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Evaluation of Fish Injury and Mortality Associated with Hydrokinetic Turbines

2011 TECHNICAL REPORT

Evaluation of Fish Injury and Mortality Associated with Hydrokinetic Turbines

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1024569
Final Report, November 2011

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Acknowledgments

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

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This report describes research sponsored by EPRI.

This material is based upon work supported by the Department of Energy Water Power Program under Award Number DE-EE0002659. Additional financial support was received from Canada Department of Fisheries & Oceans and Alaska Energy Authority.

We are grateful to Lucid Energy Technologies for providing the Lucid spherical turbine and Glades Hydropower and Dr. Manfred Kuehnle for providing the Welka UPG turbine for the purposes of biological testing. In addition to the Principal Investigators, Alden staff members who provided significant support to the performance and successful completion of this project included Nick Lucia, Jason Muise, Kevin Lamontagne, and Brian Boyce.

Constructive comments by Jocelyn Brown-Saracino and her colleagues, U.S. Department of Energy, and by Glenn Cada, Oak Ridge National Laboratory strengthened this report. We also thank Doug Dixon of EPRI for his leadership of this project during its formative stage.

This publication is a corporate document that should be cited in the literature in the following manner:

Evaluation of Fish Injury and Mortality Associated with Hydrokinetic Turbines.
EPRI, Palo Alto, CA: 2011.
1024569.

Abstract

Considerable efforts have been underway to develop hydrokinetic energy resources in tidal and riverine environments throughout North America. Potential for fish to be injured or killed if they encounter hydrokinetic turbines is an issue of significant interest to resource and regulatory agencies. To address this issue, flume studies were conducted that exposed fish to two hydrokinetic turbine designs to determine injury and survival rates and to assess behavioral reactions and avoidance. Also, a theoretical model developed for predicting strike probability and mortality of fish passing through conventional hydro turbines was adapted for use with hydrokinetic turbines and applied to the two designs evaluated during flume studies. The flume tests were conducted with the Lucid spherical turbine (LST), a Darrieus-type (cross flow) turbine, and the Welka UPG, an axial flow propeller turbine. Survival and injury for selected species and size groups were estimated for each turbine operating at two approach velocities by releasing treatment fish directly upstream and control fish downstream of the operating units. Behavioral observations were recorded with underwater video cameras during survival tests and during separate trials where fish were released farther upstream to allow them greater opportunity to avoid passage through the blade sweep of each turbine. Survival rates for rainbow trout tested with the LST were greater than 98% for both size groups and approach velocities evaluated.

Turbine passage survival rates for rainbow trout and largemouth bass tested with the Welka UPG were greater than 99% for both size groups and velocities evaluated. Injury rates of turbine-exposed fish were low for tests with both turbines and generally comparable to control fish. When adjusted for control data, descaling rates were also low (0.0 to 4.5%). Video observations of the LST demonstrated active avoidance of turbine passage by a large proportion fish despite being released about 25 cm upstream of the turbine blade sweep. Video observations from behavior trials indicated few if any fish pass through the turbines when released farther upstream. The theoretical predictions for the LST indicated that strike mortality would begin to occur at an ambient current velocity of about 1.7 m/s for fish with lengths greater than the thickness of the leading edge of the blades. As current velocities increase above 1.7 m/s, survival was predicted to decrease for fish passing through the LST, but generally remained high (greater than 90%) for fish less than 200 mm in length.

Strike mortality was not predicted to occur during passage through a Welka UPG turbine at ambient current velocities less than about 2.5 m/s. 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). 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 impacts on fish movements and migrations. Additionally, future research should focus on expanding the existing data by developing better estimates of encounter and avoidance probabilities.

Keywords

Fish
Hydrokinetic turbine
Laboratory flume
Strike modeling

Executive Summary

Background and Project Objective

With a pressing need for alternative energy sources in the U.S., Canada and around 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. 2007; Wilson et al. 2007), there is little or no information describing the magnitude or importance of these impacts for most of the new turbine technologies. Consequently, the primary objective of our research was to determine injury and survival rates and behavioral effects for fish approaching and passing downstream of hydrokinetic turbines. This objective was accomplished through the performance of flume studies and theoretical modeling. The flume studies were conducted with two turbine designs, two fish species, two size groups, and two approach velocities, and were designed to estimate injury and survival rates and describe fish behavior in the vicinity of the operating turbines. Also, a theoretical model developed for predicting strike probability and mortality of fish passing through conventional hydro turbines was adapted for use with hydrokinetic turbines and applied to the two designs evaluated during flume studies.

Methods

Biological testing was conducted with two turbine designs, the Lucid spherical turbine (LST) developed by Lucid Energy Technologies and the Welka UPG developed by Current-to-Current. The LST is a Darrieus-type (cross-flow) turbine and the Welka UPG is a horizontal-axis propeller turbine. Survival and injury for selected species and size groups were estimated for each turbine operating at two approach velocities (and corresponding turbine rotational speeds) by releasing treatment fish directly upstream and control fish downstream of the operating units. Treatment fish were forced to pass through the ducted Welka UPG using a containment net enclosing the fish release system and the upstream side of the turbine (i.e., fish could only pass downstream through the turbine with this net in place).

A containment net could not be used with the LST due to the spherical design, which allowed treatment fish the opportunity to avoid entrainment through the blade sweep after exit from the release system at a point of about 25 cm from the upstream face of the turbine (on the blade centerline). Behavioral observations were recorded with underwater video cameras during survival tests and during separate trials where fish were released farther upstream to allow them greater opportunity to avoid passage through the blade sweep of each turbine (within the confined space of the test channel).

Testing with each turbine design was conducted in a large flume with re-circulating flow. To achieve higher velocities for testing with hydrokinetic turbines, temporary walls were installed to constrict the flume width to 2.4 m with a depth of 2.4 m. The hydrokinetic turbines were installed at the downstream end of this narrowed flume section. Tests with both turbines were conducted at approach velocities of 1.5 and 2.1 m/s with two size groups of rainbow trout. Two size groups of largemouth bass were also evaluated with the Welka UPG at the same velocities.

The survival analysis for the two turbine designs involved assessments of immediate (1 hr) and delayed (48 hr) mortality. Injury and scale loss rates were also estimated. Immediate and total (1-hr plus 48-hr) 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. 1987; Skalski 1999). Survival estimates for the LST include fish that were entrained through the blade sweep and fish that avoided turbine passage and moved downstream around the margins of the unit. Because fish evaluated with the Welka UPG could only pass downstream through the turbine, the survival estimates for this design represent direct turbine mortality and do not account for avoidance behaviors that would allow fish to pass safely around the turbine.

Results

Lucid Spherical Turbine

Immediate and total survival rates for rainbow trout tested with the LST were greater than 99% for all sets of test conditions, except for total survival of the larger fish tested at an approach velocity of 2.1 m/s, which was 98.4% (Table ES-1). Immediate survival was not significantly different between the two velocities tested with each size group, or between size groups at each velocity ($P > 0.05$). For the larger fish, total survival was significantly greater at the lower velocity ($P < 0.05$). There were no statistical differences in total survival between size groups at each velocity, or between velocities for the smaller fish ($P > 0.05$). The percentage of treatment fish recovered without visible external injuries (e.g., bruising, lacerations, and eye damage) exceeded 95% for both size classes and approach velocities evaluated. The percentage of control fish classified as uninjured was similar to treatment fish for both size classes and velocities, indicating that most injuries observed for treatment fish likely resulted from handling and testing procedures and not turbine interactions. When adjusted for control data, 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 ES-1
Estimated mean survival rates for rainbow trout exposed to the LST. Survival rates greater than 100% indicate control mortality was greater than treatment mortality.

Approach Velocity (m/s)	Treatment N	Control N	Mean Length (mm)	Immediate Survival (1 hr) ± 95% CI	Total Survival (1 hr + 48 hr) ± 95% CI
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
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

A review of underwater videos from a single trial conducted with each velocity and size class demonstrated that avoidance of turbine passage by treatment fish of both size classes was high (82 to 94%) at the two approach velocities evaluated with the LST. Of the fish that were entrained through the rotor, 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 either the same speed as the flow or slower, at both approach velocities evaluated. The estimated percent of entrained fish struck by a blade during the initial passage through the blade sweep (i.e., on upstream side of turbine) was relatively high for both size groups (about 53 to 91%), and larger fish appeared to be less susceptible to strike at both approach velocities. General video observations from behavioral trials with the LST demonstrated few if any fish interacted with the turbine or were entrained through the blade sweep. Fish typically followed paths along the walls and floor of the test flume. Very few fish were observed entering or interacting with the turbine unit.

Welka UPG Tests

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 ES-2). Immediate and total survival of the larger fish evaluated at the higher velocity (2.1 m/s) were both 99.4%. The only statistical differences detected among the survival rates was between the smaller and larger size groups at an approach velocity of 2.1 m/s, for which the smaller fish had significantly higher immediate and total survival ($P < 0.05$). 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%. 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 not turbine passage. 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.

Table ES-2
Estimated mean survival rates for rainbow trout (RBT) and largemouth bass (LMB) exposed to the Welka UPG. Survival rates greater than 100% indicate control mortality was greater than treatment mortality.

Species	Approach Velocity (m/s)	Treatment N	Control N	Mean Length (mm)	Immediate Survival (1 hr) ± 95% CI	Total Survival (1 hr + 48 hr) ± 95% CI
RBT	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
	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
LMB	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
	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

Immediate turbine passage survival for largemouth bass tested with the Welka UPG turbine was 100% for both size groups and approach velocities (Table ES-2). Total turbine passage survival was greater than 99% for all test conditions. Statistically significant differences were not detected among any of the test conditions (fish size and approach velocity) evaluated with largemouth bass ($P > 0.05$). The percents of largemouth bass classified as uninjured based on the absence of visible external injuries were 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 turbine passage. After adjusting for control data, the percent of treatment fish classified as descaled was essentially 0% for both size groups and velocities.

General video observations during behavioral testing with the Welka UPG at the 1.5 m/s velocity demonstrated that fish passing downstream towards the turbine units swam or drifted along the floor or walls of the flume. Video observations at the higher velocity were difficult to make due to the presence of entrained air bubbles, which severely limited the ability to see fish approaching the turbine. Most rainbow trout observed approaching the turbine were actively swimming (i.e., tail beating was visible) and facing upstream. Largemouth bass, however, were more likely to drift passively, particularly at the higher channel velocity. Many bass were observed facing upstream but were not actively swimming. In general, video observations from Welka UPG behavioral tests demonstrated that most fish followed flow paths along the walls and floor of the flume. Very few fish were observed passing through or interacting with the turbine.

Theoretical Predictions of Blade Strike

Theoretical models for the probability of blade strike have been developed for use with conventional hydro turbines by several researchers (Von Raben 1957; Franke et al. 1997; Turnpenny et al. 2000; Ploskey and Carlson 2004; Hecker and Allen 2005). Also, some studies have investigated the effects of leading edge blade geometry (shape and thickness), blade speed, and fish orientation on strike injury and survival (Turnpenny et al. 1992; EPRI 2008, 2011b). In concept, the general theoretical model developed for predicting strike probability and mortality for conventional turbines can be applied to hydrokinetic turbines because the mechanics of fish passing through turbines of each application type are, for the most part, the same. However, an important component of strike probability and mortality models that needs to be considered for hydrokinetic turbines is the velocity of fish as they pass through the blade sweep of a turbine. For conventional hydro turbines, fish velocity is assumed to be that of the inflow velocity, which typically is very high (> 6 m/s). Hydrokinetic turbines operate at lower approach flow velocities (perhaps between 1 to 5 m/s depending on the location and turbine design), and some fish may be able to swim against these velocities to a certain degree. For simplicity and because there is little reliable information on fish speed and behavior approaching various hydrokinetic turbine designs, our application of the strike probability and mortality model to the two turbines evaluated in the flume assumes that fish are traveling at the same velocity as the approach flow. Additionally, it is important to note that theoretical predictions of blade strike do not account for avoidance of the turbine blades by fish, which this study revealed to be significant.

LST Strike Probability and Mortality Predictions

For the LST, strike mortality was predicted to occur at an ambient current velocity of about 1.7 m/s when the strike velocity (relative velocity of fish to blade) is of a sufficient magnitude (greater than about 5 m/s) to cause fatal injuries to fish with lengths that are greater than the thickness of the leading edge of the blades. Strike mortality also increased with fish speed for any given fish length due to corresponding increases in strike velocity. Turbine passage survival for single and double passes through the blade sweep decreased with increases in fish size and ambient current velocity based upon the estimated strike probability and mortality rates. With respect to the effect of fish entry location relative to the vertical plane, passage survival increased as fish move away from the turbine centerline at the same current velocity. Mortality decreases because the turbine diameter decreases above and below the turbine centerline, resulting in a reduced blade speed and therefore a lower strike velocity. As current velocities begin to exceed 1.7 m/s, turbine passage survival was predicted to decrease primarily for larger fish, but generally remained high (greater than 90%) for fish less than 200 mm in length.

The theoretical estimates of turbine passage survival for the LST and the survival estimates calculated from the flume data cannot be directly compared because the flume estimates include fish that avoided turbine passage. However, the flume data indicated survival for all fish, including those that passed through the blade sweep of the LST, was 100% at an approach velocity of 1.5 m/s. This is consistent with the theoretical predictions of turbine passage survival for this approach velocity and supports the conclusion that fish struck by turbine blades at strike velocities less than about 5 m/s will not sustain fatal injuries (strike velocity on the centerline of the LST is about 4.1 m/s at an approach velocity of 1.5 m/s). Total survival of fish tested in the flume at a velocity of 2.1 m/s was 99.0 and 98.4% for the smaller and larger-sized fish, respectively, both of which are higher estimates of survival than theoretical predictions. The differences between empirical and theoretical data at this velocity reflect the ability of fish to avoid turbine passage in the flume. Experimental and theoretical estimates of survival would be more comparable if the experimental data were sufficient to only include fish entrained through the blade sweep in the calculation of turbine passage survival rates.

Welka UPG Strike Probability and Mortality Predictions

Predicted strike probabilities for fish passing through a Welka UPG turbine increased with fish length and were the same for all ambient current velocities and strike locations along a blade for a given length. Strike probability only varies with fish size because increases in blade speeds with distance from the hub are proportional to the wider spacing between blades, and because fish pass through the turbine more quickly as approach velocity (and blade speed) increase. For fish 600 mm in length and less, strike mortality will not occur during passage through a Welka UPG turbine at ambient current velocities less than about 2.5 m/s because strike velocities will not exceed 5 m/s, which is the approximate upper limit above which fish mortality will begin to occur [depending on the ratio of fish length to blade thickness; EPRI (2008)]. Consequently, estimated turbine passage survival will be 100% for fish that pass through a Welka turbine over the entire blade length at an ambient current of 2.5 m/s or less. Also, the theoretical estimates are consistent with the experimental results from flume testing (mean survival rates ranging from 99.4 to 100%). Note that the experimental setup forced all test fish through the ducted Welka UPG turbine, thereby precluding turbine avoidance by the fish.

Conclusions

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). 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, turbine diameter, and 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.

Little, if any, mortality, injury, and scale loss are expected to occur for fish encountering an LST in an open water environment (i.e., riverine or tidal). Similarly, fish entrained through a Welka UPG turbine will suffer little or no injury and mortality over the likely range of operating conditions. The theoretical predictions of turbine passage survival for the LST differed from the lab results, but this was due to the ability of fish to avoid passage through the turbine during flume testing, whereas the strike probability and mortality model is only applied to fish that pass through the blade sweep. This highlights the limitations of theoretical strike predictions that do not account for avoidance and evasive behavior by fish. For the Welka UPG, turbine passage survival predictions were consistent with the experimental results from flume testing, suggesting that a predictive model could be used to assess turbine passage survival rates at future field installations for fish that do not avoid the turbines.

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 at Conte Anadromous Fish Research Laboratory with a Darrieus turbine (cross-flow with straight vertical blades) indicated that Atlantic salmon smolts may avoid turbine passage and that downstream passage survival is likely to be high (EPRI 2011c). 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 2009). Individually and collectively, the results from laboratory and field studies suggest that the mortality of juvenile and adult fish passing through hydrokinetic turbines of this design, and perhaps others, will 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 impacts on fish movements and migrations. Additionally, future research should focus on expanding the existing data by developing better estimates of encounter and avoidance probabilities. Encounter rates could be developed from field monitoring of fish abundance and movements or based on the proportion of channel flow that passes through a turbine (or the cross-sectional area of a channel that a turbine's blade sweep occupies).

Avoidance probabilities for fish that encounter a turbine could also be derived from field monitoring or additional flume testing. These data can then be combined with laboratory or theory-based estimates of turbine passage survival to develop a more comprehensive model that incorporates site-specific hydraulic and environmental conditions to estimate total expected fish losses 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.

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Section 1: Introduction

With growing demand for alternative energy sources in the U.S. and elsewhere, marine and hydrokinetic power generation 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 laboratory and the field, mainly for engineering and operational proof-of-concept testing; however, some studies have begun to examine environmental impacts (RESOLVE 2006; DTA 2006; Wilson et al. 2007; DOE 2009; NAI 2009). 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 identified and considered (Cada et al. 2007; Wilson et al. 2007), there is little or no information describing the relative magnitude or importance of these impacts for many 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. In particular, what is the potential for fish to be killed or injured if they pass through one or more turbines, and what is the potential for operating turbines to disrupt or block fish movements and migrations?

Environmental impacts associated with hydrokinetic turbines will depend primarily on turbine type and design and the characteristics of the environment in which the turbines are deployed (e.g., river, tidal, or ocean). Direct impacts potentially include fish injury and mortality due to blade strike and hydraulic conditions that can damage or disorient fish (Cada et al. 2007; Wilson et al. 2007). Potential indirect impacts are related to disruptions in local movements and migrations, and access to feeding, spawning, and nursery habitats in the vicinity of turbine installations. The size and numbers of turbines installed may influence the magnitude of direct and indirect impacts. The potential for injury and mortality of fish that pass through operating hydrokinetic turbines is a leading concern, particularly if installations are located in rivers with diadromous fish populations (i.e., species that undergo obligatory upstream and downstream migrations that occur during specific times of the year). Similar to rivers with numerous hydro dams, local fish populations may encounter multiple turbines and thereby experience the cumulative effects of passage at multiple turbines at a single project and at multiple projects on a given river. Fish injury and mortality may also be an important issue for hydrokinetic turbines deployed in tidal and ocean environments if the turbines are located in areas where large numbers of fish encounter and pass through the turbines. The location of turbines will also be an important factor with respect to the potential for disruption of fish movements.

The Electric Power Research Institute (EPRI) was awarded a grant by the U.S. Department of Energy (DOE) to develop information and data that can be used to assess the potential for any given project to adversely affect fish by completing the following studies:

- Review of existing information on injury mechanisms associated with fish passage through conventional hydro turbines and the relevance and applicability of this information to fish passage through hydrokinetic turbines.
- Flume testing with up to three turbine designs and several species and size classes of fish to estimate direct injury and survival rates and describe fish behavior in the vicinity of operating turbines.[1]
- Development of theoretical models for the probability of blade strike and mortality for various hydrokinetic turbine designs

EPRI contracted Alden Research Laboratory, Inc. (Alden) to conduct these studies. This report describes the study approach and results for the application of theoretical blade strike models to hydrokinetic turbines and the evaluation of fish interactions with two turbine designs installed in Alden's large flume test facility. The review of existing information on fish passage through conventional hydro turbines as it relates to hydrokinetic turbines is provided in a separate report submitted by EPRI to the DOE (EPRI 2011a).

The primary goal of the studies described herein was to provide developers and resource and regulatory agencies with data to better assess the potential impacts of hydrokinetic turbines on local and migratory fish populations. Achieving this goal will facilitate licensing of proposed hydrokinetic energy projects in the U.S. The blade strike probability and mortality models and the laboratory data that are presented likely will reduce the need and cost for expensive and logistically difficult field studies and serve as baselines for the assessment of fish impacts of any turbine design. However, because laboratory evaluations cannot fully replicate what will occur in the field, some level of in-water testing may be needed for future installations. Also, future studies can build on the results of the studies presented in this report to improve and expand the dataset, reduce uncertainties, and increase the confidence with which resource and regulatory agencies can evaluate the potential for adverse environmental impacts. The lab and desktop studies should contribute to the understanding of environmental impacts to help reduce uncertainty and risk in decision-making for permitting of hydrokinetic turbines.

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[1] Limited availability of turbine designs suitable for flume testing and the final scope of work for this project resulted in testing of two designs at Alden. A third turbine design was tested at the USGS Conte Anadromous Fish Research Laboratory, which is discussed in a separate report.

Section 2: Biological Evaluation – Test Methods

Biological testing was conducted with two turbine designs, a spherical cross-flow turbine developed by Lucid Energy Technologies and a horizontal-axis propeller turbine developed by Current-to-Current. Fish survival was estimated for each turbine and selected operating conditions (approach velocity and corresponding turbine rotational speed) by releasing test fish directly upstream and control fish downstream of the operating units. Survival estimates account for direct injury and mortality, but do not address indirect effects (e.g., higher rates of disease and predation) related to sub-lethal injuries. Behavioral observations were recorded with underwater video cameras during survival tests and during separate trials where fish were released farther upstream to allow them greater opportunity to avoid passage through the blade sweep of each turbine (within the confined space of the test channel). Detailed information on the turbines, test facility, and experimental design is provided below.

Design and Operation of Hydrokinetic Turbines Selected for Fish Testing

Lucid Spherical Turbine

The Lucid spherical turbine (LST) is a cross-flow unit designed for installation in pipes or conduits (Northwest PowerPipe^{TM}) 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 of 1.14 m (45 inches), a height of 0.97 m (38 inches), and four blades (Figure 2-5). 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 (5 to 10 ft/s). At these flow velocities, the rotational speed of the LST ranges from 64 to 127 rpm (Figure 2-2) and tangential blade velocities at the blade midpoint range from 3.8 to 7.6 m/s (Figure 2-3).

Figure 2-1
Lucid spherical turbine installed in Alden's test flume for fish testing

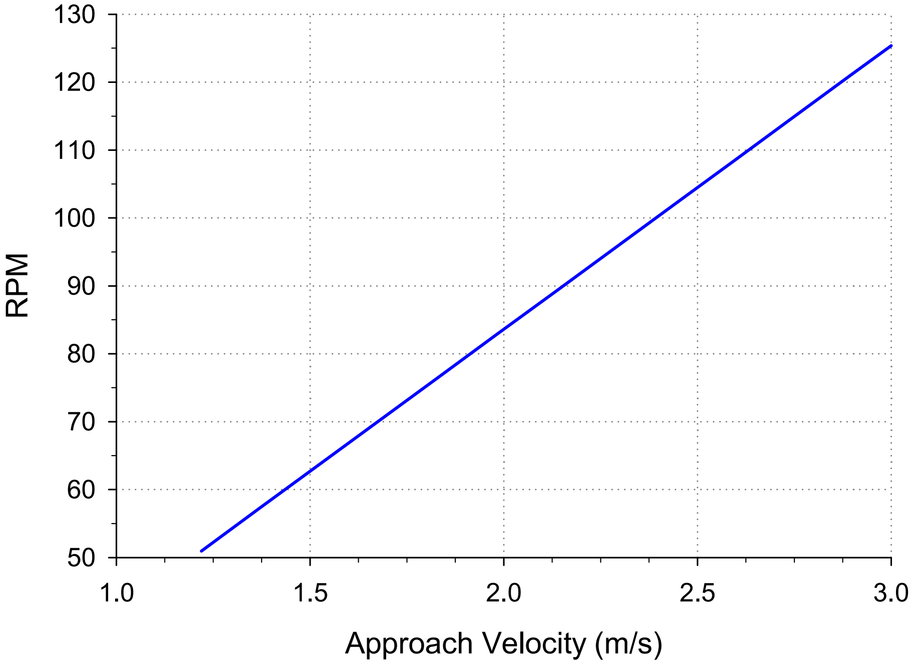


Figure 2-2
Rotational speed versus approach flow velocity for the Lucid spherical turbine

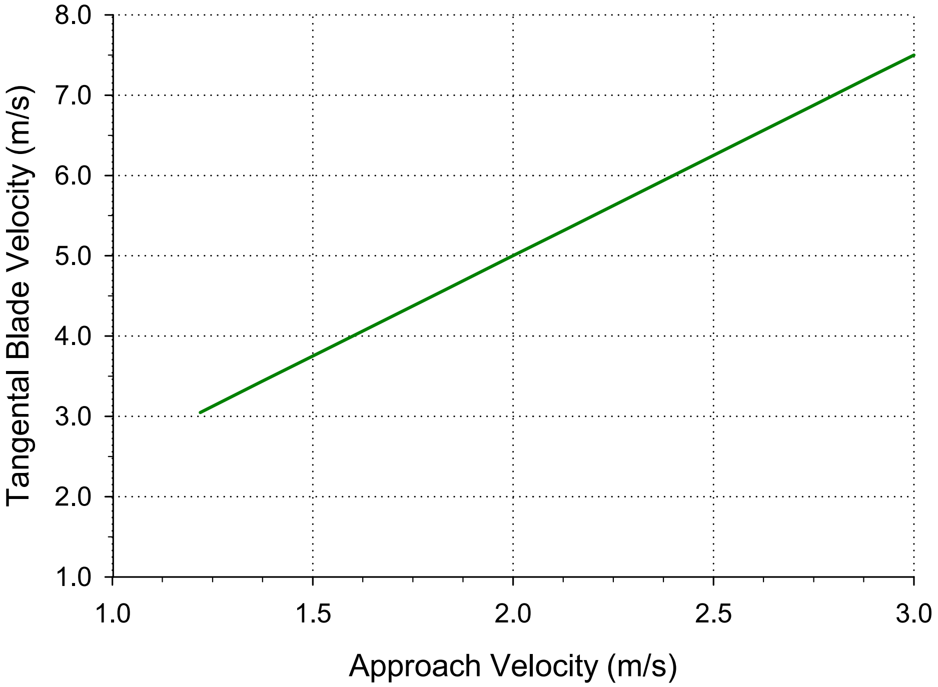


Figure 2-3
Tangential blade velocity (at blade midpoint) versus approach flow velocity for the Lucid spherical turbine

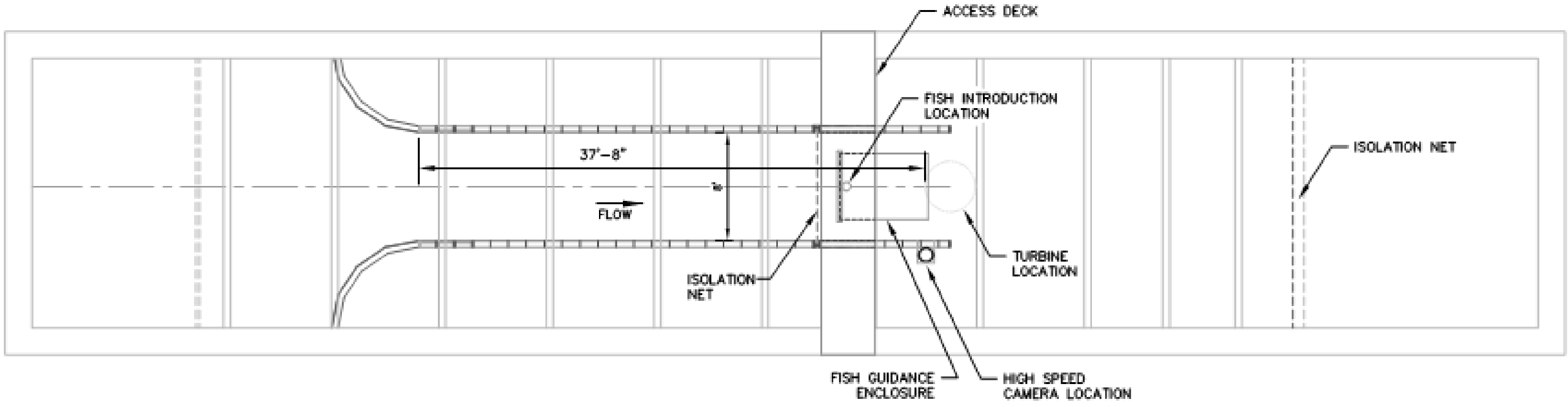
Welka Underwater Power Generator (UPG) Turbine

The Welka Underwater Power Generator turbine (UPG) is a ducted horizontal-axis turbine design with four blades. The unit provided for fish testing, which has been previously tested in Alden's large flume facility for operational performance, had a diameter of 60 inches (Figure 2-4). This unit is designed to operate at current velocities of about 0.6 to 2.1 m/s (2 to 7 ft/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 (i.e., relative velocity of fish to blade) for fish traveling at the speed of the approach 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. Strike velocities will be higher for fish passing through the blade sweep faster than the approach flow, and lower for fish passing at slower speeds.

Figure 2-4
Downstream (A) and upstream (B) views of the Welka UPG turbine installed in Alden's large flume test facility

Test Facility Design and Operation

Biological testing of each hydrokinetic turbine was conducted in Alden's large flume fish testing facility (Figure 2-5). The test flume has a concrete floor about 3 m (10 ft) below the top of the side walls. Located beneath this floor at the downstream end of the flume are two 1.7-m diameter (66 inch) bow-thrusters (400 hp each) capable of pumping up to 14.2 m^3/s (500 cfs) 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 (80 ft) with a total width of 6.1 m (20 ft) and maximum water depth of about 2.4 m (8 ft). To achieve higher velocities for testing with hydrokinetic turbines, temporary walls were installed to constrict the flume width to 2.4 m (8 ft) (Figure 2-6). 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 is equipped with a side-mounted Acoustic Doppler Current Profiler (ACDP) to measure water velocities and determine flow rates to establish specific experimental treatments.



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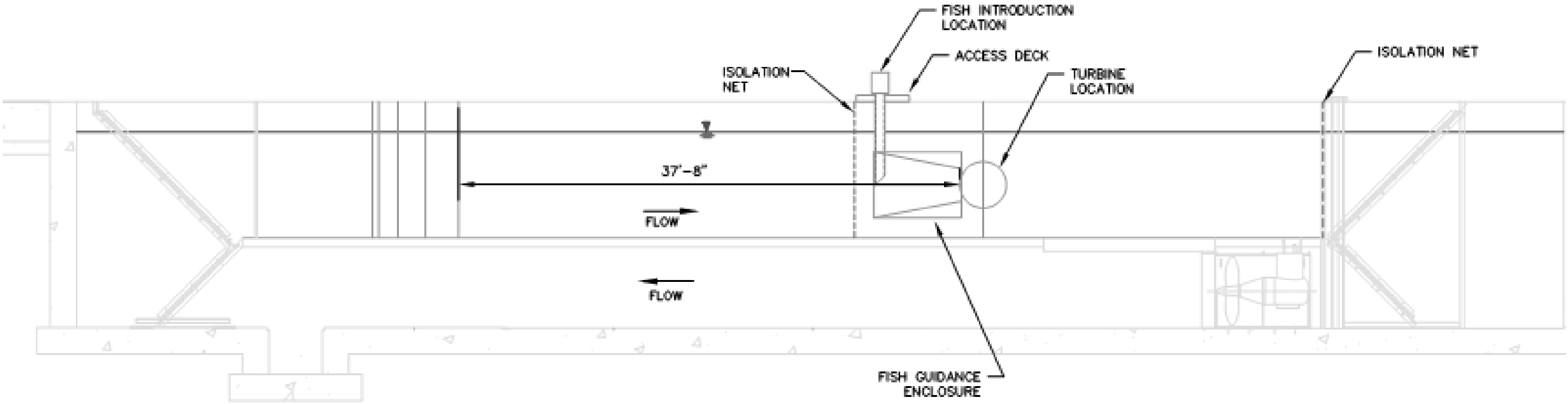

ELEVATION

Figure 2-5
Alden's large flume fish testing facility configured for the biological evaluation of hydrokinetic turbines

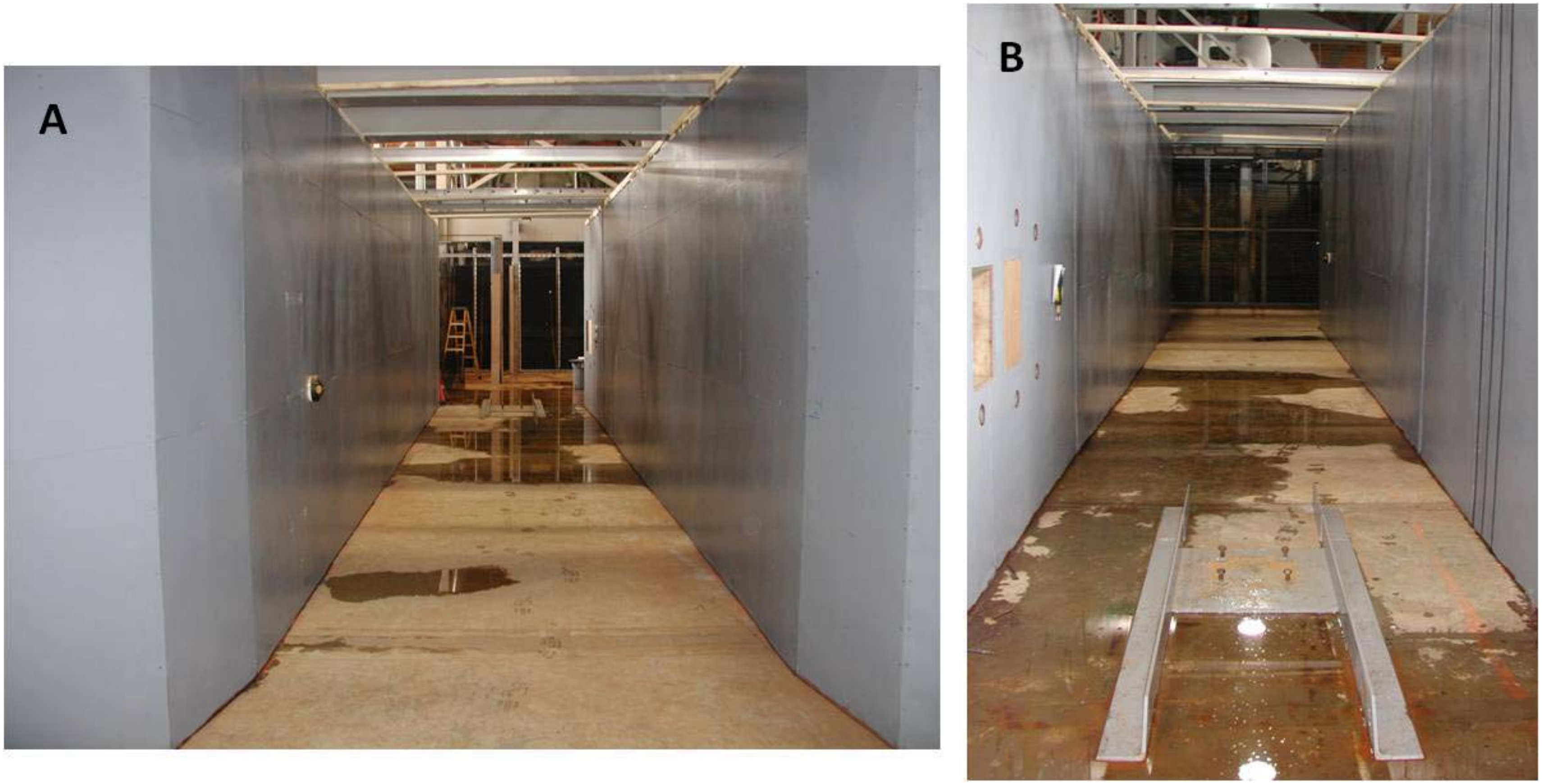

Figure 2-6
Downstream View (A) and Upstream View (B) of Alden's large flume fish testing facility configured for the biological evaluation of hydrokinetic turbines with constricting walls installed

Flume water quality was maintained using a canister filter system and ultraviolet (UV) sterilization installed on a side loop that received flume water through a 15-hp pump. Filter bags with 10-micron mesh were used in the canister filter to remove particulates and solids in order to maintain good water clarity. The UV sterilizer was used to reduce the presence of pathogens. A 100-ton chiller was used when needed to maintain water temperatures at specified levels for the species selected for testing (rainbow trout and largemouth bass).

Fish were released into the flume for each test through a vertical 20.3-cm (8-inch) diameter pipe connected to a 25.4-cm (10-inch) diameter horizontal injector tube located just upstream of each turbine (Figure 2-7). The vertical pipe was covered with an aluminum shroud elongated in the upstream and downstream directions to reduce head loss associated with the obstruction of flow. The upstream end of the horizontal injector tube was equipped with 2.2 cm (0.875-inch) knotless mesh to prevent test fish from exiting the injection system in the upstream direction (i.e., away from the turbines). During survival tests the front of the horizontal injector was approximately 10- 12 inches from the upstream face of the LST blade sweep and the shroud of the ducted Welka UPG. For survival tests with the Welka 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 injector tube (Figure 2-8). The containment netting was constructed of 2.2 cm (0.875-inch) 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 turbine's blade sweep. Therefore, test fish had the ability to avoid passage through the LST during survival testing by moving laterally or up or down in the water column when they exited from the injector tube. For behavioral tests, the injection system was moved farther upstream (and the containment netting was removed for tests with the Welka UPG) to allow fish the opportunity to avoid entrainment through the blade sweep of each turbine. Thus, the goal of these tests was to monitor behavioral reactions as fish approached each turbine and to estimate percent avoidance and entrainment. However, video quality was not sufficient to view all areas around the two turbines, preventing detection of some fish as the passed downstream. This was particularly true for tests at the higher velocity (2.1 m/s), during which air entrainment was significant and resulted in limited visibility.

Figure 2-7
Downstream view of the test fish release system configured for survival testing with the Lucid turbine

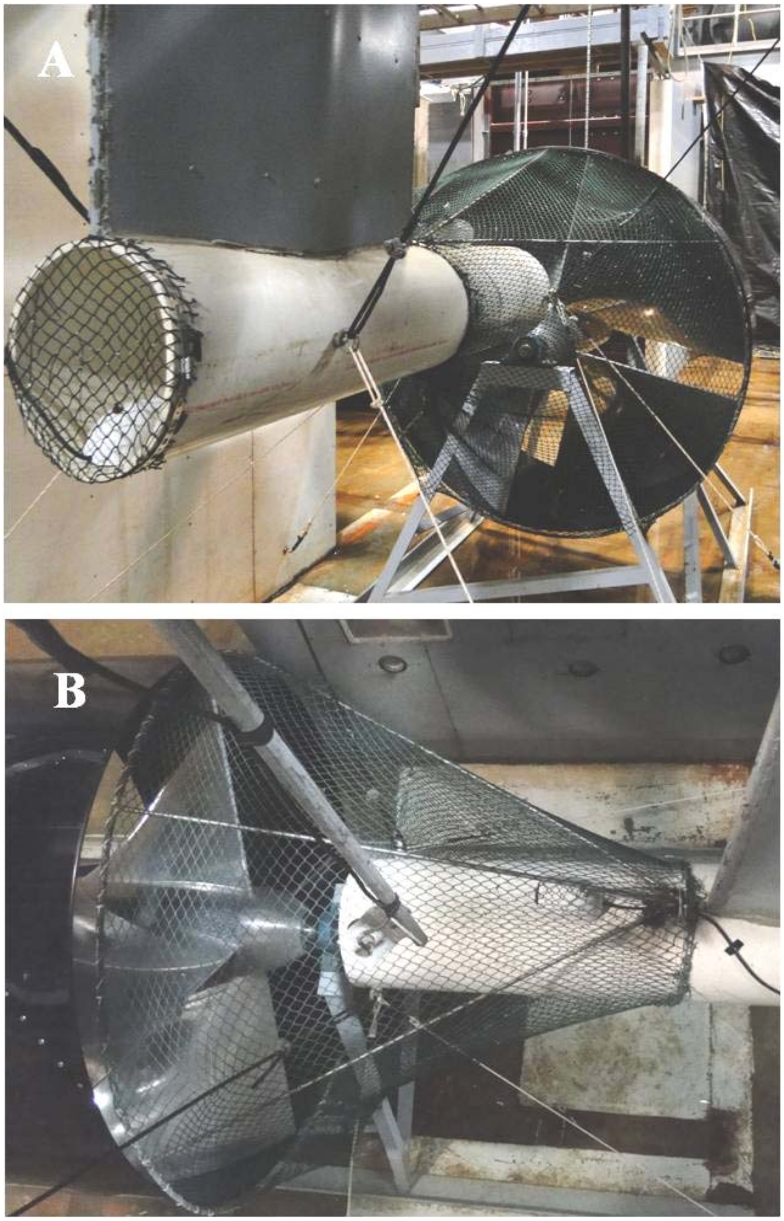

Figure 2-8
Downstream view (A) and top view (B) of the Welka UPG turbine configured with containment netting to prevent fish from passing downstream outside the turbine during survival testing.

Test Species and Fish Holding Facility Design and Operation

Two fish species, rainbow trout and largemouth bass, were selected for testing based on availability from commercial suppliers and similarity to a variety of species that are likely to encounter hydrokinetic turbines in riverine environments. Rainbow trout were acquired from Hy-On-A-Hill Trout Farm located in Plainsfield, New Hampshire, and largemouth bass were acquired from Hickling's Fish Farm Inc. located in Edmeston, New York. Both sources are certified disease-free facilities, ensuring that test fish were of high quality and in good health. Target size classes selected for testing with both species included length ranges of about 100 to 150 mm (4 to 6 inches) and 225 to 275 mm (9 to 11 inches). These ranges were considered sufficient to test for differences in survival associated with fish length, are representative of the sizes of many fish species and life stages that will encounter hydrokinetic turbines in riverine and tidal environments, are readily available from commercial sources, and can be held, handled, and tested in a laboratory environment without the need for special procedures, holding facilities, or testing equipment.

All fish were held prior to testing and during 48-hr post test observation periods in a re-circulating fish holding system located in a building adjacent to the test flume. The holding facility has seven 420-gallon circular tanks and eighteen 235-gallon circular tanks. Each holding tank is supplied with a continuous flow of about 15 to 26 l/min (4 to 7 gpm). Solid waste products and particulates are removed with coarse and fine micron bag filters. A bio-filter system was used to remove ammonia and activated carbon was used to remove other impurities. An ultraviolet sterilization filter was used to minimize the presence of pathogens. The holding system also has a chiller and submersible heaters to maintain optimum temperatures throughout the year for the species being held. Temperature, dissolved oxygen, and pH were monitored on a daily basis, and ammonia was measured several times per week. Fish physiology and behavior was visually assessed daily to screen for external signs of disease, fungus, or infection by parasites. Alarm systems with an auto-dialer were operational 24/7 and in the event of a facility malfunction (e.g., pump failure, power outage, low water levels), Alden staff was notified and responded within the hour.

Experimental Design and Test Procedures

Test conditions for the Welka UPG turbine included two species, two size groups, and two approach velocities and corresponding turbine rotational speeds (Table 2-1). Two size groups and two approach velocities were evaluated with the spherical turbine, but tests were only conducted with rainbow trout (Table 2-1). The two flow velocities selected for testing were sufficient to assess the potential effects of this parameter on turbine passage survival. Also, the lower flow velocity (1.5 m/s) is about the speed at which the test turbines begin operating, and the higher speed (2.1 m/s) is the maximum velocity that could be attained with the flume configuration used for testing. Two test types (survival and behavioral) were conducted for each turbine design. Survival testing involved releasing fish immediately upstream of each operating turbine in attempts to force fish to pass through the blade sweep, whereas behavioral trials with fish released farther upstream of the turbine focused on whether fish would actively avoid passing through the blade sweep and downstream on the outside of the turbine.

Table 2-1
Test conditions evaluated with each turbine. Test species included rainbow trout (RBT) and largemouth bass (LMB). Five replicate trials were conducted with each set of test conditions for the survival evaluation and three trials were conducted for the behavioral evaluation. Approximately 100 treatment and 100 control fish were released per replicate for survival trials; 50 fish per replicate were released for behavioral trials (no controls).

Turbine	Species	Size Group (mm)	Test Type	Velocity (m/s)	Replicate Trials
Welka UPG	RBT	125	Survival	1.5	5
				2.1	5
			Behavioral	1.5	3
				2.1	3
		250	Survival	1.5	5
				2.1	5
			Behavioral	1.5	3
				2.1	3
	LMB	125	Survival	1.5	5
				2.1	5
			Behavioral	1.5	3
				2.1	3
		250	Survival	1.5	5
				2.1	5
			Behavioral	1.5	3
				2.1	3
LST	RBT	125	Survival	1.5	5
				2.1	5
			Behavioral	1.5	3
				2.1	3
		250	Survival	1.5	5
				2.1	5
			Behavioral	1.5	3
				2.1	3

Survival Testing

Survival tests were conducted 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 samples sizes were 100 treatment and 100 control fish per trial and five replicate trials were conducted per test condition (species, size class, channel velocity). Based on a similar laboratory survival study conducted with the fish-friendly Alden turbine (Cook et al. 2003), these samples sizes and level of replication were considered adequate for achieving 95% confidence intervals that were within ± 5% of survival estimates.

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. This marking system uses compressed CO_2 to inject the photonic dye at the base of or into individual fins. Four dye colors and four fin locations were used to provide 16 unique marks. Unique marking of release groups allowed treatment and control fish to be released and recovered simultaneously and facilitated assignment of the few fish not captured immediately following a test to the appropriate prior test (most released fish were recovered at the completion of each trial, but some individuals were recovered during a later trial). Of the 11,716 treatment and control fish released during survival testing, only 90 (0.8%) did not have a discernable mark when recovered. Following marking, each marked group (treatment or control) was placed into a separate recovery tank until the day of testing.

For each trial, treatment and control groups were placed into separate mobile holding tanks and moved to the test flume area after the fin mark and total number had been confirmed. Each group was released into the flume once the flume channel velocity and turbine rotational speed were established. Treatment fish were transferred from the mobile tank into the fish injection system from which they entered the flume immediately upstream of the operating turbines. Control fish were transferred out of the mobile tank and released directly into the test flume at the surface immediately downstream of the turbines and within the channel flow to the best extent possible.

After introduction, treatment fish movement and passage through the turbine 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 tank and held for 48 hours to monitor for delayed mortality. Treatment and control fish from a given trial remained together in the same post-test holding tank from the time of collection until the end of the delayed mortality holding period.

Survival, injury, and scale loss evaluations were conducted on all recovered fish to enumerate immediate and delayed mortalities, external injuries, and percent scale loss. 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. Forty-eight hour mortalities were classified as any fish that died between 24 hours 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, eye damage, and descaled. Using methods similar to those reported by Neitzel et al. (1985) and Basham et al. (1982), percent scale loss (< 3%, 3 – 20%, 21 – 40%, and > 40%) was recorded for each of three locations along the length of the body (Figure 2-9; if greater than 20% scale loss occurred in two or more locations, then a fish was classified as descaled. During the injury evaluation, each fish was also inspected for fin mark location and color to determine release group and test number, and measured for fork length to the nearest mm.

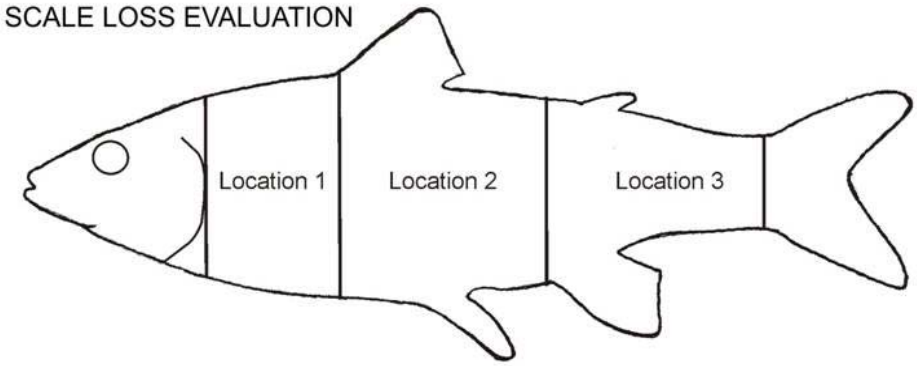

Figure 2-9
Diagram showing the body locations assessed for percent scale loss on all evaluated fish

As previously stated, due to the spherical shape of the LST, a containment net could not be used to force fish to pass through the turbine. Therefore, in an effort to estimate how many fish avoided passage through the LST or were entrained, underwater videos of several trials were reviewed to determine percent avoidance and entrainment, orientation of entrained fish, and the percent of entrained fish that were struck by a blade when they entered and exited the LST. Two observers were used to independently view one replicate per velocity condition and fish size class. Review of multiple camera views and slowing the playback speed were used to assess fish behavior and blade contacts. Observers counted the number of fish avoiding turbine passage, encountering the blade sweep, and passing through the blade sweep (i.e., entrainment). During a second review of the selected videos, the observers recorded orientation (head first, tail first, or sideways) and speed relative to flow (faster, slower, or about the same velocity as the approach flow) for entrained fish as they passed through the upstream blade sweep. During this second review, the number of blade strikes for fish passing into and out of the turbine was also recorded.

Behavioral Testing

Behavioral trials were conducted for each turbine using the same species, size classes, flow approach velocities, and turbine rotational speeds that were evaluated during survival testing (Table 2-1). For these tests, the fish release system was moved upstream of the turbine approximately 7.6 m (25 ft), which resulted in a location near the upstream end of the narrowed channel section leading to the turbines. In addition to meeting logistical constraints associated with the system design and mounting, this location was considered a reasonable distance in which fish could orient to the flow and react to the turbines. The containment netting used for Welka UPG survival tests was removed from the front of the injector tube for the behavioral trials with this turbine (Figure 2-10). Underwater cameras were used to record video from several locations to evaluate fish behavior and passage through and around each turbine unit. A digital video recording (DVR) unit was used to document and synchronize the video images for up to four camera locations.

Fifty fish were used per trial and three replicate trials were conducted for each set of test conditions (species, size group, and approach velocity) evaluated during behavioral testing. On the day of testing, each test group was placed into a mobile holding tank and moved to the test flume area. Once the flume channel velocity and turbine speed parameters had been established the fish were released. After introduction, treatment fish movement through or around the turbine was monitored and recorded via underwater cameras for 30 minutes. At the velocities being tested (1.5 and 2.1 m/s), this time period was considered sufficient for most fish, if not all, to move or be swept downstream past the turbines. Once the 30 minute trial had elapsed the next test group was released. After three trials had been completed the isolation screen was lowered immediately upstream of the turbine to prevent 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 wade in the flume. Fish were then gently crowded with a seine net to allow for collection and counting. Because the focus of these tests was to assess behavior and avoidance, injury and delayed mortality assessments were not conducted for behavioral trials. However, immediate mortalities were recorded at the time of recovery following each trial.

Survival Data Analysis

The data analysis for the biological evaluation of the two hydrokinetic turbine designs involved assessments of immediate (1 hr) and delayed (48 hr) mortality and injury and scale loss for selected turbine operating conditions (approach velocity and turbine rotational speed), species, and size groups. Immediate and total (immediate plus 48-hour) 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. 1987; Skalski 1999). 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 estimates included the following:

N_C = total number of control fish recovered (alive and dead);

c = number of control fish recovered alive;

N_T = total number of treatment fish recovered (alive and dead); and

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

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

$$S_C = \frac{c}{N_C} \qquad (1)$$

$$S_T = \frac{tN_C}{N_T c} \qquad (2)$$

with a variance for S_T of:

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

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

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

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.

The total number of fish recovered for each release group was used instead of the number released because some fish were not recovered until later tests. Although most unrecovered fish were later collected alive 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. Also, marks on a small number of fish could not be located or identified after recovery. With the exception of a few replicate trials conducted at the beginning of the study, the number of fish without identifiable marks recovered during each trial was very low and the vast majority of unmarked recoveries were collected live. The exclusion of unrecovered fish and fish without identifiable marks had little or no effect on survival estimates, mainly because most of these recovered were recovered live. Even if these fish were included in the analysis and unmarked fish recovered dead were assigned to treatment groups, survival estimates would only change by a fraction of percent (and likely would be higher than reported) because most fish recovered during later tests and unmarked fish were recovered live and they accounted for less than 1% of the total fish released. Excluding these fish from the calculation of survival estimates was considered a prudent and conservative approach.

The proportion of fish descaled was adjusted with the control data to account for the effects of handling and testing procedures. The adjusted proportion descaled was calculated by dividing the proportion of treatment fish not descaled by the proportion of control fish not descaled, then subtracting the resulting quotient from one. Similar to the survival analysis, the replicate data were pooled for each set of test conditions when calculating the adjusted proportion of fish descaled.

Figure 2-10
Downstream view of fish release system location used for behavioral trials

Velocity Measurements

Velocity measurements were recorded to verify that the flume operating conditions produced the desired approach velocities with a relatively uniform distribution upstream of the test turbine location. Velocity measurements recorded by an ADCP were used to develop a predicted bow thruster output curve, such that bow thruster rpm could be used to set the approach velocity for each test. Once the appropriate rpm for each velocity condition was determined, a complete velocity profile was measured for each velocity condition and turbine type. Velocities in the flume were also measured directly upstream of the test turbine location in a 3 by 3 grid to determine the average velocity profile for a given condition across the flume channel (Figure 2-11). These velocity measurements were recorded using a Swoffer propeller-style velocity meter and are presented in Figure 2-12. Velocity measurements were also recorded at the exit of the injector tube for both turbines at each velocity condition and were about 1.4 m/s at the lower target velocity and 2.0 m/s for the higher velocity.

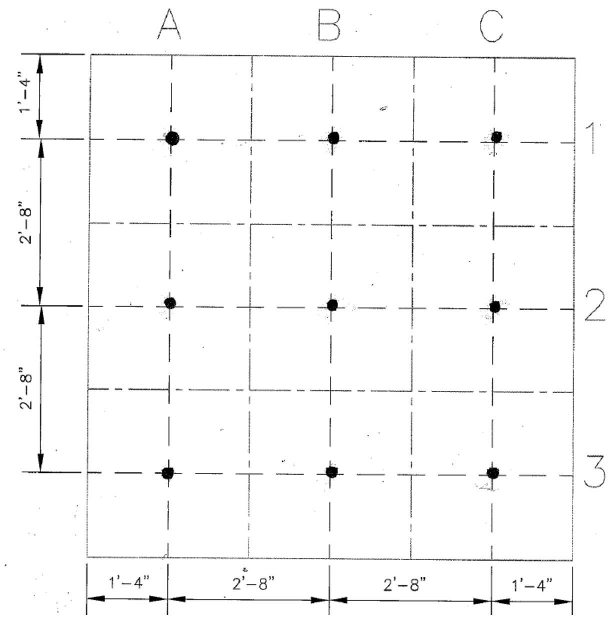

Figure 2-11
Velocity profile 3x3 grid, displaying each velocity measurement point

1.5 m/s Target Test Conditoin

	A	B	C
1	1.46	1.51	1.44
2	1.50	1.40	1.54
3	1.12	1.35	1.31

2.1 m/s Target Test Conditoin

	A	B	C
1	2.05	2.11	2.02
2	2.07	1.99	2.06
3	--	--	--

Figure 2-12
Velocity measurements recorded with a Swoffer meter directly upstream of the test turbine location. Measurements could not be recorded at the deepest transect (3) at the higher target velocity (2.1 m/s) because the meter could not be held stable for accurate readings.

Section 3: Biological Evaluation – Results

Lucid Spherical Turbine

Survival Testing

The mean fork length of rainbow trout evaluated during LST trials was 149 mm (SD = 16) for the smaller size group and 250 mm (SD = 16) for the larger size group. The range of mean fish lengths for treatment groups was 138 mm to 158 mm for smaller fish and 247 mm to 250 mm for the larger fish. Mean length for control groups ranged from 137 mm to 163 mm for the smaller fish and 250 mm to 251 mm for larger fish (Table 3-1).

Recovery rates for treatment and control groups ranged from about 91.0 to 99.6% for smaller fish and 98.4 to 100.2% for the larger fish (Table 3-1). Recovery rates greater than 100% indicate more fish were recovered for a treatment or control group than were 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. These types of sampling errors may have also contributed to recovery rates less than 100%. Also, 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. Some fish that were unaccounted for (particularly the smaller-sized fish) likely passed through the downstream isolation screen and the bow thrusters that re-circulate the flow through the flume. 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 (Table 3-1). Unmarked fish could not be assigned to a release group and, therefore, were not included in the survival analysis. As discussed previously, this is a conservative approach given almost all of these fish were recovered live (Table 3-1). The few fish that were recovered during later trials were also excluded from the survival analysis. This was also considered conservative because these fish were all recovered live.

Table 3-1
Summary of fish release, recovery, and mortality data for rainbow trout tested with the LST during the survival evaluation

Approach Velocity (m/s)	Fish Size	Number of Trials	Test Group*	Mean FL and SD (mm)	Total Released	Recovered Live	Immediate Mortalities (1 hr)	Delayed Mortalities (48 hr)	Recovered Live during Later Test	Recovered Dead during Later Test
1.5	small	5	T	157.6 (21.8)	502	456	0	1	1	0
			C	162.9 (25.3)	502	482	0	1	1	0
			NM	–	–	63	0	0	–	–
2.1	small	5	T	137.7 (7.9)	506	498	6	2	0	0
			C	137.3 (8.1)	500	479	3	0	2	0
			NM	–	–	1	1	0	–	–
1.5	large	5	T	250.4 (16.2)	502	493	1	0	0	0
			C	250.4 (15.5)	503	494	3	0	0	0
			NM	–	–	14	0	0	–	–
2.1	large	5	T	247.4 (15.6)	500	499	2	6	0	0
			C	251.1 (15.5)	501	498	0	0	1	0
			NM	–	–	–	–	–	–	–

* T= treatment group, C= control group, NM= undetermined (no visible mark)

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 3-2; Figure 3-1). Immediate survival was not significantly different between the two velocities tested with each size group, or between size groups at each velocity ($P > 0.05$; Figure 3-1). For the larger fish, total survival was significantly greater at the lower velocity ($P < 0.05$; Figure 3-1). There were no statistical differences in total survival between size groups at each velocity, or between velocities for the smaller fish ($P > 0.05$). The spherical design of the turbine did not allow for fish to be forced through the blade sweep, as was done with the ducted Welka UPG turbine using a containment net. Because all treatment fish were released within 250 to 300 mm (10 to 12 inches) of the upstream face of the turbine, the estimated survival rates represent the percentage of fish that encounter the turbine and proceed downstream by either actively passing 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 (Table 3-3). The percent of control fish classified as uninjured was similar to treatment fish for both size classes and velocities (Table 3-3), 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.

Table 3-2
Survival estimates (adjusted for control mortality) for rainbow trout evaluated with the LST. Survival rates above 100% resulted when control mortality was greater than treatment mortality.

Mean Fork Length (mm)	Approach Velocity (m/s)	Immediate Survival (1 hr) (%) ± 95% CI	Total Survival (1 hr + 48 hr) (%) ± 95% CI
161	1.5	100.00 ± 0.00	99.99 ± 0.59
138	2.1	99.43 ± 1.18	99.03 ± 1.30
250	1.5	100.40 ±0.80	100.40 ± 0.80
249	2.1	99.60 ± 0.55	98.40 ± 1.10

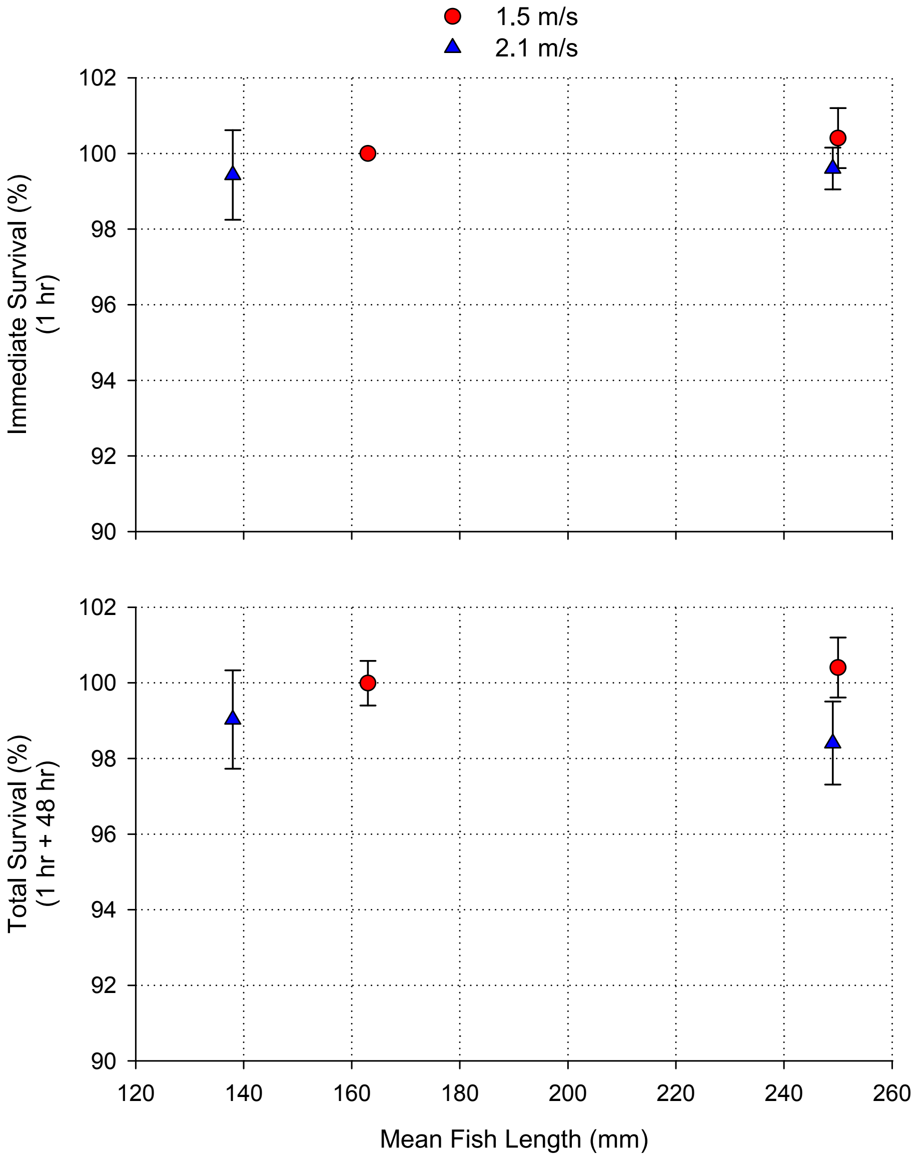

Figure 3-1
Immediate (1 hr) and total (1 hr + 48 hr) survival rates (± 95% CI) for rainbow trout tested with the LST. Non-overlapping confidence intervals indicate statistically significant differences between survival estimates.

Table 3-3
Percent of rainbow trout recovered during LST survival testing that were observed with external injuries

Approach Velocity (m/s)	Mean Fork Length (mm)	Live/ Dead	Total Number Examined		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
			T	C	T	C	T	C	T	C	T	C	T	C
1.5	161	Live	455	481	99.6	99.8	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0
		Dead	1	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
		Total	456	482	99.3	99.6	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.2
2.1	138	Live	496	479	97.0	99.4	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
		Dead	8	3	37.5	0.0	50.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total	504	482	96.0	98.8	0.8	0.6	0.2	0.0	0.0	0.0	0.0	0.0
1.5	250	Live	493	494	99.2	98.8	0.2	0.0	0.4	0.4	0.0	0.0	0.0	0.0
		Dead	1	3	100.0	100.0	0.0	66.7	0.0	33.3	0.0	0.0	0.0	33.3
		Total	494	497	99.2	98.8	0.2	0.4	0.4	0.6	0.0	0.0	0.0	0.2
2.1	249	Live	493	498	97.8	98.8	0.2	0.0	0.0	0.0	0.0	0.0	2.0	1.2
		Dead	8	0	25.0	0.0	37.5	0.0	12.5	0.0	0.0	0.0	12.5	0.0
		Total	501	498	96.6	98.8	0.8	0.0	0.2	0.0	0.0	0.0	2.2	1.2

The percent of fish classified as descaled was relatively high for both treatment and control groups, particularly for the smaller size class of fish (TWhen 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% (live and dead fish combined). Descaling was more prevalent for fish recovered dead.

Given that injury, scale loss, and survival were generally similar between treatment and control fish, a likely source of fish damage (and some of the observed mortality) was the area downstream of the turbine where flow expanded from the 8-ft channel leading to the turbine to the full 20 ft width of the flume. Portions of this area had turbulent flow and sufficient velocity to cause some fish to impinge on the downstream isolation screen. Although test durations were relatively short (10 minutes), in part to reduce the potential for injury and mortality in the area downstream of the turbines, fish that contacted the downstream screen and/or impinged on it would have been more susceptible to physical damage, as evidenced by the control group data.

A review of underwater videos from a single trial conducted with each velocity and size class demonstrated that avoidance of turbine passage by treatment fish of both size classes was high (82 to 94%) at the two approach velocities evaluated (Table 3-5). 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 (i.e., head upstream, positive rheotaxis), 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 either the same speed as the flow or slower, at both approach velocities evaluated (Table 3-5). The estimated percent of entrained fish struck by a blade during the initial passage through the blade sweep (i.e., on upstream side of turbine) was relatively high for both size groups (about 53 to 91%), and larger fish appeared to be less susceptible to strike (Table 3-5) at both approach velocities. Blade strike was less common when entrained fish passed out of the turbine through the blade sweep on the downstream side (Table 3-5). Also, the percent of fish struck by a blade was higher at the lower approach velocity for both size groups, with the exception of the smaller fish exiting the turbine. The 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 fish location relative to cameras and the approach velocity. There was considerably more air entrainment in the flume at the higher approach velocity, making it more difficult to observe fish and to determine whether they were struck during turbine passage.

Figure 3-2 demonstrates common avoidance behaviors observed during video observation of trout encountering the LST. The larger trout were able to hold position in the flow at the exit of the injection tube and immediately upstream of the turbine blade sweep, often for several minutes. As they began to move downstream, the majority of fish drifted to either side of the turbine. Many of the fish holding position in front of the turbine were seen slowly drifting back in the flow until their tail was struck by the blade, at which point these fish either swam forward or were displaced in the direction of the blade movement, passing downstream to the side of the turbine. The smaller trout had more difficulty maintaining position in the flow and most were observed exiting the injection tube and drifting immediately downstream around the turbine on either side. Other common behaviors documented by video observations of rainbow trout evaluated during survival testing with the LST included fish being entrained through the turbine (Figure 3-3) and blade strikes which occurred during these interactions. Some fish entrained into the turbine could be observed swimming within the sphere of the blades for brief periods of time prior to exiting in the downstream direction.

Table 3-4
Percent of rainbow trout classified as descaled during survival tests with the LST

Approach Velocity (m/s)	Mean Fork Length (mm)	Live/ Dead	Control		Treatment		% Treatment Descaled Adjusted for Control Data
			Number Examined	% Classified as Descaled	Number Recovered	% Classified as Descaled	
1.5	161	Live	481	70.9	455	70.8	0.0
		Dead	1	100.0	1	100.0	0.0
		Total	482	71.0	456	70.6	0.0
2.1	138	Live	479	56.8	496	57.7	2.0
		Dead	3	100.0	8	87.5	0.0
		Total	482	57.1	504	58.1	2.5
1.5	250	Live	494	19.4	493	18.7	0.0
		Dead	3	33.3	1	0.0	0.0
		Total	497	19.5	494	18.6	0.0
2.1	249	Live	498	6.6	493	9.7	3.3
		Dead	0	0.0	8	75.0	75.0
		Total	498	6.6	501	10.8	4.5

Table 3-5

Summary of fish avoidance and entrainment data from video observations recorded during rainbow trout survival tests with the LST. Video observations were recorded for a single trial conducted with each velocity and fish size group by two observers. The avoidance and entrainment data recorded by each observer were averaged. The observations are based on approximately 100 fish being released for each trial.

Approach Velocity (m/s)	Mean Fish Length (mm)	Mean Number of Fish Observed	Avoided Turbine Passage (%)	Entrained through Turbine (%)	Orientation of Entrained Fish (%)			Speed of Entrained Fish Relative to Flow Velocity (%)			Entrained Fish Struck by Blade (%)	
					Head First	Tail First	Side First	Same	Slower	Faster	Entering Turbine	Leaving Turbine
1.5	161	89.5	93.9	6.1	27.3	45.5	27.3	45.5	36.4	18.2	90.9	9.1
2.1	138	83.5	89.8	10.2	5.9	94.1	0.0	41.2	47.1	11.8	82.4	23.5
1.5	250	91.5	94.0	6.0	36.4	18.2	45.5	81.8	0.0	18.2	90.9	36.4
2.1	249	90.5	81.8	17.7	59.4	25.0	15.6	50.0	34.4	15.6	53.1	9.4

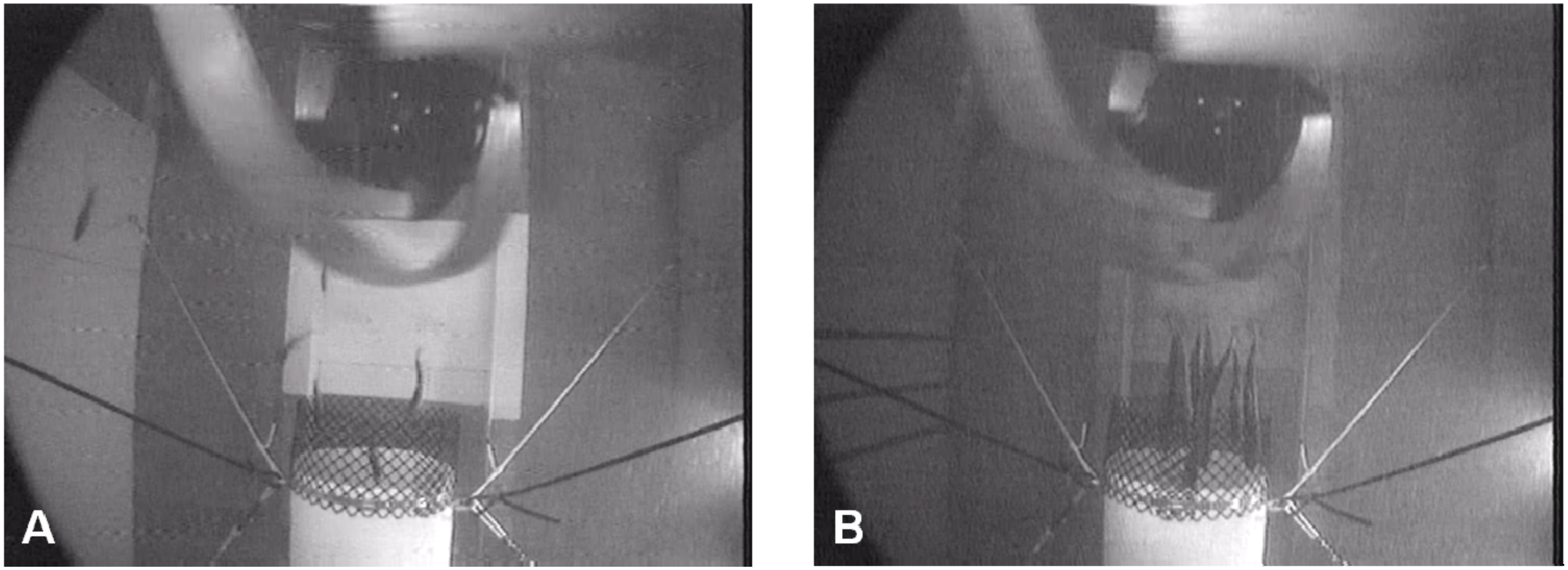

Figure 3-2
Video observations (top view) demonstrating avoidance of the LST during survival testing with of 125-mm (A) and 250-mm (B) rainbow trout avoidance at an approach velocity of 1.5 m/s. Fish of both size groups were observed moving to the sides of the turbine and the larger trout typically maintained position between the exit of the release tube and the upstream face of the turbine blade sweep (B) for several minutes before passing downstream through or around the turbine.

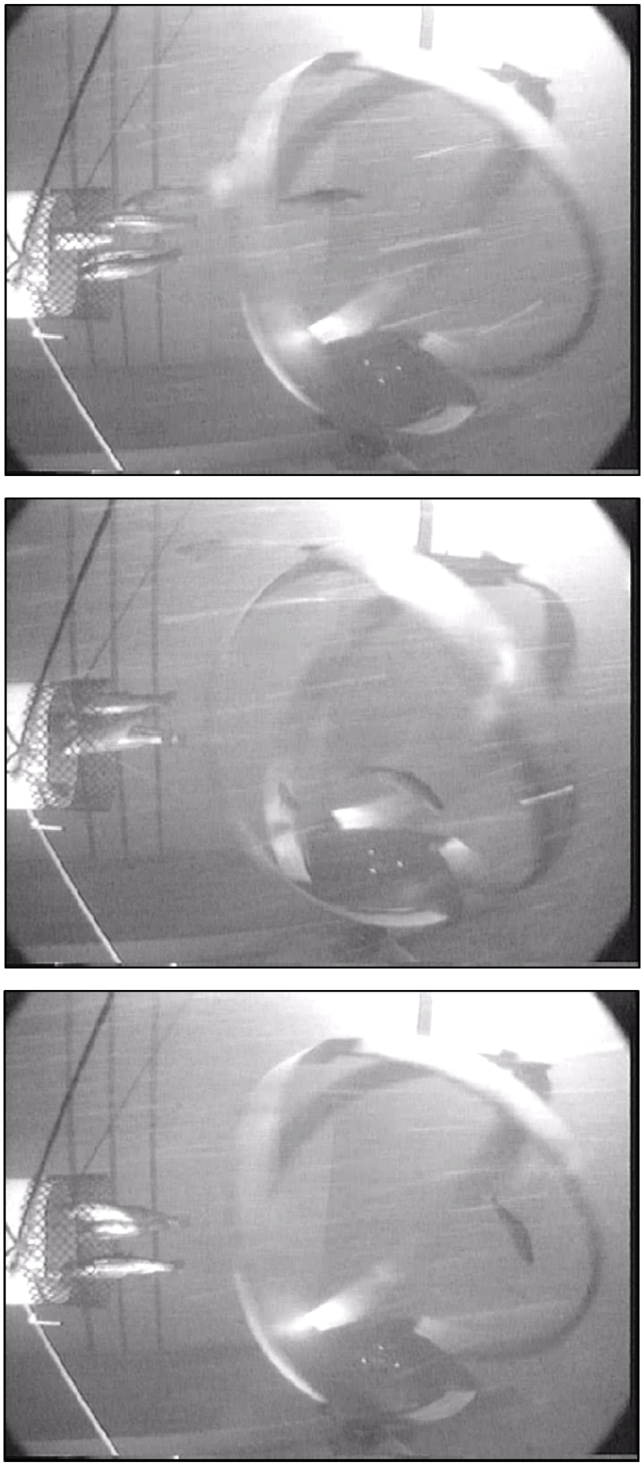

Figure 3-3
Side view from underwater camera showing 250 mm rainbow trout maintaining position directly upstream of the turbine blade sweep and a fish passing through turbine during survival testing

Behavioral Tests

For behavioral tests, the release system was moved to the upstream end of the test channel to allow fish the opportunity to completely avoid interaction with the turbine. At the start of each behavioral trial, rainbow trout were observed on video as they were placed inside the injection pipe. All fish quickly oriented in the upstream direction while still inside the pipe, eventually falling back and exiting into the test channel. No cameras were located in the channel upstream of the turbine unit so it was not possible to observe the approximate number of fish that moved downstream and those that held positions upstream for extended durations. However, at the completion of each test trial an isolation screen was lowered immediately upstream of the turbine to prevent fish from moving up or downstream past the turbine. During collection, fish recovered downstream and upstream of the turbine, along with any immediate mortalities, were enumerated (Table 3-6). As expected based on swimming ability, almost all of the smaller fish moved downstream past the LST and a greater proportion of larger fish remained upstream at both approach velocities evaluated (Table 3-6). No mortalities occurred during behavioral tests with the LST.

General video observations during behavioral testing at the 1.5 m/s velocity demonstrated that fish passing downstream towards the turbine units swam or drifted along the floor or walls of the flume. Consequently, few if any fish interacted with the turbine or were entrained through the blade sweep. Several fish were observed drifting along the flume bottom and, after encountering the turbine anchoring frame, maintained position below the turbine for brief periods of time before proceeding downstream. Video quality at the higher velocity (2.1 m/s) was poor, mainly due to the presence of entrained air bubbles which severely restricted all camera views of fish approaching the turbine. In general, video observations from the LST behavior tests demonstrated that most fish followed paths along the walls and floor of the test flume. Very few fish were observed entering or interacting with the turbine unit. The few rainbow trout that were observed approaching the turbine at either velocity were actively swimming (i.e., tail beating was visible) and facing upstream (positive rheotaxis).

Table 3-6
Summary of release and recapture for behavioral tests with conducted with rainbow trout and the LST

Fish Size Group	Approach Velocity (m/s)	Total Number Released	Number Recovered Downstream	Number Recovered Upstream	Number Recovered Dead	Total Number Recovered
Small	1.5	151	146	5	0	151
	2.1	150	149	2	0	151
Large	1.5	150	90	60	0	150
	2.1	150	124	26	0	150

Welka UPG Turbine

Survival Tests

Rainbow Trout

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. Mean length of smaller fish for all treatment groups was 125 mm. The range of mean fish lengths was 231 mm to 247 mm for treatment groups of the larger fish. Control groups had a range of mean lengths of 124 mm to 125 mm for smaller size groups and 232 mm to 250 mm for larger size groups (Table 3-7).

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 (Table 3-7). Recovery rates greater than 100% indicate more fish were recovered than 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 evaluations. Some fish were not recovered during the trial of their release, but were collected during subsequent 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. Fish recovered during later trials accounted for about 2% or less of the total number released and most (73%) were recovered live. As a conservative approach, these fish were excluded from the survival analysis. During survival testing with the Welka UPG turbine, all recovered rainbow trout had a detectable mark.

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 3-8). Immediate and total survival of the larger fish evaluated at the higher velocity (2.1 m/s) were both 99.4% (Table 3-8). The only statistical differences detected among the survival rates was between the smaller and larger size groups at an approach velocity of 2.1 m/s, for which the smaller fish had significantly higher immediate and total survival ($P < 0.05$; Figure 3-4). 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 a Welka UPG turbine at the approach velocities and resulting rotation speeds evaluated. This is in contrast to the tests with the LST, for which survival estimates were for fish that encountered the turbine and passed either downstream through or around it.

Table 3-7
Summary of fish release, recovery, and mortality data for rainbow trout tested with the Welka UPG turbine during the survival evaluation

Approach Velocity (m/s)	Fish Size	Number of Trials	Test Group	Mean FL and SD (mm)	Total Released	Recovered Live	Immediate Mortalities (1 hr)	Delayed Mortalities (48 hr)	Recovered Live during Later Test	Recovered Dead during Later Test
1.5	small	5	T	125.2 (6.5)	502	463	2	1	8	3
			C	125.1 (6.4)	500	461	6	1	4	2
2.1	small	5	T	125.1 (6.6)	500	451	1	0	4	2
			C	124.3 (5.7)	500	445	8	0	6	1
1.5	large	5	T	230.8 (16.1)	499	504	0	0	3	0
			C	231.9 (15.7)	498	496	0	0	1	1
2.1	large	5	T	247.4 (17.5)	496	496	3	0	1	0
			C	250.4 (15.4)	501	499	0	0	0	1

Table 3-8
Turbine passage survival estimates (adjusted for control mortality) for rainbow trout evaluated with the Welka UPG turbine. Survival rates above 100% resulted when control mortality was greater than treatment mortality.

Mean Fork Length (mm)	Approach Velocity (m/s)	Immediate Survival (1 hr) (%) ± 95% CI	Total Survival (1 hr + 48 hr) (%) ± 95% CI
125	1.5	100.87 ± 1.21	100.87 ± 1.35
125	2.1	101.57 ± 1.33	101.57 ± 1.33
231	1.5	100.00 ± 0.00	100.00 ± 0.00
248	2.1	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% (Table 3-9). For control groups, the rates of uninjured fish were similar to treatment groups, ranging from about 75 to 95% (Table 3-9). The percent of treatment and control fish collected uninjured was higher during trials with the larger size groups than with the smaller fish. Bruising was the most common injury observed, with only a few fish experiencing lacerations or eye injuries (Table 3-9). One treatment fish recovered during a trial with the larger size class at a velocity of 2.1 m/s suffered a severed body. The cause of this injury could not be determined, but because of the low strike velocity of the Welka UPG turbine, it likely did not occur from a blade strike. 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 was lower for larger fish and for trials at the lower velocity (1.5 m/s) for both treatment and control groups (Table 3-10). 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. These results indicate that observed descaling of treatment fish was the result of handling and testing procedures and not passage through the Welka UPG turbine.

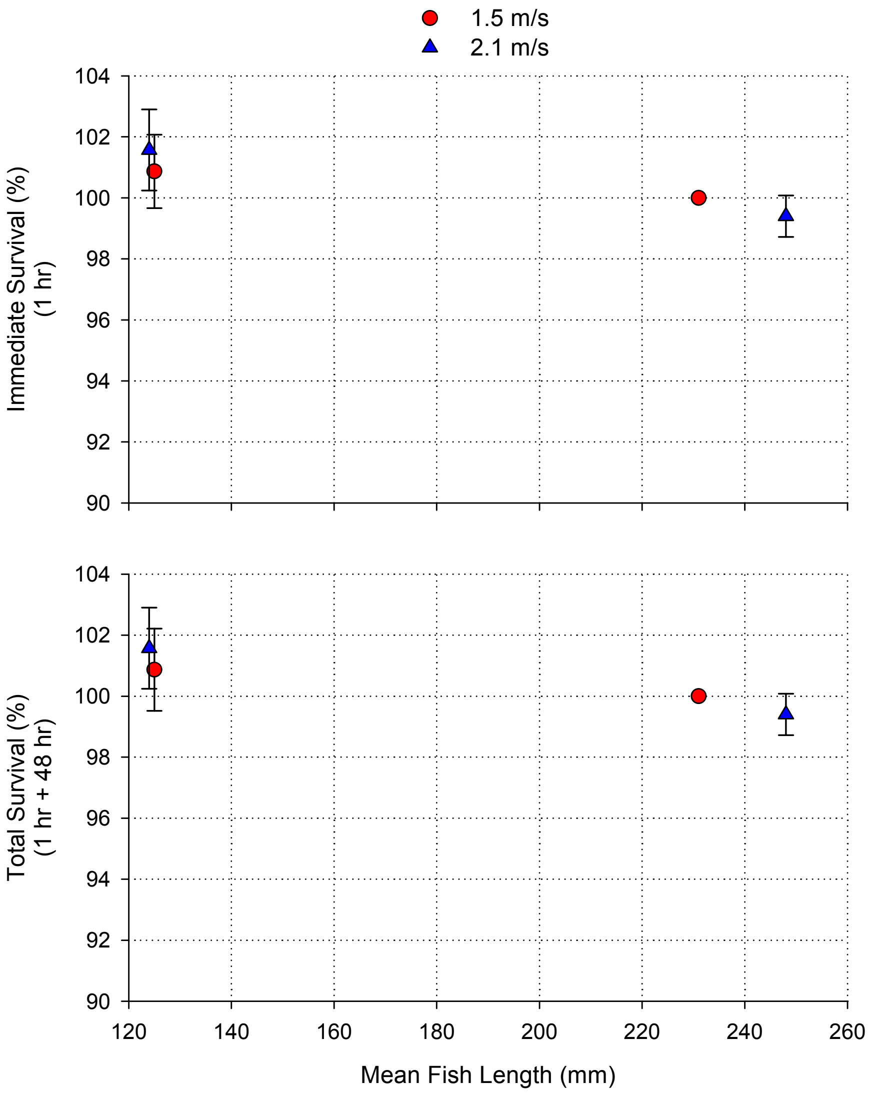

Figure 3-4
Immediate (1 hr) and total (1 hr + 48 hr) survival rates (± 95% CI) for rainbow trout tested with the Welka UPG. Non-overlapping confidence intervals indicate statistical differences between survival estimates.

Largemouth Bass

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. There was little variability in the range of mean lengths for treatment control groups with the smaller fish. Mean lengths of the larger size treatment groups ranged from 237 to 247 mm and control groups with the larger fish ranged from 239 to 246 mm for larger size groups (Table 3-11).

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 fish and 99.4 to 100.2% for the larger size group (Table 3-11). Recovery rates greater than 100% indicate more fish were recovered than 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 evaluations. These types of sampling error may have also contributed to the small percentage of fish that were unaccounted for during some of the trials. Unlike rainbow trout, no unrecovered largemouth bass were collected during subsequent trials. Nine largemouth bass did not have identifiable marks following recovery (Table 3-11), most of these occurred with the smaller fish tested at the lower velocity. All of the largemouth bass without a discernable mark were recovered live.

Immediate mortalities only occurred during the trials with the smaller bass and were greater for both control and treatment fish at the higher velocity. Control and treatment delayed mortality was relatively high for this test condition (i.e., smaller fish, higher velocity), but given that immediate and delayed mortality were greater for control fish, the observed mortality of treatment fish was likely due to handling and testing procedures and not associated with turbine passage. 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 ft/s at the two test channel approach velocities that were evaluated).

Table 3-9
Percent of rainbow trout recovered during Welka UPG turbine survival testing that were observed with external injuries

Approach Velocity (m/s)	Mean Fork Length (mm)	Live/ Dead	Total Number Examined		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
			T	C	T	C	T	C	T	C	T	C	T	C
1.5	125	Live	462	460	75.3	76.5	24.5	23.0	0.0	0.0	0.0	0.0	0.0	0.0
		Dead	3	7	33.3	0.0	0.0	57.1	0.0	0.0	0.0	0.0	0.0	14.3
		Total	465	467	75.1	75.4	24.3	23.6	0.0	0.0	0.0	0.0	0.0	0.2
2.1	125	Live	451	445	85.4	88.1	12.6	14.2	0.0	0.2	0.0	0.0	0.0	0.0
		Dead	1	8	0.0	0.0	0.0	87.5	0.0	12.5	0.0	0.0	0.0	25.0
		Total	452	453	85.2	86.5	12.6	15.5	0.0	0.4	0.0	0.0	0.0	0.0
1.5	231	Live	504	496	94.0	95.2	5.6	4.8	0.2	0.0	0.0	0.0	0.2	0.0
		Dead	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total	504	496	94.0	95.2	5.6	4.8	0.2	0.0	0.0	0.0	0.2	0.0
2.1	248	Live	496	499	89.7	90.0	6.9	6.4	0.0	0.2	0.4	0.0	3.4	3.4
		Dead	3	0	0.0	0.0	66.7	0.0	0.0	0.0	33.3	0.0	33.3	0.0
		Total	499	499	89.2	90.0	7.2	6.4	0.0	0.2	0.6	0.0	3.6	3.4

Table 3-10
Percent of rainbow trout classified as descaled during survival tests with Welka UPG turbine

Approach Velocity (m/s)	Mean Fork Length (mm)	Live/ Dead	Control		Treatment		% Treatment Descaled Adjusted for Control Data
			Number Examined	% Classified as Descaled	Number Recovered	% Classified as Descaled	
1.5	125	Live	460	22.8	462	26.6	4.9
		Dead	7	42.9	3	0.0	0.0
		Total	467	23.1	465	26.5	4.3
2.1	125	Live	445	35.3	451	29.3	0.0
		Dead	8	37.5	1	0.0	0.0
		Total	453	35.3	452	29.2	0.0
1.5	231	Live	496	5.6	504	4.4	0.0
		Dead	0	–	0	0.0	0.0
		Total	496	5.6	504	4.4	0.0
2.1	248	Live	499	20.8	496	19.4	0.0
		Dead	0	–	3	66.7	66.7
		Total	499	20.8	499	19.6	0.0

Table 3-11
Summary of fish release, recovery, and mortality data for largemouth bass tested with the Welka UPG turbine during the survival evaluation

Approach Velocity (m/s)	Fish Size	Number of Trials	Test Group	Mean FL and SD (mm)	Total Released	Recovered Live	Immediate Mortalities (1 hr)	Delayed Mortalities (48 hr)	Recovered Live during Later Test	Recovered Dead during Later Test
1.5	small	5	T	124.8 (11.4)	499	498	1	2	0	0
			C	124.5 (10.3)	497	488	2	0	0	0
			NM	–	–	7	0	0	–	–
2.1	small	5	T	125.2 (10.7)	502	499	3	15	0	0
			C	123.3 (11.1)	496	483	7	24	0	0
			NM	–	–	2	0	1	–	–
1.5	large	5	T	237.0 (20.1)	498	499	0	1	0	0
			C	239.1 (21.0)	499	497	0	1	0	0
			NM	–	–	–	–	–	–	–
2.1	large	5	T	246.6 (18.0)	501	498	0	2	0	0
			C	246.1 (18.9)	499	499	0	0	0	0
			NM	–	–	–	–	–	–	–

Immediate turbine passage survival for largemouth bass tested with the Welka UPG turbine was 100% for both size groups and approach velocities (Table 3-12). Total turbine passage survival was greater than 99% for all test conditions. Statistically significant differences were not detected among any of the test conditions (fish size and approach velocity) evaluated with largemouth bass ($P >$ 0.05; Figure 3-5). Some of the survival estimates were greater than 100% for tests with the smaller fish due to control mortality being slightly higher than treatment mortality for several trials. The control release point was closer to the downstream isolation screen and may not have allowed the smaller fish sufficient time to orient to the flow and avoid contact with and impingement on the screen, particularly at the higher approach velocity. 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 rotational speeds evaluated. This is in contrast to the tests with the LST, for which survival estimates were for fish that encountered the turbine and either passed downstream through or around the turbine.

Table 3-12
Turbine passage survival estimates (adjusted for control mortality) for largemouth bass evaluated with the Welka UPG turbine. Survival rates above 100% resulted when control mortality was greater than treatment mortality.

Mean Fork Length (mm)	Approach Velocity (m/s)	Immediate Survival (1 hr) (%) ± 95% CI	Total Survival (1 hr + 48 hr) (%) ± 95% CI
125	1.5	100.21 ± 0.69	99.81 ± 0.89
124	2.1	100.84 ± 1.27	102.93 ± 2.94
238	1.52	100.00 ± 0.00	100.00 ± 0.56
246	2.1	100.00 ± 0.00	99.60 ± 0.56

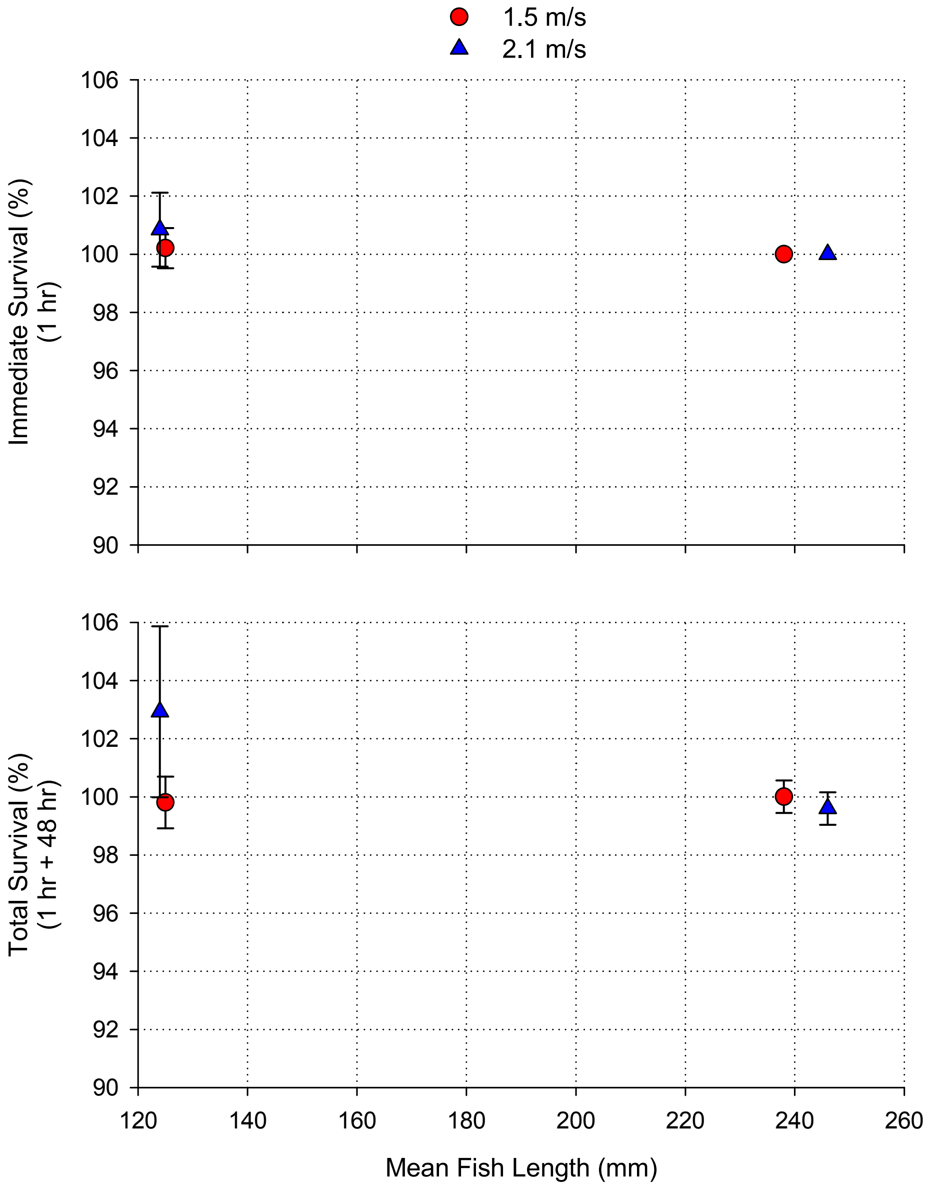

Figure 3-5
Immediate (1 hr) and total (1 hr + 48 hr) survival rates (± 95% CI) for largemouth bass tested with the Welka UPG. Non-overlapping confidence intervals indicate statistically significant differences between survival estimates.

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 (Table 3-13). 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.

Table 3-13
Percent of largemouth bass recovered during Welka UPG turbine survival testing that were observed with external injuries

Approach Velocity (m/s)	Mean Fork Length (mm)	Live/ Dead	Total Number Examined		Uninjured (%)		Bruising (%)		Laceration (%)		Severed Body (%)		Eye Injury (%)	
			T	C	T	C	T	C	T	C	T	C	T	C
1.5	125	Live	496	488	98.6	99.6	0.0	0.0	0.2	0.0	0.0	0.0	0.4	0.0
		Dead	3	2	33.3	100.0	33.3	50.0	0.0	0.0	0.0	0.0	33.3	0.0
		Total	499	490	98.2	99.6	0.2	0.2	0.2	0.0	0.0	0.0	0.6	0.0
2.1	124	Live	484	459	99.0	97.8	0.0	0.0	0.8	1.7	0.0	0.0	0.4	0.2
		Dead	18	31	61.1	58.1	16.7	19.4	0.0	3.2	0.0	0.0	0.0	0.0
		Total	502	490	97.6	95.3	0.6	1.2	0.8	1.8	0.0	0.0	0.4	0.2
1.5	238	Live	498	496	97.2	95.0	0.0	0.0	3.2	4.6	0.0	0.0	0.0	0.0
		Dead	1	1	0.0	0.0	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total	499	497	97.0	94.8	0.2	0.2	3.2	4.6	0.0	0.0	0.0	0.0
2.1	246	Live	496	499	98.6	98.6	0.0	0.0	1.4	1.6	0.0	0.0	0.0	0.0
		Dead	2	0	50.0	0.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total	498	499	98.4	98.6	0.2	0.0	1.4	1.6	0.0	0.0	0.0	0.0

Descaling rates were variable, but greater for both treatment and control fish at the higher approach velocity (Table 3-14). Percent descaled was also typically higher 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.

As stated previously, during survival tests with the Welka UPG turbine fish were forced to pass through the turbine by using a containment net around the fish release system and upstream perimeter of the turbine. Fish were not able to swim outside the blade sweep of a turbine as they passed downstream. The containment net and the duct around the turbine made detailed video observations of fish behavior difficult, particularly at the higher velocity, for which underwater video was also obstructed by entrained air. Therefore, data on fish orientation, swim speeds, and blade strikes were not collected as was done for survival trials with the LST.

Figure 3-6 shows some of the common behaviors that were observed at the lower velocity (1.5 m/s)

Behavioral Tests

At the start of each behavioral trial, rainbow trout and largemouth bass were observed on video as they were placed inside the injection pipe. All fish quickly oriented in the upstream direction while still inside the pipe, eventually falling back and exiting into the test channel. No cameras were located upstream of the turbine unit so it was not possible to observe the approximate number of fish that moved downstream and that held positions upstream for extended durations. However, at the completion of each test trial an isolation screen was lowered immediately upstream of the turbine to prevent fish from moving up or downstream of the turbine at the end of each behavioral trial. During collection, fish recovered downstream and upstream of the turbine were documented, along with any immediate mortality (Table 3-15). A relatively high number of mortalities occurred for the smaller bass, most likely due to impingement on the downstream screen, particularly at the higher approach velocity. Several mortalities were also observed for the larger bass and the smaller rainbow trout. The smaller fish of both species and the larger bass likely did not have sufficient swimming ability to avoid impingement on the downstream screen for the extended duration of the behavioral trials (30 minutes). Also, video observations, as described below, indicated most fish passed downstream below or to the side of the Welka turbine.

General video observations during behavioral testing at the 1.5 m/s velocity demonstrated that fish passing downstream towards the turbine units swam or drifted along the floor or walls of the flume. Both species appeared to use these structures as guidance mechanism which allowed them to pass downstream without encountering the turbine blade sweep. Several fish were observed drifting along the flume bottom and holding position when they encountered the supporting frame on the flume floor below the turbine. Video observations at the higher velocity were difficult to make due to the presence of entrained air bubbles, which severely limited the ability to see fish approaching the turbine.

Table 3-14
Percent of largemouth bass recovered during Welka turbine trials that were observed with descaling

Approach Velocity (m/s)	Mean Fork Length (mm)	Live/ Dead	Control		Treatment		% Treatment Descaled Adjusted for Control
			Number Examined	% Classified as Descaled	Number Recovered	% Classified as Descaled	
1.5	124.6	Live	488	1.4	496	0.0	0.0
		Dead	2	0.0	3	0.0	0.0
		Total	490	1.4	499	0.0	0.0
2.1	124.2	Live	459	55.6	484	34.5	0.0
		Dead	31	58.1	18	55.6	0.0
		Total	490	55.7	502	35.3	0.0
1.5	238.1	Live	496	0.4	498	0.6	0.2
		Dead	1	100.0	1	100.0	0.0
		Total	497	0.6	499	0.8	0.2
2.1	246.4	Live	499	28.5	496	20.6	0.0
		Dead	0	0.0	2	50.0	50.0
		Total	499	28.5	498	20.7	0.0

Most rainbow trout observed approaching the turbine were actively swimming (i.e., tail beating was visible) and facing upstream. Largemouth bass, however, were more likely to drift passively, particularly at the higher channel velocity. Many bass were observed facing upstream but were not actively swimming. In general, video observations from Welka turbine behavior tests demonstrated that most fish followed flow paths along the walls and floor of the test flume. Very few fish were observed passing through or interacting with the turbine.

Figure 3-6
Side camera view (A) showing a fish being struck by a blade and top view (B) showing fish swimming immediately upstream of the blade sweep during testing at an approach velocity of 1.5 m/s.

Table 3-15
Summary of release and recapture data for behavioral tests with largemouth bass (LMB) and rainbow trout (RBT) and the Welka UPG turbine

Species	Fish Size	Approach Velocity (m/s)	Total Number Released	Number Recovered Downstream	Number Recovered Upstream	Number Recovered Dead	Total Number Recovered
LMB	small	1.5	150	136	1	10	147
		2.1	150	112	0	36	148
	large	1.5	150	147	0	1	148
		2.1	150	141	0	9	150
RBT	small	1.5	150	117	21	3	141
		2.1	150	137	4	2	143
	large	1.5	150	89	61	0	150
		2.1	150	145	5	0	150

Section 4: Theoretical Predictions of Blade Strike Probablity and Mortality

Theoretical models for the probability of blade strike have been developed for use with conventional hydro turbines by several researchers (Von Raben 1957; Franke et al. 1997; Turnpenny et al. 2000; Ploskey and Carlson 2004; Hecker and Allen 2005). Also, some studies have investigated the effects of leading edge blade geometry (shape and thickness), blade speed, and fish orientation on strike injury and survival (Turnpenny et al. 1992; EPRI 2008, 2011b). The blade strike data have been incorporated into existing theoretical models in order to predict blade strike mortality, as well as the probability of strike, for fish passing through conventional hydro turbines.

In concept, the general theoretical model developed for predicting strike probability and mortality for conventional turbines can be applied to hydrokinetic turbines because the mechanics of fish passing through turbines of each application type are, for the most part, the same. That is, strike probability for fish passing through conventional and hydrokinetic turbine designs will be a function of fish length, the number of blades, turbine rotational speed, relative velocity of fish to blade, and the axial angle of the approach flow. Strike morality for both turbine types is dependent on the ratio of fish length to leading edge blade thickness, strike velocity (relative velocity of fish to blade), and fish orientation. However, an important component of strike probability and mortality models that needs to be considered in their application to hydrokinetic turbines is the velocity of fish as they pass through the blade sweep of a turbine. For conventional hydro turbines, fish velocity is assumed to be that of the inflow velocity, which typically is very high (> 6 m/s). Hydrokinetic turbines operate at lower approach flow velocities (perhaps between 1 to 5 m/s depending on the location and turbine design), and some fish may be able to swim against these velocities to a certain degree.

Because fish velocity is inversely related to strike probability (i.e., slower fish speeds will result in greater strike probabilities and higher speeds will result in lower strike probabilities), the probability that fish will be struck by a turbine blade will be greater if fish attempt to swim against the flow as they move downstream rather than simply travel at the speed of the ambient current. Alternatively, fish could exhibit downstream movement faster than the flow velocity which would result in lower strike probabilities. This also means that fish approaching a hydrokinetic turbine may be able to take evasive actions that include swimming faster or slower than the flow velocity in order to avoid being struck by a blade. For simplicity and because there is little or no reliable information on fish speed and behavior approaching various hydrokinetic turbine designs, our application of the strike probability and mortality model to the two turbines evaluated in the flume assumes that fish are traveling at the same velocity as the approach flow. Without more reliable data on fish behavior, fish velocity and avoidance coefficients cannot be incorporated into the theoretical model for predicting turbine passage survival. This type of information should be a focus of future research in order to develop total project passage survival rates. Also, the models presented in this report describe the prediction of strike probability and mortality and overall turbine passage survival only for fish that pass through the blade sweep of turbine (i.e., the probability that fish will encounter a turbine or avoid entrainment if they do, are not factored into the theoretical models).

With respect to design and operation, there are several factors that will affect strike probabilities associated with fish passage through hydrokinetic turbines. Because increases in blade speed associated with increases in approach velocity will typically be linear, and because strike probability decreases with increased approach flow (and fish) velocity and increases with increased blade speed, these factors offset each other, and strike probabilities will remain constant across the range of approach velocities that most hydrokinetic turbines will operate. However, strike mortality will increase with approach velocity due to greater injury associated with higher strike speeds. Also, for axial flow turbines, strike probability will remain relatively constant from the hub to the blade tip because, despite increasing blade speeds with distance from the hub, the gap between blades increases towards the tip. Similar to the effects of increasing approach velocities, strike mortality will increase with distance from the hub because blade (strike) speed increases linearly from the hub to the tip.

As determined by blade strike studies, the ratio of fish length to blade thickness will also affect strike mortality rates, with lower ratios resulting in less injury (EPRI 2008). Consequently, the primary factors affecting turbine passage survival of fish passing through hydrokinetic turbines will be approach velocity (and resulting blade speed), location of passage (near hub, mid, or tip regions), fish length, and leading edge blade thickness. As discussed previously, when more information becomes available on the actual speed of fish as they pass through a hydrokinetic turbine and potential for fish to actively avoid blade strike, coefficients that describe these parameters may be developed and incorporated into theoretical blade strike probability models. In the mean time, strike probabilities using the theoretical approach described here should be considered conservative.

Based on the methods and data developed from studies of fish passage through conventional hydro turbines, we present a model (and its assumptions) for predicting strike probability and mortality and total turbine passage survival for fish passing through the two hydrokinetic turbine designs (LST and Welka UPG) that were evaluated with fish during flume studies (Chapter 3).

Strike Probability and Mortality Model

The probability that a fish will be struck by a turbine blade is a function of the distance that blade leading edges move, compared to the total distance between two consecutive leading edges, in the time it takes a fish to be carried or swim past the arc of leading edge motion (Figure 4-4). Consequently, the probability of strike is given by the following equation (Ploskey and Carlson 2004, Hecker and Allen 2005):

$P_s = n\,[L\sin\alpha]N/60V_r$ (dimensionless) (1)

where:

P_s=probability of strike

n=runner rpm

N=number of leading edges (blades)

L=fish length

α= angle of absolute inflow

V_r=radial component of inflow velocity

Note that α is the angle between the absolute inflow velocity and a tangent line to the runner circumference (Figure 4-4). The parameter $L\sin\alpha$ is the projected fish length in the axial (or radial) direction.

For the purposes of our analysis, fish are assumed to orient with their body length parallel to the ambient current, which is considered typical behavior when fish are moving in fast currents. Rheotactic behavior (i.e., whether fish are oriented head or tail first relative to flow direction) may vary, but observations at dams indicate fish will exhibit positive rheotaxis (head facing upstream) when approaching objects or zones of rapidly increasing water velocities. Side to side movement may occur in front of a turbine and fish may turn (to head facing downstream) as they pass into a region of rapid flow acceleration. The assumption that fish are oriented parallel with the flow as they pass through a hydrokinetic turbine is a conservative one, because it takes more time for the total fish length to pass between the moving blades and injury potential would likely be less if fish were angled less than 90 degrees to a turbine blade (EPRI 2011b).

Mortality due to strike is determined by multiplying P_s by a coefficient K based on experimental data for the proportion of fish that are killed after being struck by a blade. From blade strike tests under controlled conditions (Hecker et al. 2007; Amaral et al. 2008; and EPRI 2008), we have determined that K varies with the relative water to blade velocity (i.e., strike velocity) and the ratio of fish length to leading edge blade thickness (L/t).

For the purposes of the analysis of turbine passage survival, we use K values derived from blade strike tests conducted with rainbow trout. The following is Equation 1 with the inclusion of the coefficient K:

$P_{sm} = Kn\ [L\sin\alpha]N/60V_r$ (dimensionless) (2)

where:

P_{sm} = probability of mortality from blade strike

Using Equation 2, an estimate of turbine passage survival ($1 - P_{sm}$), based on blade strike injury only, can be generated for fish passing through the blade sweep of most hydrokinetic turbine designs. The adaptation of this model to the two turbines evaluated with fish in Alden's large flume test facility is presented below.

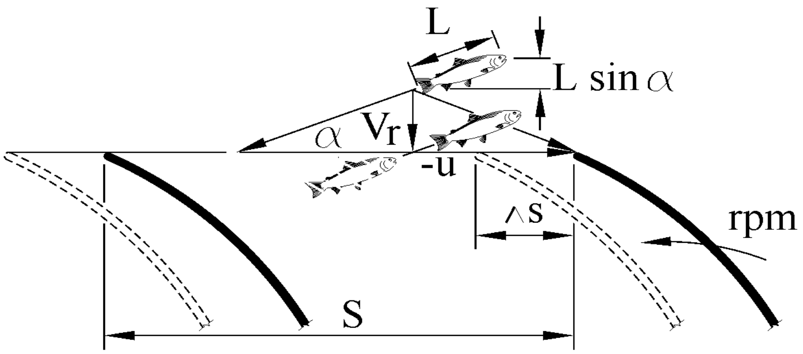

Figure 4-1
Absolute inflow, axial (or radial) component and relative velocity to blade. The parameter Δs is the incremental blade motion in the time fish move through the leading edge circumference.

Application of Strike Model to Lucid Spherical Turbine

Model Parameters and Assumptions

The Lucid spherical turbine is designed for open water and in-line pipe or conduit applications. Our analysis was conducted for the full-size turbine model that was tested with fish in the Alden large flume test facility. The following turbine design and operation parameters were used to estimate strike probability and mortality of fish passing through the LST operating at the three approach velocities, of which the two lower velocities were evaluated during flume testing with fish:

- Approach velocities 1.5, 2.1, and 3.0 m/s (5, 7, and 10 ft/s)
- Runner rotational speeds, n 63.7, 89.2, and 127.4 rpm
- Blade tip radius at vertical centerline 0.57 m (1.88 ft)
- Runner diameter at vertical centerline 1.14 m (3.75 ft)

- Blade tip radius at quarter height 0.52 m (1.71 ft)
- Runner diameter at quarter height 1.04 m (3.42 ft)
- Number of blades, N 4
- Blade leading edge thickness, t 19 mm (0.75 in)

The absolute velocity immediately upstream of the blade leading edges, $V_{a,}$ is equal to the ambient water velocity. Vector addition of the absolute velocity and the (negative) blade leading edge speed (which depends on the distance from the center of rotation) gives the relative velocity (speed and direction) of the flow to the blade (Figure 4-2 and Figure 4-3). The relative velocity is the speed at which the fish strike the leading edge of the blade.

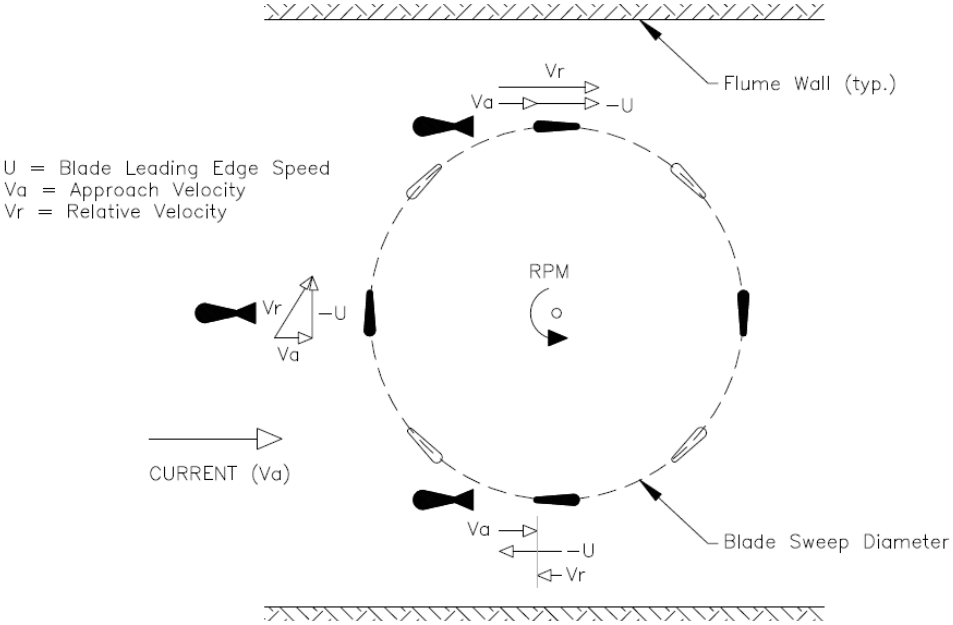

Figure 4-2
Schematic plan view of fish approach locations and corresponding velocity vectors for the Lucid spherical turbine

The blade speed can be calculated from:

$u = 2\pi rn/60$ (3)

where:

u=blade speed

r=radius from center of rotation to the leading edge

n =rpm

The mortality coefficient *K* was derived from data reported by EPRI (2008) that describes the relationship between strike mortality and relative water to blade velocity (i.e., strike velocity) and the ratio of fish length to leading edge blade thickness. The blade thickness at the leading edge for the LST was determined by measuring the physical properties of the lab-tested turbine and then fitting a circle within the actual shape of the leading edge. The diameter of that circle was determined to be 1.9 cm (0.75 inches).

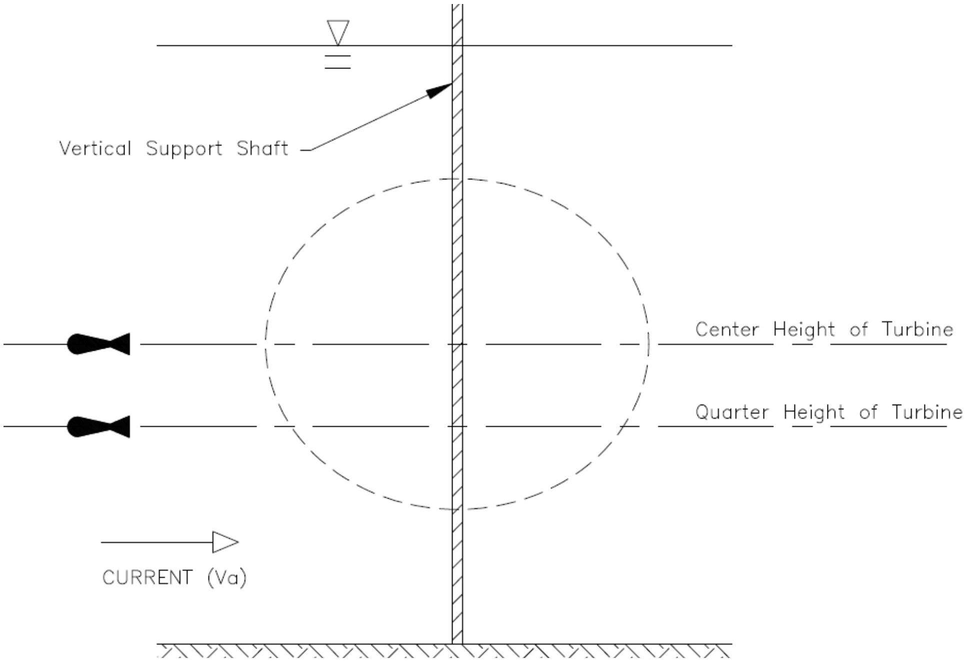

Figure 4-3
Schematic elevation view of fish approach locations and corresponding velocity vectors for the Lucid hydrokinetic turbine

At each approach velocity (and corresponding rotational speed), the probability of strike and mortality due to strike were calculated for fish lengths ranging from 50 to 600 mm. This range encompasses the vast majority of fish (species and life stages) that are likely to encounter hydrokinetic turbines in most flowing water environments, and it represents the ratios of fish length to blade thickness for which mortality data have been developed in lab studies (EPRI 2008). For the LST, it was determined that strike mortality will not occur at ambient current velocities less than 1.7 m/s for the range of fish lengths assessed because resulting strike velocities are not sufficient to cause injury [i.e., strike velocities will be less than about 4.5 m/s (15 ft/s), above which strike-related mortality may begin to occur (EPRI 2008, 2011b), depending on fish length and leading edge blade thickness]. Because the LST is a cross flow design with an enclosed spherical shape, fish that pass through the blade sweep to the interior will pass through the blade sweep a second time when they exit. Therefore, in addition to estimates of strike probability and mortality for a single pass through the blade sweep, turbine passage survival was calculated for two passes through the turbine blade sweep, where two passes represents fish entering and exiting a turbine. It was assumed that fish moving out of the interior of the turbine will be perpendicular to the blade motion (as during entry) and the approach and relative (strike) velocities are the same as when fish enter the upstream portion of the blade sweep.

Strike probability and mortality were calculated for fish passing through the blade sweep at locations on the upstream face where the vertical and horizontal centerlines meet and at half the distance along a blade between the horizontal centerline and the top (or bottom) of the turbine (Figure 4-2 and Figure 4-3). Using the installation of the LST in Alden's large flume test facility (Chapter 2) as an example, the relative (fish to blade) velocity is highest where the fish and blades are moving in exactly opposite directions (fish moving downstream and blade moving upstream parallel to flow) (Figure 4-2). However, the length of the fish exposed to a blade ($L\sin\alpha$) at this location is the shortest it can be relative to being struck by a blade. The lowest relative velocity occurs where fish and blades are moving in the same direction (downstream), which also has the shortest fish exposure length. The two locations of fish passing through the blade sweep selected for our calculations represent a strike speed that is an approximate average of the highest and lowest speeds at each of the two vertical positions (i.e., vertical/horizontal midpoint and half the distance between this location and the top/bottom of the turbine, also referred to as quarter height) (Figure 4-3). These positions also represent where the maximum exposure length of the fish to a blade will occur if fish are oriented parallel to the flow (i.e., the angle of fish relative to an approaching blade is perpendicular), which was assumed for the model predictions. It was also assumed that fish will be perpendicular to the blade at the point of impact with a relative velocity close to the blade speed. Fish leaving the interior portion of the turbine may exit at any direction from the hub. However, for simplicity, it was assumed that fish moving out of the interior will be perpendicular to the blade motion.

Turbine Passage Survival Estimates

As expected, the predicted strike probability associated with the Lucid spherical turbine increases with fish size (Figure 4-4). However, observations from flume testing indicated that strike probability for entrained fish was greater for the larger of the two size groups tested (see Table 3-5), as well as being higher than predicted by the theoretical model for both size groups. These results suggest that larger fish may have had greater ability to avoid blade strike, but that both size groups were more susceptible to blade strike than would be predicted by the theoretical model. For any given fish length, predicted strike probability does not change with approach velocity or the location of fish entry into the blade sweep in the vertical plane because the changes in the speed of fish passing through the turbine at different approach velocities are proportional to corresponding changes in blade velocity (Table 4-1 and Table 4-2). That is, as the ambient current velocity increases, the velocity of approaching fish and the blades increase proportionally, resulting in no change in strike probability within the range of current velocities that the turbine is expected to operate.

Also, with respect to vertical location of entry into the blade sweep, strike probability does not change because the narrower distance between blades at the quarter point is offset by a slower blade speed compared to the midpoint location (i.e., location of maximum diameter and blade speed). Strike probability through the LST blade sweep is predicted to be 100% when fish length exceeds 350 mm (Figure 4-4).

The predicted mortality for fish struck by a blade also increases with fish size, as well as approach velocity (Figure 4-5; Table 4-1 and Table 4-2). Strike mortality begins to occur at an ambient current velocity of about 1.7 m/s when the strike velocity (relative velocity of fish to blade) is of a sufficient magnitude (greater than about 5 m/s) to cause fatal injuries to fish with lengths that are greater than the thickness of the leading edge of the blades. Strike mortality also increases with fish speed for any given fish length and approach velocity due to corresponding increases in strike velocity.

Predicted turbine passage survival for single and double passes through the blade sweep decreases with increases in fish size and ambient current velocity based upon the estimated strike probability and mortality rates (Figure 4-6; Table 4-1 and Table 4-2). With respect to the effect of fish entry location relative to the vertical plane, passage survival increases as fish move away from the turbine centerline at the same current velocity. Mortality decreases because the turbine diameter decreases above and below the turbine centerline, resulting in a reduced blade speed and therefore a lower strike velocity. As current velocities begin to exceed 1.7 m/s, turbine passage survival begins to decrease primarily for larger fish, but generally remains high (greater than 90%) for fish less than 200 mm in length.

The theoretical estimates of turbine passage survival and the survival estimates calculated from the flume data cannot be directly compared because the flume estimates include fish that avoided turbine passage. However, the flume data indicated survival for all fish, including those that passed through the blade sweep of the LST, was 100% at an approach velocity of 1.5 m/s. This is consistent with the theoretical predictions of turbine passage survival for this approach velocity and supports the conclusion that fish of these species and sizes that are struck by turbine blades at strike velocities less than about 5 m/s will not sustain fatal injuries (strike velocity on the centerline of the LST is about 4.1 m/s at an approach velocity of 2.1 m/s). Total survival of fish tested in the flume at a velocity of 2.1 m/s was 99.0 and 98.4% for the smaller and larger-sized fish (mean lengths of 138 and 249 mm), respectively, both of which are higher estimates of survival than theoretical predictions. The differences between empirical and theoretical data at this velocity reflect the ability of fish to avoid turbine passage in the flume. Experimental and theoretical estimates of survival would be more comparable if the experimental data were sufficient to only include fish entrained through the blade sweep calculation of turbine passage survival rates. These observations highlight the limitations of theoretical models of hydrokinetic turbine-fish interactions that do not account for avoidance and evasion behavior.

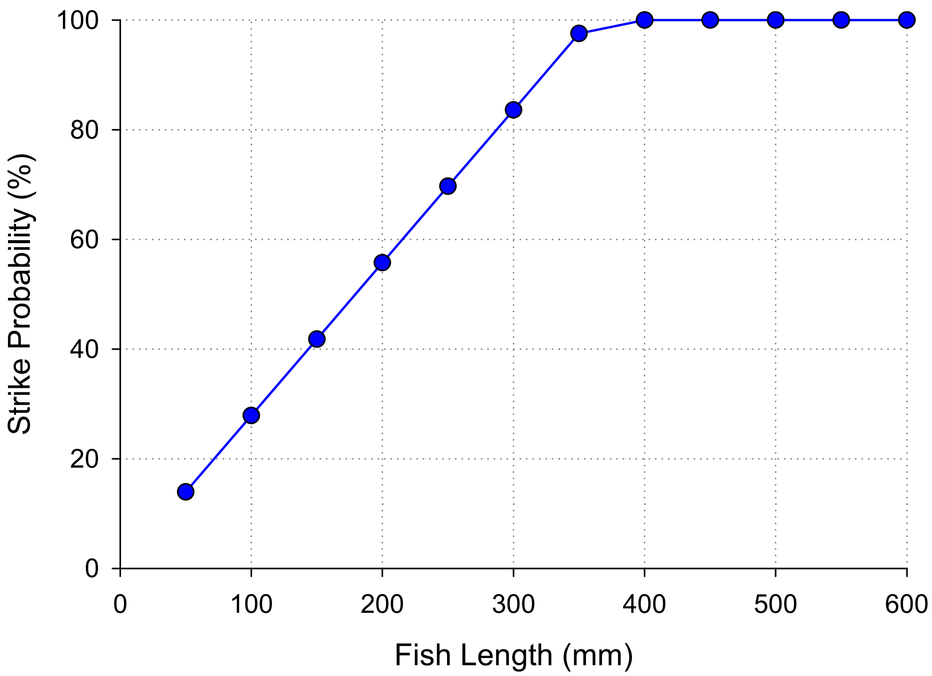

Figure 4-4
Strike probability versus fish length for a single pass through the blade sweep of a Lucid spherical turbine with fish approaching the turbine at the same speed as the flow. For any given fish length, strike probability is the same for all flow approach velocities and for all strike locations along a blade (i.e., strike probability at the mid and quarter blade points will be the same).

Table 4-1

Summary of blade strike probability, predicted strike mortality, and predicted turbine passage survival for a Lucid spherical turbine operated at three current velocities with fish passing through at the blade midpoint. Turbine passage survival is presented for fish passing through the blade sweep once and twice (i.e., entry into and exit from turbine).

Fish Length (mm)	Strike Probability for All Current Velocities (%)	Strike Mortality (%)			Turbine Passage Survival (%) for Single Pass through Blades			Turbine Passage Survival (%) for Double Pass through Blades		
		1.5 m/s	2.1 m/s	3.0 m/s	1.5 m/s	2.1 m/s	3.0 m/s	1.5 m/s	2.1 m/s	3.0 m/s
50	13.9	0.0	8.9	26.5	100.0	98.8	96.3	100.0	97.5	92.8
100	27.9	0.0	13.6	40.3	100.0	96.2	88.8	100.0	92.6	78.8
150	41.8	0.0	16.3	48.4	100.0	93.2	79.8	100.0	86.9	63.6
200	55.7	0.0	18.2	54.1	100.0	89.9	69.8	100.0	80.7	48.8
250	69.7	0.0	19.7	58.6	100.0	86.3	59.2	100.0	74.4	35.0
300	83.6	0.0	20.9	62.2	100.0	82.5	48.0	100.0	68.1	23.0
350	97.5	0.0	22.0	65.3	100.0	78.6	36.3	100.0	61.8	13.2
400	100.0	0.0	22.8	67.9	100.0	77.2	32.1	100.0	59.5	10.3
450	100.0	0.0	23.6	70.3	100.0	76.4	29.7	100.0	58.3	8.8
500	100.0	0.0	24.3	72.4	100.0	75.7	27.6	100.0	57.2	7.6
550	100.0	0.0	25.0	74.3	100.0	75.0	25.7	100.0	56.3	6.6
600	100.0	0.0	25.6	76.0	100.0	74.4	24.0	100.0	55.4	5.7

Table 4-2
Summary of blade strike probability, predicted strike mortality, and predicted passage survival for a Lucid spherical turbine operated at three current velocities with fish passing through the blade quarter point. Turbine passage survival is presented for fish passing through the blade sweep once and twice (i.e., entry into and exit from turbine).

Fish Length (mm)	Strike Probability for All Current Velocities (%)	Strike Mortality (%)			Turbine Passage Survival (%) for Single Pass through Blades			Turbine Passage Survival (%) for Double Pass through Blades		
		1.5 m/s	2.1 m/s	3.0 m/s	1.5 m/s	2.1 m/s	3.0 m/s	1.5 m/s	2.1 m/s	3.0 m/s
50	13.9	0.0	5.8	22.1	100.0	99.2	96.9	100.0	98.4	93.9
100	27.9	0.0	8.8	33.6	100.0	97.5	90.6	100.0	95.1	82.2
150	41.8	0.0	10.6	40.3	100.0	95.6	83.1	100.0	91.3	69.1
200	55.7	0.0	11.9	45.1	100.0	93.4	74.9	100.0	87.2	56.0
250	69.7	0.0	12.9	48.8	100.0	91.0	66.0	100.0	82.9	43.6
300	83.6	0.0	13.7	51.8	100.0	88.6	56.7	100.0	78.5	32.1
350	97.5	0.0	14.3	54.4	100.0	86.0	46.9	100.0	74.0	22.0
400	100.0	0.0	14.9	56.6	100.0	85.1	43.4	100.0	72.4	18.8
450	100.0	0.0	15.4	58.6	100.0	84.6	41.4	100.0	71.5	17.2
500	100.0	0.0	15.9	60.3	100.0	84.1	39.7	100.0	70.7	15.7
550	100.0	0.0	16.3	61.9	100.0	83.7	38.1	100.0	70.0	14.5
600	100.0	0.0	16.7	63.3	100.0	83.3	36.7	100.0	69.4	13.4

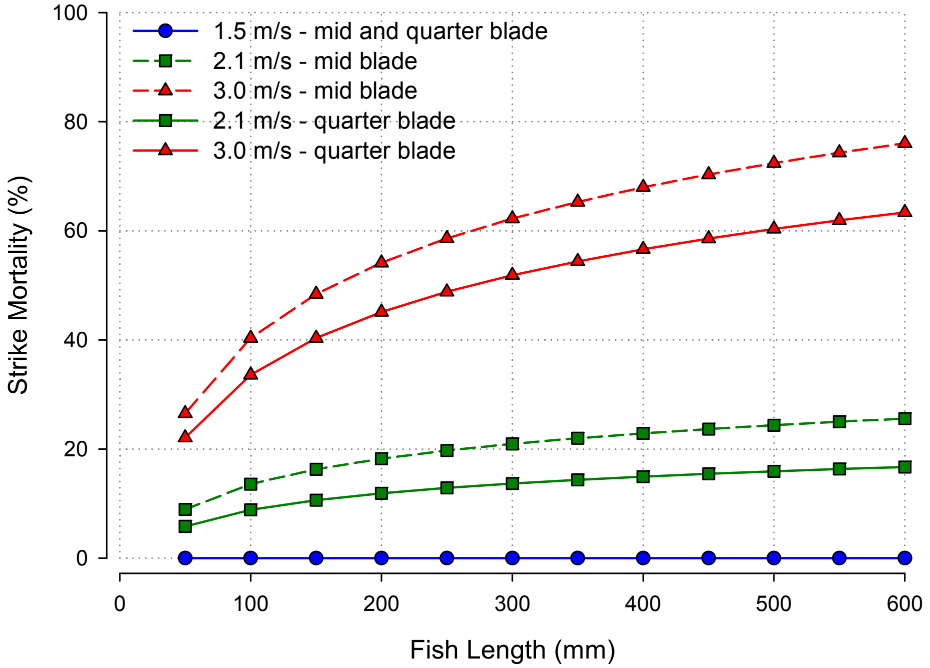

Figure 4-5
Predicted strike mortality (i.e., probability a fish is killed if struck by a blade) for fish passing through the LST blade sweep once at three approach velocities (i.e., fish speed equals flow speed) and two vertical locations (mid and quarter blade).

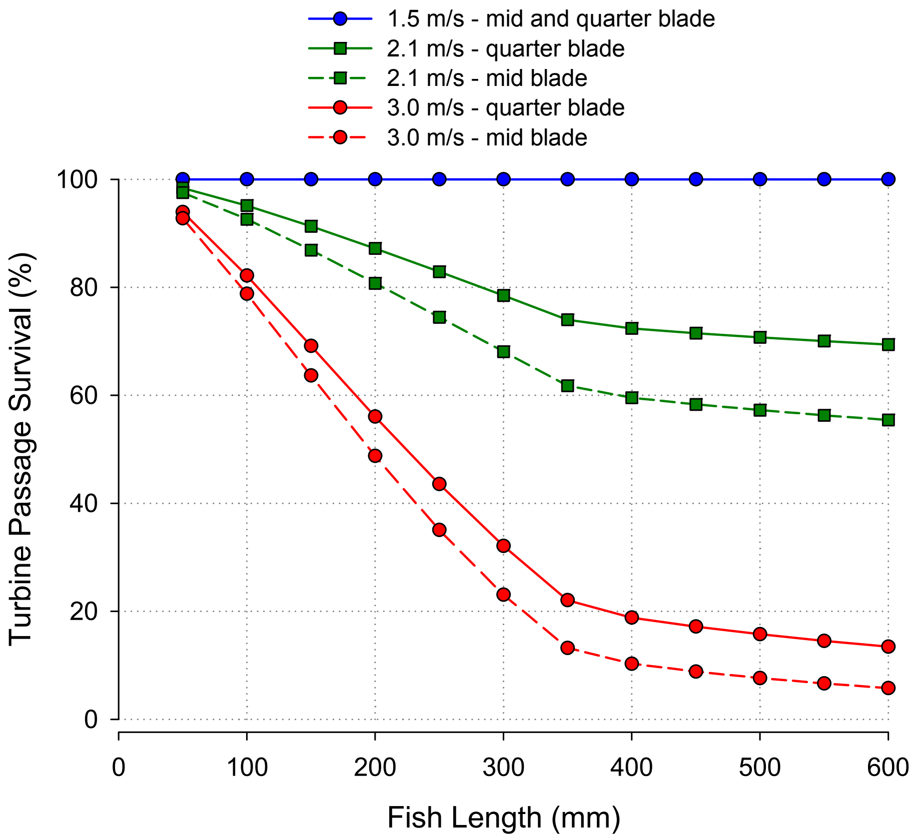

Figure 4-6
Predicted turbine passage survival (combining strike probability and strike mortality) for fish up to 600 mm in length passing through the LST at three approach velocities (i.e., fish speed equals flow speed) and two vertical locations (mid and quarter blade). Survival rates account for fish passing through the blade sweep twice.

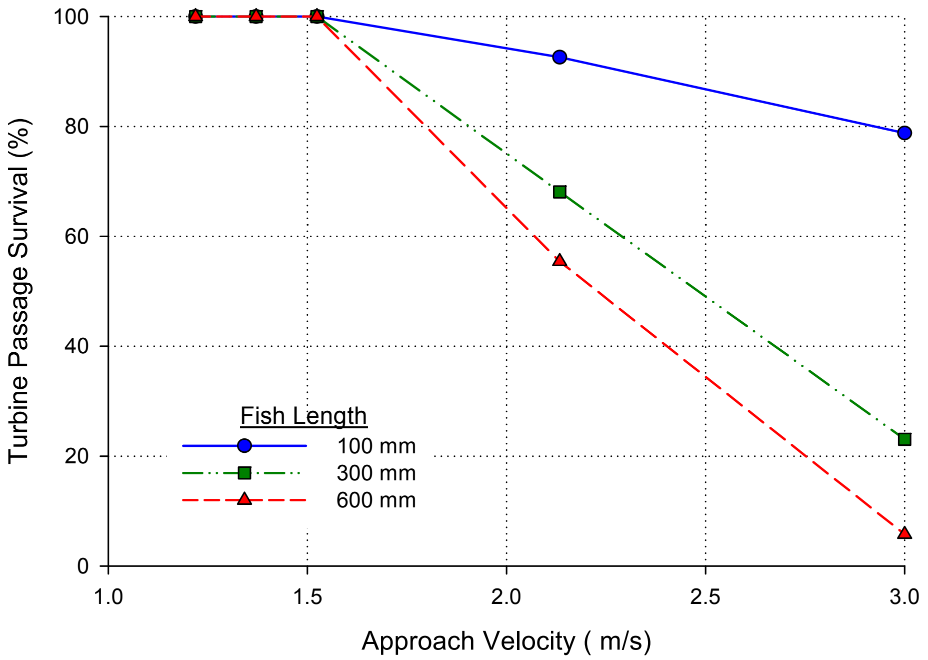

Figure 4-7
Turbine passage survival rates (combining strike probability and strike mortality) versus ambient current velocity for different lengths of fish. These estimates are based on the assumption that fish are approaching a turbine at the same speed as the ambient current and they pass through the blade sweep twice.

Application of Strike Model to the Welka UPG Turbine

Model Parameters and Assumptions

The following turbine design and operation parameters were used to estimate strike probability and mortality of fish passing through the Welka UPG turbine at the two approach velocities evaluated during flume tests:

- Approach velocities 1.5 and 2.1 m/s (5 and 7 ft/s)
- Runner rotational speed, n 15 and 35 rpm
- Blade tip radius at blade tip 0.76 m (2.50 ft)
- Runner diameter at blade tip 1.52 m (5.00 ft)
- Blade tip radius at mid-bladelength 0.38 m (1.25 ft)
- Runner diameter at mid-blade length 0.76 m (2.5 ft)
- Number of blades, N 4
- Blade leading edge thickness, t 12.7 mm (0.5 in)

The absolute velocity immediately upstream of the blade leading edges, V_a, is equal to the ambient water velocity. Vector addition of the absolute velocity and the (negative) blade leading edge speed (which depends on the distance from the center of rotation) provides the relative velocity (speed and direction) of the flow to the blade (Figure 4-8). The relative velocity is the speed at which the fish strike the leading edge of the blade.

The blade speed at the radius of interest can be calculated from:

$$u = 2\pi rn/60 \quad (3)$$

where:

u=blade speed (ft/s)

r=radius from center of rotation a point on the leading edge (ft)

n =rpm

The mortality coefficient K was derived from data reported by EPRI (2008) that describes the relationship between strike mortality and relative water to blade velocity (i.e., strike velocity) and the ratio of fish length to leading edge blade thickness. The blade thickness at the leading edge for the Welka UPG turbine was determined by measuring the physical properties of the lab-tested turbine and then fitting a circle within the actual shape of the leading edge. The diameter of that circle was determined to be 0.5 inch.

At each approach velocity (and corresponding rotational speed), the probability of strike and mortality due to strike were calculated for fish lengths ranging from 50 to 600 mm passing through the blade sweep at the blade midpoint and tip. The selected length range encompasses the vast majority of fish (species and life stages) that are likely to encounter hydrokinetic turbines in most flowing water environments, and it represents the ratios of fish length to blade thickness for which mortality data have been developed in laboratory studies (EPRI 2008). For the Welka UPG, it was determined that strike mortality will not occur at ambient current velocities less than 2.5 m/s for the range of fish lengths assessed because resulting strike velocities are not sufficient to cause injury [i.e., strike velocities will be less than about 5 m/s, above which strike-related mortality may begin to occur (EPRI 2008), depending on fish length and leading edge blade thickness].

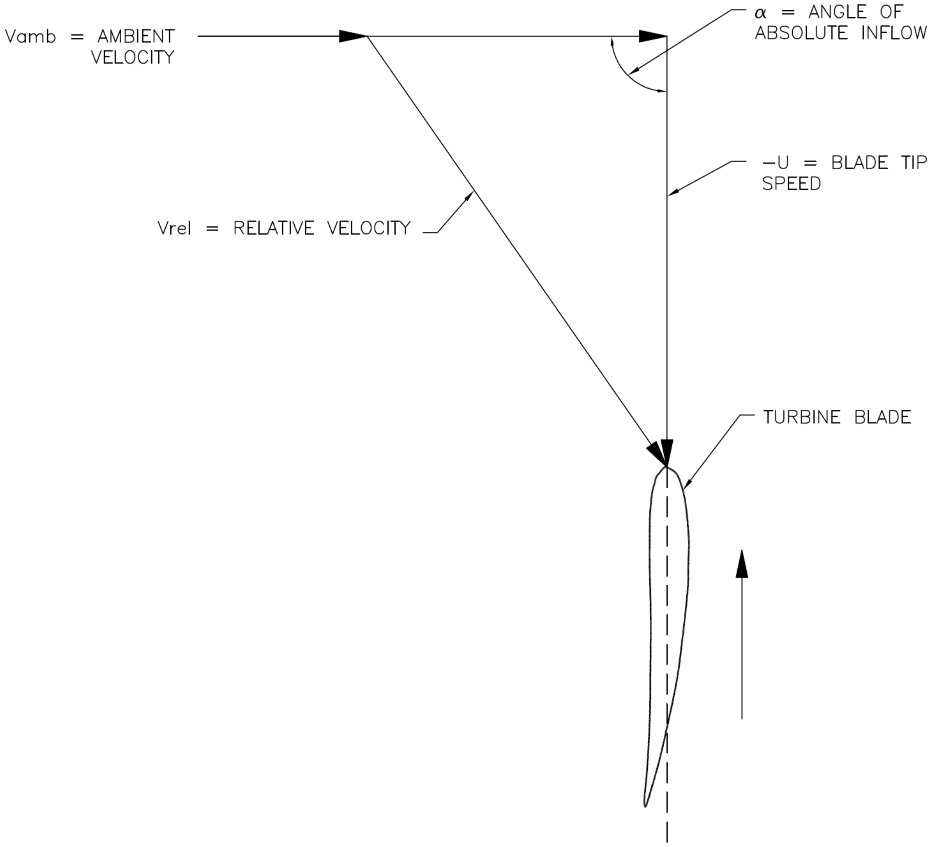

Figure 4-8
Velocity vector triangle for the Welka UPG hydrokinetic turbine

Turbine Passage Survival Estimates

Strike probability estimates for fish passing through a Welka UPG turbine increase with fish length and are the same for all ambient current velocities and strike locations along a blade for a given length (Table 4-3). Strike probability only varies with fish size because increases in blade speeds with distance from the hub are proportional to the wider spacing between blades, and because fish pass through the turbine more quickly as approach velocity (and blade speed) increase. For fish 600 mm in length and less, strike mortality is not predicted to occur during passage through a Welka UPG turbine at ambient current velocities less than about 2.5 m/s because strike velocities will not exceed 5 m/s, which is the approximate upper limit above which fish mortality will begin to occur [depending on the ratio of fish length to blade thickness; EPRI (2008)]. Consequently and as estimated, predicted turbine passage survival will be 100% for fish that pass through a Welka turbine over the entire blade length at an ambient current of 2.5 m/s or less. Also, the theoretical estimates are consistent with the experimental results from flume testing (99.4 to 100%). Note, however, that both the experimental apparatus and the theoretical model assumptions precluded turbine avoidance by the fish; turbine avoidance is an important factor when fish are not forced through the turbine.

Table 4-3
Estimated blade strike probability and predicted survival rates for fish of various sizes passing through the Welka UPG turbine at two ambient current velocities and blade locations

Fish Length (mm)	Blade Strike Probability (%)	Turbine Passage Survival (%)			
		1.5 m/s		2.1 m/s	
		Mid	Tip	Mid	Tip
50	5.5	100.0	100.0	100.0	100.0
100	10.9	100.0	100.0	100.0	100.0
150	16.4	100.0	100.0	100.0	100.0
200	21.9	100.0	100.0	100.0	100.0
250	27.3	100.0	100.0	100.0	100.0
300	32.8	100.0	100.0	100.0	100.0
350	38.3	100.0	100.0	100.0	100.0
400	43.7	100.0	100.0	100.0	100.0
450	49.2	100.0	100.0	100.0	100.0
500	54.7	100.0	100.0	100.0	100.0
550	60.1	100.0	100.0	100.0	100.0
600	65.6	100.0	100.0	100.0	100.0

Section 5: Conclusions and 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). 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 estimation of turbine passage survival using flume data and theoretical models presented in this report only accounts for direct mortality resulting from lethal injuries sustained during passage through the two turbines evaluated. Increased stress and sub-lethal injuries may also occur during turbine passage and can lead to indirect (or delayed) mortality associated with reduced fitness and greater susceptibility to disease and predation (Budy et al. 2002; Ferguson et al. 2006). Indirect mortality can be more difficult to evaluate and quantify than direct mortality, but some longer term tagging studies have examined the indirect effects of turbine passage on survival rates associated with downstream movement through one or more conventional hydro projects. Although evaluations of indirect mortality can only be evaluated in the field for fish passing through conventional hydro turbines, future lab studies may be able to examine this parameter in more detail for hydrokinetic turbines.

The following are the primary conclusions from the biological evaluation of the LST and the theoretical estimation of strike probability and mortality:

Immediate and total survival rates of rainbow trout encountering the Lucid spherical turbine were greater than 99% for both size classes and velocities tested, with the exception of 250-mm fish evaluated at the higher velocity (2.1 m/s), for which total survival was 98.4%. These survival rates represent fish that passed downstream by actively avoiding entrainment and those that were entrained through the operating unit. Because the LST is a cross-flow design, fish that were entrained passed through the blade sweep twice.

Injury and scale loss rates for rainbow trout encountering the LST were negligible based on the rates observed for control fish released downstream of the turbine (i.e., most injury and scale loss was attributed to pre-test condition of fish and/or handling and testing procedures, not passage around or through the turbine).

Despite exiting the release system within 250 to 300 mm (about 10 to 12 inches) of the upstream face of the turbine blade sweep, observations from underwater video demonstrated that many treatment fish actively avoided entrainment through the LST by swimming to the sides, top, or bottom of the operating turbine. A review of the underwater video indicated between about 82 and 94% of rainbow trout avoided passage through the turbine in this manner. The lowest estimates of avoidance were recorded at the higher test velocity for both size groups of trout.

Behavioral tests, in which rainbow trout were released about 7.6 m (25 ft) upstream from the LST, indicated that most, if not all, fish moving downstream in the 8-ft by 8-ft test channel did not encounter the turbine either through active avoidance or downstream movement along the channel walls or floor.

The theoretical predictions of blade strike probability and mortality of fish passing through the blade sweep of the LST twice (i.e., into and out of the turbine) indicate that turbine passage survival could be relatively low (13 to 90% depending on fish length) at approach velocities of 2.1 m/s and higher.

The experimental data from flume tests indicated survival was higher than predicted by the models. This is because a large proportion of fish were able to avoid turbine passage during flume tests. This highlights the limitations of the theoretical models, which do not incorporate avoidance behavior by the fish. Survival estimates based solely on fish that passed through the LST likely would be comparable to the theoretical predictions.

Based on these conclusions, little, if any, mortality, injury, and scale loss are expected to occur for fish encountering an LST in an open water environment (i.e., riverine or tidal). However, for pipe or conduit installations of the LST at sites where fish can be entrained with the intake flow and will have to pass through the blade sweep twice, the theoretical predictions indicate that mortality could be high under certain operational conditions (approach velocities greater than 1.5 m/s) for fish greater than about 100 mm (4 inches). Consequently, pipe or conduit applications may require protective screening to minimize fish entrainment and resulting turbine passage mortality.

The primary conclusions from testing with the Welka UPG turbine and the theoretical estimates of blade strike probability and mortality include:

Immediate and total turbine passage survival for the two size groups of rainbow trout and largemouth bass evaluated at approach velocities of 1.5 and 2.1 m/s were greater than 99.5%.

Based on control fish data, observed injury and scale loss for turbine-passed fish can primarily be attributed to the pre-test condition of fish and/or handling and testing procedures.

Underwater video observations during survival testing with the Welka UPG turbine were not reliable due to obstruction of cameras associated with the containment net, the turbine runner duct, and air entrainment in the flume.

Behavioral tests indicated that most, if not all, rainbow trout moving downstream in the 2.4-m by 2.4-m test channel did not encounter the turbine either due to active avoidance or downstream movement along the channel walls or floor. Similar observations were made for largemouth bass.

Theoretical estimates of blade strike probability ranged from about 5 to 60% for fish 50 to 600 mm in length (about 2 to 24 inches) and estimates of strike mortality were 0% for all fish lengths and the two approach velocities evaluated (1.5 and 2.1 m/s). Consequently, turbine passage survival was estimated to be 100% for these fish size and velocity conditions, concurring with the survival estimates developed from the flume tests in which all fish were forced through the turbine.

These conclusions indicate that fish entrained through a Welka UPG turbine will suffer little or no injury and mortality over the likely range of operating conditions (this turbine is designed for operation in relatively low velocities similar to those tested in the flume). The theoretical predictions were consistent with the experimental results from flume testing, suggesting that a predictive model could be used to assess turbine passage survival rates at future installations if they have operational conditions that differ from those tested during the laboratory evaluation. For such field applications, however, additional factors, such as fish movement routes and turbine avoidance would need to be incorporated into the analysis in order to estimate overall passage success.

Despite very precise estimates of turbine passage survival (i.e., confidence intervals typically were less than ± 2% of the survival estimates), only a few statistically significant differences were detected when comparing the survival data among treatments. For the LST, total survival was significantly greater for larger rainbow trout tested at the lower velocity (1.5 m/s) than at the higher velocity (2.1 m/s). This was mainly due to a higher rate of delayed mortality (48-hr) at the faster velocity and could be indicative of increased mortality associated with greater strike speeds (strike velocities are sufficient to result in some mortality when approach velocities to the LST exceed 1.7 m/s). The only other statistical difference in survival rates that was detected occurred with rainbow trout tested at a velocity of 2.1 m/s during tests with the Welka UPG. At this velocity, the smaller trout had significantly higher immediate and total survival than the larger fish. However, this statistical significance was mainly due to the survival estimates for the smaller fish exceeding 100% (i.e., mortality was higher for control fish than it was for treatment fish). In fact, if survival estimates are capped at 100% for tests with both turbines when control mortality exceeded that of treatment fish, there would be no significant differences among the treatments for any of the tests with each unit. The lack of significant differences in treatment conditions reflects the high and narrow ranges of the survival estimates that occurred among all of the treatments. To some extent, the lack of statistically significant differences may also have been a product of the selected fish sizes and velocities over which tests with each turbine were conducted. In particular, testing with larger or smaller fish and/or faster approach velocities could have produced more significant differences between measured survival rates. Survival data for fish lengths and flow velocities greater than those tested as part of the current would only be useful for sites where larger fish and faster velocities are expected to occur. Future lab testing could be conducted to address this potential information gap and broaden the current dataset. Conversely, survival rates for smaller fish and lower approach velocities may be similar or higher than those observed in the Alden flume studies.

To date, only one other study has been completed that was specifically designed to estimate direct survival of fish passing through a hydrokinetic turbine. This study was conducted in the field with an axial-flow ducted propeller turbine developed by Hydro Green Energy (NAI 2009). The Hydro Green turbine was installed in the tailrace of an operating conventional hydro project and evaluated with several species and life stages of fish using a release-recapture methodology (i.e., fish were introduced into the turbine duct upstream of the blades and recovered following passage after balloon tags attached to the musculature of each fish inflated and brought them to the surface). The results of this study indicated total (48-hr) survival rates were 99% for yellow perch (118-235 mm in length), bluegill (115-208 mm), channel catfish (451-627 mm), and smallmouth and bigmouth buffalo (388-710 mm). These survival rates are similar to the estimates for rainbow trout and largemouth bass evaluated with the ducted Welka UPG turbine, and are most likely the result of a low strike probability (due to low rotational speed and only three blades) and strike velocity (relative velocity of fish to blade, assuming fish are traveling at the speed of the flow). The tip speed of the Hydro Green turbine was estimated to be about 4 m/s based on a diameter of 3.7 m and rotational speed of 21 rpm. Strike velocity will be higher than the tip speed, but for the Hydro Green turbine it probably was about the same or less than the velocity at which strike mortality begins to occur (4.5 m/s, depending on the ratio of fish length to blade leading edge thickness) over most of the blade leading edge from the hub to the tip. The maximum strike velocity of the Welka UPG, which has 4 blades, was 3.5 m/s. The lab and field tests with these axial-flow ducted turbines demonstrate that this design type is likely to cause little or no mortality to entrained fish, particularly when strike velocities are relatively low (about 4.5 m/s or less). The field evaluation of the Hydro Green turbine also demonstrated that survival rates were very high and similar for a relatively wide range of species and over a broad range of fish sizes. The survival estimates for the two size groups of rainbow trout and largemouth bass that were tested during the Alden flume study are consistent with these observations from the field testing.

The results of the flume studies and the predictive modeling provide some important insights into how fish might react to and be affected by hydrokinetic turbines installed in the field. Both of the turbines that were tested were full-size units (although, the developers of both turbines will likely make available units of varying sizes) and the velocities that were evaluated covered the lower and upper limits of the expected range for field operation for the Welka UPG and included the lower half of the expected design range for the LST (1.2 to 3.0 m/s). Therefore, based on the size of the units and flow velocities tested, the lab results are directly applicable to the operation of these units in field applications (but the actual velocities that both turbines are likely to operate at in the field will vary depending on site-specific conditions). However, fish behavior in a controlled laboratory environment is not always representative to what occurs in natural environments. In particular, avoidance reactions to the turbines in the flume may differ from how fish react to them in the field. The flume data from testing with the LST demonstrate that, even when released very close to an operating turbine, fish will actively avoid passage through the blade sweep. At the two approach velocities tested, video observations indicated that rainbow trout detected the rotating blades, typically maintained positive rheotaxis (head facing upstream), slowed or stopped their downstream movement, and then mainly proceeded around the LST despite the close proximity of their release to the turbine and the relatively confined space of the flume (i.e., a 1.2 m diameter turbine in a 2.4 m deep and wide flow passage). These reactions are typical for fish approaching flow obstructions and/or hydraulic disturbances (Haro et al. 1998) and would be expected to occur at field installations, but avoidance may be even greater in the field because fish will have more time to detect and react to an operating turbine, and would have more space to move around the blade sweep. Also, fish were released on the centerline of the turbine in the flume, whereas in the field, many fish may approach off center and be more likely to follow flow lines around a turbine. On the other hand, under conditions of lower water temperature or reduced visibility, avoidance may be lower, and smaller fish may be less able to avoid the turbine.

The potential for fish to be injured or killed when encountering hydrokinetic turbines in flowing water environments is a major issue that can impede the development of proposed projects and lead to costly field studies. Alteration or blockage of fish movements and migrations also may be an important concern that needs to be addressed. Recently, some field studies have been conducted to examine these types of impacts, but the data collected have not always been sufficient to draw definitive conclusions or are not publicly available. Assessment of the behavior and movement of fish approaching and passing hydrokinetic turbines in the field, including entrainment through blade sweeps and any resulting injuries, is problematic, and the tools and techniques for conducting these types of studies are still being developed and evaluated. The laboratory flume evaluation and application of theoretical blade strike models that were completed as part of the current study, as well as flume testing conducted by the Conte Anadromous Fish Research Laboratory (CAFRL), provide valuable data and information for a better understanding of the outcomes of interactions between fish and hydrokinetic turbines. Quantitative data and visual observations from the laboratory studies clearly demonstrate the outcomes of fish approaching and passing downstream of hydrokinetic turbines for the turbine designs, flow and operational conditions, and fish species and size classes evaluated. The turbine types and fish species tested may be considered representative of other turbine designs and species based on a comparison of operational conditions and biological characteristics (e.g., swimming abilities, body shape and morphology).

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 at CAFRL with a Darrieus 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 2011c). 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 2009). Individually and collectively, the results from laboratory and field studies suggest that the mortality of juvenile and adult fish passing through hydrokinetic turbines of this design, and perhaps others, will be below levels of concern. However, because the results generally are applicable to passage through a single turbine, more analysis is needed to assess the potential for multiple units to lead to greater mortality rates or impacts on fish movements and migrations. Quantification of avoidance behavior is also needed.

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 (excluding Pelton turbines) has been shown to range from about 80 to 95%, depending on turbine design and fish size (Franke et al. 1997). 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 (Franke et al. 1997). This will also be true for hydrokinetic turbines because damaging pressure changes and shear levels are not expected to occur or will be limited in their presence. Also, given that hydrokinetic turbines are not operated under head and hydraulic and mechanical injury mechanisms will be less severe (EPRI 2011a), 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 hydrokinetic devices may be 100% or slightly less depending on design features and operational conditions. When encounter and avoidance probabilities are also considered, overall passage survival rates of 98 to 100% are likely for many turbine designs. Future research should focus on expanding the existing data on potential fish losses associated with hydrokinetic turbine installations by developing better estimates of encounter and avoidance probabilities. Encounter rates could be developed from field monitoring of fish abundance and movements or based on the proportion of river or channel flow that passes through a turbine (or the cross-sectional area of a channel that a turbine's blade sweep occupies (Schweizer *et al.* 2011)). Avoidance probabilities for fish that encounter a turbine could also be derived from field monitoring, or additional flume testing. These data can then be combined with laboratory or theory-based estimates of turbine passage survival to develop a more comprehensive model that incorporates site-specific hydraulic and environmental conditions to estimate total expected fish losses 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.

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