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

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Program Manager

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Program Team

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Sponsors

- U.S. Department of Energy
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- Aurora Research Institute
- Indian and Northern Affairs Canada
In-Kind Support

WELKA UPG

New Energy Corporation

Lucid Energy Technologies
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
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.

  - 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.
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**

- **Total Survival (%)**
- **Strike Speed (m/s)**
- **L/t Ratio**
  - 0.75
  - 1
  - 2
  - 4
  - 10
  - 25

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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

\[ P_s = n(L\sin\alpha)Nl \]

- \( n = \text{rpm} \)
- \( N = \text{Number of blades} \)
- \( L = \text{Fish Length} \)
- \( V_r = \text{Radial Velocity} \)

\[ P_{SM} = K \frac{n(L\sin\alpha)Nl}{60V_r} \]

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
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).
Estimation of BladeStrike 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**

- **Strike Probability (%)**
  - 0
  - 20
  - 40
  - 60
  - 80
  - 100

- **Fish Length (mm)**
  - 0
  - 100
  - 200
  - 300
  - 400
  - 500
  - 600

The graph shows the relationship between fish length and strike probability for the LUCID SPHERICAL TURBINE.
Estimation of Blade Strike Probability/Mortality

**LUCID SPHERICAL TURBINE**

**Vertical Centerline**

- **Fish Length (mm)**
- **Strike Mortality (%)**

- **Cruise Speeds**
  - 5 ft/s (1.5 m/s)
  - 7 ft/s (2.1 m/s)
  - 10 ft/s (3 m/s)
Estimation of Blade Strike Probability/Mortality

**LUCID SPHERICAL TURBINE**

Vertical Centerline

- Turbine Passage Survival (%)
- Fish Length (mm)
- 5 ft/s (1.5 m/s)
- 7 ft/s (2.1 m/s)
- 10 ft/s (3.0 m/s)
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

TEST FACILITY DESIGN AND OPERATION
# Results

## LUCID TURBINE – FISH PASSAGE SURVIVAL

### RAINBOW TROUT

<table>
<thead>
<tr>
<th>Mean Fork Length (mm)</th>
<th>Approach Velocity (ft/s)</th>
<th>Immediate Survival (1 hr) (%) ± 95% CI</th>
<th>Total Survival (1 hr + 48 hr) (%) ± 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>161</td>
<td>5</td>
<td>99.8 ± 0.43</td>
<td>99.8 ± 0.73</td>
</tr>
<tr>
<td>138</td>
<td>7</td>
<td>100.4 ± 0.80</td>
<td>100.4 ± 0.80</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
<td>99.4 ± 1.18</td>
<td>99.0 ± 1.30</td>
</tr>
<tr>
<td>249</td>
<td>7</td>
<td>99.6 ± 0.55</td>
<td>98.4 ± 1.10</td>
</tr>
</tbody>
</table>
Results

**LUCID TURBINE – FISH PASSAGE SURVIVAL**

- Fish Length (mm)
- Turbine Passage Survival (%)
- 5 ft/s (1.5 m/s)
- 7 ft/s (2.1 m/s)
- 10 ft/s (3.0 m/s)
Results

LUCID TURBINE – VIDEO OBSERVATIONS

100-150 mm Rainbow Trout; 5 ft/s
## Results

### Welka UPG – FISH PASSAGE SURVIVAL

**RAINBOW TROUT**

<table>
<thead>
<tr>
<th>Mean Fork Length (mm)</th>
<th>Approach Velocity (ft/s)</th>
<th>Immediate Survival (1 hr) (%) ± 95% CI</th>
<th>Total Survival (1 hr + 48 hr) (%) ± 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>5</td>
<td>100.9 ± 1.21</td>
<td>100.9 ± 1.35</td>
</tr>
<tr>
<td>124</td>
<td>7</td>
<td>100.0 ± 0.00</td>
<td>100.0 ± 0.00</td>
</tr>
<tr>
<td>230</td>
<td>5</td>
<td>101.6 ± 1.33</td>
<td>101.6 ± 1.33</td>
</tr>
<tr>
<td>248</td>
<td>7</td>
<td>99.4 ± 0.68</td>
<td>99.4 ± 0.68</td>
</tr>
</tbody>
</table>
## Results

### Welka UPG – FISH PASSAGE SURVIVAL

#### LARGEMOUTH BASS

<table>
<thead>
<tr>
<th>Mean Fork Length (mm)</th>
<th>Approach Velocity (ft/s)</th>
<th>Immediate Survival (1 hr) (%) ± 95% CI</th>
<th>Total Survival (1 hr + 48 hr) (%) ± 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>5</td>
<td>100.2 ± 0.69</td>
<td>99.8 ± 0.89</td>
</tr>
<tr>
<td>124</td>
<td>7</td>
<td>100.0 ± 0.00</td>
<td>100.0 ± 0.56</td>
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<tr>
<td>238</td>
<td>5</td>
<td>100.8 ± 1.27</td>
<td>102.9 ± 2.94</td>
</tr>
<tr>
<td>246</td>
<td>7</td>
<td>100.0 ± 0.00</td>
<td>99.6 ± 0.56</td>
</tr>
</tbody>
</table>
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.
Test Flume Facility at Conte Lab
Detail of Test Area

- Raised Floor
- Wall-mounted video cameras
- PIT Antenna
- Turbine
- Hydrophones
- Cameras below floor

Ramp

0 5 m
Downstream Staging and Recovery Area
Encurrent Turbine in S.O. Conte Flume
Survivorship Curves for Atlantic Salmon Smolts and American Shad

- **Atlantic salmon smolts**
  - Pr > Chi Square
  - Log-Rank: $P = 0.407$
  - Wilcoxon: $P = 0.293$

- **Adult American shad**
  - Pr > Chi Square
  - Log-Rank: $P = 0.383$
  - Wilcoxon: $P = 0.255$
Groundspeed of Atlantic Salmon Smolts

![Groundspeed of Atlantic Salmon Smolts](image-url)
American Shad – Maximum Distance of Ascent

![Bar Chart]

- Percent of Observations on the Y-axis
- Antenna numbers (1, 2, 3, 4) on the X-axis
- Two categories: Turbine Out and Turbine In

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