Survival and Behavior of Fish Interacting with Hydrokinetic Turbines

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Abstract

Greater demand for renewable energy has led to considerable interest in the development and application of hydrokinetic turbines designed for river, tidal, and marine environments. A major concern associated with hydrokinetic applications is the potential for aquatic organisms to be struck and injured or killed by rotating blades or foils. To provide data that can be used to address this issue, we conducted laboratory studies that exposed fish to two hydrokinetic turbine designs installed in a large flume with flowing water. The turbines that were evaluated included a cross-flow spherical turbine developed by Lucid Technologies and a ducted axial-flow turbine developed by Current-to-Current (referred to as the Welka UPG turbine). Testing included the estimation of survival and observations of behavior as fish approached and passed by or through each unit. Testing was conducted with two size groups of rainbow trout (both turbines) and largemouth bass (Welka UPG only) at approach velocities of 1.5 and 2.1 m/s using paired releases of treatment (turbine-exposed) and control groups. Treatment fish were released upstream at a point where the probability of passage through each turbine was expected to be high and control fish were released immediately downstream of the turbines. Treatment and control fish were collected together at the end of a test and examined for injury, scale loss, and mortality (1-hr and 48-hr). An underwater video system was used to observe treatment fish as they approached and passed downstream of each turbine. Immediate (1-hr) and total (1-hr and 48-hr combined) survival rates for were greater than 99% for all sets of test conditions evaluated with both turbines, with the exception of the larger trout tested at an approach velocity of 2.1 m/s with the Lucid turbine (98.4% total survival). Injury and scale loss rates were typically low (< 5%) for treatment fish and were comparable to controls, indicating most injury and scale loss was due to handling and testing and not interactions with the turbines. Behavioral observations demonstrated rainbow trout actively avoided passage though the Lucid spherical turbine despite being released 10-inches upstream of the blade sweep. The results of this study indicate that injury and mortality are unlikely to occur should fish be entrained through the blade sweep of either turbine design, but also because avoidance of turbine passage is likely to be high. These results may also be applicable to other hydrokinetic turbines that are similar in design and operation to the two units that we tested.

1.0 Introduction

With a pressing need for alternative energy sources throughout the world, hydrokinetic turbine technologies have been garnering considerable interest and have recently been experiencing a period of rapid research and development. Many new technologies are being evaluated both in the lab and the field, mainly for engineering and operational proof-of-concept testing, but some studies have begun to examine environmental impacts. As the number of experimental and permanent field applications increase, so will concerns with the effects of installation and operation on aquatic organisms. Although potential impacts to fish and other organisms have been considered (Cada et al. [1]; Wilson et al. [2]), there is little or no information describing the magnitude or importance of these impacts for most of the new turbine technologies. A primary issue of concern for regulatory and resource agencies is how the operation of hydrokinetic turbines installed in flowing water environments will affect or impact local and migratory fish populations. Consequently, the primary objective of our research was to assess turbine passage survival, injury and scale loss rates, and behavioral effects for fish approaching and passing downstream of operating turbines. This was accomplished by exposing selected fish species and size groups to two hydrokinetic turbine designs installed in a large laboratory test flume.

2.0 STUDY METHODS

2.1 Design and Operation of Hydrokinetic Turbines Selected for Fish Testing

The Lucid Spherical Turbine (LST) is a cross-flow unit designed for installation in pipes or conduits (Northwest PowerPipe™) or in free-flowing unbounded systems (i.e., rivers and tidal areas). The LST used for fish testing was a full-scale model with a diameter (width) of 1.14 m at mid blade, a height of 0.97 m, and four blades (Figure 1). The blades are curved from the top mounting plate to the bottom plate, but they do not twist like the blades of a Gorlov helical turbine. The 1.14-m diameter model is expected to operate at current velocities ranging from about 1.5 to 3.0 m/s. At these flow velocities, the rotational speed of the LST ranges from 64 to 127 rpm and tangential blade velocities at the blade midpoint range from 3.8 to 7.6 m/s.

The Welka Underwater Power Generator turbine (UPG) is a ducted axial-flow turbine design with four blades (Figure 2). The unit provided for fish testing had a diameter of 1.5 m. The Welka UPG is designed to operate at current velocities of about 0.6 to 2.1 m/s with rotational speeds of 15 to 35 rpm. For the minimum and maximum current velocities, blade speeds range from 0.6 to 1.4 m/s at the blade midpoint and 1.2 to 2.8 m/s at the tip. Corresponding strike velocities (assuming fish are traveling at the same speed as the flow) range from 1.6 to 2.5 m/s at the blade midpoint and 1.9 to 3.5 m/s at the tip.

2.2 Model Boundaries and Internal Details

Biological testing was conducted in Alden's large flume fish testing facility (Figure 3). This flume has a concrete floor about 3 m below the top of the side walls. Located beneath this floor at the downstream end of the flume are two 1.7-m diameter bow-thrusters (400 hp each) capable of pumping up to 14.2 m^3/s through the test channel with the assistance of turning vanes at both ends (i.e., flume water is circulated vertically at either end of the flume). The length of the test area is approximately 24.4 m with a total width of 6.1 m and maximum water depth of about 2.4 m. To achieve higher velocities for testing with hydrokinetic turbines, temporary walls were installed to constrict the flume width to 2.4 m (Figure 3). The hydrokinetic turbines were installed at the downstream end of the narrowed flume section. To minimize flow separation and turbulence, the entrance to the narrowed section had rounded walls. The flume was equipped with a side-mounted Acoustic Doppler Current Profiler (ACDP) to measure water velocities and determine flow rates.

Figure 1. The Lucid Spherical Turbine (LST) installed in Alden's large flume test facility (looking upstream with fish release tube in background).

Figure 2. Downstream (A) and upstream (B) views of the he Welka UPG turbine installed in Alden's large flume test facility.

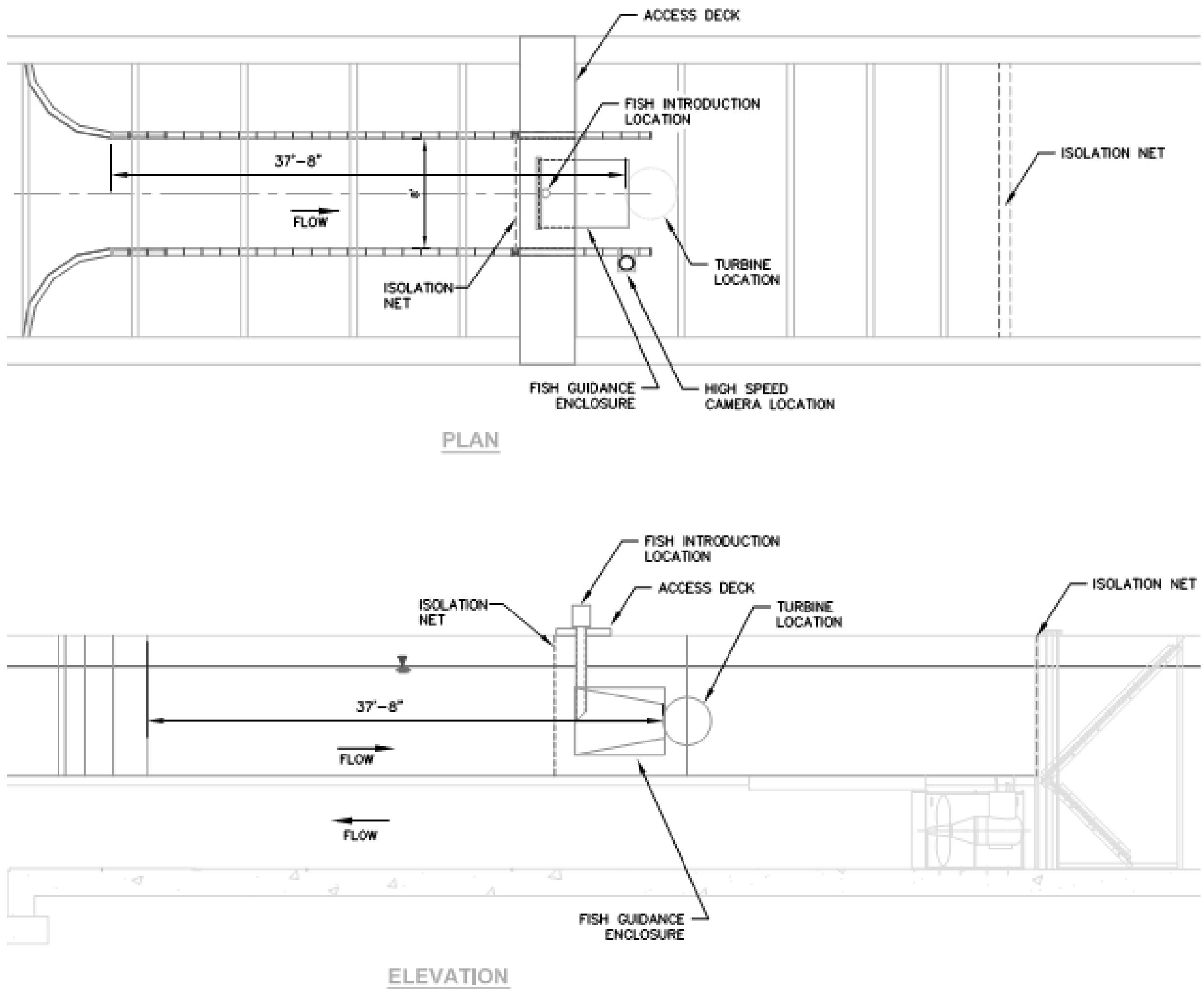

Figure 3. Alden's large flume fish testing facility configured for the biological evaluation of hydrokinetic turbines.

Fish were released into the flume for each test through a vertical 20.3-cm diameter pipe connected to a 25.4-cm diameter horizontal pipe. The upstream end of the horizontal pipe was open and equipped with 2.2-cm knotless mesh to allow the passage of flow and prevent test fish from exiting in the upstream direction. During survival tests, the exit of the horizontal pipe was approximately 25 to 30 cm upstream from the turbines. For survival tests with the Welka UPG turbine, a containment net was used to prevent fish from swimming away from the turbine (either upstream or outside the turbine duct), thereby forcing them to pass downstream through the turbine blade sweep after leaving the release pipe. The containment netting was constructed of 2.2-cm knotless mesh. Due to the spherical shape of the LST and a lack of any type of duct structure, a containment net could not be used to restrict downstream movement of fish through the blade sweep of this turbine design. Therefore, test fish had the ability to avoid passage through the LST by moving laterally or up or down in the water column when they exited from the release pipe.

3.0 Experimental Design and Test Procedures

Survival tests were designed to estimate blade strike injury and mortality associated with fish passage through each turbine (assuming little or no damage to fish would occur due to other injury mechanisms, such as hydraulic shear or pressure changes). To estimate survival, groups of marked fish were released immediately upstream (treatment) and downstream (control) of the test turbines while the turbines were operating at the selected approach flow velocities and rotational speeds. Treatment and control groups were handled and released in the same manner, with the only difference being release location and the subsequent exposure of treatment fish to the operating turbines. The use of controls allowed for injury and mortality associated with handling and test procedures (e.g., marking, release, collection) to be determined and distinguished from that of exposure to the turbines. Target sample sizes were 100 treatment and 100 control fish per trial, with five replicate trials conducted for each set of test conditions (species, size class, channel velocity). All treatment and control fish were marked with biologically inert, encapsulated photonic dyes 24 hours or more prior to testing using a New West POW'R-Ject marking gun. Four dye colors and four fin locations were used to provide 16 unique marks. Uniquely marked release groups allowed treatment and control fish to be released and recovered simultaneously.

After introduction, treatment fish movement and passage through or around the turbines was monitored and recorded with underwater video cameras. Individual tests were terminated after all treatment fish had passed the turbine or approximately ten minutes after introduction. At the completion of each test trial, an isolation screen was lowered immediately upstream of the release location to preclude fish from moving up or downstream of the turbine. The test flume was turned off at this time and the water level was lowered to allow for personnel to enter the flume. Fish were then crowded with a seine net for recovery, counting, and transfer to the holding facility. Live fish were placed in holding tanks and held for 48 hours to monitor delayed mortality.

Survival, injury, and scale loss were determined for all recovered fish. Immediate mortalities were classified as any fish that died within one hour from the completion of a test. Twenty-four hour mortalities were classified as any fish that died after one hour and up to 24 hours of the test completion, and forty-eight hour mortalities were classified as any fish that died between 24 and 48 hours. Injury and scale loss evaluations were conducted at the end of the 48 hour post-test holding period for live fish and at the time of recovery for immediate and delayed mortalities. External injuries were recorded as bruising/hemorrhaging, lacerations, severed body, and eye damage. Using methods similar to those reported by Neitzel et al. [3] and Basham et al. [4], percent scale loss (< 3%, 3 – 20%, 20 – 40%, and > 40%) was recorded for three locations along the length of the body.

The data analysis included assessments of immediate (1 hr) and total (1 hr and 48 hr combined) mortality and injury and scale loss for the selected turbine operating conditions (approach velocity and rotational speed), species, and size groups. Immediate and total passage survival rates were estimated and statistically analyzed using a maximum likelihood estimation (MLE) model developed for paired release-recapture studies with a single recapture event (Burnham et al. [5]; Skalski [6]). Turbine survival and 95% confidence intervals were calculated using pooled-replicate data for each set of test conditions (treatments) following procedures described by Skalski (1999). There were no statistical differences in survival detected among replicate trials within treatments for any of the test conditions evaluated (i.e., fish size and velocity), allowing the data to be pooled.

The input parameters for survival model 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 recovered live.

Immediate (1 hr) and total (1 hr + 48 hr) control survival (S_C) and turbine survival (S_T) were calculated as:

$$S_C = \frac{c}{N_C} \tag{1}$$

$$S_T = \frac{tN_C}{N_T c} \tag{2}$$

with a variance for S_T of:

$$Var(S_T) = S_T^2 \left[\frac{1 - S_C S_T}{N_T S_C S_T} + \frac{(1 - S_C)}{N_C S_C}\right] \tag{3}$$

and a 95% confidence interval ($\alpha = 0.05$) of:

$$S_T \pm 1.96\sqrt{Var(S)} \tag{4}$$

Statistical differences in survival rates between treatment conditions (i.e., between size groups within velocity and between velocities within size group) were determined by non-overlapping confidence intervals. Assumptions associated with this model include: (1) all treatment fish have the same probability of survival; (2) all control fish have the same probability of survival; (3) survival probabilities from the point of the control release to recapture are the same for control and treatment fish; and (4) survival from the point of control release to recapture is conditionally independent of turbine survival.

4.0 RESULTS

4.1 Lucid Spherical Turbine

The mean fork length of rainbow trout (treatment and control fish combined) evaluated during LST trials was 149 mm (SD = 16 mm) for the smaller size group and 250 mm (SD = 16 mm) for the larger size group. Recovery rates for treatment and control groups at the end of each survival test with the LST ranged from 95.0 to 99.6% for smaller fish and 98.4 to 100.2% for the larger fish. Recovery rates greater than 100% indicate more fish were recovered for a treatment or control group than was counted at the time of release. This may have occurred due to errors in the release counts or in the identification or recording of mark colors and fin locations during post-test fish evaluations. Some fish were not recovered during the trial of their release, but were collected during subsequent trials. All treatment and control fish that were recovered during later trials were live at the time of recovery. Seventy-nine fish recovered during survival evaluation trials with the LST did not have marks that could be identified during the post-test injury evaluation. After completing the trials with the first set of test conditions, improvements in marking techniques resulted in very few fish with unidentifiable marks in subsequent tests. Unmarked fish could not be assigned to a release group, but almost all of these fish were recovered live.

Immediate and total survival rates for rainbow trout were greater than 99% for all sets of test conditions evaluated with the LST, except for total survival of the larger fish tested at an approach velocity of 2.1 m/s, which was 98.4% (Table 1). The spherical design of the turbine did not allow for fish to be forced through the blade sweep. Therefore, the estimated survival rates represent the percent of fish that encounter the turbine and proceed downstream by either actively swimming around the turbine or via entrainment through the blade sweep, both without lethal injuries.

The percent of treatment fish recovered without visible external injuries exceeded 95% for both size classes and approach velocities evaluated with the LST. The percent of control fish classified as uninjured was similar to treatment fish, indicating that most injuries observed for treatment fish likely resulted from handling and testing procedures and not interactions with the turbine. Also, turbine-related injury was expected to be minimal given that many fish were observed avoiding entrainment through the turbine blade sweep. Bruising appeared to be the most prevalent injury type, with few lacerations and eye injuries observed among treatment and control fish. The percent of fish classified as descaled ranged from about 6 to 68% for both treatment and control groups. When adjusted for control data, however, the percent of turbine-exposed fish (which either passed around or through the turbine) that were descaled was low, ranging from 0.0% to 4.5%.

Table 1. Estimated survival rates for rainbow trout exposed to the LST. Survival rates greater than 100% indicate control mortality was greater than treatment mortality.

Size Group	Approach Velocity (m/s)	Treatment *N*	Control *N*	Mean Length (mm)	Immediate Survival (1 hr) ± 95% CI	Total Survival (1 hr + 96 hr) ± 95% CI
small	1.5	456	482	161	100.0 ± 0.00	99.99 ± 0.59
	2.1	494	497	138	99.43 ± 1.18	99.03 ± 1.30
large	1.5	504	482	250	100.4 ± 0.80	100.4 ± 0.80
	2.1	501	498	249	99.60 ± 0.55	98.40 ± 1.10

Estimated avoidance of turbine passage by treatment fish of both size classes was high (83 to 94%) at the two approach velocities evaluated with the LST. For both size classes, avoidance was greater at the lower velocity (1.5 m/s). Of the fish that were entrained, most of the smaller fish passed through the blade sweep tail first, whereas larger fish had a greater tendency to enter the blade sweep sideways at the lower test velocity and head first at the higher velocity. Most entrained fish of both size classes passed through the upstream blade sweep at about the same speed as the flow or slower, at both approach velocities evaluated. The estimated percent of fish struck by a blade was relatively high for both size groups (about 53 to 96%), and larger fish appeared to be less susceptible to blade strike. Also, the percent of fish struck by a blade was higher at the lower approach velocity for both size groups. Variability in the video observation data likely represents sampling error resulting from the difficulty in ascertaining the path of all entrained fish through the turbine, which depended on location relative to the underwater cameras and the approach velocity. There was considerably more air entrainment in the flume at the higher approach velocity, which made it more difficult to observe fish and to determine whether they were struck by a blade during turbine passage.

4.2 Welka UPG Turbine

The mean fork length of rainbow trout evaluated during survival tests with the Welka turbine was 124 mm (SD =6) for the smaller size class and 240 mm (SD = 16) for the larger size group. Recovery rates of treatment and control groups evaluated during Welka survival testing ranged from 90.4 to 93.4% for smaller rainbow trout and 99.6 to 101% for the larger size group. Recovery rates greater than 100% may have occurred due to errors in the release counts or in the identification or recording of mark colors and fin locations during post-test evaluations. Some fish were not recovered during the trial of their release, but were collected during subsequent trials. Most unrecovered fish (about 73% for all release groups combined) were collected live during later trials. The percent of unrecovered fish was greater for the smaller size class, most likely because some smaller fish were capable of passing through the mesh of the downstream isolation screen.

Immediate and total turbine passage survival rates for rainbow trout were 100% for the smaller fish evaluated at both approach velocities and the larger fish tested at the lower velocity (1.5 m/s) (Table 2). Immediate and total survival of the larger fish evaluated at the higher velocity (2.1 m/s) were both 99.4% (Table 2). Higher rates of control mortality may have occurred due to greater impingement on the downstream isolation screens compared to treatment fish. Control fish were released closer to the downstream screen and had less time to orient in the flow before encountering the screen. Although velocities were lower downstream of the turbine due to the expansion to full flume width, they were still relatively high at both test velocities (about 0.9 m/s and 1.5 m/s at the two test channel approach velocities that were evaluated). The use of a containment net with the Welka UPG turbine resulted in all treatment fish passing downstream through the turbine's blade sweep. Consequently, the survival estimates represent the expected survival of fish entrained through a Welka UPG turbine at the approach velocities and resulting rotational speeds that were evaluated. This is in contrast to the tests with the Lucid spherical turbine, for which survival estimates were for fish that encountered the turbine and either passed downstream through or around it.

Table 2. Estimated survival rates for rainbow trout exposed to the Welka UPG. Survival rates greater than 100% indicate control mortality was greater than treatment mortality.

Size Group	Approach Velocity (m/s)	Treatment *N*	Control *N*	Mean Length (mm)	Immediate Survival (1 hr) ± 95% CI	Total Survival (1 hr + 96 hr) ± 95% CI
small	1.52	465	467	125	100.87 ± 1.21	100.87 ± 1.35
	2.13	504	496	124	101.57 ± 1.33	101.57 ± 1.33
large	1.52	452	453	230	100.00 ± 0.00	100.00 ± 0.00
	2.13	499	499	248	99.40 ± 0.68	99.40 ± 0.68

The percent of uninjured rainbow trout from treatment groups recovered during survival trials with the Welka UPG turbine ranged from about 75 to 94%. For control groups, the rates of uninjured fish were similar to treatment groups, ranging from about 75 to 95%. Bruising was the most common injury observed, with only a few fish experiencing lacerations or eye injuries. The overall similarity in treatment and control fish injury rates indicates that most injuries suffered by treatment fish were likely due to handling and testing procedures and were not associated with passage through the Welka UPG turbine.

The percent of rainbow trout classified as descaled ranged from about 4 to 29% for treatment fish and 5 to 35% for control fish. Descaling was lower for larger fish and for trials at the lower velocity (1.5 m/s) for both treatment and control groups. However, although similar, descaling of control fish was greater than it was for treatment fish for three of the four sets of test conditions. Consequently, when adjusted for control data, the percent of treatment fish descaled was 0% for all test conditions, except for the smaller fish evaluated at the lower velocity (4.4% descaled). These results indicate that observed descaling of treatment fish was primarily the result of handling and testing procedures and not passage through the Welka UPG turbine.

The mean fork length of largemouth bass evaluated during Welka turbine survival testing was 125 mm (SD =11) for the smaller size class and 242 mm (SD = 20) for the larger fish. Recovery rates of largemouth bass treatment and control groups evaluated for survival with the Welka UPG turbine ranged from 98.6% to 100% for smaller largemouth bass and 99.4 to 100.2% for the larger size group. Unlike rainbow trout, no unrecovered largemouth bass were collected during subsequent trials. Nine largemouth bass did not have identifiable marks following recovery, most of these occurred with the smaller fish tested at the lower velocity. All of largemouth bass without a discernible mark were recovered live.

Immediate turbine passage survival for largemouth bass tested with the Welka UPG turbine was 100% for both size groups and approach velocities (Table 3). Total turbine passage survival was greater than 99% for all test conditions. The use of a containment net with the Welka UPG turbine resulted in all released treatment fish passing downstream through the turbine's blade sweep. Consequently, the survival estimates represent the expected survival of fish entrained through Welka UPG turbine at the approach velocities and resulting rotation speeds evaluated. This is in contrast to the tests with the Lucid spherical turbine, for which survival estimates were for fish that encountered the turbine and either passed downstream through or around the turbine.

Table 3. Estimated survival rates for largemouth bass exposed to the Welka UPG. Survival rates greater than 100% indicate control mortality was greater than treatment mortality.

Size Group	Approach Velocity (m/s)	Treatment *N*	Control *N*	Mean Length (mm)	Immediate Survival (1 hr) ± 95% CI	Total Survival (1 hr + 96 hr) ± 95% CI
small	1.52	499	490	125	100.21 ± 0.69	99.81 ± 0.89
	2.13	499	497	124	100.84 ± 1.27	102.93 ± 2.94
large	1.52	502	490	238	100.00 ± 0.00	100.00 ± 0.56
	2.13	498	499	246	100.00 ± 0.00	99.60 ± 0.56

The percent of largemouth bass classified as uninjured based on the absence of visible external injuries was 97% or greater for both size groups and approach velocities evaluated. The percent of uninjured control fish was similar, exceeding 94% for all test conditions. Consequently, most injuries observed for treatment fish can be attributed to handling and testing procedures and not passage through the Welka UPG turbine. Descaling rates were variable, but greater for both treatment and control fish at the higher approach velocity. The percent of bass classified as descaled ranged from 0 to 35% for treatment fish and about 1 to 56% for control fish. After adjusting for control data, the percent of treatment fish classified as descaled was essentially 0% for both size groups and velocities evaluated.

5.0 DISCUSSION

The information and data developed from this research effort has resulted in a better understanding of the interactions between fish and hydrokinetic turbines for two general design types (vertical cross-flow and ducted axial flow units). However, the ability to apply the study results to other turbines will depend, in part, on differences in design and operation (e.g., blade shape and spacing, number of blades, rotational speeds) compared to the two turbines that were evaluated as part of the current study. Regardless of turbine differences, the observations of fish behavior, particularly avoidance at a very close distance to moving blades, provide strong evidence as to how fish are likely to react when approaching a wide range of hydrokinetic turbine designs in the field.

The evidence that a large proportion of fish will avoid passage through hydrokinetic turbines and that overall survival rates will be high for fish that encounter turbines in open water settings is growing. In addition to the observations from the Alden tests, results from flume testing with a Darreius turbine (cross-flow with straight vertical blades) indicated that Atlantic salmon smolts may avoid turbine passage and that downstream passage survival is likely high (EPRI [7]). In a recent field study, turbine passage survival for several freshwater species with mean lengths ranging from about 100 to 700 mm (about 4 to 30) inches was estimated to be 99% for a ducted axial-flow hydrokinetic turbine (NAI [8]). Individually and collectively, the results from laboratory and field studies suggest that the mortality of juvenile and adult fish encountering hydrokinetic turbine installations may be below levels of concern. However, because the results generally are applicable to the presence of a single turbine, more analysis is needed to assess the potential for multiple units to lead to greater mortality rates or affects on fish movements and migrations.

Fish passage through conventional hydro turbines has been extensively studied resulting in a thorough understanding of potential injury mechanisms. In general, turbine passage survival through conventional turbines has been shown to range from about 80 to 95%, depending on turbine design and fish size. Survival of fish passing through some propeller type turbine designs (e.g., large Kaplans, bulb turbines) may exceed 95%). For many conventional hydro projects, particularly low head sites (less than 30 m), blade strike is considered to be the predominant source of injury and mortality. Given that hydrokinetic turbines are not operated under head and hydraulic and mechanical injury mechanisms are less severe, it is logical to conclude that survival of fish passing through hydrokinetic turbines will be greater than it is for fish passing through conventional hydro turbines. The results of the flume tests described in this report support this conclusion and suggest that survival of fish passing through the blade sweeps of some turbine designs may approach 100% depending on operational conditions. When encounter and avoidance probabilities are considered (and which may exceed 80%), overall downstream passage survival rates of 98 to 100% may be likely for most turbine designs. Future research should focus on expanding the existing data by improving the robustness of estimates of encounter and avoidance probabilities. These data can then be combined with laboratory or theory-based estimates of turbine passage survival to develop turbine and site-specific overall downstream passage survival rates for single and multiple unit installations. The use of computational fluid dynamics (CFD) modeling may also play an important role in such analyses, particularly if fish behavior can be incorporated.

REFERENCES

[1] Čada, G., J. Ahlgrimm, M. Bahleda, T. Bigford, S. Stavrakas, D. Hall, R. Moursund, and M. Sale. "Potential impacts of hydrokinetic and wave energy conversion technologies on aquatic environments", *Fisheries*, 32(4), (2007), pp 174-181.

[2] Wilson, B., R.S. Batty, F. Daunt, and C. Carter, *"Collision Risks between Marine Renewable Energy Devices and Mammals, Fish and Diving Birds",* Scottish Association for Marine Science, Oban, Scotland, (2007), PA25 1QA, 110 p.

[3] Neitzel, D. A., C. S. Abernethy, E. W. Lusty, and L. A. Prohammer, *"A Fisheries Evaluation of the Sunnyside Canal Fish Screening Facility*, *Spring 1985",* Annual Report prepared for U.S. Department of Energy Contract DE-AC06-76RLO 1830, (1985).

[4] Basham, L. R., M. R. Delarm, J. B. Athern, and S. W. Pettit, *"Fish Transportation Oversight Team Annual Report, FY 1981",* NOAA Technical Memorandum NMFS F/NNR-2, Environmental and Technical Services Division, Northwest Regional Office, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Portland, OR, (1982).

[5] Burnham, K. P., D. R. Anderson, G. C. White, C. Brownie, and K. H. Pollock, "*Design and Analysis for Fish Survival Experiments Based on Release-Recapture*", American Fisheries Society Monograph 5, (1987).

[6] Skalski, J. R., "Statistical Input to the Design and Analysis of the ARL/NREC Pilot Scale Fish-Friendly Turbine", prepared for Alden Research Laboratory, Inc., (1999).

[7] EPRI (Electric Power Research Institute), "Biological Testing of Effects of EnCurrent Model ENC-005-F4 Hydrokinetic Turbine on Juvenile Atlantic Salmon and Adult American Shad", prepared by the USGS Conte Anadromous Fish Research Laboratory, (2011).

[8] NAI (Normandeau Associates, Inc.), "An Estimation of Survival and Injury of Fish Passed through the Hydro Green Energy Hydrokinetic System, and a Characterization of Fish Entrainment Potential at the Mississippi Lock and Dam No. 2 Hydroelectric Project (P-4306), Hastings, Minnesota", prepared for Hydro Green Energy LLC, Houston, Texas, (2009).