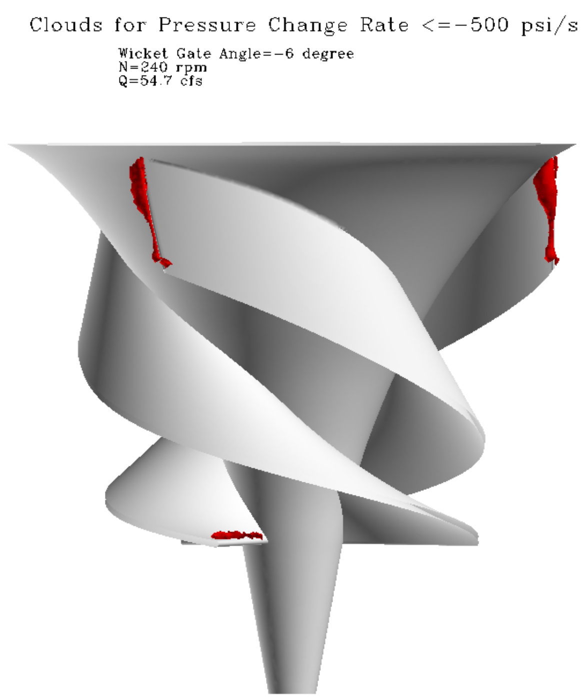


(b)

FIGURE P-22 CLOUDS FOR POSITIVE AND NEGATIVE PRESSURE CHANGE RATE EXCEEDING 500 PSI/SEC (CASE NO. 4, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)



(a)



(b)

FIGURE P-23 CLOUDS FOR POSITIVE AND NEGATIVE PRESSURE CHANGE RATE EXCEEDING 500 PSI/SEC (CASE NO. 5) , 16° WICKET GATE ANGLE FROM FULL CLOSED

The pressure change volumes shown on Figures P-19 through P-23 are relatively small compared to the size of a fish, and a fish would pass through these volumes so quickly that no physical response may be possible. For example, using pilot scale dimensions, the volume may be a maximum length of 0.5 ft and the local velocity is 40 ft/sec. Therefore, fish pass through the volume in 0.0125 seconds (0.04 seconds in the full scale turbine).

As shown on the figures, the volumes of pressure change rate exceeding -500 psi/sec are similar for the BEP wicket gate position (Cases Nos. 1 and 2) and the off-BEP conditions (Case Nos. 3, 4, and 5). These similar pressure change rates may partially explain why there was not a significant change in fish mortality over the turbine operating range tested.

Maximum Strain Rate

When fish are subjected to velocities that vary over relatively short distances, they experience different forces on different parts of their body, which may result in injury. Experiments reported by Nietzel et al. (2000) concluded that "juvenile salmonids and American shad should survive shear environments where strain rates do not exceed 500 cm/sec/cm" (500/sec). Therefore, the results of the CFD simulations have been presented as areas and volumes ("clouds") in which the strain rate is 500/sec or larger. The CFD simulations determine strain rates at each cell by noting the difference in each of the three velocity components between adjacent cells of known spacing.

Figure P-24 shows the strain rate on the central plane of the scroll case in the radial space (wicket gates) for Case No. 2. Areas where the strain rate exceeds 500/sec are limited and located very close to the leading edge of the wicket gates.

The volumes and areas where the strain rate exceeds 500/sec in the runner for the different wicket gate operating conditions simulated are shown as red clouds and strain rate contours on the mid-span surfaces on Figures P-25 through P-29. These figures all show that the high strain rate areas are relatively small and limited to spots near the leading edges, the trailing edges and the blade surfaces. Larger strain rates near solid boundaries are unavoidable since the velocity at all boundaries is zero, producing a high velocity gradient in the boundary layer. However, there are no areas of excessive strain rate within the main flow of the turbine. Therefore, the small volumes of strain rates at the runner surfaces that are over 500/sec should not cause significant fish injury.

The volume of strain rates over 500/sec is reasonably constant for the BEP condition (Case Nos. 1 and 2) and the off-BEP conditions (Case Nos. 3 through 5) at the lower head. These essentially constant strain rates at the different gate positions may explain why fish injury/survival in the pilot scale turbine tests was similar for the different gate positions. The volume of strain rates over 500/sec was only slightly larger at the higher head scenarios compared to the lower head conditions (i.e., Case Nos. 1 and 2 versus Case Nos. 3, 4 and 5).

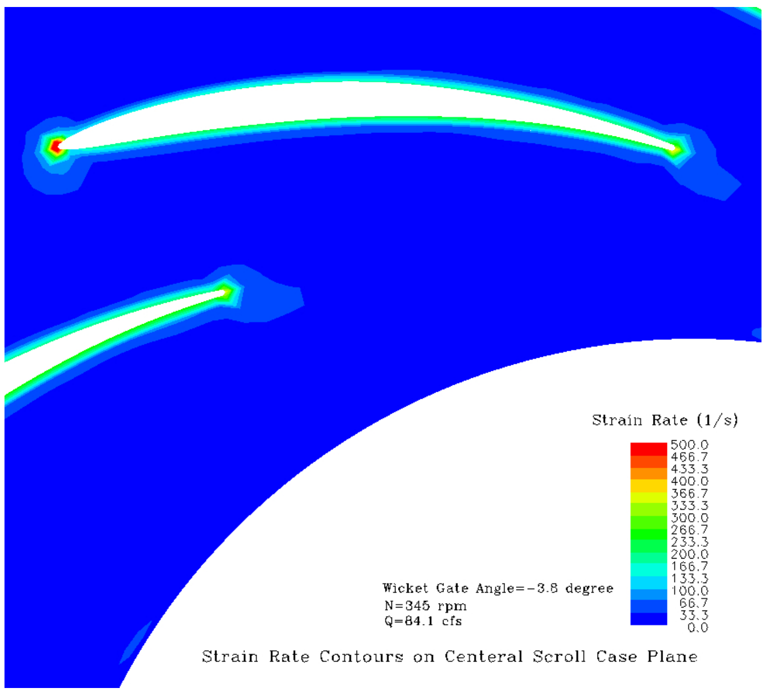
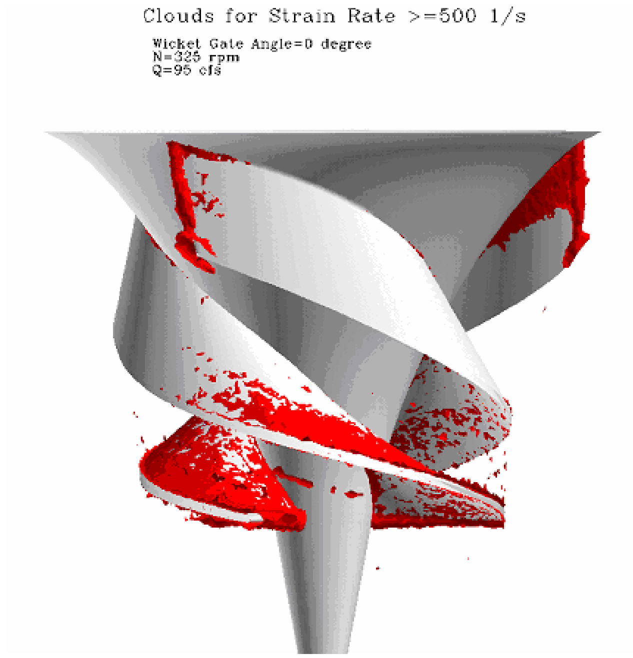
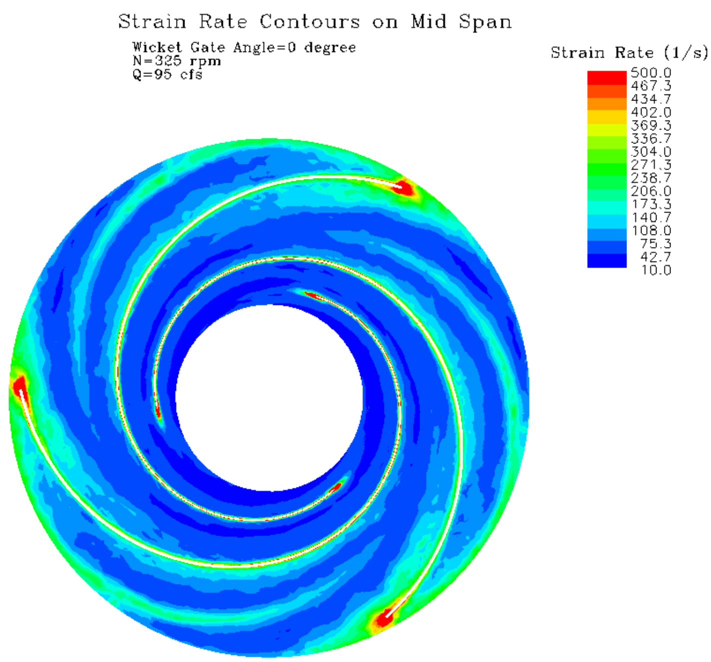


FIGURE P-24 STRAIN RATE CONTOURS ON CENTRAL SCROLL CASE PLANE, 18.2° WICKET GATE ANGLE FROM FULL CLOSED

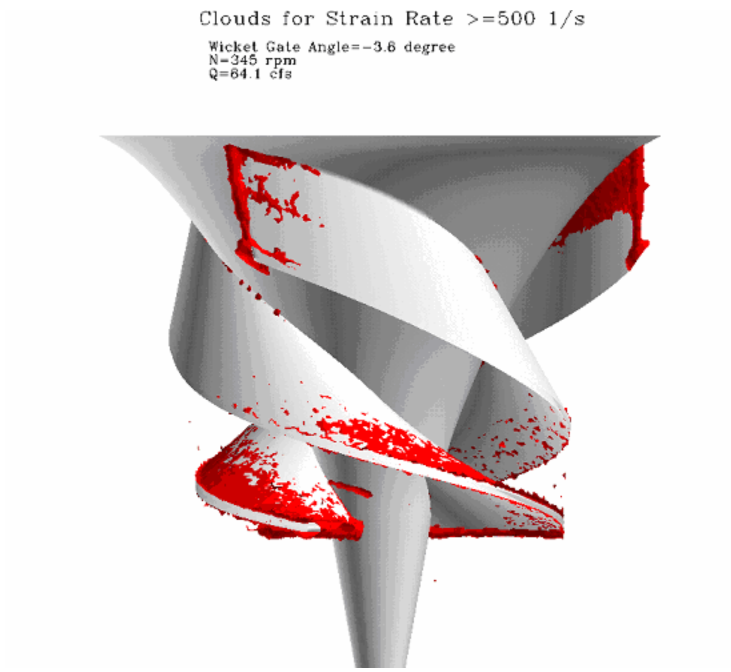


(a)

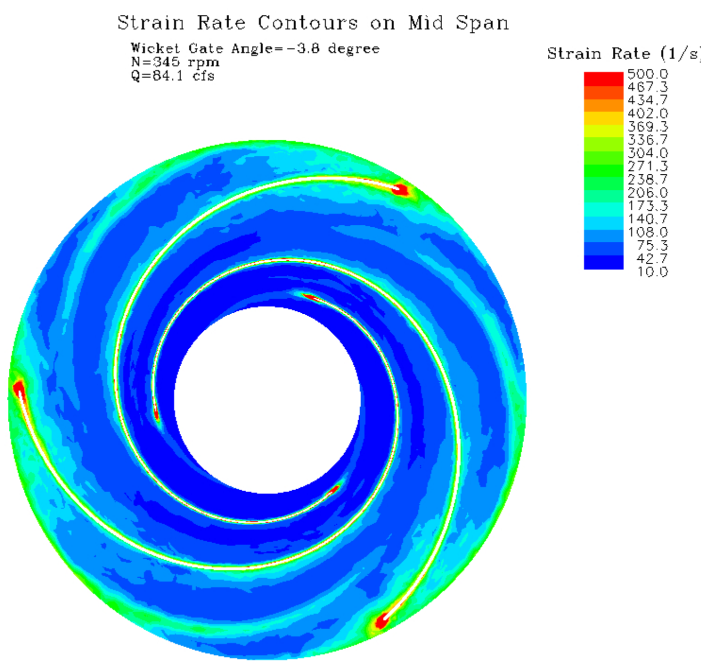


(b)

FIGURE P-25 STRAIN RATES IN TURBINE RUNNER (CASE NO. 1, 22° WICKET GATE ANGLE FROM FULL CLOSED)

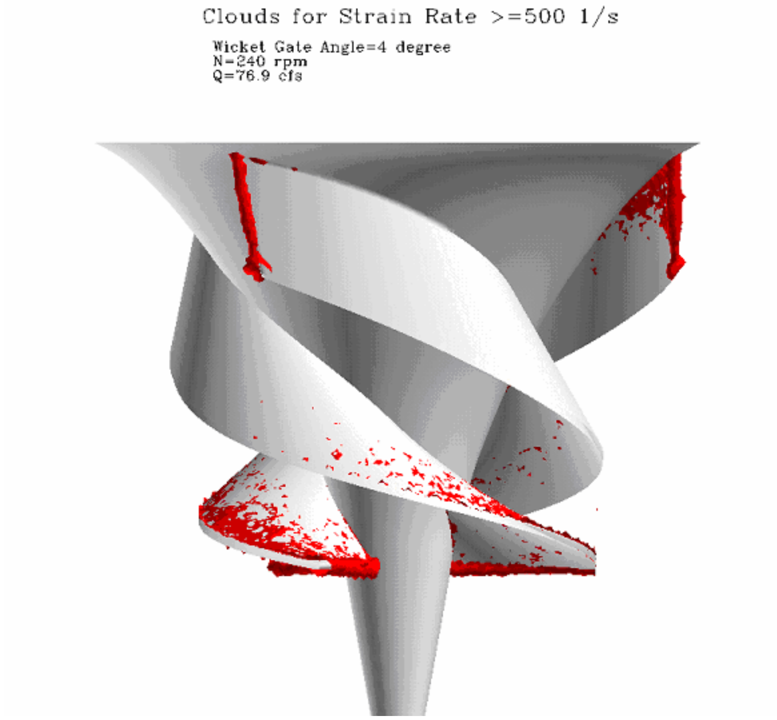


(a)

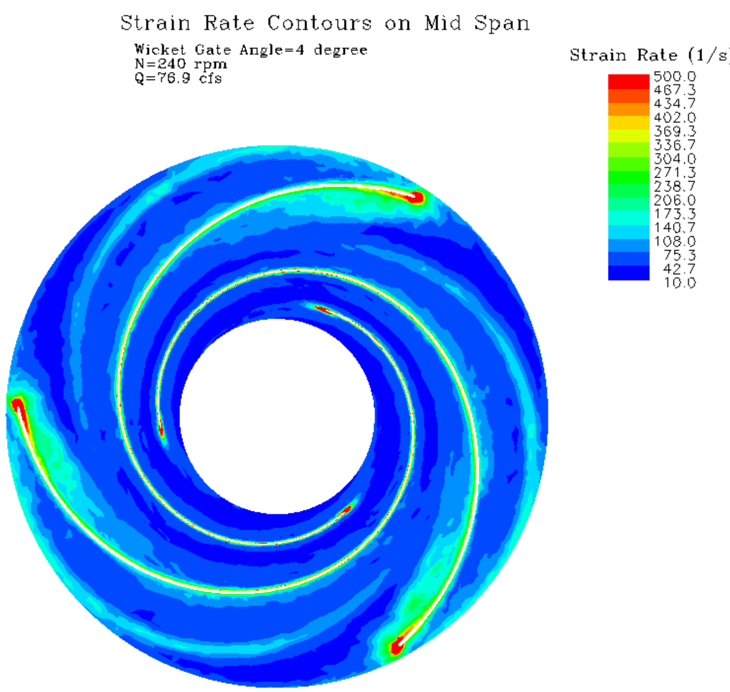


(b)

FIGURE P-26 STRAIN RATES IN TURBINE RUNNER (CASE NO. 2, 18.2° WICKET GATE ANGLE FROM FULL CLOSED)

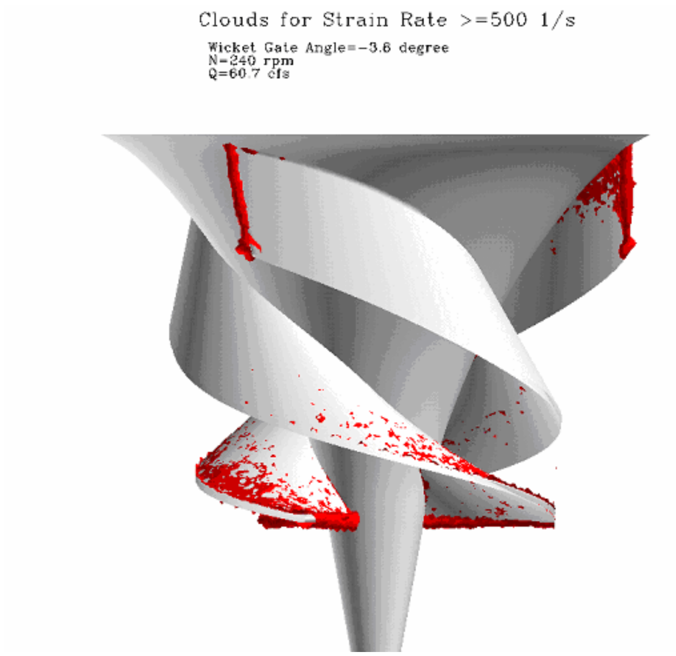


(a)

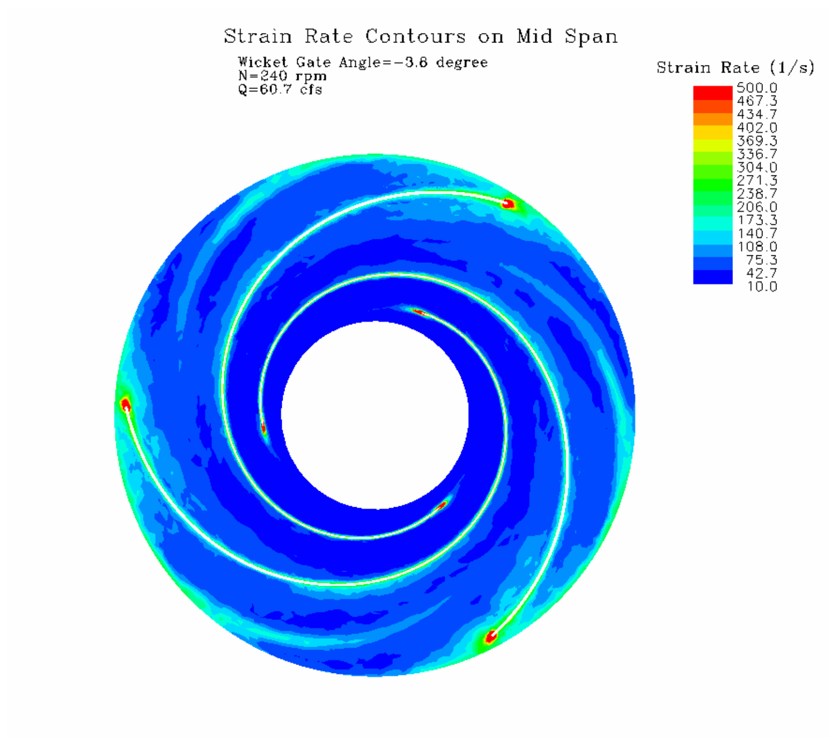


(b)

FIGURE P-27 STRAIN RATES IN TURBINE RUNNER (CASE NO. 3, 26° WICKET GATE ANGLE FROM FULL CLOSED)

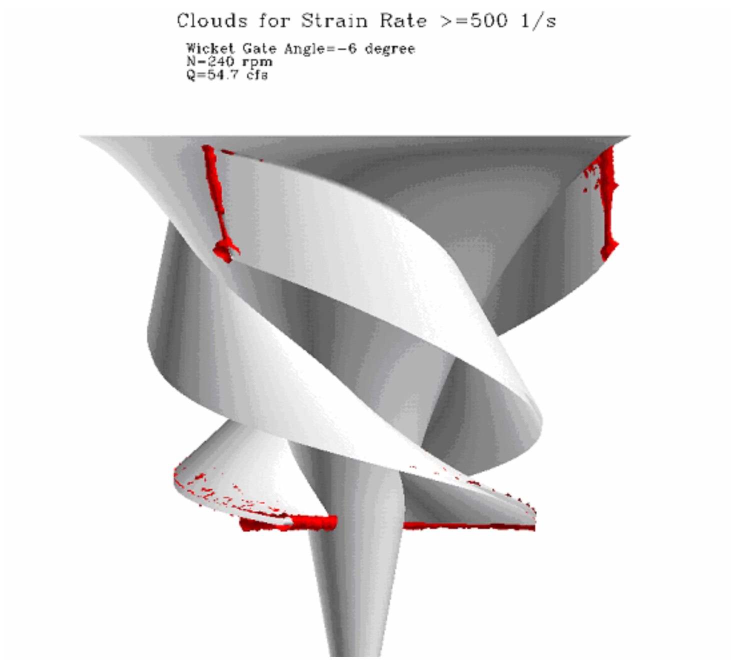


(a)



(b)

FIGURE P-28 STRAIN RATES IN TURBINE RUNNER (CASE NO. 4, 22° WICKET GATE ANGLE FROM FULL CLOSED)



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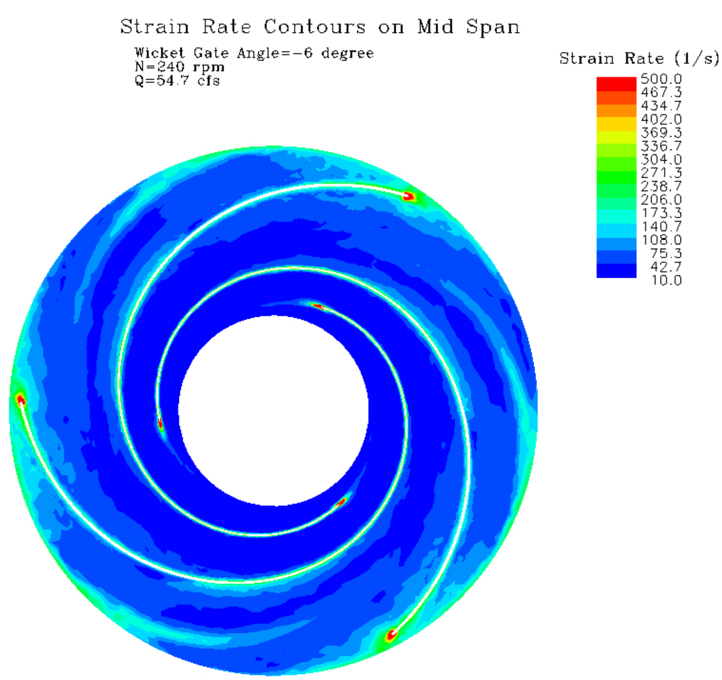

(b)

FIGURE P-29 STRAIN RATES IN TURBINE RUNNER (CASE NO. 5, 22° WICKET GATE ANGLE FROM FULL CLOSED)

APPENDIX Q

DATABASE OF FISH SURVIVAL AT HYDROELECTRIC PROJECTS

(FRANKE ET AL. 1997)

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table rows continue across the facing page for ease in reading.

Site	TurbTyp	SampMeth	Spp	Nt	Nc	AvgLen	TurbDisch	TurbDisFT	Blades
Morrow, MI	Kaplan		Northern Pike	21	1	Adults	6.7	237	
Hadley Falls, MA	Kaplan	HI-Z Turb'N Tag	American Shad	100	100	82	118.9	4199	5
Hadley Falls, MA	Kaplan	HI-Z Turb'N Tag	American Shad	100	100	82	43.9	1550	5
Craggy Dam, NC	Kaplan	HI-Z Turb'N Tag	Bluegill	33	40	100	5.7	201	4
Hadley Falls, MA	Propeller	HI-Z Turb'N Tag	American Shad	120	120	82	118.9	4199	5
Rocky Reach, WA (10', U.8)	Propeller	HI-Z Turb'N Tag	Chinook Salmon	265	265	114	566.4	20002	5
Craggy Dam, NC	Kaplan	HI-Z Turb'N Tag	Bluegill	72	54	155	5.7	201	4
Crescent, NY	Kaplan	HI-Z Turb'N Tag	Blueback Herring	125	125	91	43	1519	5
Feeder Dam, NY	Kaplan	Full discharge netting	Largemouth Bass			87.7	29.5	1042	6
Conowingo, MD	Kaplan	HI-Z Turb'N Tag	American Shad	108	108	125	226.6	8002	6
Safe Harbor, PA (Unit 8)	Propeller	HI-Z Turb'N Tag	American Shad	100	100	118	260.5	9200	7
Hadley Falls, MA	Kaplan	Radio telemetry	Atlantic Salmon	108	89	285	118.9	4199	5
Craggy Dam, NC	Kaplan	HI-Z Turb'N Tag	Channel Catfish	43	28	180	17	600	4
Morrow, MI	Kaplan	Full discharge netting	Black Crappie	90	33	Adults	6.7	237	
Feeder Dam, NY	Kaplan	Full discharge netting	Brown Trout			205.5	29.5	1042	6
Chalk Hill, MI-WI	Kaplan	HI-Z Turb'N Tag	W. Sucker/ R. Trout	77	70	119	37.7	1331	4
Feeder Dam, NY	Kaplan	Full discharge netting	Golden Shiner			88	29.5	1042	6
Chalk Hill, MI-WI	Kaplan	HI-Z Turb'N Tag	Bluegill	60	43	103	37.7	1331	4
Chalk Hill, MI-WI	Kaplan	HI-Z Turb'N Tag	Bluegill	50	67	153	37.7	1331	4
Craggy Dam, NC	Kaplan	HI-Z Turb'N Tag	Channel Catfish	63	28	180	5.7	201	4
Feeder Dam, NY	Kaplan	Full discharge netting	Largemouth Bass			190	29.5	1042	6
Craggy Dam, NC	Kaplan	HI-Z Turb'N Tag	Channel Catfish	39	22	277	5.7	201	4
Wanapum, WA (10 ft, Unit 9)	Kaplan	HI-Z Turb'N Tag	Coho Salmon	160	160	154	311.5	11001	5
Wanapum, WA (30 ft, Unit 9)	Kaplan	HI-Z Turb'N Tag	Coho Salmon	160	160	154	311.5	11001	5
Rocky Reach, WA (30', U.5)	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	241	220	184	396.5	14002	6
Rocky Reach, WA (30', U.6)	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	235	220	184	396.5	14002	6
Craggy Dam, NC	Kaplan	HI-Z Turb'N Tag	Channel Catfish	32	22	277	17	600	4
Wanapum, WA (30 ft, Unit 9)	Kaplan	HI-Z Turb'N Tag	Coho Salmon	160	160	154	424.8	15002	5
Wanapum, WA (30 ft, Unit 9)	Kaplan	HI-Z Turb'N Tag	Coho Salmon	160	160	154	481.5	17004	5
Wanapum, WA (10 ft, Unit 9)	Kaplan	HI-Z Turb'N Tag	Coho Salmon	160	160	154	424.8	15002	5
Feeder Dam, NY	Kaplan	Full discharge netting	Bluegill			128.6	29.5	1042	6
Lower Granite, WA	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	820	821	134	594.7	21002	6
Townsend Dam, PA	Kaplan	HI-Z Turb'N Tag	Largemouth Bass	51	50	102	22.7	802	3
Safe Harbor, PA (Unit 8)	Propeller	HI-Z Turb'N Tag	American Shad	100	100	118	260.5	9200	7
Lower Granite, WA	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	320	320	150	509.8	18004	6
Herrings, NY	Kaplan	Full discharge netting	Centrarchid	90	65	100	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Centrarchid	74	65	100	34	1201	4
Lower Granite, WA	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	320	320	151	509.8	18004	6
Lower Granite, WA	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	320	320	150	509.8	18004	6
Lower Granite, WA	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	250	250	148	382.3	13501	6
Foster, OR (tests combined)	Kaplan	Full discharge netting	Chinook Salmon			120	22.7	802	6
Hadley Falls, MA	Kaplan	Radio telemetry	American Shad	36	69	560	118.9	4199	5
Wanapum, WA (10 ft, Unit 9)	Kaplan	HI-Z Turb'N Tag	Coho Salmon	158	160	154	254.9	9002	5
Wanapum, WA (30 ft, Unit 9)	Kaplan	HI-Z Turb'N Tag	Coho Salmon	160	160	154	254.9	9002	5
Rocky Reach, WA (30', U.3)	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	250	250	161	453.1	16001	6
Rocky Reach, WA (10', U.3)	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	350	350	161	453.1	16001	6
Rocky Reach, WA (10', U.5)	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	235	300	184	396.5	14002	6
Rocky Reach, WA (10', U.6)	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	420	300	184	396.5	14002	6
Safe Harbor, PA (Unit 7)	Kaplan	HI-Z Turb'N Tag	American Shad	100	100	118	235.1	8303	5
Foster, OR (tests combined)	Kaplan	Full discharge netting	Chinook Salmon			120	22.7	802	6
Herrings, NY	Kaplan	Full discharge netting	Percid	46	51	100	34	1201	4
Feeder Dam, NY	Kaplan	Full discharge netting	Largemouth Bass			292.1	29.5	1042	6
Lower Granite, WA	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	300	300	148	538.1	19003	6
Foster, OR (tests combined)	Kaplan	Full discharge netting	Chinook Salmon			120	22.7	802	6
Wanapum, WA (10 ft, Unit 9)	Kaplan	HI-Z Turb'N Tag	Coho Salmon	160	160	154	481.5	17004	5
Lower Granite, WA	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	250	250	151	509.8	18004	6
Chalk Hill, MI-WI	Kaplan	HI-Z Turb'N Tag	W. Sucker/ R. Trout	38	45	261	37.7	1331	4
Fourth Lake, NS	Kaplan	Full dschrg/dye or brand	Alewife	675	627	96	15	530	6
Fourth Lake, NS	Kaplan	Full dschrg/dye or brand	Brook Trout	1,908	NA	105.5	15	530	6
Fourth Lake, NS	Kaplan	Full dschrg/dye or brand	Atlantic Salmon	503	494	163	15	530	6
Marshall, NC	Kaplan	Partial netting	Resident spp.	2,544	2,544		35.4	1250	4
Feeder Dam, NY	Kaplan	Full discharge netting	Bluegill			91.6	29.5	1042	6
Herrings, NY	Kaplan	Full discharge netting	Centrarchid	77	63	175	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Centrarchid	80	65	250	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Salmonids	31	57	100	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Salmonids	74	63	175	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Centrarchid	90	69	175	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Centrarchid	90	77	250	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Percid	185	78	100	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Percid	179	139	175	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Percid	138	137	250	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Salmonids	91	74	100	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Salmonids	95	72	175	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Salmonids	111	77	250	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Soft ray	188	144	100	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Soft ray	201	159	175	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Soft ray	175	125	250	34	1201	4
Herrings, NY	Kaplan	Full discharge netting	Clupeids	196	166	100	34	1201	4
Morrow, MI	Kaplan	Full discharge netting	Brown Bullhead	117	39	Adults	6.7	237	

Site	Buckets	RunSp	Head	HeadFT	RunDia	RunDiaFt	Sc	TPerRec	CPerRec	ImmSur	Ref
Morrow, MI		175.0	3.7	12.1	1.37	4.5	0.0	95.2	100.0	45.0	EPRI (1992)
Hadley Falls, MA		128.0	15.8	51.8	4.32	14.2	75.0	76.0	76.0	97.3	Malhur et al. (1994)
Hadley Falls, MA		128.0	15.8	51.8	4.32	14.2	77.0	81.0	78.0	100.0	Malhur et al. (1994)
Craggy Dam, NC		229.0	6.4	21.0	1.75	5.7	90.0	85.0	90.0	96.0	Malhur et al. (1993)
Hadley Falls, MA		150.0	15.8	51.8	4.32	14.2	83.3	74.2	83.3	89.1	RMC (1992)
Rocky Reach, WA (10', U.8)		85.7	26.4	86.6	7.9	25.9	88.7	85.7	88.7	96.9	RMC & Skalski (1994)
Craggy Dam, NC		229.0	6.4	21.0	1.75	5.7	96.0	90.0	96.0	86.0	Malhur et al. (1993)
Crescent, NY		144.0	8.2	26.9	2.74	9.0	90.0	84.0	86.0	96.0	Malhur et al. (1996)
Feeder Dam, NY		120.0	5.5	18.0	2.92	9.6	90.1			98.0	Acres (1995)
Conowingo, MD		120.0	27.4	89.9	5.72	18.8	91.7	88.0	97.6	94.9	RMC (1994)
Safe Harbor, PA (Unit 8)		75.0	16.8	55.1	6.15	20.2	92.0	92.0	92.0	97.8	Heisey et al. (1992)
Hadley Falls, MA		128.0	15.8	51.8	4.32	14.2	92.5	100.0	100.0	93.7	Kynard et al. (1982)
Craggy Dam, NC		229.0	6.4	21.0	1.75	5.7	100.0	93.0	100.0	93.0	Malhur et al. (1993)
Morrow, MI		175.0	3.7	12.1	1.37	4.5	93.0	67.8	90.9	74.0	EPRI (1992)
Feeder Dam, NY		120.0	6.4	21.0	2.92	9.6	93.1	80.5	93.1	86.4	Acres (1995)
Chalk Hill, MI-WI		150.0	8.8	28.9	2.59	8.5	94.3	80.5	94.3	91.0	RMC (1994)
Feeder Dam, NY		120.0	6.7	22.0	2.92	9.6	95.0	92.8	95.8	96.8	Acres (1995)
Chalk Hill, MI-WI		150.0	8.8	28.9	2.59	8.5	95.3	86.7	97.7	97.0	RMC (1994)
Chalk Hill, MI-WI		150.0	8.8	28.9	2.59	8.5	95.5	94.0	97.0	98.0	RMC (1994)
Craggy Dam, NC		229.0	6.4	21.0	1.75	5.7	100.0	90.0	100.0	90.0	Malhur et al. (1993)
Feeder Dam, NY		120.0	5.8	19.0	2.92	9.6	96.3			90.0	Acres (1995)
Craggy Dam, NC		229.0	6.4	21.0	1.75	5.7	100.0	90.0	100.0	81.0	Malhur et al. (1993)
Wanapum, WA (10 ft, Unit 9)		85.7	22.9	75.1	7.24	23.7	96.9	93.1	96.9	92.4	Normandeau et al.(1996)
Wanapum, WA (30 ft, Unit 9)		85.7	22.9	75.1	7.24	23.7	96.9	95.6	96.9	96.8	Normandeau et al.(1996)
Rocky Reach, WA (30', U.5)		90.0	28.0	91.8	7.11	23.3	97.3	96.3	97.7	94.4	Normandeau & Skalski (1996)
Rocky Reach, WA (30', U.6)		90.0	28.0	91.8	7.11	23.3	97.3	97.1	97.7	95.8	Normandeau & Skalski (1996)
Craggy Dam, NC		229.0	6.4	21.0	1.75	5.7	100.0	88.0	100.0	93.0	Malhur et al. (1993)
Wanapum, WA (30 ft, Unit 9)		85.7	22.9	75.1	7.24	23.7	97.4	98.1	97.4	100.0	Normandeau et al.(1996)
Wanapum, WA (30 ft, Unit 9)		85.7	22.9	75.1	7.24	23.7	97.4	96.2	99.4	96.8	Normandeau et al.(1996)
Wanapum, WA (10 ft, Unit 9)		85.7	22.9	75.1	7.24	23.7	97.5	93.8	97.5	94.8	Normandeau et al.(1996)
Feeder Dam, NY		120.0	5.2	17.1	2.92	9.6	97.7			92.3	Acres (1995)
Lower Granite, WA		90.0	29.9	98.1	7.92	26.0	97.8	94.5	98.8	94.6	RMC et al. (1994)
Townsend Dam, PA		152.0	4.9	16.1	2.87	9.4	98.0	98.0	98.0	100.0	RMC (1994)
Safe Harbor, PA (Unit 8)		75.0	16.8	55.1	6.15	20.2	98.0	96.0	98.0	98.9	Heisey et al. (1992)
Lower Granite, WA		90.0	29.9	98.1	7.92	26.0	98.1	98.2	98.1	97.5	Normandeau et al.(1995)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	98.2	96.7	95.4	95.0	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	98.3	74.3	90.8	98.3	KA (1996)
Lower Granite, WA		90.0	29.9	98.1	7.92	26.0	98.4	96.8	98.7	94.9	Normandeau et al.(1995)
Lower Granite, WA		90.0	29.9	98.1	7.92	26.0	98.4	96.6	98.7	95.3	Normandeau et al.(1995)
Lower Granite, WA		90.0	29.9	98.1	7.92	26.0	98.4	96.4	99.6	97.2	Normandeau et al.(1995)
Foster, OR (tests combined)		257.0	30.8	101.0	2.54	8.3				82.1	Bell (1981)
Hadley Falls, MA		128.0	15.8	51.8	4.32	14.2	98.6			78.2	Bell and Kynard (1988)
Wanapum, WA (10 ft, Unit 9)		85.7	22.9	75.1	7.24	23.7	98.8	92.4	98.8	89.7	Normandeau et al.(1996)
Wanapum, WA (30 ft, Unit 9)		85.7	22.9	75.1	7.24	23.7	98.8	95.7	98.8	94.9	Normandeau et al.(1996)
Rocky Reach, WA (30', U.3)		90.0	28.0	91.8	7.11	23.3	98.9	96.4	98.8	94.7	Malhur et al. (1996)
Rocky Reach, WA (10', U.3)		90.0	28.0	91.8	7.11	23.3	98.9	95.0	96.0	93.9	Malhur et al. (1996)
Rocky Reach, WA (10', U.5)		90.0	28.0	91.8	7.11	23.3	99.0	98.3	99.0	97.3	Normandeau & Skalski (1996)
Rocky Reach, WA (10', U.6)		90.0	28.0	91.8	7.11	23.3	99.0	97.6	99.0	94.2	Normandeau & Skalski (1996)
Safe Harbor, PA (Unit 7)		109.0	16.8	55.1	5.64	18.5	99.0	99.0	99.0	98.0	Heisey et al. (1992)
Foster, OR (tests combined)		257.0	33.5	109.9	2.54	8.3				93.9	Bell (1981)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	99.1	84.8	88.2	91.1	KA (1996)
Feeder Dam, NY		120.0	6.1	20.0	2.92	9.6	99.2			86.8	Acres (1995)
Lower Granite, WA		90.0	29.9	98.1	7.92	26.0	99.3	96.7	99.3	94.6	Normandeau et al.(1995)
Foster, OR (tests combined)		257.0	33.5	109.9	2.54	8.3				88.8	Bell (1981)
Wanapum, WA (10 ft, Unit 9)		85.7	22.9	75.1	7.24	23.7	99.4	88.2	99.4	88.5	Normandeau et al.(1996)
Lower Granite, WA		90.0	29.9	98.1	7.92	26.0	99.6	98.1	98.1	97.5	Normandeau et al.(1995)
Chalk Hill, MI-WI		150.0	8.8	28.9	2.59	8.5	100.0	97.4	100.0	97.0	RMC (1994)
Fourth Lake, NS		360.0	22.9	75.1			83.1	70.8	83.1	89.0	Ruggles et al. (1990)
Fourth Lake, NS		360.0	22.9	75.1			96.5	24.5		87.1	Ruggles et al. (1990)
Fourth Lake, NS		360.0	22.9	75.1			99.4	74.4	74.3	83.7	Ruggles et al. (1990)
Marshall, NC		212.0	9.6	31.5	3.79	12.4			39.0	92.3	EPRI (1992)
Feeder Dam, NY		120.0	4.7	15.4	2.92	9.6	100.0			97.3	Acres (1995)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	96.0	100.0	97.3	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	91.3	70.8	93.2	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	32.3	22.8	90.0	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	32.4	1.6	87.5	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	92.2	97.1	96.4	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	88.9	97.4	92.5	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	83.8	84.6	94.9	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	91.1	94.2	98.2	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	84.8	94.2	96.2	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	24.2	18.9	95.5	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	78.9	73.6	98.7	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	64.0	72.7	98.6	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	63.3	85.4	97.5	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	74.1	94.7	91.7	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	95.4	99.2	85.1	KA (1996)
Herrings, NY		138.0	5.8	19.0	2.87	9.4	100.0	90.3	90.4	92.8	KA (1996)
Morrow, MI		175.0	3.7	12.1	1.37	4.5	100.0	75.2	84.6	97.0	EPRI (1992)

Site	TurbTyp	SampMeth	Spp	Nt	Nc	AvgLen	TurbDisch	TurbDisFT	Blades
Morrow, MI	Kaplan	Full discharge netting	Pumpkinseed	88	22	Adults	6.7	237	
Morrow, MI	Kaplan	Full discharge netting	White Sucker	64	29	Adults	6.7	237	
Morrow, MI	Kaplan	Full discharge netting	Yellow Perch	39	5	Adults	6.7	237	
Morrow, MI	Kaplan	Full discharge netting	Redhorse	31	10	Adults	6.7	237	
Morrow, MI	Kaplan	Full discharge netting	Largemouth Bass	24	5	Adults	6.7	237	
Morrow, MI	Kaplan	Full discharge netting	Yellow Bullhead	39	5	Adults	6.7	237	
Rock Island, WA (bulb turbine)	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	280	140	162	4984.4	176024	4
Rock Island, WA (PH 1, Unit 4)	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	280	140	162	481.5	17004	6
Rock Island, WA (PH 1, Unit 5)	Kaplan	HI-Z Turb'N Tag	Chinook Salmon	280	140	162	481.5	17004	6
Townsend Dam, PA	Kaplan	HI-Z Turb'N Tag	Rainbow Trout	54	52	139	22.7	802	3
Townsend Dam, PA	Kaplan	HI-Z Turb'N Tag	Rainbow Trout	52	51	344	22.7	802	3
Townsend Dam, PA	Kaplan	HI-Z Turb'N Tag	Largemouth Bass	50	NA	217	22.7	802	3
Wilder, VT-NH	Kaplan	HI-Z Turb'N Tag	Atlantic Salmon	125	125	191	127.4	4499	5
Youghlogheny, PA	Francis	Full discharge netting	White Sucker				21.2	749	
Annapolis, NS	Kaplan	Radio telemetry	American Shad	20	29		404.6	14288	
Big Cliff, OR (1964)	Kaplan	Full discharge netting	Chinook Salmon	3,500	3,500	100	52.5	1854	6
Big Cliff, OR (1964)	Kaplan	Full discharge netting	Chinook Salmon	2,750	2,750	100	71.1	2511	6
Big Cliff, OR (1964)	Kaplan	Full discharge netting	Chinook Salmon	3,500	3,500	100	71.1	2511	6
Big Cliff, OR (1966)	Kaplan	Full discharge netting	Chinook Salmon	2,750	2,750	100	52.5	1854	6
Big Cliff, OR (1966)	Kaplan	Full discharge netting	Chinook Salmon	3,750	3,750	100	71.1	2511	6
Big Cliff, OR (1966)	Kaplan	Full discharge netting	Chinook Salmon	2,500	2,500	100	71.1	2511	6
Big Cliff, OR (1967)	Kaplan	Full discharge netting	Steelhead			152	71.1	2511	6
Bonneville, OR/WA	Kaplan	Brand, CWT, Seine	Chinook Salmon	850,406	435,099	91	498.4	17601	5
Essex,MA (bulb turbine)	Kaplan	Radio telemetry	Atlantic Salmon	50	0	288	124.6	4400	3
T.W. Sullivan, OR (Unit 7)	Kaplan	Full discharge netting	Steelhead Trout	1,800	500	128	11	388	6
T.W. Sullivan, OR (Unit 7)	Kaplan	Full discharge netting	Chinook Salmon	1,800	500	112	11	388	6
T.W. Sullivan, OR (Unit 8)	Kaplan	Full discharge netting	Chinook Salmon	1,800	631	112	7.4	261	6
Greenup Dam, OH (Vanceburg)	Kaplan	Radio telemetry	Sauger	48	NA	231	336.1	11869	5
Herrings, NY	Kaplan	Full discharge netting	Salmonids	82	72	250	34	1201	4
Kleber Dam, MI	Kaplan	Full discharge netting	Mixed resident fish			Adults	5.7	201	
la centrale de Beauharnois, Quebec, Canada	Kaplan	Float tag	American Eel	122		881	262.7	9277	6
Little Goose, WA	Kaplan	PIT tag	Chinook Salmon				509.8	18004	6
Lowell, MA	Kaplan	Radio telemetry	Atlantic Salmon	50	0	265	127.4	4499	5
Lower Granite, WA	Kaplan	PIT tagging	Chinook Salmon	3,200	1,600	151	509.8	18004	6
Lower Monumental, WA	Kaplan	PIT tag	Chinook Salmon				509.8	18004	6
T.W. Sullivan, OR (Unit 8)	Kaplan	Full discharge netting	Steelhead Trout	1,800	500	128	7.4	261	6
McNary, WA	Kaplan	Brand/partial netting	Chinook Salmon	120,000	120,000	52	348.3	12300	6
Racine, WI	Kaplan	Full discharge netting	Gizzard Shad				226.6	8002	4
Racine, WI	Kaplan	Partial netting	Drum				226.6	8002	4
Racine, WI	Kaplan	Partial netting	Game Species				226.6	8002	4
Raymondville, NY	Kaplan	Full discharge netting	Eel			625	46.4	1639	6
Rock Island, WA (bulb turbine)	Kaplan	Brand/partial netting	Coho Salmon	203,336	203,843	115	509.8	18004	4
Rock Island, WA (bulb turbine)	Kaplan	Brand/partial netting	Steelhead	58,571	57,864	166	509.8	18004	4
Thornapple, WI	Kaplan	Full discharge netting	Indigenous spp.	3,378			19.8	699	6
Thornapple, WI	Kaplan	Full discharge netting	Bullheads/Catfish						6
Thornapple, WI	Kaplan	Full discharge netting	Suckers/Redhorse						6
Thornapple, WI	Kaplan	Full discharge netting	Panfish/Yellow Perch						6
Thornapple, WI	Kaplan	Full discharge netting	N. Pike/Muskellunge						6
Thornapple, WI	Kaplan	Full discharge netting	Burbot						6
Thornapple, WI	Kaplan	Full discharge netting	Mnnw/Dace/Drtr						6
Thornapple, WI	Kaplan	Full discharge netting	Sm/Lgmth Bass						6
Thornapple, WI	Kaplan	Full discharge netting	Walleye						6
Townsend Dam, PA	Kaplan	HI-Z Turb'N Tag	Largemouth Bass	31	NA	217	42.5	1501	3
Townsend Dam, PA	Kaplan	HI-Z Turb'N Tag	Rainbow Trout	21		139	42.5	1501	3
Tusket, NS	Kaplan	Draft tube net	Atlantic Salmon		300				
Twin Branch, IN	Kaplan	Full discharge netting	Steelhead Trout	300	450	186	11.6	410	4
Twin Branch, IN	Kaplan	Full discharge netting	Chinook Salmon	600	300	121	11.6	410	4
Twin Branch, IN	Kaplan	Full discharge netting	Bluegill	300	500	126	11.6	410	4
Walterville, OR (61% wckt)	Kaplan	Brand, full dschrg netting	Rainbow Trout	991	631	fingerling	56.9	2009	
Walterville, OR (77% wckt)	Kaplan	Brand, full dschrg netting	Rainbow Trout	991	30,000	fingerling	56.9	2009	
Walterville, OR	Kaplan	Brand, dwnstr bypass trap	Chinook Salmon	30,000	160	135	56.6	1999	
Wells, WA (Unit 1)	Kaplan	Brand, partial netting	Steelhead Trout			smolts	566.4	20002	6
West Enfield, ME	Kaplan	Radio telemetry	Atlantic Salmon	148	NA	212	150.1	5301	3
Alcona, MI	Francis	Full discharge netting	Bluegill	97		118	47	1660	
Alcona, MI	Francis	Full discharge netting	Bluegill	102		170	47	1660	
Alcona, MI	Francis	Full discharge netting	Gold/Common Shiner	51		114	47.1	1663	
Alcona, MI	Francis	Full discharge netting	Gold/Common Shiner	58		154	47.1	1663	
Alcona, MI	Francis	Full discharge netting	Grass Pickerel	30		235	47.1	1663	
Alcona, MI	Francis	Full discharge netting	Northern Pike	44		352	47.2	1667	
Alcona, MI	Francis	Full discharge netting	Rainbow Trout	40		108	47.2	1667	
Alcona, MI	Francis	Full discharge netting	Rainbow Trout	40		317	47.2	1667	
Alcona, MI	Francis	Full discharge netting	Spottail Shiner	40		116	47.2	1667	
Alcona, MI	Francis	Full discharge netting	Walleye	47		162	47.3	1670	
Alcona, MI	Francis	Full discharge netting	Walleye	45		385	47.3	1670	
Alcona, MI	Francis	Full discharge netting	White Sucker	60		180	47.3	1670	
Alcona, MI	Francis	Full discharge netting	White Sucker	54		290	47.4	1674	
Alcona, MI	Francis	Full discharge netting	Yellow Perch	55		107	47.4	1674	
Alcona, MI	Francis	Full discharge netting	Yellow Perch	45		186	47.4	1674	
Baker, WA	Francis	Fyke net	Sockeye Salmon				15.6	551	

Site	Buckets	RunSp	Head	HeadFT	RunDia	RunDiaFt	Sc	TPerRec	CPerRec	ImmSur	Ref
Morrow, MI		175.0	3.7	12.1	1.37	4.5	100.0	86.4	100.0	90.0	EPRI (1992)
Morrow, MI		175.0	3.7	12.1	1.37	4.5	100.0	79.7	100.0	67.0	EPRI (1992)
Morrow, MI		175.0	3.7	12.1	1.37	4.5	100.0	82.1	100.0	78.0	EPRI (1992)
Morrow, MI		175.0	3.7	12.1	1.37	4.5	100.0	87.1	100.0	71.0	EPRI (1992)
Morrow, MI		175.0	3.7	12.1	1.37	4.5	100.0	87.5	100.0	81.0	EPRI (1992)
Morrow, MI		175.0	3.7	12.1	1.37	4.5	100.0	82.1	100.0	92.0	EPRI (1992)
Rock Island, WA (bulb turbine)		85.7	12.2	40.0	7.01	23.0	100.0	100.0	100.0	96.1	Normandeau & Skalski (1997)
Rock Island, WA (PH 1, Unit 4)		100.0	13.7	44.9	5.74	18.8	100.0	100.0	100.0	95.0	Normandeau & Skalski (1997)
Rock Island, WA (PH 1, Unit 5)		100.0	13.7	44.9	5.74	18.8	100.0	100.0	100.0	96.1	Normandeau & Skalski (1997)
Townsend Dam, PA		152.0	4.9	16.1	2.87	9.4	100.0	96.3	100.0	94.4	RMC (1994)
Townsend Dam, PA		152.0	4.9	16.1	2.87	9.4	100.0	92.3	94.1	86.5	RMC (1994)
Townsend Dam, PA		152.0	4.9	16.1	2.87	9.4	100.0	100.0	100.0	86.0	RMC (1994)
Wilder, VT-NH		112.5	15.5	50.8	4.57	15.0	100.0	99.2	100.0	96.0	RMC (1994)
Youghlogheny, PA			36.6	120.0						9.5	RMC (1992a)
Annapolis, NS		50.0	6.7	22.0	6.78	22.2		NA	NA	53.7	Hogan (1986)
Big Cliff, OR (1964)		163.6	27.7	90.9	3.76	12.3		98.1	97.0	91.1	Oligher & Donaldson (1966)
Big Cliff, OR (1964)		163.6	24.7	81.0	3.76	12.3		98.1	97.0	94.5	Oligher & Donaldson (1966)
Big Cliff, OR (1964)		163.6	21.6	70.8	3.76	12.3		98.1	97.0	89.7	Oligher & Donaldson (1966)
Big Cliff, OR (1966)		163.6	27.7	90.9	3.76	12.3		93.2	98.9	92.2	Oligher & Donaldson (1966)
Big Cliff, OR (1966)		163.6	24.7	81.0	3.76	12.3		93.2	98.9	89.8	Oligher & Donaldson (1966)
Big Cliff, OR (1966)		163.6	21.6	70.8	3.76	12.3		93.2	98.9	90.6	Oligher & Donaldson (1966)
Big Cliff, OR (1967)		163.6	21.6	70.8	3.76	12.3				90.4	Oligher & Donaldson (1966)
Bonneville, OR/WA		69.2	18.3	60.0	8.38	27.5				97.5	EPRI (1992)
Essex,MA (bulb turbine)		128.6	8.8	28.9	4	13.1		50.0		98.0	Knight (1982)
T.W. Sullivan, OR (Unit 7)		240.0	12.8	42.0	1.78	5.8	92.8	6.6	44.6	92.3	Massen (1967)
T.W. Sullivan, OR (Unit 7)		240.0	12.8	42.0	1.78	5.8	97.3	23.6	89.6	88.2	Massen (1967)
T.W. Sullivan, OR (Unit 8)		240.0	12.8	42.0	1.78	5.8	98.4	61.1	100.0	89.5	Massen (1967)
Greenup Dam, OH (Vanceburg)		90.0	9.1	29.8	6.1	20.0		85.4		85.4	Olson (1990)
Herrings, NY		138.0	5.8	19.0	2.87	9.4		96.2	0.0	96.2	KA (1996)
Kleber Dam, MI		450.0	13.4	44.0						59.0	EPRI (1992)
la centrale de Beauharnois, Quebec, Canada		94.7	24.1	79.0	6.32	20.7		95.9		76.1	Desrochers (1995)
Little Goose, WA		90.0	28.3	92.8	7.92	26.0				92.0	Muir et al. (1995)
Lowell, MA		120.0	11.9	39.0	3.86	12.7		100.0		88.5	Nelson et al. (1989)
Lower Granite, WA		90.0	29.9	98.1	7.92	26.0				92.7	Muir et al. (1995)
Lower Monumental, WA		90.0	28.7	94.1	7.92	26.0				86.5	Muir et al. (1995)
T.W. Sullivan, OR (Unit 8)		240.0	12.8	42.0	1.78	5.8	99.0	43.2	97.0	90.1	Massen (1967)
McNary, WA		82.5	24.4	80.0	7.11	23.3		<5.0	<5.0	89.0	Schoeneman et al. (1961)
Racine, WI		62.1	6.7	22.0	7.71	25.3				93.5	EPRI (1992)
Racine, WI		62.1	6.7	22.0	7.71	25.3				94.0	EPRI (1992)
Racine, WI		62.1	6.7	22.0	7.71	25.3				94.0	EPRI (1992)
Raymondville, NY		120.0	6.4	21.0	3.33	10.9		85.0	90.0	63.0	KA (1996)
Rock Island, WA (bulb turbine)		85.7	12.2	40.0	7.01	23.0		18.4	19.5	93.0	Olson & Kaczynski (1980)
Rock Island, WA (bulb turbine)		85.7	12.2	40.0	7.01	23.0		17.9	18.5	96.9	Olson & Kaczynski (1980)
Thornapple, WI		120.0	4.6	15.1	2.79	9.2				95.3	EPRI (1992)
Thornapple, WI		120.0			2.79	9.2				91.9	EPRI (1992)
Thornapple, WI		120.0			2.79	9.2				93.4	EPRI (1992)
Thornapple, WI		120.0			2.79	9.2				93.5	EPRI (1992)
Thornapple, WI		120.0			2.79	9.2				94.1	EPRI (1992)
Thornapple, WI		120.0			2.79	9.2				96.9	EPRI (1992)
Thornapple, WI		120.0			2.79	9.2				97.1	EPRI (1992)
Thornapple, WI		120.0			2.79	9.2				97.4	EPRI (1992)
Thornapple, WI		120.0			2.79	9.2				97.6	EPRI (1992)
Townsend Dam, PA		152.0	4.9	16.1	2.87	9.4		96.8	NA	96.8	RMC (1994)
Townsend Dam, PA		152.0	4.9	16.1	2.87	9.4		100.0	NA	100.0	RMC (1994)
Tusket, NS		225.0	8.2	26.9						84.5	Ruggles et al. (1990)
Twin Branch, IN		241.0	6.5	21.3				65.0	79.7	93.2	RMC (1994)
Twin Branch, IN		241.0	6.5	21.3				97.5	99.3	99.3	RMC (1994)
Twin Branch, IN		241.0	6.5	21.3				73.0	57.7	94.7	RMC (1994)
Walterville, OR (61% wckt)			16.8	55.1	3.05	10.0		63.0	94.9	97.5	Eicher Associates (1987)
Walterville, OR (77% wckt)			16.8	55.1	3.05	10.0		36.4	68.3	92.5	Eicher Associates (1987)
Walterville, OR			16.8	55.1	3.05	10.0				87.0	Eicher Associates (1987)
Wells, WA (Unit 1)		85.7	19.8	64.9	7.43	24.4				84.0	Parametrix (1986)
West Enfield, ME		89.0	6.4	21.0	4.88	16.0		100.0	NA	96.0	Shepard (1988)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		97.0		90.2	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		86.0		84.1	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		96.0		80.9	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		90.0		84.7	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		100.0		86.7	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		98.0		51.2	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		70.0		100.0	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		70.0		89.4	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		88.0		59.5	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		100.0		16.4	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		100.0		38.7	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		100.0		94.4	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		100.0		90.4	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		100.0		65.1	LMS (1991)
Alcona, MI	16	90.0	13.1	43.0	2.54	8.3		89.0		55.1	LMS (1991)
Baker, WA	19	300.0	76.2	249.9	1.52	5.0				64.0	Eicher Associates (1987)

Site	TurbTyp	SampMeth	Spp	Nt	Nc	AvgLen	TurbDisch	TurbDisFT	Blades
Baker, WA	Francis	Fyke net	Coho Salmon				15.6	551	
Buchanan, MI	Francis	Full discharge netting	Chinook Salmon	600	400	420	2.8	99	
Buchanan, MI	Francis	Full discharge netting	Steelhead Trout	600	400	420	6.2	219	
Bond Falls, MI	Francis	Full discharge netting	Rainbow Trout	350	225	210	12.7	449	
Bond Falls, MI	Francis	Full discharge netting	Yellow Perch	360	225	102	12.7	449	
Bond Falls, MI	Francis	Full discharge netting	Golden Shiner	405	225	70	12.7	449	
Bond Falls, MI	Francis	Full discharge netting	Bluegill	660	450	115	12.7	449	
Caldron Falls, WI (Unit 1)	Francis	Full discharge netting	Centrarchiforms	144	94	76	18.4	650	
Caldron Falls, WI (Unit 1)	Francis	Full discharge netting	Centrarchiforms	141	90	127	18.4	650	
Caldron Falls, WI (Unit 1)	Francis	Full discharge netting	Centrarchiforms	76	35	178	18.4	650	
Caldron Falls, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	145	86	76	18.4	650	
Caldron Falls, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	139	92	127	18.4	650	
Caldron Falls, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	125	58	178	18.4	650	
Caldron Falls, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	136	63	229	18.4	650	
Caldron Falls, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	146	94	292	18.4	650	
Caldron Falls, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	153	76	>292	18.4	650	
Centralia, WI (Unit 2)	Francis	Full discharge netting	White Sucker			125	14.4	509	
Centralia, WI (Unit 1)	Francis	Full discharge netting	Bluegill			125	14.4	509	
Centralia, WI (Unit 1)	Francis	Full discharge netting	Bluegill			175	14.4	509	
Centralia, WI	Francis	Full discharge netting	Resident spp.			<100	variable		
Colton, NY	Francis	Full discharge netting	Centrarchid			<100	14.1	498	
Colton, NY	Francis	Full discharge netting	Centrarchid			175	14.1	498	
Colton, NY	Francis	Full discharge netting	Centrarchid			>250	14.1	498	
Colton, NY	Francis	Full discharge netting	Percid			<100	14.1	498	
Colton, NY	Francis	Full discharge netting	Percid			175	14.1	498	
Colton, NY	Francis	Full discharge netting	Percid			>250	14.1	498	
Colton, NY	Francis	Full discharge netting	Salmonid			<100	14.1	498	
Colton, NY	Francis	Full discharge netting	Salmonid			175	14.1	498	
Colton, NY	Francis	Full discharge netting	Salmonid			>250	14.1	498	
Colton, NY	Francis	Full discharge netting	Soft ray			100	14.1	498	
Colton, NY	Francis	Full discharge netting	Soft ray			175	14.1	498	
Colton, NY	Francis	Full discharge netting	Soft ray			>250	14.1	498	
Crown Zellerback, OR (Unit 20)	Francis	Full discharge netting	Steelhead Trout	1,777	500		11.6	410	
Crown Zellerback, OR (Unit 20)	Francis	Full discharge netting	Chinook Salmon	1,800	500		11.6	410	
Crown Zellerback, OR (Unit 21)	Francis	Full discharge netting	Steelhead Trout	17,999	500		14.8	523	
Crown Zellerback, OR (Unit 21)	Francis	Full discharge netting	Chinook Salmon	1,798	500		14.8	523	
E.J. West, NY	Francis	Full discharge netting	Centrarchid	320	320	<100	76.5	2702	
E.J. West, NY	Francis	Full discharge netting	Centrarchid	159	160	175	76.5	2702	
E.J. West, NY	Francis	Full discharge netting	Centrarchid	128	128	>250	76.5	2702	
E.J. West, NY	Francis	Full discharge netting	Percid	240	240	<100	76.5	2702	
E.J. West, NY	Francis	Full discharge netting	Soft ray	157	159	<100	76.5	2702	
E.J. West, NY	Francis	Full discharge netting	Soft ray	160	159	175	76.5	2702	
E.J. West, NY	Francis	Full discharge netting	Soft ray	160	160	>250	76.5	2702	
E.J. West, NY	Francis	Full discharge netting	Salmonid	280	280	<100	76.5	2702	
E.J. West, NY	Francis	Full discharge netting	Salmonid	160	160	175	76.5	2702	
E.J. West, NY	Francis	Full discharge netting	Salmonid	160	160	>250	76.5	2702	
Elwha, WA	Francis	Partial netting	Chinook Salmon	42,168	20,030		14.2	501	
Faraday, OR	Francis	Partial netting	Chinook Salmon	1,700	0		14.2	501	
Finch Pruyn, NY (Unit 4)	Francis	Balloon tag	Smallmouth Bass	61	44	191	20.1	710	
Finch Pruyn, NY (Unit 4)	Francis	Balloon tag	Smallmouth Bass	49	37	210	20.1	710	
Finch Pruyn, NY (Unit 4)	Francis	Balloon tag	Smallmouth Bass	28	44	271	20.1	710	
Finch Pruyn, NY (Unit 5)	Francis	Balloon tag	Smallmouth Bass	25	44	191	23.7	837	
Finch Pruyn, NY (Unit 5)	Francis	Balloon tag	Smallmouth Bass	32	37	210	23.7	837	
Finch Pruyn, NY (Unit 5)	Francis	Balloon tag	Smallmouth Bass	43	44	271	23.7	837	
Five Channels, MI	Francis	Full discharge netting	Bluegill	95		118	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Bluegill	91		170	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Gold/Common Shiner	59		114	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Gold/Common Shiner	60		154	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Northern Pike	31		352	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Rainbow Trout	40		108	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Rainbow Trout	46		317	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Spottail Shiner	30		116	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Walleye	55		162	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Walleye	60		385	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	White Sucker	56		180	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	White Sucker	60		290	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Yellow Perch	25		107	33.1	1169	
Five Channels, MI	Francis	Full discharge netting	Yellow Perch	30		186	33.1	1169	
Glines, WA	Francis	Partial netting	Silver Salmon	31,256	23,442		42.5	1501	
Grand Rapids, WI (U 1,2,4 comb)	Francis	Full discharge netting	Bluegill			76	18.3	646	
Grand Rapids, WI (U 1,2,4 comb)	Francis	Full discharge netting	Bluegill			127	18.3	646	
Grand Rapids, WI (U 1,2,4 comb)	Francis	Full discharge netting	Bluegill			178	18.3	646	
Grand Rapids, WI (U 1,2,4 comb)	Francis	Full discharge netting	White Sucker			76	18.3	646	
Grand Rapids, WI (U 1,2,4 comb)	Francis	Full discharge netting	White Sucker			127	18.3	646	
Grand Rapids, WI (U 1,2,4 comb)	Francis	Full discharge netting	White Sucker			178	18.3	646	
Grand Rapids, WI (U 1,2,4 comb)	Francis	Full discharge netting	White Sucker			229	18.3	646	
Grand Rapids, WI (U 1,2,4 comb)	Francis	Full discharge netting	White Sucker			292	18.3	646	
Grand Rapids, WI (U 1,2,4 comb)	Francis	Full discharge netting	White Sucker			>292	18.3	646	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Bluegill	63		118	14.4	509	

Site	Buckets	RunSp	Head	HeadFT	RunDia	RunDiaFt	Sc	TPerRec	CPerRec	ImmSur	Ref
Baker, WA	19	300.0	76.2	249.9	1.52	5.0				72.0	Eicher Associates (1987)
Buchanan, MI								79.7	98.3	79.6	RMC (1992)
Buchanan, MI								75.3	87.8	79.4	RMC (1992)
Bond Falls, MI		300.0	64.0	209.9				82.0	97.8	83.8	RMC (1996)
Bond Falls, MI		300.0	64.0	209.9				82.5	98.7	79.5	RMC (1996)
Bond Falls, MI		300.0	64.0	209.9				70.4	93.3	77.9	RMC (1996)
Bond Falls, MI		300.0	64.0	209.9				82.1	97.3	81.7	RMC (1996)
Caldron Falls, WI (Unit 1)	15	226.0	24.4	80.0	1.83	6.0		99.3	87.2	100.0	Harza (1995)
Caldron Falls, WI (Unit 1)	15	226.0	24.4	80.0	1.83	6.0		87.2	92.2	98.2	Harza (1995)
Caldron Falls, WI (Unit 1)	15	226.0	24.4	80.0	1.83	6.0		100.0	100.0	86.8	Harza (1995)
Caldron Falls, WI (Unit 1)	15	226.0	24.4	80.0	1.83	6.0		86.9	95.3	80.3	Harza (1995)
Caldron Falls, WI (Unit 1)	15	226.0	24.4	80.0	1.83	6.0		95.7	91.3	84.8	Harza (1995)
Caldron Falls, WI (Unit 1)	15	226.0	24.4	80.0	1.83	6.0		95.2	100.0	70.3	Harza (1995)
Caldron Falls, WI (Unit 1)	15	226.0	24.4	80.0	1.83	6.0		100.0	98.4	64.3	Harza (1995)
Caldron Falls, WI (Unit 1)	15	226.0	24.4	80.0	1.83	6.0		97.9	85.0	59.5	Harza (1995)
Caldron Falls, WI (Unit 1)	15	226.0	24.4	80.0	1.83	6.0		95.4	81.6	35.5	Harza (1995)
Centralia, WI (Unit 2)	15	90.0	6.1	20.0	0.71	2.3				97.9	Harza (1995)
Centralia, WI (Unit 1)	15	90.0	6.1	20.0	0.71	2.3				98.2	Harza (1995)
Centralia, WI (Unit 1)	15	90.0	6.1	20.0	0.71	2.3				86.8	Harza (1995)
Centralia, WI	15	90.0	4.7	15.4	0.71	2.3				64.0	BVMCA, (1991)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				3.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				1.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				0.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				65.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				14.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				17.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				68.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				31.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				7.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				75.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				47.0	KA (1996)
Colton, NY	19	360.0	80.8	265.0	1.5	4.9				17.0	KA (1996)
Crown Zellerback, OR (Unit 20)		277.0	11.9	39.0				52.1	96.0	69.4	Eicher Associates (1987)
Crown Zellerback, OR (Unit 20)		277.0	11.9	39.0				52.2	98.6	71.6	Eicher Associates (1987)
Crown Zellerback, OR (Unit 21)		255.0	13.0	42.6				51.0	70.8	80.0	Eicher Associates (1987)
Crown Zellerback, OR (Unit 21)		255.0	13.0	42.6				74.3	91.8	81.2	Eicher Associates (1987)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		62.5	79.1	71.7	KA (1996)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		73.0	62.8	85.5	KA (1996)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		86.7	94.9	59.8	KA (1996)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		69.6	62.0	56.1	KA (1996)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		54.8	49.7	32.3	KA (1996)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		67.5	79.9	71.3	KA (1996)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		71.3	58.1	67.5	KA (1996)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		41.1	31.8	65.2	KA (1996)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		72.5	53.8	90.6	KA (1996)
E.J. West, NY	15	113.0	19.2	63.0	3.33	10.9		99.4	49.4	95.6	KA (1996)
Elwha, WA		300.0	31.7	104.0	1.49	4.9		13.1	9.9	100.0	Eicher Associates (1987)
Faraday, OR		360.0	36.6	120.0	1.01	3.3				50.0	Eicher Associates (1987)
Finch Pruyn, NY (Unit 4)	15	225.0	14.0	45.9	0.91	3.0		96.7	97.8	95.0	RMC (1990a)
Finch Pruyn, NY (Unit 4)	15	225.0	14.0	45.9	0.91	3.0		89.8	97.4	91.0	RMC (1990a)
Finch Pruyn, NY (Unit 4)	15	225.0	14.0	45.9	0.91	3.0		96.4	93.6	93.0	RMC (1990a)
Finch Pruyn, NY (Unit 5)	15	225.0	14.0	45.9	0.91	3.0		68.0	97.8	94.0	RMC (1990a)
Finch Pruyn, NY (Unit 5)	15	225.0	14.0	45.9	0.91	3.0		84.4	97.5	91.0	RMC (1990a)
Finch Pruyn, NY (Unit 5)	15	225.0	14.0	45.9	0.91	3.0		95.3	93.6	71.0	RMC (1990a)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		99.0		93.6	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		86.0		89.2	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		86.0		81.8	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		87.0		85.5	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		97.0		91.3	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		60.0		95.8	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		20.0		70.0	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		37.0		36.4	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		100.0		71.2	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		100.0		76.7	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		86.0		88.6	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		82.0		71.4	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		88.0		72.7	LMS (1991)
Five Channels, MI	16	150.0	11.0	36.1	1.4	4.6		93.0		77.1	LMS (1991)
Glines, WA		225.0	59.1	193.8	2.35	7.7		5.0	49.3	69.6	Eicher Associates (1987)
Grand Rapids, WI (U 1,2,4 comb)	15	90.0	8.5	27.9	1.47	4.8				96.7	NAI (1994)
Grand Rapids, WI (U 1,2,4 comb)	15	90.0	8.5	27.9	1.47	4.8				100.0	NAI (1994)
Grand Rapids, WI (U 1,2,4 comb)	15	90.0	8.5	27.9	1.47	4.8				94.9	NAI (1994)
Grand Rapids, WI (U 1,2,4 comb)	15	90.0	8.5	27.9	1.47	4.8				100.0	NAI (1994)
Grand Rapids, WI (U 1,2,4 comb)	15	90.0	8.5	27.9	1.47	4.8				100.0	NAI (1994)
Grand Rapids, WI (U 1,2,4 comb)	15	90.0	8.5	27.9	1.47	4.8				94.9	NAI (1994)
Grand Rapids, WI (U 1,2,4 comb)	15	90.0	8.5	27.9	1.47	4.8				93.7	at
Grand Rapids, WI (U 1,2,4 comb)	15	90.0	8.5	27.9	1.47	4.8				90.4	NAI (1994)
Grand Rapids, WI (U 1,2,4 comb)	15	90.0	8.5	27.9	1.47	4.8				80.5	NAI (1994)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		56.0		89.5	LMS (1991)

Site	TurbTyp	SampMeth	Spp	Nt	Nc	AvgLen	TurbDisch	TurbDisFT	Blades
Hardy, MI (Unit 2)	Francis	Full discharge netting	Bluegill	30		170	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Gold/Common Shiner	30		114	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Gold/Common Shiner	59		154	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Largemouth Bass	60		118	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Northern Pike	58		352	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Rainbow Trout	59		108	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Rainbow Trout	60		317	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Walleye	60		385	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	White Sucker	59		180	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	White Sucker	60		290	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Yellow Perch	60		107	14.4	509	
Hardy, MI (Unit 2)	Francis	Full discharge netting	Yellow Perch			186	14.4	509	
High Falls (Unit 5)	Francis	Full discharge netting	Centrarchiforms	154	88	76	7.8	275	
High Falls (Unit 5)	Francis	Full discharge netting	Centrarchiforms	90	48	127	7.8	275	
High Falls (Unit 5)	Francis	Full discharge netting	Centrarchiforms	111	70	178	7.8	275	
High Falls (Unit 5)	Francis	Full discharge netting	Fusiforms	146	95	76	7.8	275	
High Falls (Unit 5)	Francis	Full discharge netting	Fusiforms	81	49	127	7.8	275	
High Falls (Unit 5)	Francis	Full discharge netting	Fusiforms	184	79	178	7.8	275	
High Falls (Unit 5)	Francis	Full discharge netting	Fusiforms	96	66	229	7.8	275	
High Falls (Unit 5)	Francis	Full discharge netting	Fusiforms	160	58	292	7.8	275	
High Falls (Unit 5)	Francis	Full discharge netting	Fusiforms	71	41	>292	7.8	275	
Highley, NY	Francis	Full discharge netting	Centrarchid			<100	19.1	675	
Highley, NY	Francis	Full discharge netting	Centrarchid			175	19.1	675	
Highley, NY	Francis	Full discharge netting	Centrarchid			>250	19.1	675	
Highley, NY	Francis	Full discharge netting	Percid			<100	19.1	675	
Highley, NY	Francis	Full discharge netting	Percid			>250	19.1	675	
Highley, NY	Francis	Full discharge netting	Salmonid			<100	19.1	675	
Highley, NY	Francis	Full discharge netting	Salmonid			175	19.1	675	
Highley, NY	Francis	Full discharge netting	Salmonid			>250	19.1	675	
Highley, NY	Francis	Full discharge netting	Soft ray			<100	19.1	675	
Highley, NY	Francis	Full discharge netting	Soft ray			175	19.1	675	
Highley, NY	Francis	Full discharge netting	Soft ray			>250	19.1	675	
Hoist, MI	Francis	Full discharge netting	Brown Trout	150	150	85	8.5	300	
Hoist, MI	Francis	Full discharge netting	Brook Trout	150	150	135	8.5	300	
Hoist, MI	Francis	Full discharge netting	Brown Trout	150	150	220	8.5	300	
Hoist, MI	Francis	Full discharge netting	Bluegill	150	150	65	8.5	300	
Hoist, MI	Francis	Full discharge netting	Bluegill	150	150	115	8.5	300	
Holtwood, PA (U10/single runner)	Francis	Balloon tag	American Shad	100	100	125	99.1	3500	
Holtwood, PA (U3/double runner)	Francis	Balloon tag	American Shad	100	80	125	99.1	3500	
la centrale de Beauharnois, Quebec, Canada	Francis	Float tag	American Eel	100		888	198.2	6999	
Leaburg, OR	Francis	Full discharge netting	Rainbow Trout	1,249	624		31.2	1102	
Lequille,NS	Francis	Full discharge netting	Atlantic Salmon				9.9	350	
Luray, VA	Francis	Full discharge netting	American Eel	393		853	10.5	371	
McClure, MI	Francis	Full discharge netting	Resident spp.				4.4	155	
Minetto, NY	Francis	Full discharge netting	Centrarchid	164	104	<100	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Centrarchid	236	110	175	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Centrarchid	165	120	>250	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Percid	133	117	<100	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Percid	243	142	175	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Soft ray	348	220	<100	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Soft ray	214	133	175	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Soft ray	177	160	>250	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Salmonids	237	160	<100	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Salmonids	184	107	175	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Salmonids	178	159	>250	42.5	1501	
Minetto, NY	Francis	Full discharge netting	American Eel	107	92	625	42.5	1501	
Minetto, NY	Francis	Full discharge netting	Alewife	189	140	<100			
North Fork, OR	Francis	Partial netting	Coho Salmon	4,076	5,158		70.8	2500	
Peshtigo, WI (Unit 4)	Francis	Full discharge netting	Centrarchiforms	146	84	76	13	459	
Peshtigo, WI (Unit 4)	Francis	Full discharge netting	Centrarchiforms	140	77	127	13	459	
Peshtigo, WI (Unit 4)	Francis	Full discharge netting	Centrarchiforms	121	75	178	13	459	
Peshtigo, WI (Unit 4)	Francis	Full discharge netting	Fusiforms	158	103	76	13	459	
Peshtigo, WI (Unit 4)	Francis	Full discharge netting	Fusiforms	141	90	127	13	459	
Peshtigo, WI (Unit 4)	Francis	Full discharge netting	Fusiforms	166	109	178	13	459	
Peshtigo, WI (Unit 4)	Francis	Full discharge netting	Fusiforms	158	93	229	13	459	
Peshtigo, WI (Unit 4)	Francis	Full discharge netting	Fusiforms	166	105	292	13	459	
Peshtigo, WI (Unit 4)	Francis	Full discharge netting	Fusiforms	128	79	>292	13	459	
Potato Rapids, WI (Unit 1)	Francis	Full discharge netting	Centrarchiforms	134	94	76	14.2	501	
Potato Rapids, WI (Unit 1)	Francis	Full discharge netting	Centrarchiforms	154	93	127	14.2	501	
Potato Rapids, WI (Unit 1)	Francis	Full discharge netting	Centrarchiforms	111	70	178	14.2	501	
Potato Rapids, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	168	104	76	14.2	501	
Potato Rapids, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	104	69	127	14.2	501	
Potato Rapids, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	150	91	178	14.2	501	
Potato Rapids, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	160	96	229	14.2	501	
Potato Rapids, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	136	83	292	14.2	501	
Potato Rapids, WI (Unit 1)	Francis	Full discharge netting	Fusiforms	145	112	>292	14.2	501	
Potato Rapids, WI (Unit 2)	Francis	Full discharge netting	Centrarchiforms	166	105	76	14.2	501	
Potato Rapids, WI (Unit 2)	Francis	Full discharge netting	Centrarchiforms	137	104	127	12.5	441	
Potato Rapids, WI (Unit 2)	Francis	Full discharge netting	Centrarchiforms	58	28	178	12.5	441	

Site	Buckets	RunSp	Head	HeadFT	RunDia	RunDiaFt	Sc	TPerRec	CPerRec	ImmSur	Ref
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		80.0		91.5	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		82.0		85.5	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		81.0		88.7	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		65.0		76.2	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		86.0		76.0	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		44.0		71.4	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		60.0		68.6	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		95.0		77.3	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		65.0		76.9	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		76.0		64.5	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		63.0		83.1	LMS (1991)
Hardy, MI (Unit 2)	16	163.6	30.5	100.0	2.13	7.0		82.0		95.5	LMS (1991)
High Falls (Unit 5)	12	358.0	25.3	83.0	0.99	3.2		90.9	84.1	85.5	Harza (1995)
High Falls (Unit 5)	12	358.0	25.3	83.0	0.99	3.2		90.0	81.3	78.1	Harza (1995)
High Falls (Unit 5)	12	358.0	25.3	83.0	0.99	3.2		90.9	84.0	58.9	Harza (1995)
High Falls (Unit 5)	12	358.0	25.3	83.0	0.99	3.2		80.1	82.1	87.8	Harza (1995)
High Falls (Unit 5)	12	358.0	25.3	83.0	0.99	3.2				67.9	Harza (1995)
High Falls (Unit 5)	12	358.0	25.3	83.0	0.99	3.2				48.4	Harza (1995)
High Falls (Unit 5)	12	358.0	25.3	83.0	0.99	3.2				46.2	Harza (1995)
High Falls (Unit 5)	12	358.0	25.3	83.0	0.99	3.2				20.1	Harza (1995)
High Falls (Unit 5)	12	358.0	25.3	83.0	0.99	3.2				2.7	Harza (1995)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				81.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				14.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				17.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				59.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				40.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				70.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				44.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				61.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				60.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				72.0	KA (1996)
Highley, NY	13	257.0	14.0	45.9	1.22	4.0				40.0	KA (1996)
Hoist, MI		360.0	43.3	142.0				56.0	99.3	45.1	RMC (1993c)
Hoist, MI		360.0	43.3	142.0				73.3	1.0	43.0	RMC (1993c)
Hoist, MI		360.0	43.3	142.0				90.7	1.0	22.8	RMC (1993c)
Hoist, MI		360.0	43.3	142.0				44.0	98.7	19.7	RMC (1993c)
Hoist, MI		360.0	43.3	142.0				65.3	1.0	75.0	RMC (1993c)
Holtwood, PA (U10/single runner)	16	94.7	18.9	62.0	3.8	12.5		81.0	90.0	89.4	RMC (1992d)
Holtwood, PA (U3/double runner)	17	102.8	18.9	62.0	2.84	9.3		78.0	93.8	83.5	RMC (1992d)
la centrale de Beauharnois, Quebec, Canada	13	75.0	24.1	79.0	5.38	17.6		97.1	_	84.2	Desrochers (1995)
Leaburg, OR		225.0	27.1	88.9	2.29	7.5		67.0	96.2	95.2	Eicher Associates (1987)
Lequille,NS	13	519.0	118.0	387.0	1.37	4.5				52.0	Eicher Associates (1987)
Luray, VA	12	164.0	4.9	16.1	1.59	5.2				99.0	RMC (1995)
McClure, MI		600.0	129.2	423.8					NA		RMC (1993b)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		64.0	86.5	62.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		90.7	91.3	83.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		85.5	91.7	84.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		44.4	47.0	80.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		68.7	85.2	86.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		49.7	42.3	82.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		72.9	98.5	94.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		94.4	90.0	84.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		62.5	83.3	92.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		81.5	84.1	91.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		78.1	67.9	92.0	KA (1996)
Minetto, NY	16	72.0	5.2	17.1	3.53	11.6		43.9	66.3	94.0	KA (1996)
Minetto, NY								74.1	90.0	80.0	KA (1996)
North Fork, OR		139.0	41.5	136.1	2.95	9.7		18.2	23.1	74.0	Eicher Associates (1987)
Peshtigo, WI (Unit 4)	15	100.0	4.0	13.1	2.03	6.7		88.4	91.7	100.0	Harza (1995)
Peshtigo, WI (Unit 4)	15	100.0	4.0	13.1	2.03	6.7		79.3	79.2	98.9	Harza (1995)
Peshtigo, WI (Unit 4)	15	100.0	4.0	13.1	2.03	6.7		71.9	69.3	100.0	Harza (1995)
Peshtigo, WI (Unit 4)	15	100.0	4.0	13.1	2.03	6.7		85.4	97.1	94.0	Harza (1995)
Peshtigo, WI (Unit 4)	15	100.0	4.0	13.1	2.03	6.7		86.5	95.6	93.7	Harza (1995)
Peshtigo, WI (Unit 4)	15	100.0	4.0	13.1	2.03	6.7		92.2	93.6	96.6	Harza (1995)
Peshtigo, WI (Unit 4)	15	100.0	4.0	13.1	2.03	6.7		94.9	91.4	95.4	Harza (1995)
Peshtigo, WI (Unit 4)	15	100.0	4.0	13.1	2.03	6.7		85.5	84.8	85.5	Harza (1995)
Peshtigo, WI (Unit 4)	15	100.0	4.0	13.1	2.03	6.7		83.6	79.7	82.8	Harza (1995)
Potato Rapids, WI (Unit 1)	15	123.0	5.2	17.1	2.13	7.0		94.0	93.6	100.0	Harza (1995)
Potato Rapids, WI (Unit 1)	15	123.0	5.2	17.1	2.13	7.0		75.3	96.8	84.7	Harza (1995)
Potato Rapids, WI (Unit 1)	15	123.0	5.2	17.1	2.13	7.0		49.5	98.6	83.0	Harza (1995)
Potato Rapids, WI (Unit 1)	15	123.0	5.2	17.1	2.13	7.0		87.5	92.3	89.2	Harza (1995)
Potato Rapids, WI (Unit 1)	15	123.0	5.2	17.1	2.13	7.0		93.3	98.6	76.5	Harza (1995)
Potato Rapids, WI (Unit 1)	15	123.0	5.2	17.1	2.13	7.0		98.0	93.4	68.4	Harza (1995)
Potato Rapids, WI (Unit 1)	15	123.0	5.2	17.1	2.13	7.0		75.6	96.9	61.1	Harza (1995)
Potato Rapids, WI (Unit 1)	15	123.0	5.2	17.1	2.13	7.0		89.0	100.0	53.3	Harza (1995)
Potato Rapids, WI (Unit 1)	15	123.0	5.2	17.1	2.13	7.0		89.7	94.6	34.5	Harza (1995)
Potato Rapids, WI (Unit 2)	15	123.0	5.2	17.1	2.13	7.0		89.2	97.1	93.4	Harza (1995)
Potato Rapids, WI (Unit 2)	15	135.0	5.2	17.1	2.03	6.7		74.5	98.1	83.7	Harza (1995)
Potato Rapids, WI (Unit 2)	15	135.0	5.2	17.1	2.03	6.7		100.0	96.4	91.4	Harza (1995)

Site	TurbTyp	SampMeth	Spp	Nt	Nc	AvgLen	TurbDisch	TurbDisFT	Blades
Potato Rapids, WI (Unit 2)	Francis	Full discharge netting	Fusiforms	179	123	76	12.5	441	
Potato Rapids, WI (Unit 2)	Francis	Full discharge netting	Fusiforms	134	93	127	12.5	441	
Potato Rapids, WI (Unit 2)	Francis	Full discharge netting	Fusiforms	138	92	178	12.5	441	
Potato Rapids, WI (Unit 2)	Francis	Full discharge netting	Fusiforms	158	98	229	12.5	441	
Potato Rapids, WI (Unit 2)	Francis	Full discharge netting	Fusiforms	156	91	292	12.5	441	
Potato Rapids, WI (Unit 2)	Francis	Full discharge netting	Fusiforms	149	85	>292	12.5	441	
Pricket, MI	Francis	Full discharge netting	Bluegill	256	150	52	9.2	325	
Pricket, MI	Francis	Full discharge netting	Golden Shiner	182	120	<100	9.2	325	
Pricket, MI	Francis	Full discharge netting	Bluegill	131	90	102	9.2	325	
Pricket, MI	Francis	Full discharge netting	Bluegill	21	21	>127	9.2	325	
Pricket, MI	Francis	Full discharge netting	Mixed resident fish				9.2	325	
Pricket, MI	Francis	Full discharge netting	White Sucker	201	119	165	9.2	325	
Pricket, MI	Francis	Full discharge netting	White Sucker	15	10	>254	9.2	325	
Publishers, OR (1960)	Francis	Full discharge netting	Steelhead Trout	1,768	500		7.8	275	
Publishers, OR (1960)	Francis	Full discharge netting	Chinook Salmon	1,798	503		7.8	275	
Publishers, OR (1961)	Francis	Full discharge netting	Steelhead Trout	1,800	500		7.8	275	
Publishers, OR (1961)	Francis	Full discharge netting	Chinook Salmon	1,800	500		7.8	275	
Puntledge, BC	Francis	Floating net	Steelhead Trout	1,500		124			
Puntledge, BC	Francis	Floating net	Kamploops	1,500		69			
Puntledge, BC	Francis	Floating net	Kamploops	1,500		46			
Puntledge, BC	Francis	Floating net	Salmon	1,500		36			
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Bluegill	90		118	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Bluegill	92		170	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Gold/Common Shiner	60		114	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Gold/Common Shiner	34		154	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Largemouth Bass	60		118	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Northern Pike	47		352	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Rainbow Trout	30		108	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Rainbow Trout	30		317	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Spottail Shiner	31		116	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Walleye	40		385	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	White Sucker	55		180	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	White Sucker	57		290	10.8	381	
Rogers, MI (Units 1 & 2)	Francis	Full discharge netting	Yellow Perch	78		107	10.8	381	
Ruskin, BC	Francis	Fyke netting dwnstrm	Sockeye Salmon	12,125	12,159	86	113.3	4001	
Sandstone Rapids, WI	Francis	Full discharge netting	Centrarchiforms	165	99	76	18.4	650	
Sandstone Rapids, WI	Francis	Full discharge netting	Centrarchiforms	141	90	127	18.4	650	
Sandstone Rapids, WI	Francis	Full discharge netting	Centrarchiforms	61	53	178	18.4	650	
Sandstone Rapids, WI	Francis	Full discharge netting	Fusiforms	169	100	76	18.4	650	
Sandstone Rapids, WI	Francis	Full discharge netting	Fusiforms	132	96	127	18.4	650	
Sandstone Rapids, WI	Francis	Full discharge netting	Fusiforms	145	97	178	18.4	650	
Sandstone Rapids, WI	Francis	Full discharge netting	Fusiforms	127	78	229	18.4	650	
Sandstone Rapids, WI	Francis	Full discharge netting	Fusiforms	119	71	292	18.4	650	
Sandstone Rapids, WI	Francis	Full discharge netting	Fusiforms	144	92	>292	18.4	650	
Schaghiticoke, NY	Francis	Full discharge netting	Centrarchid	149	144	<100	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Centrarchid	160	160	175	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Centrarchid	200	200	>250	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Percid	239	237	<100	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Percid	80	80	175	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Soft ray	160	160	<100	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Soft ray	241	240	175	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Soft ray	149	150	>250	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Salmonid	159	160	<100	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Salmonid	240	240	175	11.6	410	
Schaghiticoke, NY	Francis	Full discharge netting	Salmonid	162	160	>250	11.6	410	
Seton Creek,BC	Francis	Fyke net in tailrace	Sockeye Salmon			86	127.4	4499	
Stevens Creek, SC	Francis	Balloon tag	Bluegill	110	110	122	28.3	999	
Stevens Creek, SC	Francis	Balloon tag	Blueback Herring	131	120	203	28.3	999	
Stevens Creek, SC	Francis	Balloon tag	Spotted Sucker/Y. Perch	120	120	165	28.3	999	
T.W. Sullivan, OR	Francis	Discharge netting	Steelhead Trout						
T.W. Sullivan, OR	Francis	Discharge netting	Chinook Salmon				7.4	261	
Vernon, VT/NH	Francis	Balloon tag	American Shad	153	150	95	51.9	1833	
White Rapids, WI	Francis	Balloon tag	White Sucker	42	36	204	25.5	901	
White Rapids, WI	Francis	Balloon tag	White Sucker	58	64	112	25.5	901	
White Rapids, WI	Francis	Balloon tag	Bluegill	56	62	90	25.5	901	
White Rapids, WI	Francis	Balloon tag	Bluegill	44	38	155	25.5	901	
Youghiogheny, PA	Francis	Full discharge netting	Alewife			51	21.2	749	
Youghiogheny, PA	Francis	Full discharge netting	Walleye			376	21.2	749	
Youghiogheny, PA	Francis	Full discharge netting	Rock Bass				21.2	749	
Youghiogheny, PA	Francis	Full discharge netting	Yellow Perch				21.2	749	
Youghiogheny, PA	Francis	Full discharge netting	Crappies				21.2	749	

Site	Buckets	RunSp	Head	HeadFT	RunDia	RunDiaFt	Sc	TPerRec	CPerRec	ImmSur	Ref
Potato Rapids, WI (Unit 2)	15	135.0	5.2	17.1	2.03	6.7		74.3	67.5	84.5	Harza (1995)
Potato Rapids, WI (Unit 2)	15	135.0	5.2	17.1	2.03	6.7		90.3	100.0	61.7	Harza (1995)
Potato Rapids, WI (Unit 2)	15	135.0	5.2	17.1	2.03	6.7		97.8	98.9	75.1	Harza (1995)
Potato Rapids, WI (Unit 2)	15	135.0	5.2	17.1	2.03	6.7		91.8	99.0	61.0	Harza (1995)
Potato Rapids, WI (Unit 2)	15	135.0	5.2	17.1	2.03	6.7		89.7	97.8	57.8	Harza (1995)
Potato Rapids, WI (Unit 2)	15	135.0	5.2	17.1	2.03	6.7		92.3	94.1	48.2	Harza (1995)
Pricket, MI	15	257.0	16.5	54.1	1.36	4.5		57.0	62.7	97.7	RMC (1991c)
Pricket, MI	15	257.0	16.5	54.1	1.36	4.5		93.3	70.0	93.9	RMC (1991c)
Pricket, MI	15	257.0	16.5	54.1	1.36	4.5		80.9	80.0	92.5	RMC (1991c)
Pricket, MI	15	257.0	16.5	54.1	1.36	4.5		100.0	90.5	85.7	RMC (1991c)
Pricket, MI	15	257.0	16.5	54.1	1.36	4.5				97.8	RMC (1991c)
Pricket, MI	15	257.0	16.5	54.1	1.36	4.5		81.6	80.7	70.8	RMC (1991c)
Pricket, MI	15	257.0	16.5	54.1	1.36	4.5		93.3	70.0	35.7	RMC (1991c)
Publishers, OR (1960)		255.0	12.2	40.0				36.2	58.0	87.9	Eicher Associates (1987)
Publishers, OR (1960)		255.0	12.2	40.0				51.2	100.0	87.4	Eicher Associates (1987)
Publishers, OR (1961)		255.0	12.2	40.0				24.9	36.0	84.5	Eicher Associates (1987)
Publishers, OR (1961)		255.0	12.2	40.0				43.5	69.6	87.1	Eicher Associates (1987)
Puntledge, BC		277.0	103.6	339.8	2.16	7.1		3.5		58.1	Eicher Associates (1987)
Puntledge, BC		277.0	103.6	339.8	2.16	7.1		3.4		72.5	Eicher Associates (1987)
Puntledge, BC		277.0	103.6	339.8	2.16	7.1		4.9		71.2	Eicher Associates (1987)
Puntledge, BC		277.0	103.6	339.8	2.16	7.1		2.5		67.4	Eicher Associates (1987)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		96.0		96.0	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		96.0		85.2	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		98.0			LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		53.0		92.5	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		92.0		77.4	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		89.0		83.4	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		100.0		89.9	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		83.0		61.2	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		100.0		73.5	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		95.0		86.2	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		73.0		91.2	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		88.0		88.1	LMS (1991)
Rogers, MI (Units 1 & 2)	15	150.0	11.9	39.0	1.52	5.0		96.0		91.8	LMS (1991)
Ruskin, BC		120.0	39.6	129.9	3.78	12.4				89.5	Eicher Associates (1987)
Sandstone Rapids, WI	15	150.0	12.8	42.0	2.21	7.2		89.1	94.9	97.0	Harza (1995)
Sandstone Rapids, WI	15	150.0	12.8	42.0	2.21	7.2		97.8	100.0	80.7	Harza (1995)
Sandstone Rapids, WI	15	150.0	12.8	42.0	2.21	7.2		100.0	98.1	79.9	Harza (1995)
Sandstone Rapids, WI	15	150.0	12.8	42.0	2.21	7.2		62.1	94.0	64.9	Harza (1995)
Sandstone Rapids, WI	15	150.0	12.8	42.0	2.21	7.2		86.4	99.0	75.0	Harza (1995)
Sandstone Rapids, WI	15	150.0	12.8	42.0	2.21	7.2		97.2	100.0	76.0	Harza (1995)
Sandstone Rapids, WI	15	150.0	12.8	42.0	2.21	7.2		91.3	91.0	69.8	Harza (1995)
Sandstone Rapids, WI	15	150.0	12.8	42.0	2.21	7.2		87.3	98.6	58.4	Harza (1995)
Sandstone Rapids, WI	15	150.0	12.8	42.0	2.21	7.2		93.1	89.1	47.1	Harza (1995)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		84.3	95.1	27.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		92.8	84.4	59.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		80.5	89.0	7.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		74.4	79.7	68.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		100.0	87.5	39.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		67.5	85.6	60.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		92.9	92.5	17.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		66.4	74.0	22.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		86.2	76.3	56.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		92.5	89.2	27.0	KA (1996)
Schaghiticoke, NY	17	300.0	43.6	143.0	2.03	6.7		80.2	60.6	11.0	KA (1996)
Seton Creek,BC		120.0	43.3	142.0	3.66	12.0				90.8	Andrew & Geen (1958)
Stevens Creek, SC	14	75.0	8.5	27.9	3.43	11.3		95.5	99.1	95.4	RMC (1994d)
Stevens Creek, SC	14	75.0	8.5	27.9	3.43	11.3		90.8	89.2	95.3	RMC (1994d)
Stevens Creek, SC	14	75.0	8.5	27.9	3.43	11.3		96.7	98.3	98.3	RMC (1994d)
T.W. Sullivan, OR		242.0	12.5	41.0						74.1	Eicher Associates (1987)
T.W. Sullivan, OR		242.0	12.5	41.0						85.7	Eicher Associates (1987)
Vernon, VT/NH	15	74.0	10.4	34.1	3.96	13.0		93.5	98.7	94.7	NAI (1996b)
White Rapids, WI	14	100.0	8.8	28.9	3.4	11.2		90.5	91.7	93.0	RMC (1993)
White Rapids, WI	14	100.0	8.8	28.9	3.4	11.2		96.6	98.4	100.0	RMC (1993)
White Rapids, WI	14	100.0	8.8	28.9	3.4	11.2		92.9	98.4	95.0	RMC (1993)
White Rapids, WI	14	100.0	8.8	28.9	3.4	11.2		93.2	97.4	100.0	RMC (1993)
Youghlogheny, PA			36.6	120.0						0.1	RMC (1992a)
Youghlogheny, PA			36.6	120.0						39.5	RMC (1992a)
Youghlogheny, PA			36.6	120.0						4.0	RMC (1992a)
Youghlogheny, PA			36.6	120.0						7.0	RMC (1992a)
Youghlogheny, PA			36.6	120.0						0.2	RMC (1992a)