ELECTRIC POWER
RESEARCH INSTITUTE

# Assessment of the Environmental Effects of Hydrokinetic Turbines on Fish: Desktop and Laboratory Flume Studies

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Program Manager

August 29, 2011

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

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# Program Team

- **EPRI – Project Management: Paul Jacobson & Doug Dixon**
- **Alden Research Laboratory, Holden, MA – Steve Amaral, Principal Investigator**
- **U.S.G.S. Silvio Conte Anadromous Fish Research Center, Turner Falls, MA – Ted Castro-Santos, Principal Investigator**

# Sponsors

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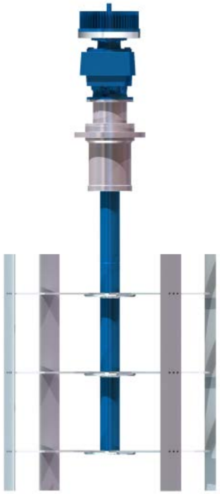
**WELKA UPG**



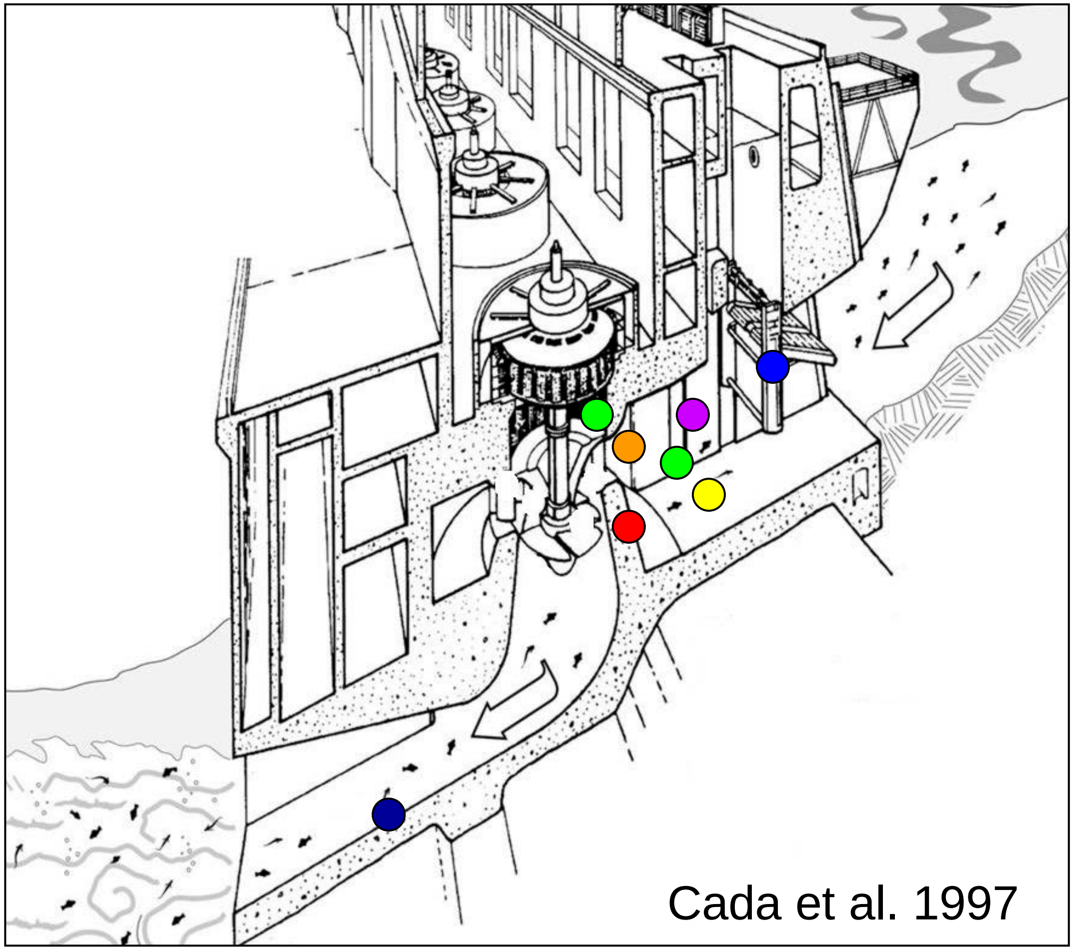
# Program Objective

**Determine injury, survival rates and behavioral effects for fish passing through hydrokinetic turbines by:**

1. Conducting a review of existing information on injury mechanisms
2. Developing theoretical models for the probability of blade strike and mortality for various hydrokinetic turbine designs; and
3. Conducting flume studies with three turbine designs and several species and size classes of fish at the Conte Anadromous Fish Research Laboratory and Alden

# Conventional Hydro Turbine Biocriteria

## *Turbine Passage Injury Mechanisms*



Cada et al. 1997

- ● Increasing Pressure
- ● Rapidly Decreasing Pressure
- ● Cavitation
- ● Strike
- ● Grinding
- ● Shear
- ● Turbulence

# Conventional Hydro Turbine Biocriteria

## PRESSURE

***Pressure-related injury is dependent on***:

- Magnitude of pressure change
- How rapidly pressure changes occur
- How quickly fish can adjust to changes
    - ***Physostomous species***: Connection between swim bladder and esophagus allows for relatively rapid intake and venting of gas in response to pressure changes.
    - ***Physoclistus species***: Gas diffusion through blood stream makes it difficult to quickly adjust to large pressure changes.
- Acclimation pressure

# Conventional Hydro Turbine Biocriteria

## PRESSURE

- **HK turbines do not experience extensive and rapid changes in pressure which have been shown to damage fish during passage through conventional hydro turbines.**
- **Fish will be acclimated to pressure upstream and downstream of hydrokinetic turbines.**
- **If pressure-related injury and mortality occur, they will be associated with cavitation areas.**

# Conventional Hydro Turbine Biocriteria

## CAVITATION

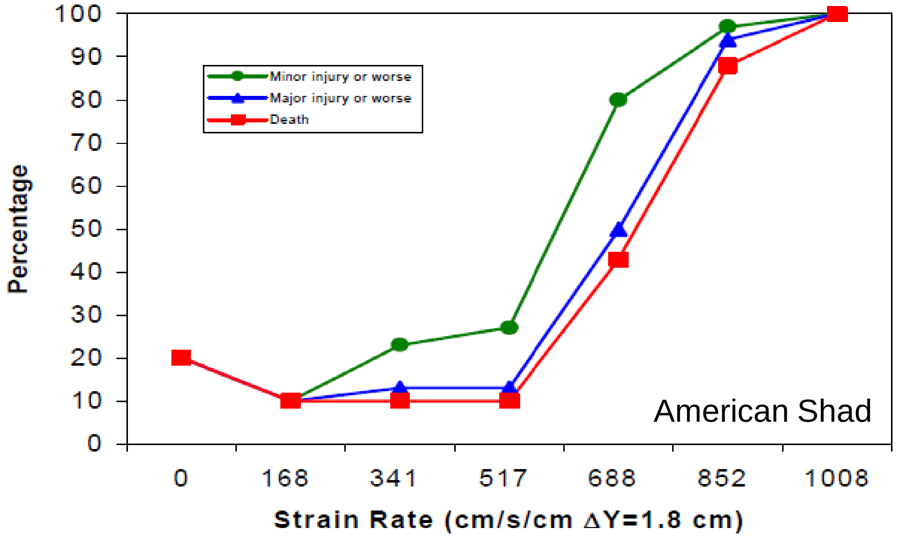
- Flow separation from HK blades and relatively low submergence could lead to cavitation.
  - However, cavitation associated with HK turbines is likely to be limited to small regions around blades.
    - Design blades and operate turbines in a manner that minimizes the potential for cavitation.

- Maintaining pressure at levels equal to or greater than 60% of ambient pressure should prevent cavitation and resulting potential for fish injury (Cada 2007).

# Conventional Hydro Turbine Biocriteria

## SHEAR

- Shear stresses sufficient to injure fish may occur near HK turbine rotors/blades (Cada et al. 2007; DOE 2009).
- Shear strain rates sufficient to cause injury (> 500/s) correspond to jet velocities of 29.5 ft/s. Such high velocities are unlikely to occur with HK turbines.



(Nietzel et al. 2000)

- Locations of shear in conventional turbines are typically near boundaries or where there are changes in flow paths (stay vanes, wicket gates, and turbine blade leading and trailing edges).
- Because HK turbines lack many of the structures that produce shear in conventional turbines, the presence of damaging shear levels will be less likely.

# Conventional Hydro Turbine Biocriteria

## *MECHANICAL – BLADE STRIKE AND GRINDING*

**Contact with structural components leading to injury and mortality, including:**

- Collisions between fish and moving turbine blades and fixed structures, such as stay vanes, wicket gates, and other types of guides or flow straighteners.
- Grinding or pinching from passage through narrow openings or gaps between stationary and/or moving components (e.g., blade tips and outer ring)
- Abrasion from contact with a stationary or moving surface.

# Conventional Hydro Turbine Biocriteria

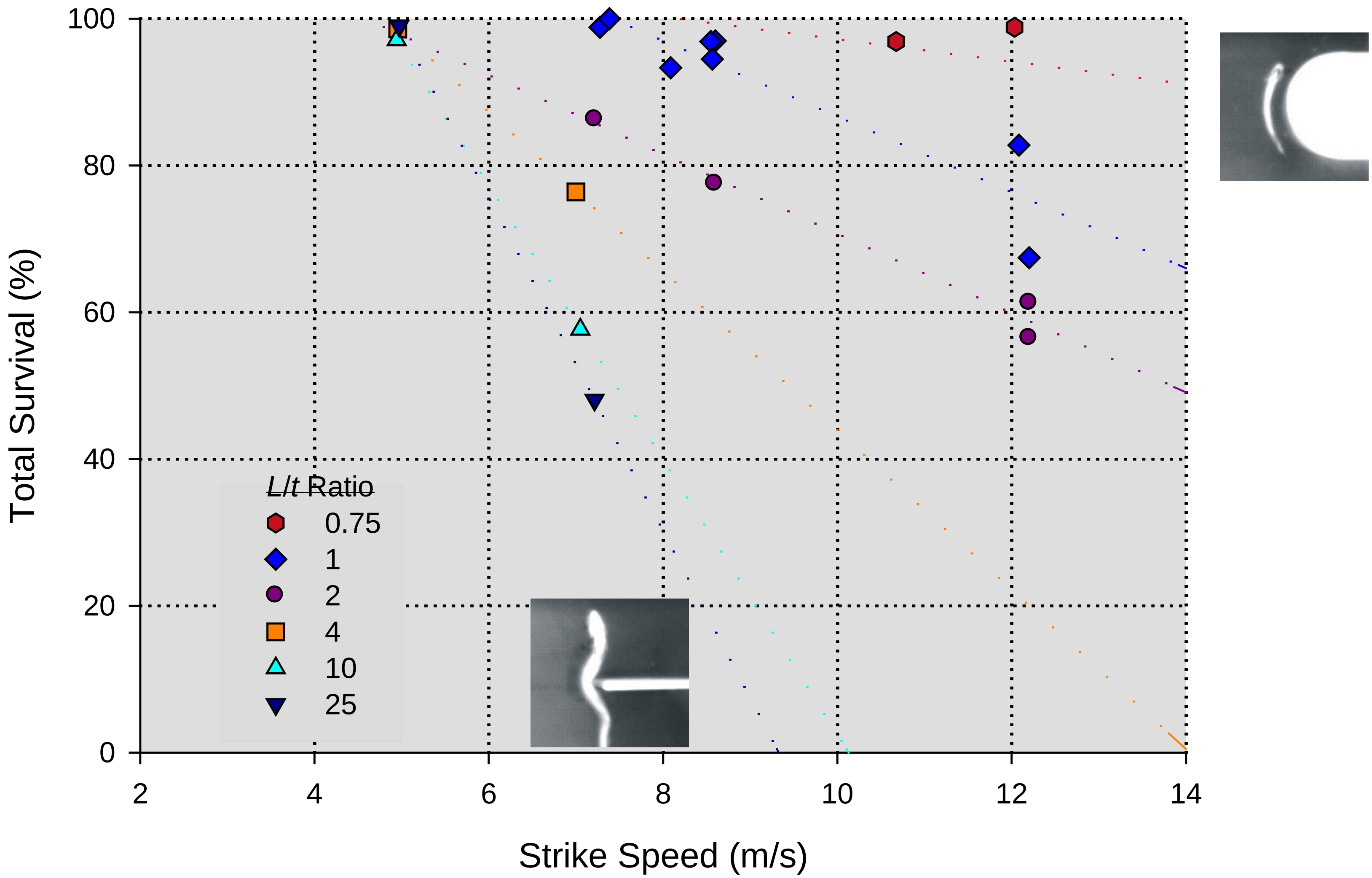
## *BLADE STRIKE*

- Primary mechanism of fish injury and mortality at many hydro projects.
- Strike probability depends on blade spacing, rotational speed, relative velocity of fish to blade, and fish length.

- Blade strike mortality is dependent on blade shape and thickness, impact velocity, and fish length .
- Little difference in mortality rates among typical teleost (boney) fishes.
- Recent studies have shown that blade strike survival can be greater than 90% at strike speeds up to 40 ft/s (12.1 m/s) (EPRI 2008).

# Conventional Hydro Turbine Biocriteria

## BLADE STRIKE



# Estimation Blade Strike Probability/Mortality

## *PREDICTIVE MODELING*

- Theoretical models for predicting strike probability are well established for conventional hydro turbines (Von Rabon 1957; Monten 1985; Solomon 1988; Bell 1991; Turnpenny 1992, 2000; Ploskey and Carlson 2003; Deng et al. 2005; Hecker and Allen 2005)
- The more recent studies have incorporated strike mortality rates to predict turbine passage survival (assuming other sources of mortality are inconsequential)
- These models can be modified and applied to hydrokinetic turbines to predict strike probability and survival rates.

# Estimation of Blade Strike Probability/Mortality

## *BLADE STRIKE PROBABILITY AND MORTALITY*

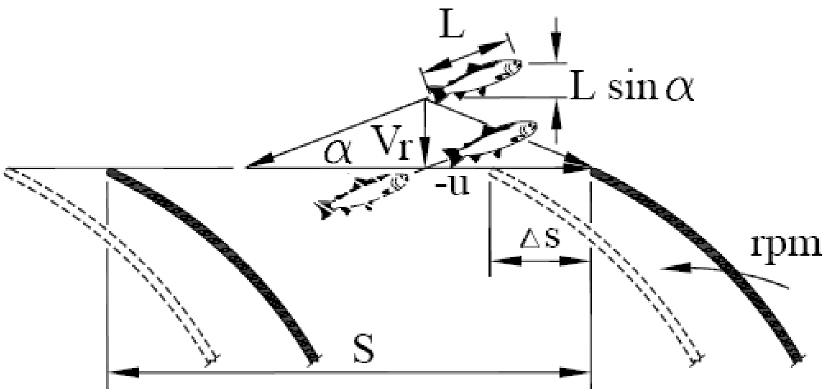
$$P_S = n(L\sin\alpha)N/$$

$n$ = rpm

$N$ = Number of bl

$L$ = Fish Lengt

$V_r$ = Radial Velo



$$P_{SM} = K\, n(L\sin\alpha)N/(60V_r)$$

where $K$ is the strike mortality rate

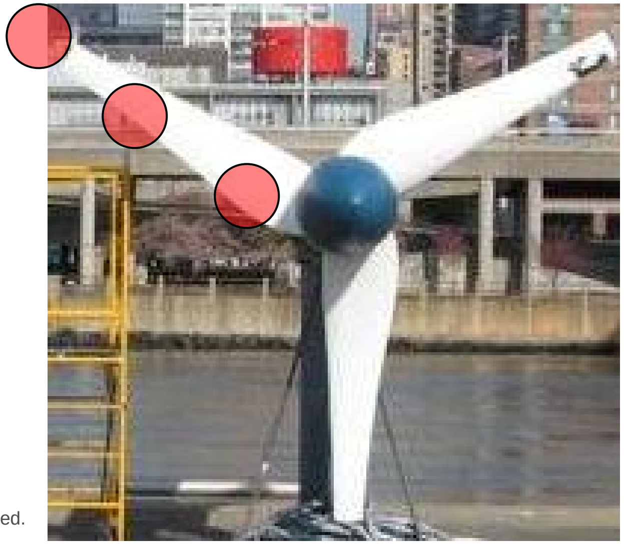
***STRIKE MORTALITY IS NOT EXPECTED TO OCCUR AT STRIKE SPEEDS***

***LESS THAN ABOUT 15.7 FT/S (4.8 m/s) FOR ANY SIZE FISH***

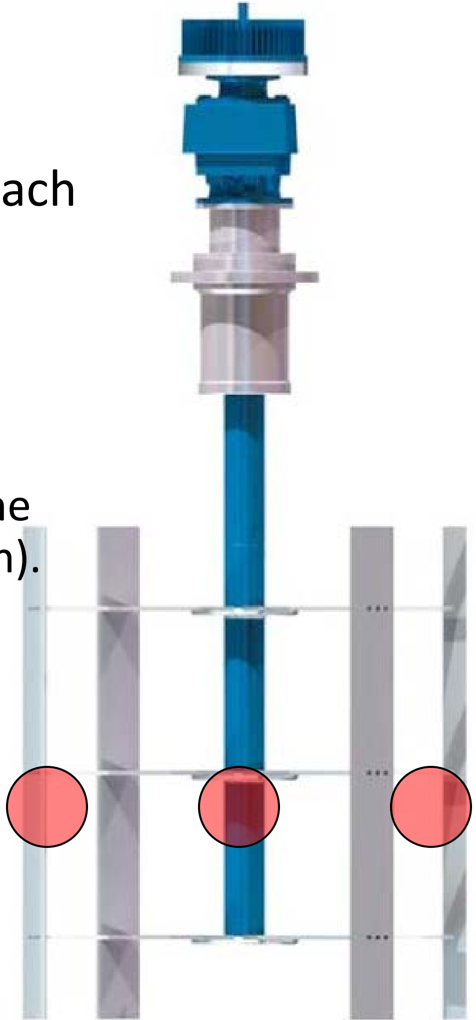
# Estimation of Blade Strike Probability/Mortality

## *MODEL ASSUMPTIONS FOR HK TURBINES*

- Orientation of fish relative to approach flow and blade leading edge.
- Fish velocity (equal to, greater than, or less than approach flow velocity).
- Location of passage:
  - Horizontal-axis turbines: near hub, mid-point, or tip
  - Darreous/Gorlov turbines: near middle or edges of turbine (fish may either be moving with or against blade direction).



**Verdant Power**



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# Estimation of Blade Strike Probability/Mortality

## *TURBINE PASSAGE SURVIVAL*

**Passage survival rates need to be estimated for:**

- Species of primary interest
- Expected fish length ranges
- Approach velocity range (rpm, blade speed, fish speed)
- Locations of passage (hub, mid, tip)

**Adjust estimates for:**

- Proportion of fish populations expected to encounter turbine(s)
- For each species, proportion by life stage (size group)
- Proportion of time that various approach velocities occur
- Area of passage by blade region

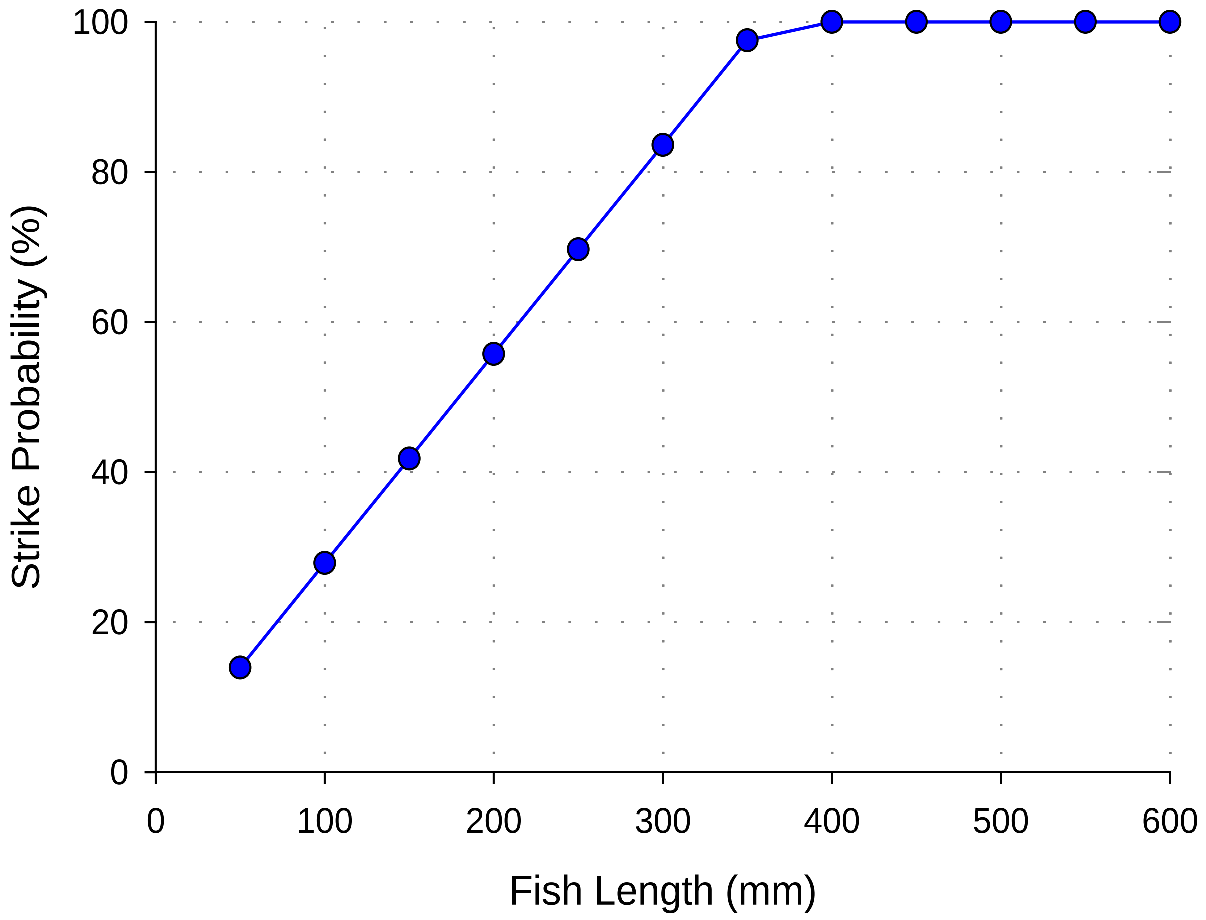
# Estimation of Blade Strike Probability/Mortality

## *LUCID SPHERICAL TURBINE*

- Number of blades: 4
- Diameter: 45-inch (114-cm)
- Operational range: 5 to 10 ft/s (1.5 to 3.0 m/s)

# Estimation of Blade Strike Probability/Mortality

## *LUCID SPHERICAL TURBINE*



# Estimation of Blade Strike Probability/Mortality

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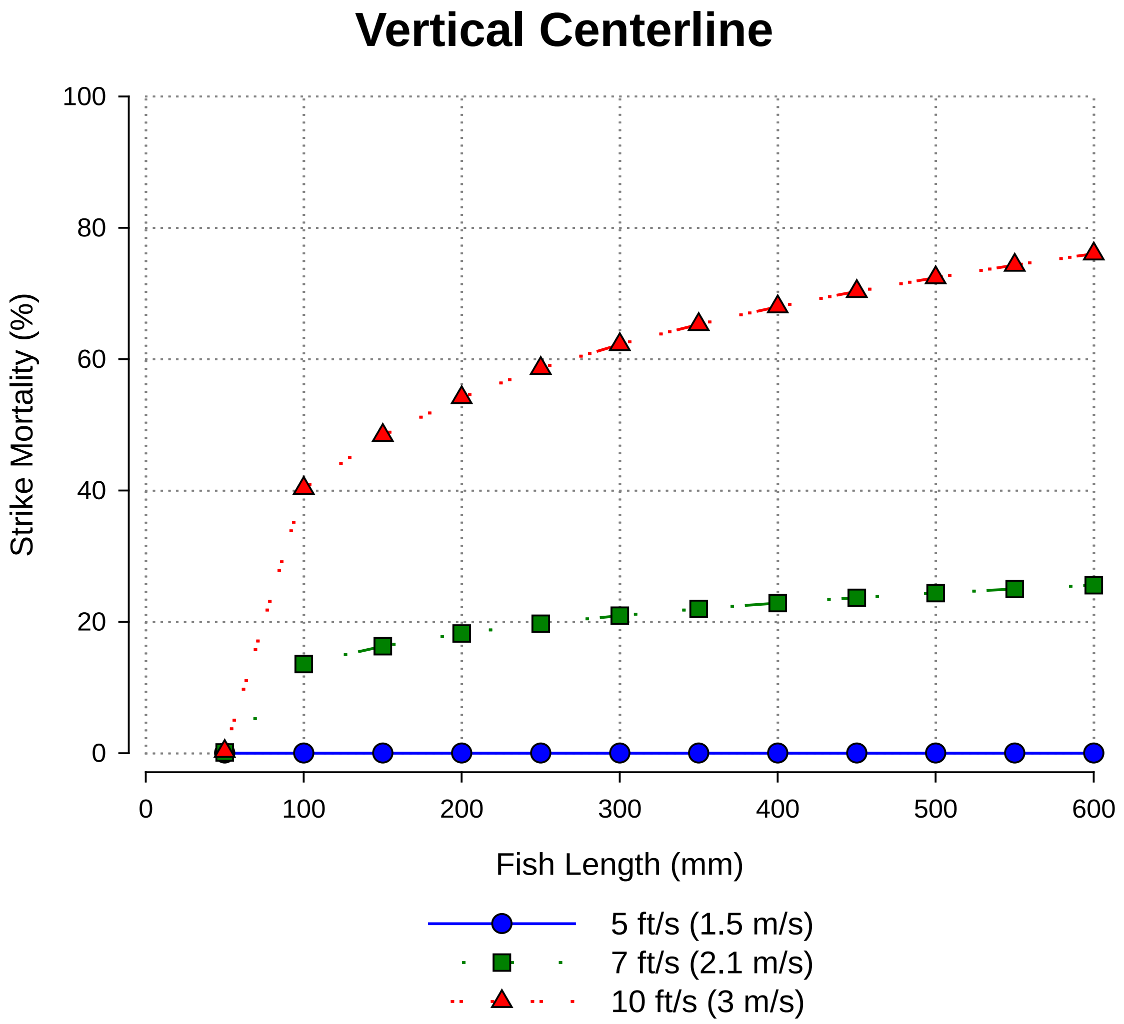

# Estimation of Blade Strike Probability/Mortality

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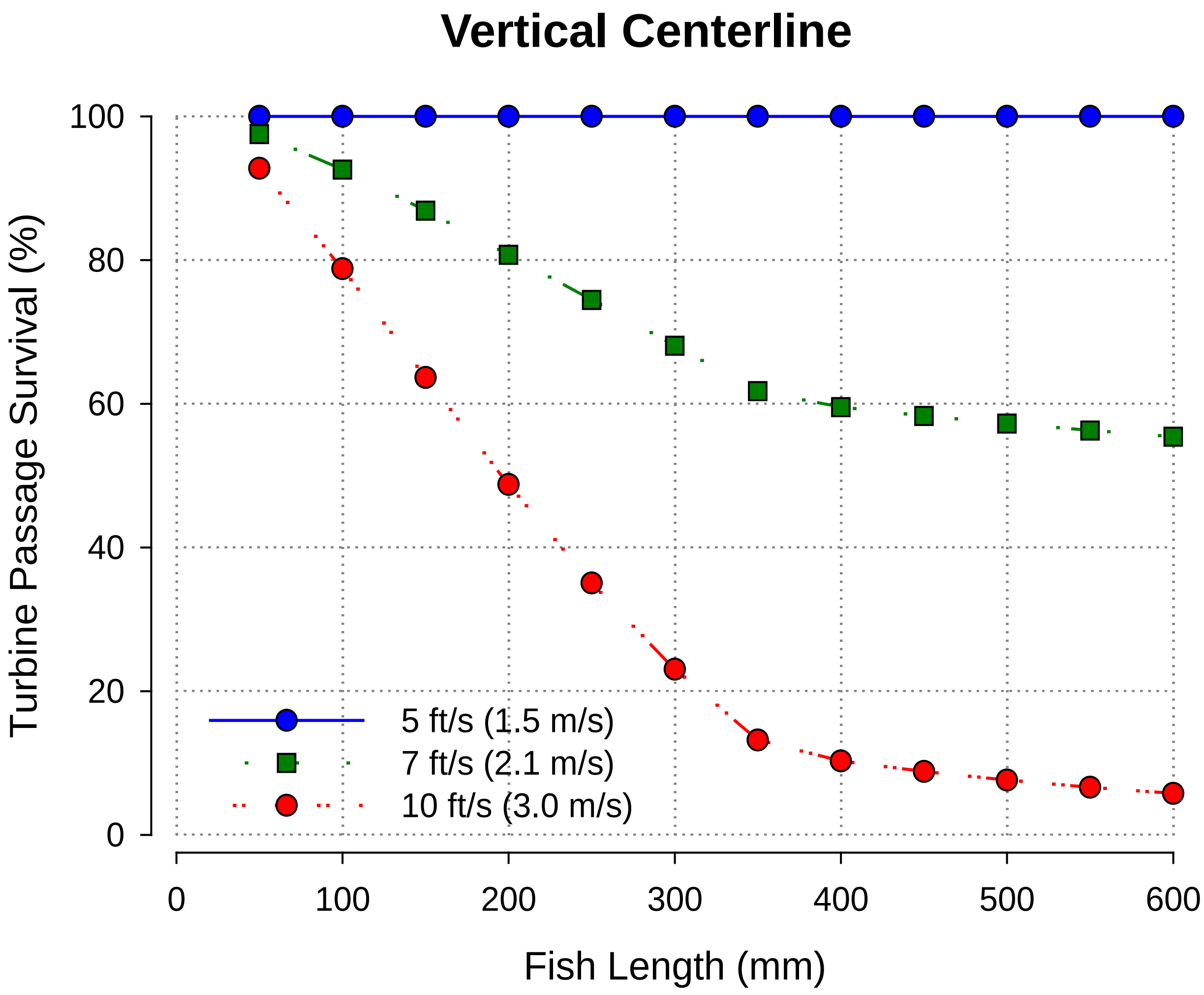
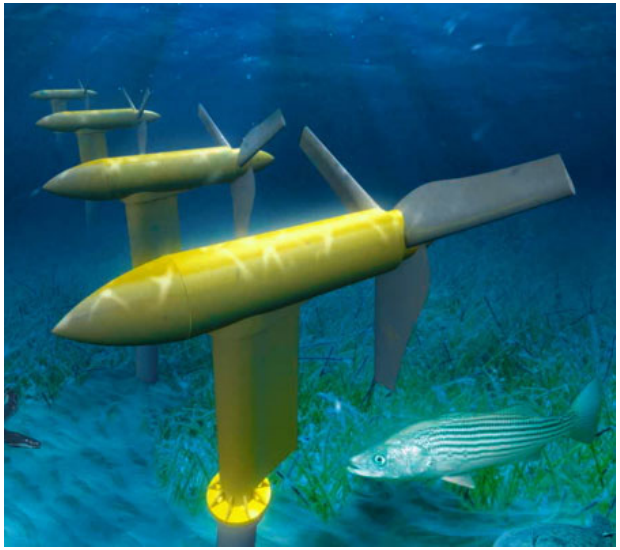


# Flume Testing Study Goal and Objectives



- ***Study Goal***: Provide information and data that can be used by developers, regulators, and resource agencies to reliably assess the potential impacts of hydrokinetic turbines on fish.

- ***Objectives***:
  - Describe the behavior of fish approaching and passing through selected hydrokinetic turbine designs
  - Estimate injury and survival rates for fish that pass through the blade sweep of each turbine type

# Study Approach and Methods

## *TEST TURBINES – Lucid Spherical Turbine*

- 4 Blades
- Diameter: 3.75 ft
- Rotational speed = 64 – 127 rpm
- Approach velocity = 5 – 10 ft/s
- Blade thickness: 0.75 in

# Study Approach and Methods

## *TEST TURBINES – WELKA UPG*

- 3 blades
- Diameter: 5 ft
- Rotational speed: 3 – 16 rpm
- Approach velocity: 2 – 5 ft/s
- Blade thickness: 2.5 in

# Study Approach and Methods

## *SURVIVAL TESTS*

- Rainbow trout and largemouth bass (WELKA turbine only)
- Two size groups: 100-150 mm and 225-275 mm
- Two approach Velocities:
  - Lucid: 5 and 7 ft
  - WELKA : 3 and 5 ft/s
- 5 replicate trials for each set of test conditions
- 100 treatment and 100 control fish per trial
- Each test group uniquely marked (combination of fin location and photonic dye color)
- 48-hr delayed mortality post-test holding period
- $S = S_t / S_c$

# Study Approach and Methods

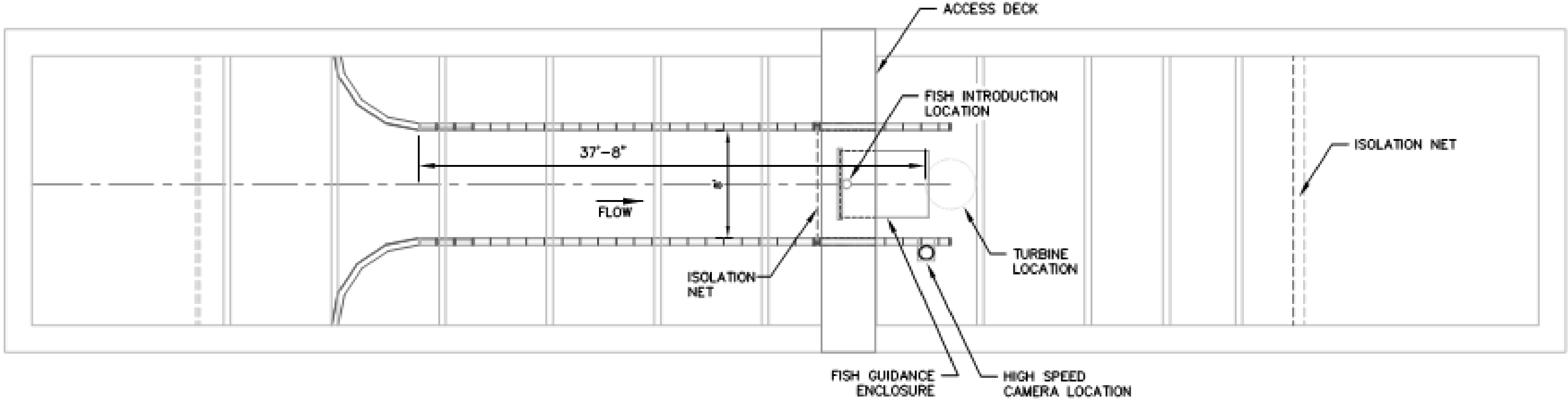
## *BEHAVIORAL TESTS*

- Same species, size classes, and approach velocities
- 3 trials for each set of test conditions
- 100 fish released per trial
- Video observations of fish behavior and passage through turbines

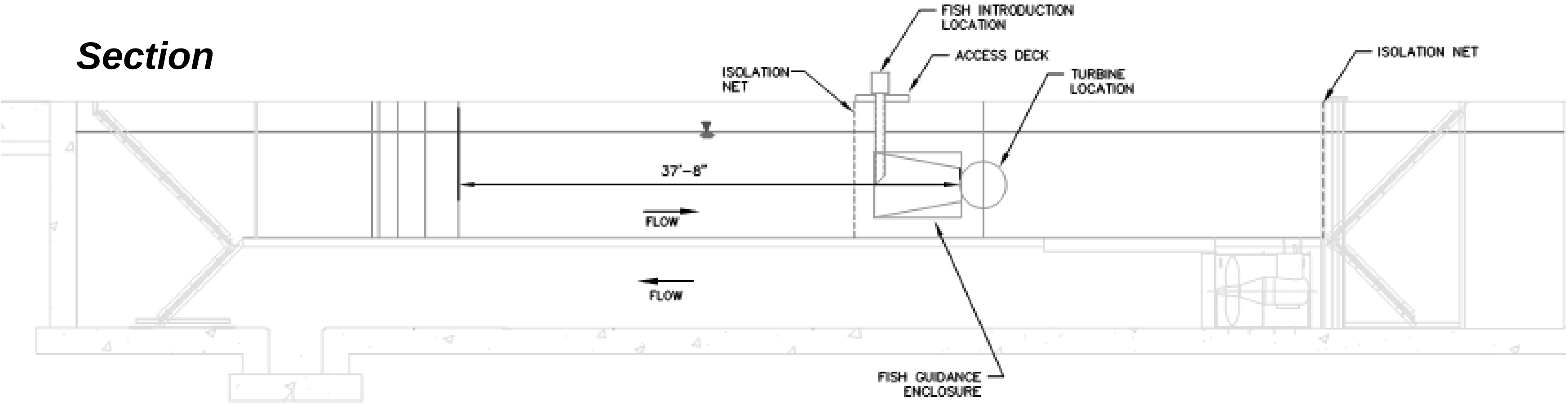
# Study Approach and Methods

# *TEST FACILITY DESIGN AND OPERATION*

***Plan***



***Section***



# Study Approach and Methods

## *TEST FACILITY DESIGN AND OPERATION*

# Study Approach and Methods

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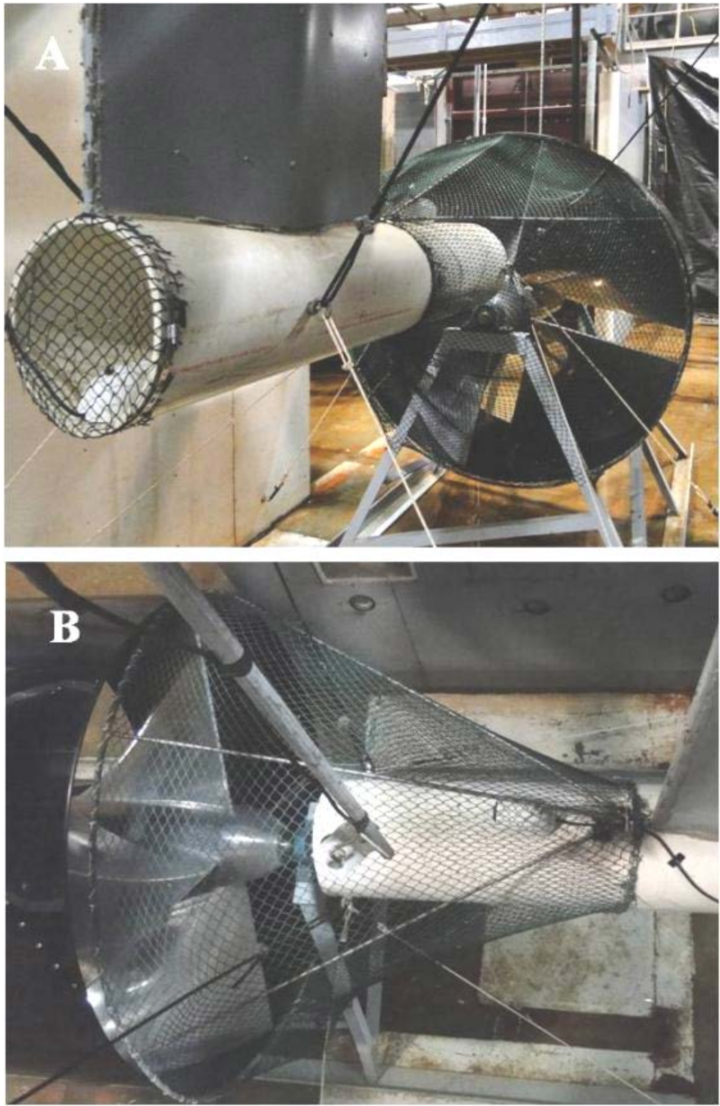


# Results

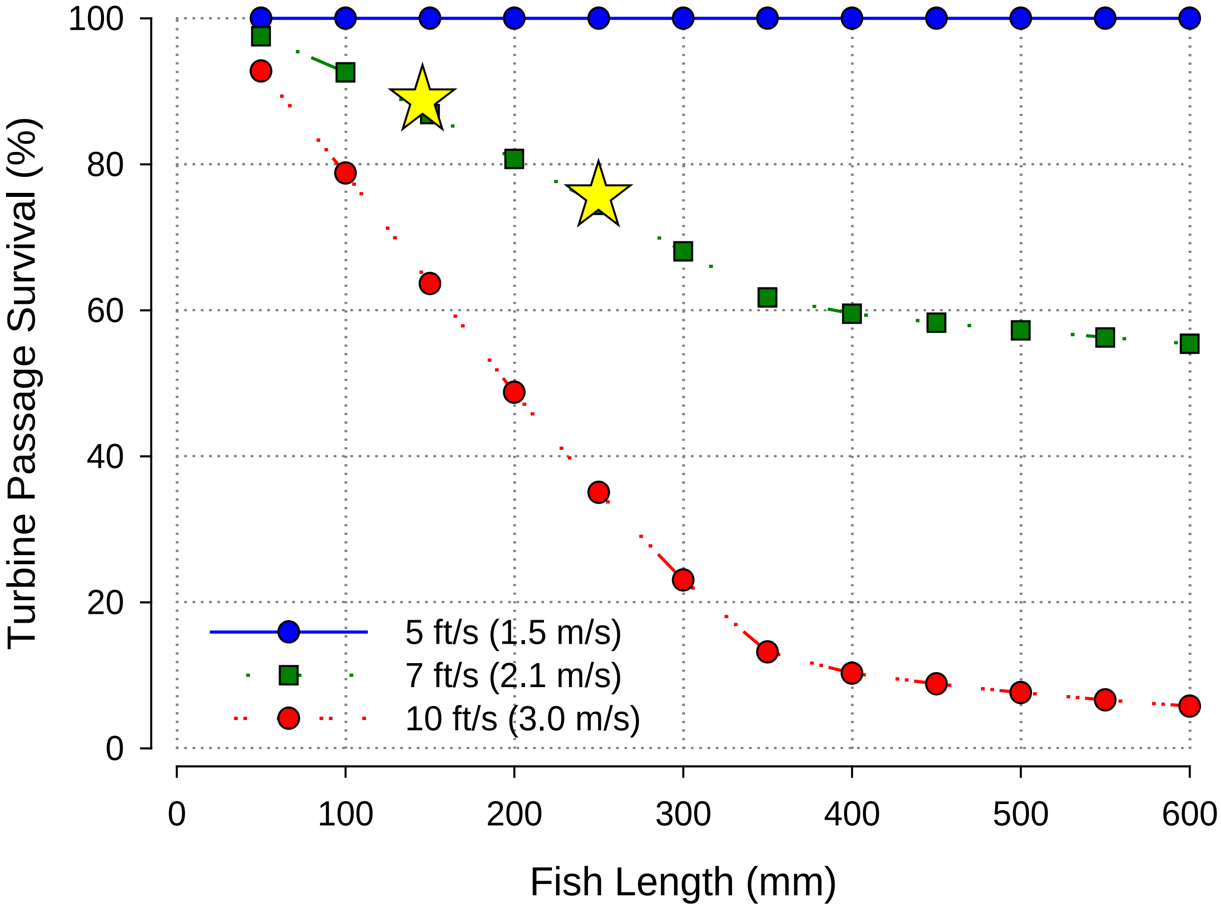
## *LUCID TURBINE – FISH PASSAGE SURVIVAL*

***RAINBOW TROUT***

| Mean Fork Length (mm) | Approach Velocity (ft/s) | Immediate Survival (1 hr) (%) ± 95% CI | Total Survival (1 hr + 48 hr) (%) ± 95% CI |
|---|---|---|---|
| 161 | 5 | 99.8 ± 0.43 | 99.8 ± 0.73 |
| 138 | 7 | 100.4 ±0.80 | 100.4 ± 0.80 |
| 250 | 5 | 99.4 ± 1.18 | 99.0 ± 1.30 |
| 249 | 7 | 99.6 ± 0.55 | 98.4 ± 1.10 |

# Results

# *LUCID TURBINE – FISH PASSAGE SURVIVAL*



# Results

# *LUCID TURBINE – VIDEO OBSERVATIONS*

**100-150 mm Rainbow Trout; 5 ft/s**

# Results

# *Welka UPG – FISH PASSAGE SURVIVAL*

***RAINBOW TROUT***

| Mean Fork Length (mm) | Approach Velocity (ft/s) | Immediate Survival (1 hr) (%) ± 95% CI | Total Survival (1 hr + 48 hr) (%) ± 95% CI |
|---|---|---|---|
| 125 | 5 | 100.9 ± 1.21 | 100.9 ± 1.35 |
| 124 | 7 | 100.0 ± 0.00 | 100.0 ± 0.00 |
| 230 | 5 | 101.6 ± 1.33 | 101.6 ± 1.33 |
| 248 | 7 | 99.4 ± 0.68 | 99.4 ± 0.68 |

# Results

# *Welka UPG – FISH PASSAGE SURVIVAL*

***LARGEMOUTH BASS***

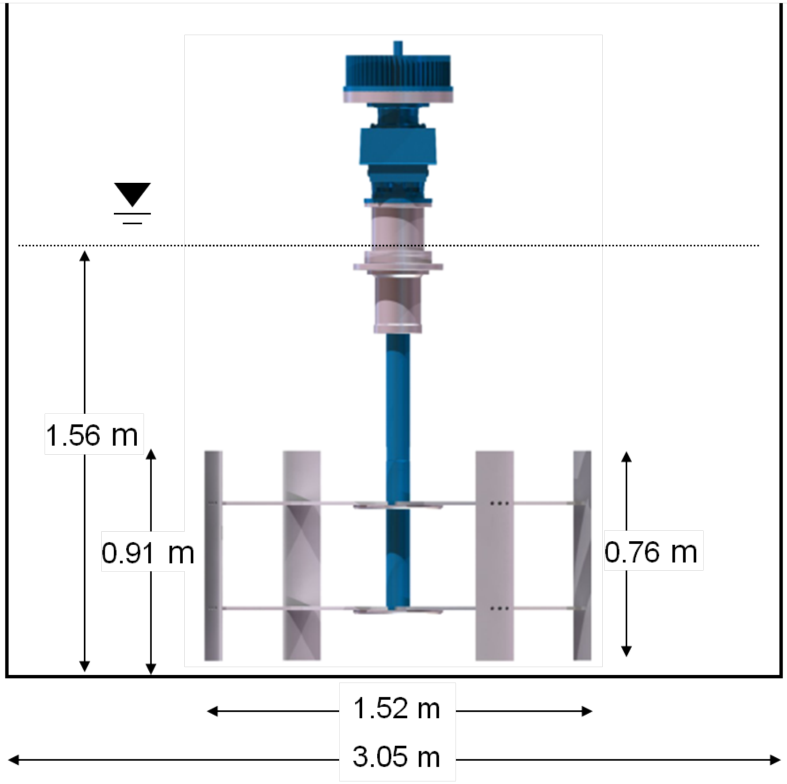
| Mean Fork Length (mm) | Approach Velocity (ft/s) | Immediate Survival (1 hr) (%) ± 95% CI | Total Survival (1 hr + 48 hr) (%) ± 95% CI |
|---|---|---|---|
| 125 | 5 | 100.2 ± 0.69 | 99.8 ± 0.89 |
| 124 | 7 | 100.0 ± 0.00 | 100.0 ± 0.56 |
| 238 | 5 | 100.8 ± 1.27 | 102.9 ± 2.94 |
| 246 | 7 | 100.0 ± 0.00 | 99.6 ± 0.56 |

# Flume Testing Conclusions and Observations

- Difficult to force fish through Lucid turbine.
- Fish exhibited active avoidance of the Lucid turbine by either swimming upstream or passing around the margins.
- Video observations of blade strikes indicated fish were not stunned or severely injured.
- High survival (98-100%) rates for the size groups and operational conditions evaluated with both turbines.
- Injury and scale loss rates were comparable between treatment and control fish tested with each turbine.

# Ted Castro-Santos and Alex Haro

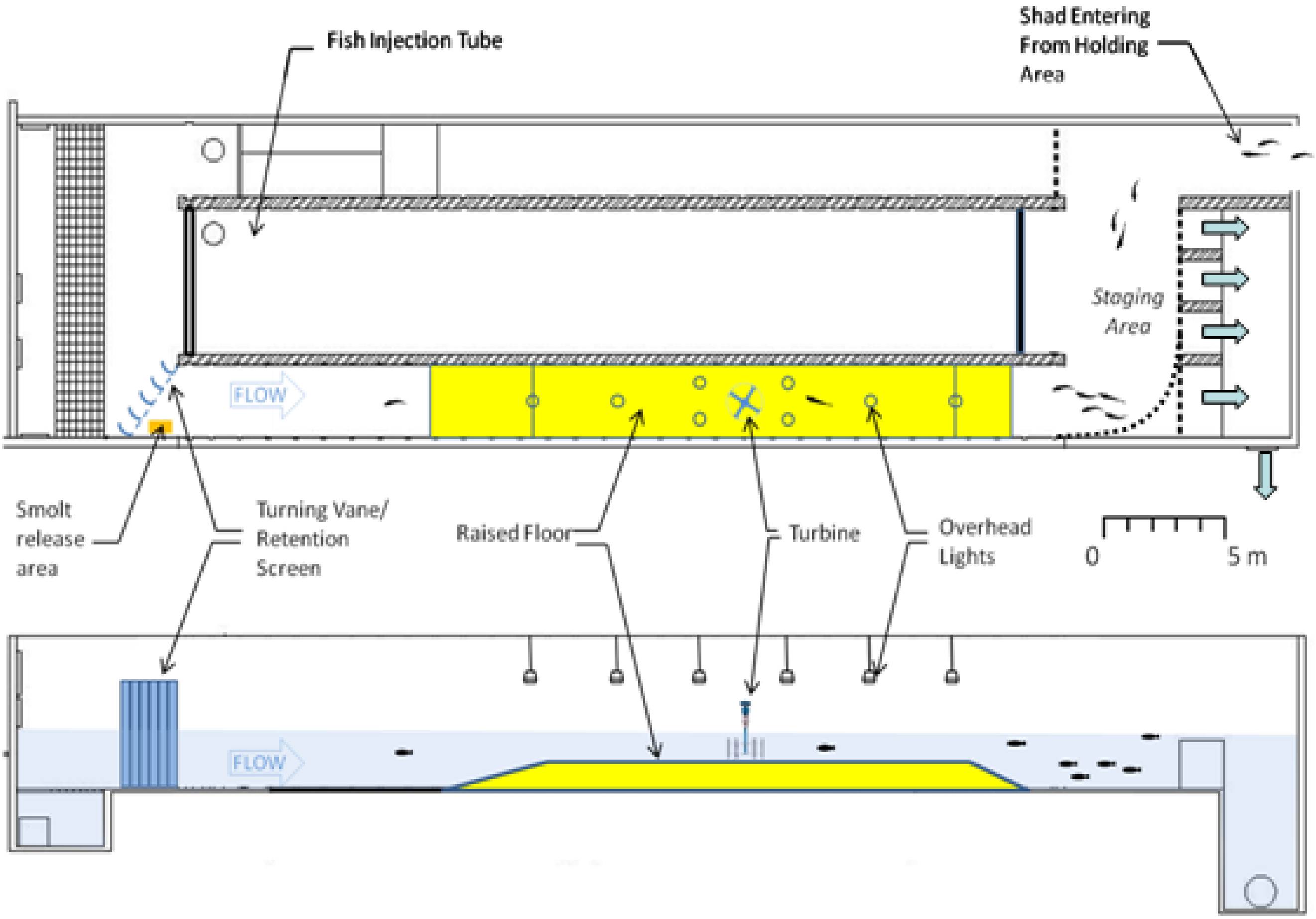
Encurrent Model ENC-0050F4



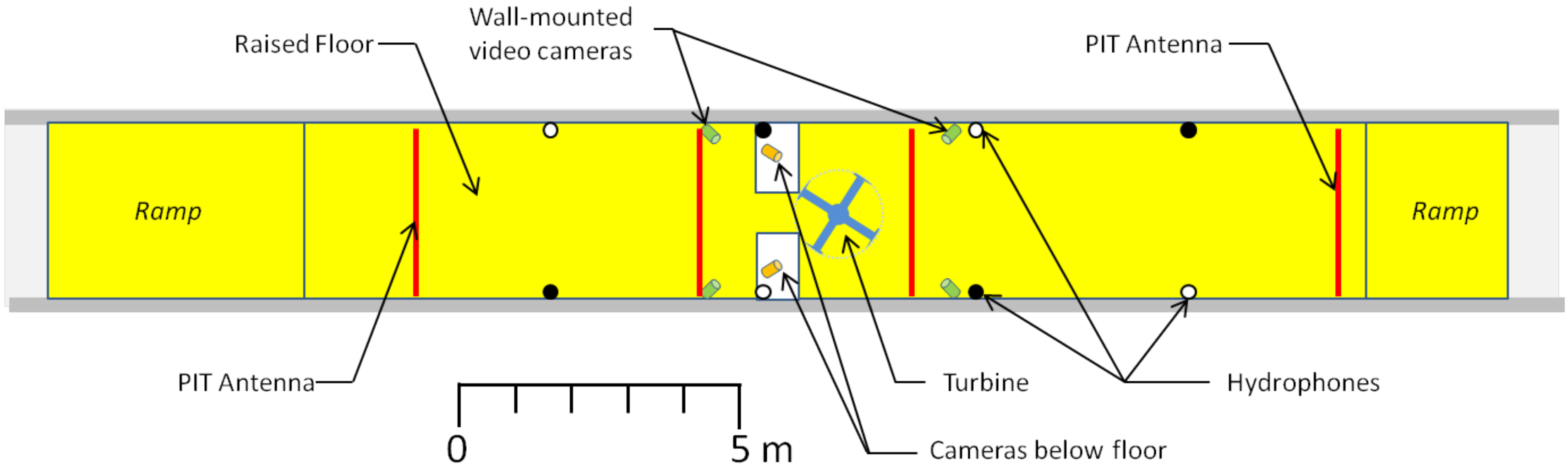
S.O. Conte Anadromous Fish Research Center

Turners Falls, MA

# Test Flume Facility at Conte Lab



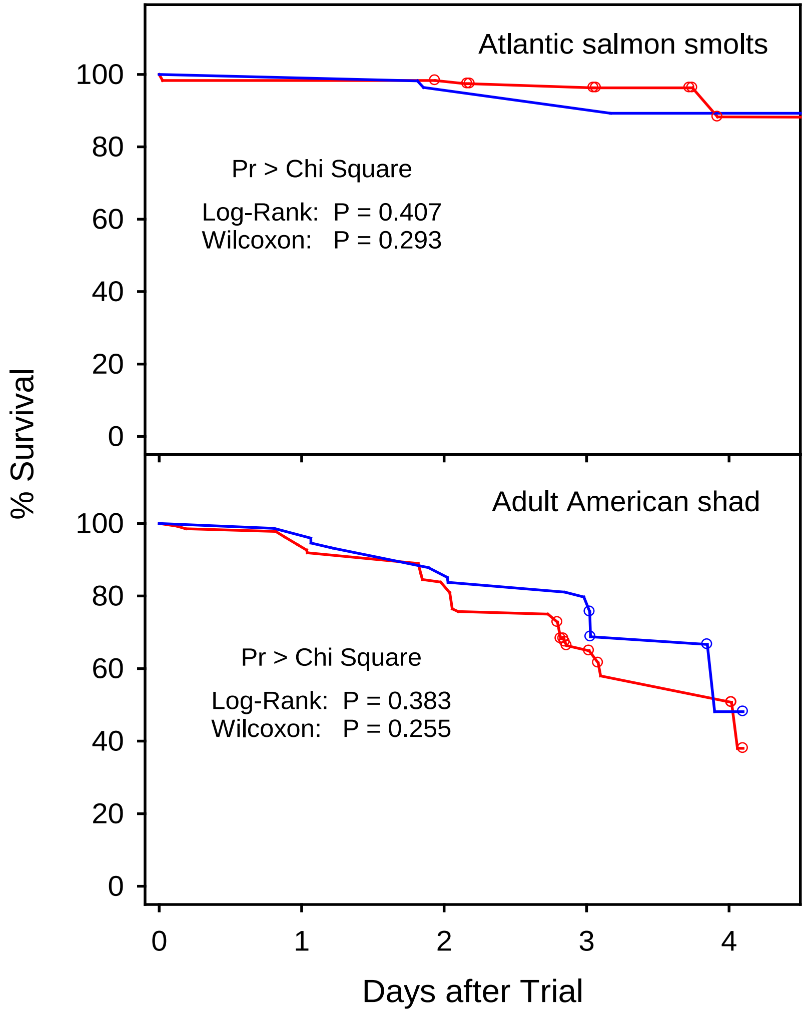
# Detail of Test Area



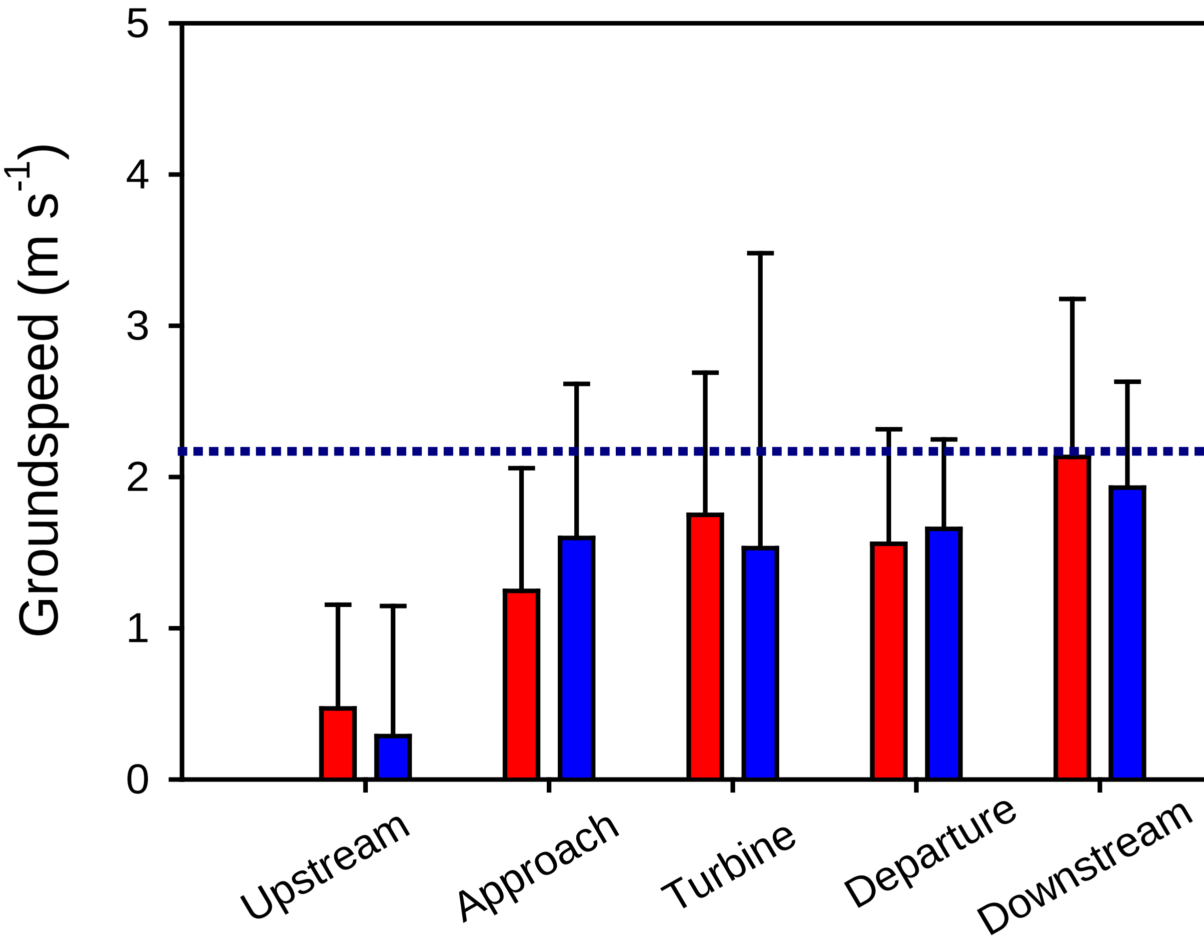
# Downstream Staging and Recovery Area

# Encurrent Turbine in S.O. Conte Flume

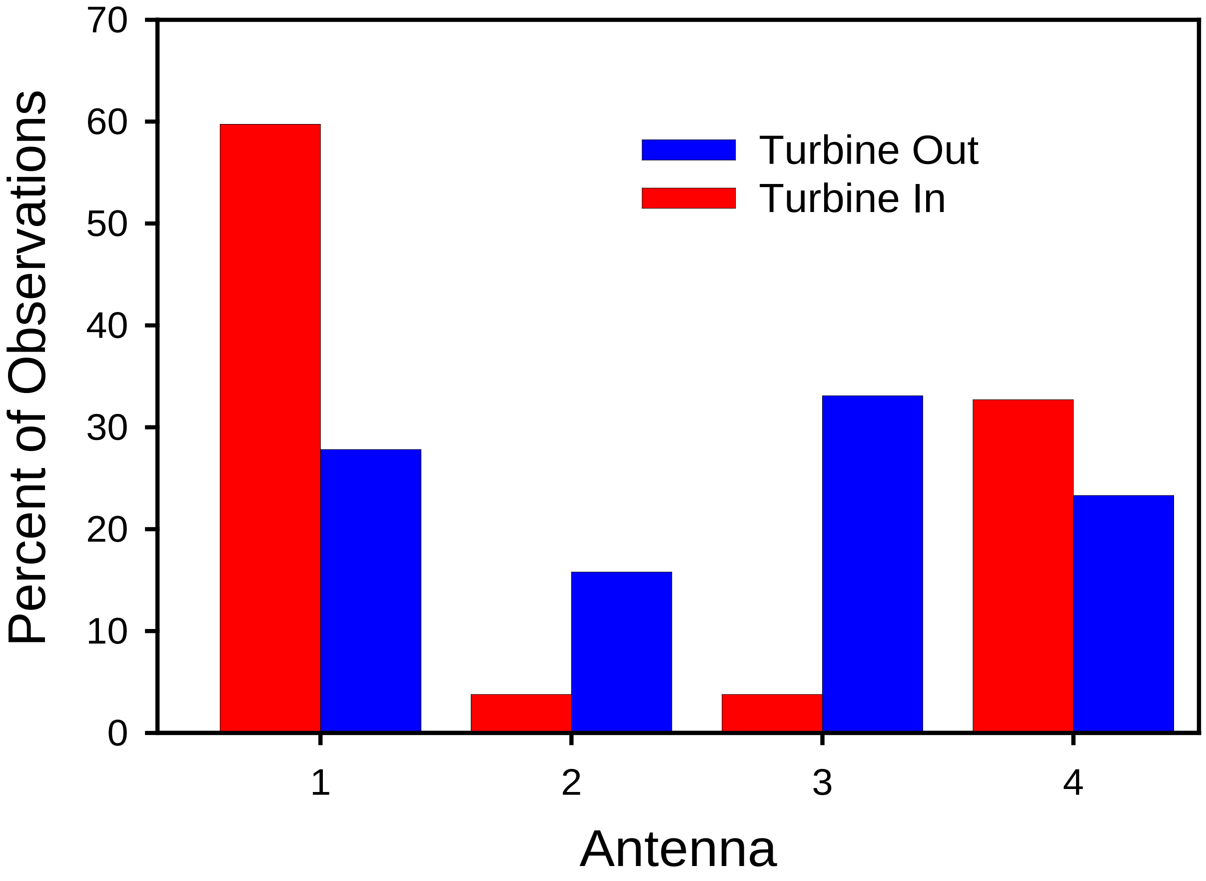
# Survivorship Curves for Atlantic Salmon Smolts and American Shad



# Groundspeed of Atlantic Salmon Smolts



# American Shad – Maximum Distance of Ascent



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