Fish-friendly turbine technology

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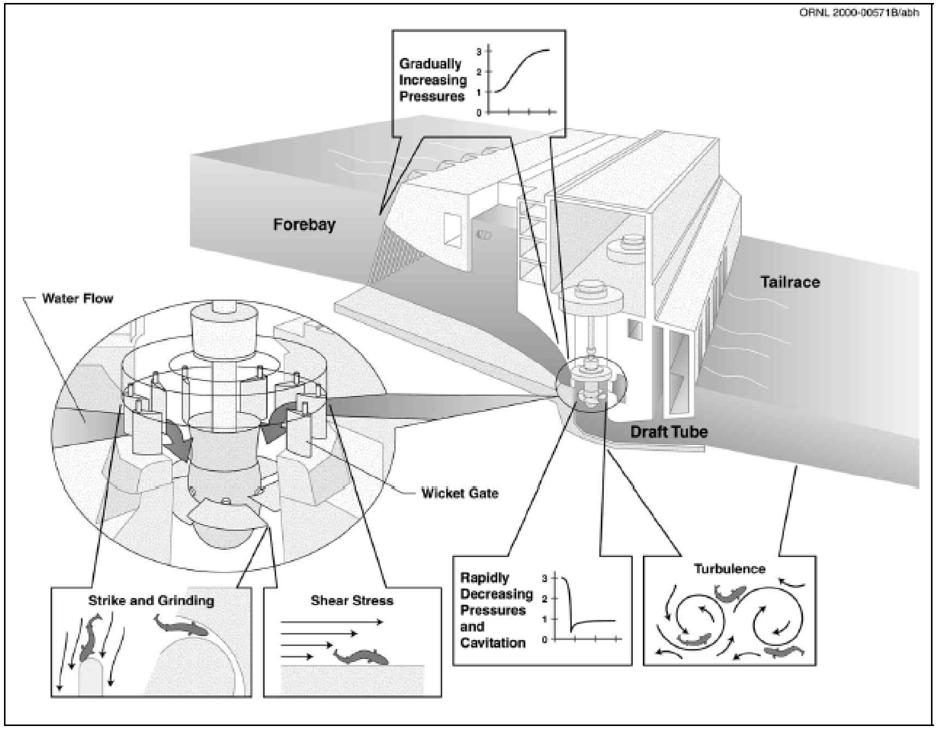
Fish Survival Assessment (Overview)

1st Step – Injury Mechanisms

- **Identify potential fish injury mechanisms present in turbines**
  - **<u>Direct</u>: injuries sustained during turbine passage leading to death**
  - **<u>Indirect</u>: non-lethal effects of turbine passage (sub-lethal injuries, disorientation, stress) leading to:**
    - **Downstream predation**
    - **Increased chances of illness**
    - **Adversely affected behavior**
  - **Indirect mechanisms usually neglected from analysis**
    - **Hard to evaluate**



Fish injury mechanisms in a hydraulic power plant[3]

[3] **Čada, Glenn F**.: "*The Development of Advanced Hydroelectric Turbines to Improve Fish Passage Survival*", Article presented in Fisheries, vol. 26 no 9, September 2001, pp14-23

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Fish Survival Assessment (Overview)

2nd Step – Stressors

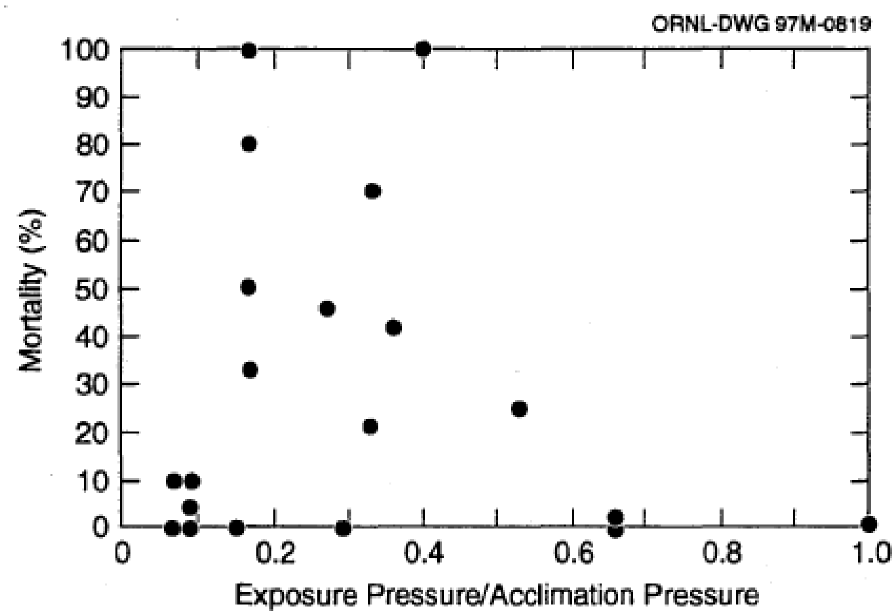
- **Stressors = measureable physical quantities linked to a given injury mechanism**
- **Evaluate fish exposure to stressors ➔ obtain mortality estimate by injury mechanism**

Injury mechanism	Stressor
Rapid pressure drop	Absolute pressure
Cavitation	Absolute pressure
Shear stress	Vorticity or strain rate
Turbulence	Velocity and pressure fluctuations
Blade strikes	Impact intensity
Other mechanical Injuries: vane strikes, grinding, abrasion, etc.	Fish trajectory and velocities (see following pages)

Fish Survival Assessment (Overview)

3rd Step – Dose-Response

- **Find dose-response for given injury**
  - **Dose-response: mortality risk resulting from stressor level**
  - **Requires sufficient data**
- **If insufficient data available, set threshold values for stressors**
  - **Delimit conditions where fish “risk” injury**



Typical dose-response graph (mortality vs. ratio of exposure pressure to acclimation pressure)[4]

[4] **Čada, Glenn. F., Coutant, Charles C. and Whitney, Richard R**.: “*Development of Biological Criteria for the Design of Advanced Hydropower Turbines*” Report for U.S. DOE,1997

ANDRITZ Hydro

Fish Survival Assessment

Fish survival assessment Tools used by Andritz Hydro

Input data				
n	[rpm]	100.000		Rotational speed
z2	[-]	4.000		Number of blades
R_N	[m]	0.600		Inner radius (hub)
R1	[m]	2.000		Outer radius (discharge ring)
Q	[m3/s]	160.000		Turbine discharge
H	[m]	5.000		net Head
eta	[-]	0.940		Turbine efficiency
g	[m/s2]	9.810		gravity accelleration
Lmean	[m]	0.300		Average fish length
lambda	[-]	0.300		correlation coefficient (do not change)
Result				
Mortality	[%]	5.3		Mortality rate for tubine passed fish

Layout Phase

- **Blade Strike Mortality - Tool**

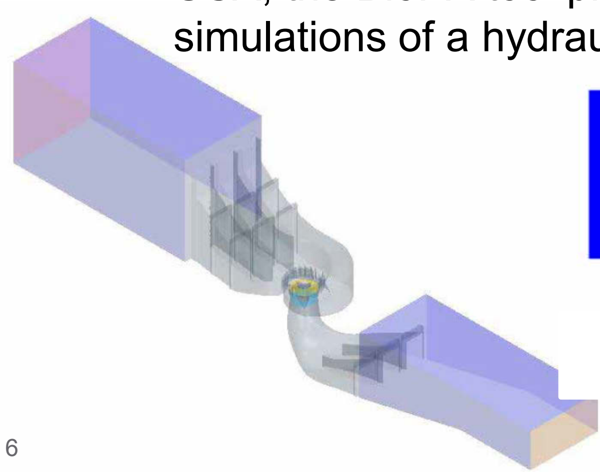
Design Phase

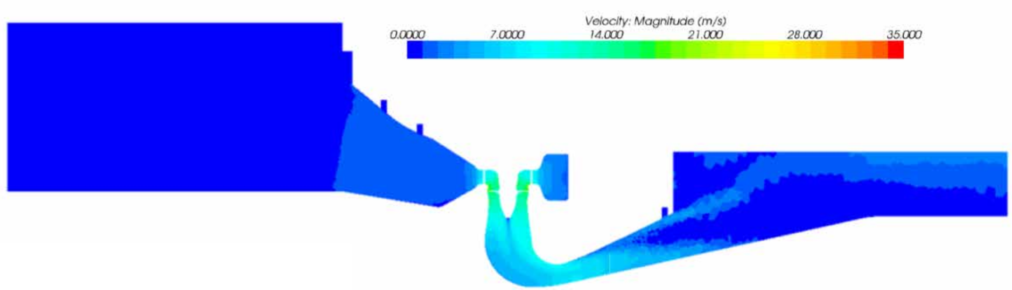
- **Fish trajectory modeling with CFD**

  Particle Tracks, Streamlines

- **BioPA**

  Developed by the Pacific Northwest National Laboratory (PNNL) in Richland, WA, USA, the BioPA tool provides a fish survival assessment based on the CFD simulations of a hydraulic turbine



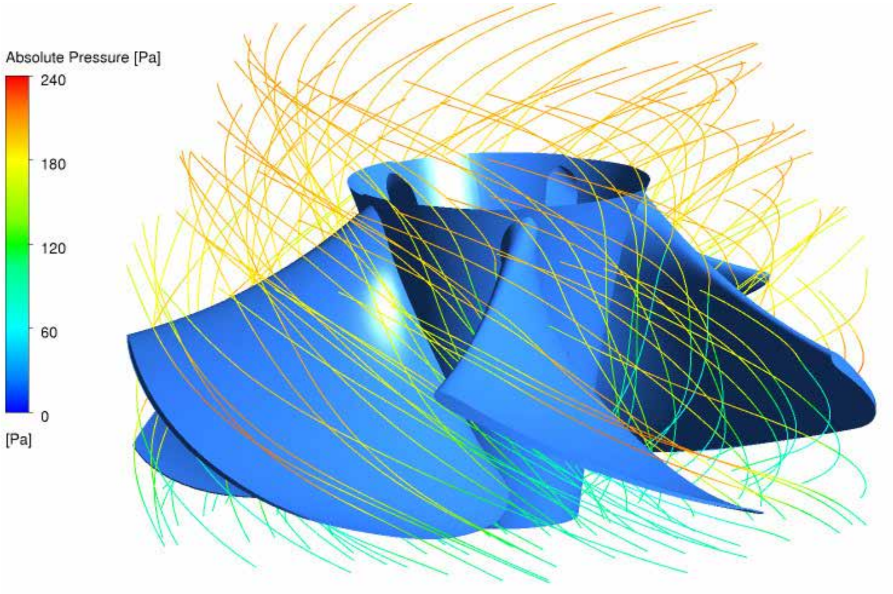


ANDRITZ Hydro

Fish trajectory modeling

Calculation method: Streamlines

- **Streamlines**
  - **1st approximation of fish trajectories**
  - **Fish exposure calculated along each streamline**
  - **Simple to use, but:**
    - **Massless, dimensionless fish**
    - **➔ No strike injury predictions**



Example of streamlines as fish surrogates (colored by absolute pressure)

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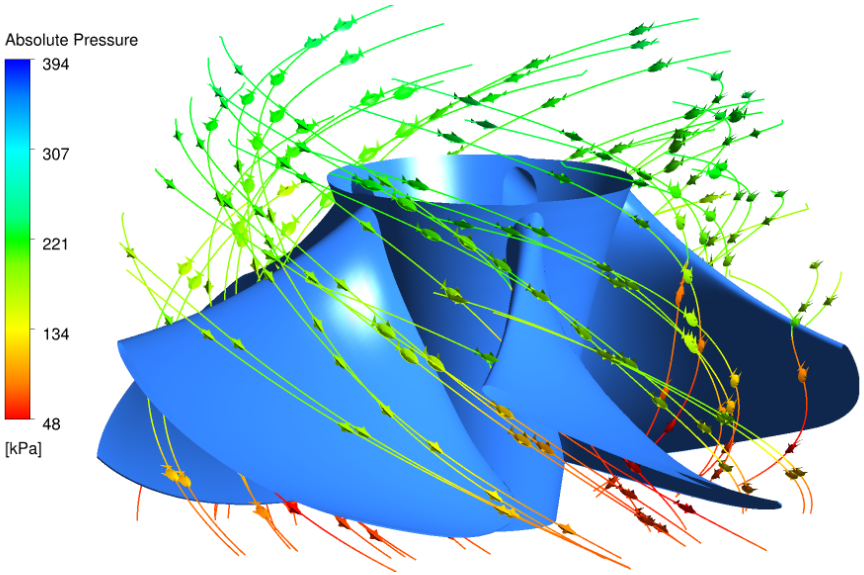
Fish trajectory modeling

Calculation method: Particle Tracks

- **Particle Tracks**
  - **Add inertia to simulated fish trajectories**
  - **Fish exposure calculated along each particle track**
  - **Improvement over streamlines:**
    - **More accurate trajectories**
    - **Possible to detect impacts on blades & walls**
  - **But:**
    - **Dimensionless particles**
    - **Equivalent to passive fish**
    - **Time-consuming post-processing**



Example of particle tracks as fish surrogates (colored by absolute pressure)

ANDRITZ Hydro

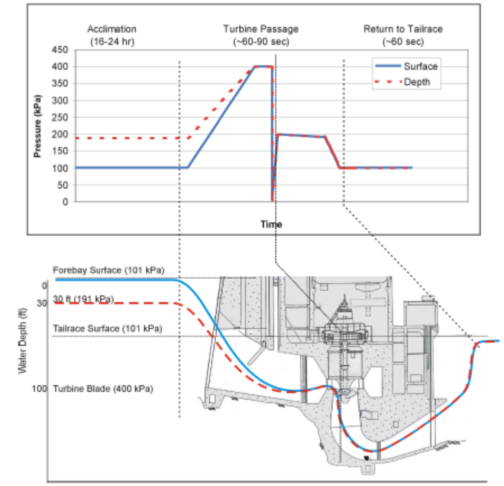
Fish Survival Assessment

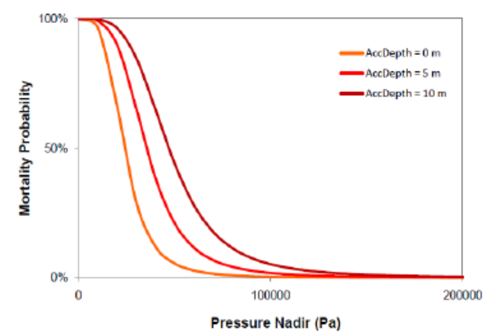
Biological Performance Assessment (BioPA) Tool

Developed by the Pacific Northwest National Laboratory (PNNL) in Richland, WA, USA, the BioPA tool provides a fish survival assessment based on the CFD simulations of a hydraulic turbine.

- The BioPA tool provides a performance indicator that can be used to compare different turbine design layouts and geometries. It was developed to assess whether proposed replacement turbines for the Priest Rapids power plant (Columbia River, WA, USA) could match or exceed the existing Turbine's performance.

- The BioPA tool showed itself as a powerful tool for evaluating comparative fish survival performance, even though it was calibrated for the specific considerations of the Priest Rapids project. However, if properly treated, the BioPA's could be generalized to analyze just about any type of turbine. In addition, running the BioPA on existing turbines where good fish mortality data is available could help calibrate the BioPA tool and it could eventually be used to make reliable fish survival estimates.

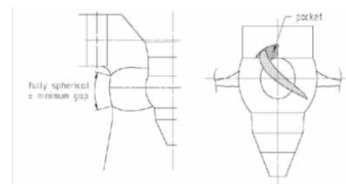
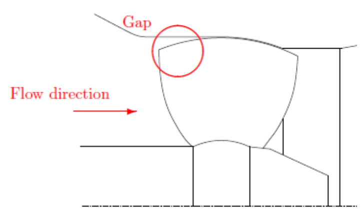
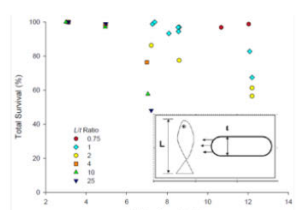




ANDRITZ Hydro

Fish Friendly Turbine Design Concepts

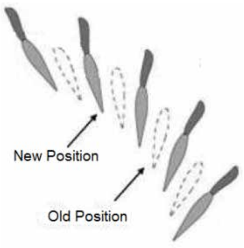
Design features

Injury Mechanism	Fish-friendly design features	Description
Grinding/ shear	Reducing gaps  Minimum guide vane overhang  Discharge ring contour and runner hub pockets[22]  (a) Semi-spherical discharge ring (Linne)	Reducing the gap between rotating and stationary components reduces chance of fish getting trapped in gaps Wicket gate overhang creates a region of high grinding and shear danger
Strike	Blunt leading edge  Direct mortality to leading edge strike as function of strike speed and L/t ratio (rainbow trout)[14]	Blunt leading edges on runner blades reduce impact severity

ANDRITZ Hydro

Fish Friendly Turbine Design Concepts

Design features

Injury Mechanism	Fish-friendly design features	Description
Strike	Guide vane alignment 	Aligning the stay vanes and wicket gates (at least in the most important range of operation) reduces the probability that a fish will hit the wicket gate
	Reduced runner rotational speed	Lower rotating speed reduces the impact velocity between fish and runner, reducing strike severity
	Minimize number of runner blades	Fewer runner blades mean lower strike probability and larger inter-blade passages

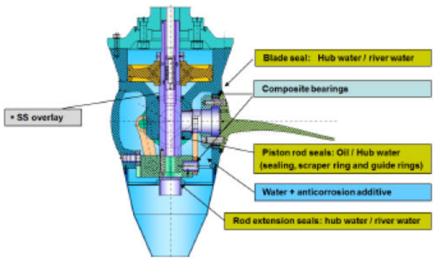
Fish Friendly Turbine Design Concepts

Design features

Injury Mechanism	Fish-friendly design features	Description
Turbulence	High performance runner Variable speed for very high efficiencies across a wide operating range	Modern high performance runners generally have a very low turbulence level to improve the fish-survival rate, decrease noise level and reduce energy losses.
Cavitation	Bubble free runner or at least minimum cavitation runner	The damage of fish tissues by micro-jets will be reduced
Rapid pressure change	Blade design (e.g. longer blade) with CFD monitoring	CFD tools can be applied during the hydraulic design to monitor the pressure gradient and to compare with critical values

Fish Friendly Turbine Design Concepts

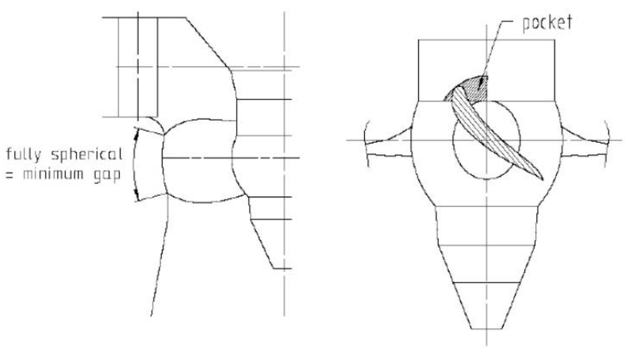
Design features

Injury Mechanism	Fish-friendly design features	Description
Water quality	Oil free hub 	With this design there is no risk of oil leakage into the river water and the blade seal arrangement prevents water exchange

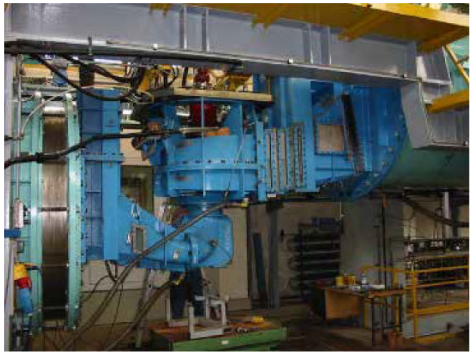
Fish Friendly Turbine Design Concepts

Reduced Gap Runner

- **Kaplan runner design incorporating fish-friendly design features**
  - **Fully spherical discharge ring → minimize blade tip gap**
  - **Spherical hub with "pockets" → minimize hub gap**
  - **Thicker blade leading edge → decreased blade strike mortality**
- **Model tests showed improved performance for Reduced Gap Runner while CFD and bead passage tests showed improved fish passage impact**
  - **Bead impact tests showed less severe impacts and direction changes**
  - **CFD showed very low maximum flow velocity gradients in runner passage**
- **These runners show how new designs & refurbishment projects can incorporate high turbine efficiency without sacrificing fish survival**



Discharge ring contour and runner hub pockets[22]


Lower Granite performance model in Linz, Austria

[22] **Nichtawitz, A., Habertheurer, N., Sebestyen, A., Wittinger, R. J.** *"Discussion on Kaplan Turbines and Potential Environmental Improvements ",* Paper presented at HydroVision 2002

Fish Friendly Turbine Design Concepts

Selection of variable speed turbines for optimum fish protection

Swansea Bay Tidal Lagoon

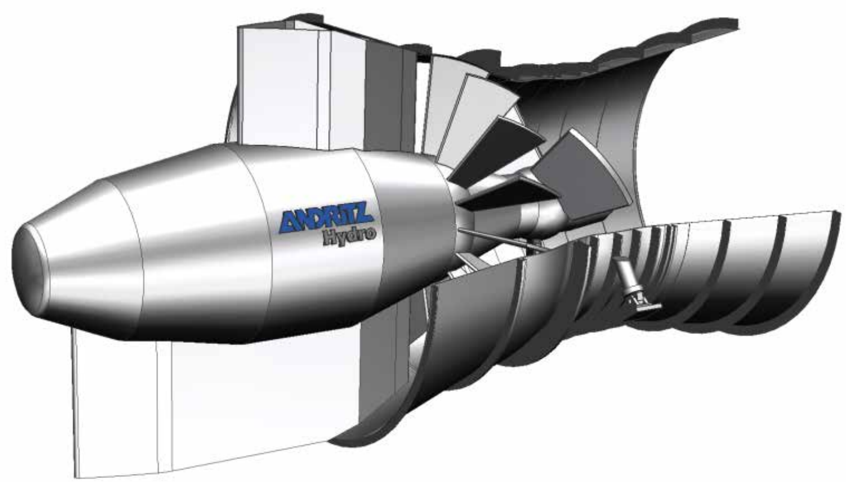
Triple regulated „Bi directional bulb Pump Turbine“

Variable speed bulb turbine has a very high efficiencies across a wide operating range. Conventional synchronous turbines have high efficiency over a much narrower opaerating range. This is one of the fundamental advantages of varspeed technology in reducing impacts on fish.

Location: Coast of Swansea, Wales

Unit Data

- **No. of units = 16**
- **D1 = 7.2 m**
- **H_{Max} = 7 m**
- **$P_{max/unit}$ = 22 MW**
- **n = 10 – 80 rpm**



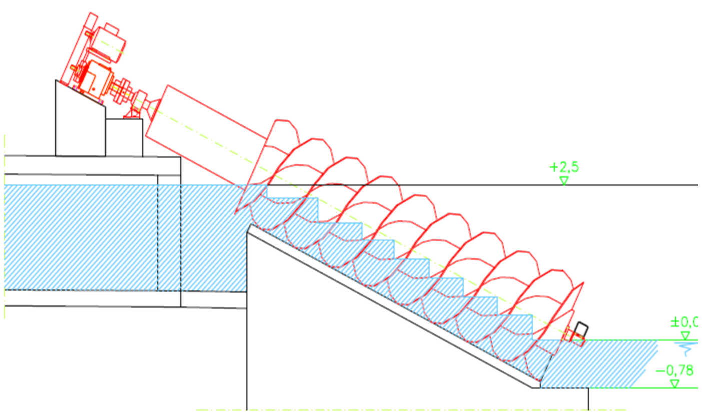
[xx] **Case, M., Turnpenny, A., Michelcic, J.** *“Selection of variable speed turbines for optimum fish protection at Swansea Bay Tidal Lagoon”,* Paper presented at HydroVision 2015

Fish Friendly Turbine Design Concepts

Hydrodynamic Screw Turbine - Description

- **Created by ANDRITZ Atro GmbH (Formerly Ritz Atro)**
  - **Product aimed at very small applications (small head and flow)**
  - **Over 100 installed turbines since 2000**
  - **Head up to 10 m, flow up to 10 m^3/s**
  - **Power up to 500 kW**

- **Several advantages**
  - **Stand-alone solution for remote locations**
  - **Low installation and maintenance costs**
    - **Minimal civil works, generator above water level, low wear due to slow speed**
  - **Very fish-friendly solution**



ANDRITZ Hydro

Fish Friendly Turbine Design Concepts

Hydrodynamic Screw Turbine (Continued)

- **Safe passage through turbine for small fish**
  - **Slow rotating speeds, large passages → no blade strike injuries**
  - **Low head → no rapid pressure drops**
  - **Low turbulence levels → No fish disorientation**
  - **No stationary components → no shear, abrasion, etc.**
  - **Larger fish passage blocked by trash racks**

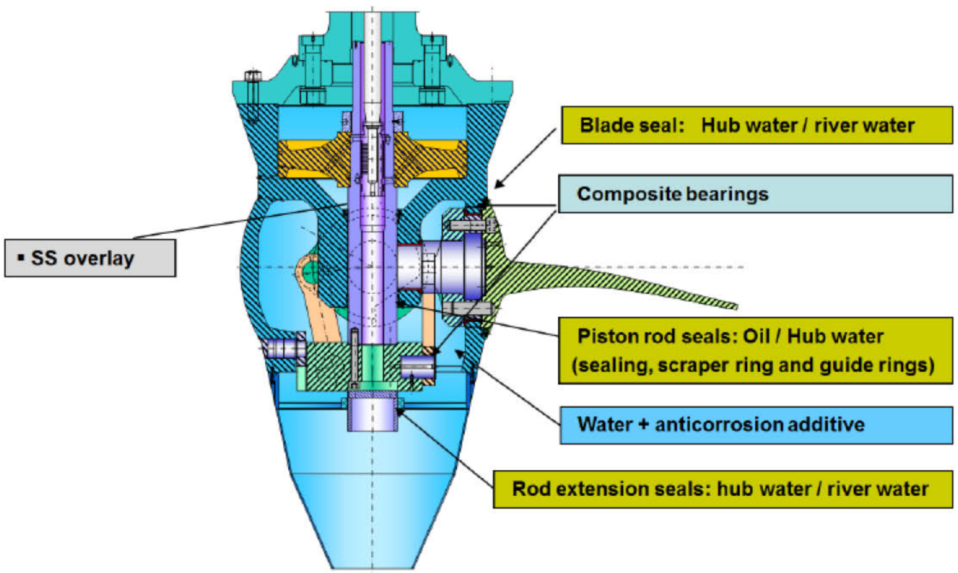
- **Safe passage of fish confirmed by live fish monitoring and trials on prototype turbine[24]**
  - **Screw installed on river Dart (U.K.),**
  - **Healthy fishes inserted upstream and verified downstream**
  - **Whole passage controlled and filmed**
  - **Result : No dead or injured fish!**

[24] **Kibel,P.**: “*Fish Monitoring and Live Fish Trials. Archimedes Screw Turbine, River Dart*” , Report prepared by Fishtek Consulting Ltd. for Mann Power Conulting, September 2007.

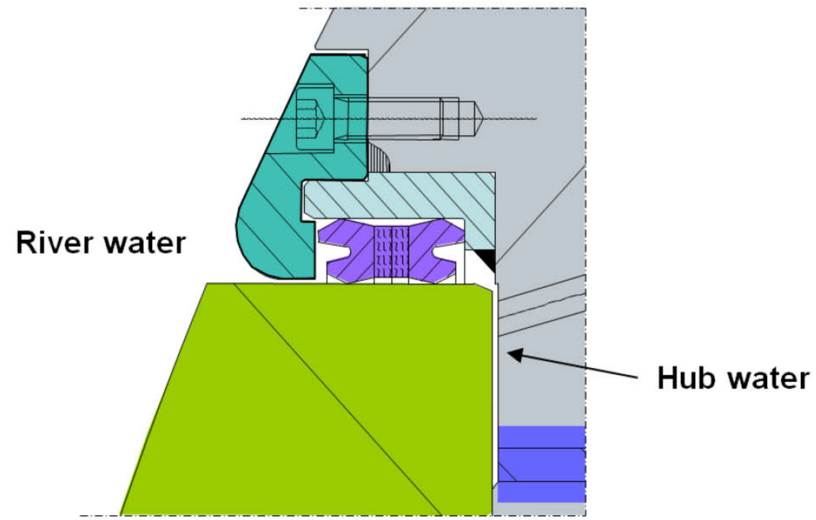
Fish Friendly Turbine Design Concepts

Oil free hub - keeping the Water Clean

- **Typical double-regulated machines have oil-filled hubs, where pressure inside the runner hub is higher than outside**
- **In case of seal failure the oil will leak out of the hub**
- **"oil free hub" design is aimed to safely prevent any oil from leaking into the river**



Oil free hub (ANDRITZ design example)

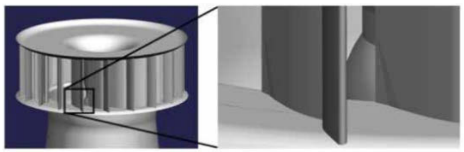


Detail of Runner Blade Seal

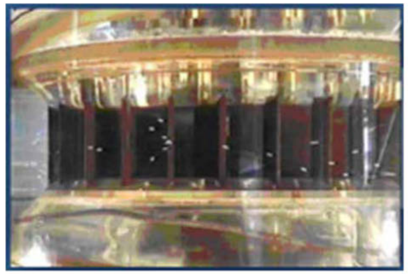
ANDRITZ Hydro

Fish Friendly Turbine Design Concepts

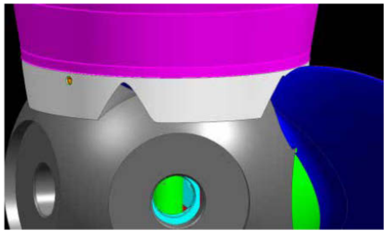
Overview of Andritz Hydro projects in Fish friendly design

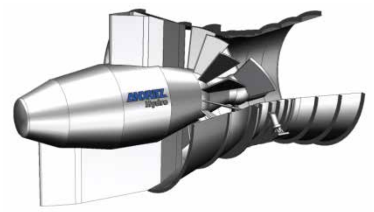


Sharpened Guide Vane TE[19]



Beads in model distributor (from high speed video)[20]





Rock Island

McNary

Priest Rapids

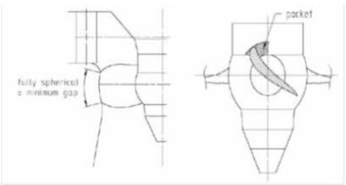
Swansea

Lower Granite

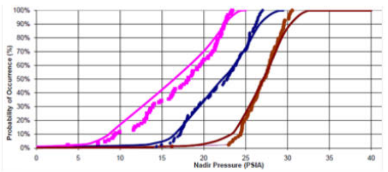
John Day Dam

Borgharen

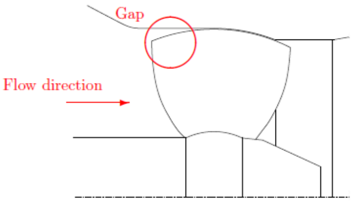
Xayaburi



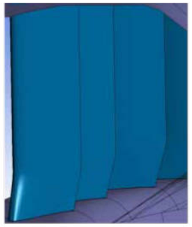
Discharge ring contour and runner hub pockets[22]



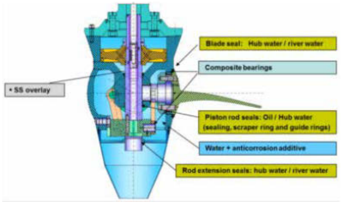
Nadir pressure probability distribution - CFD vs. sensor fish[8]



(a) Semi-spherical discharge ring (Linne)



Minimum guide vane overhang



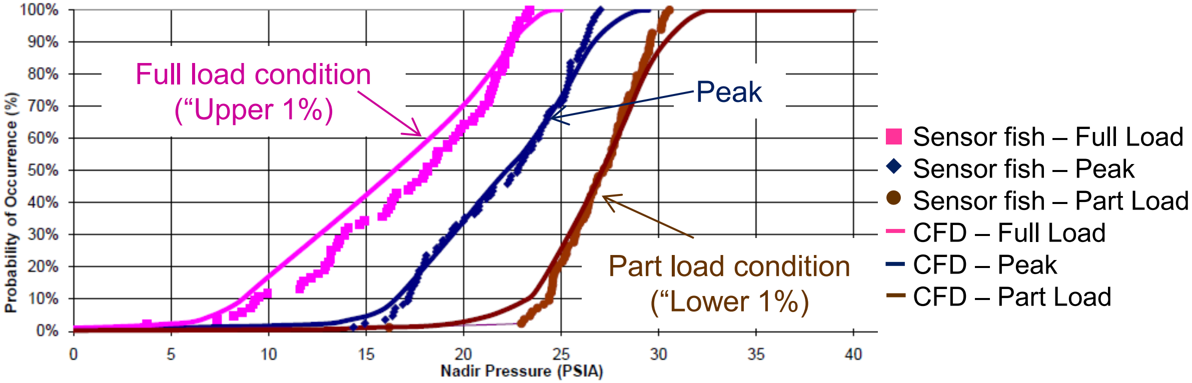
Oil free hub (ANDRITZ design example)

Fish Friendly Turbine Design Concepts

Example: John Day Dam

- **Study performed at John Day plant (Kaplan runners, Columbia River, WA / OR, 2008)**
  - **Goal: Demonstrate use of CFD to provide accurate representation of flow regime**
    - **➔ Validate use of CFD data for comparative fish safety risk analysis**
  - **Results: (nadir pressures along CFD streamlines and sensor fish measurements)**
    - **Good agreement between CFD and measurements with linear offset applied to CFD (5 PSI near casing, 0 PSI near hub)**
    - **➔ Quality of different turbines can be safely compared to each other based on CFD results**
  - **Modern CFD of similar quality as John Day Dam study**

John Day Dam[7]



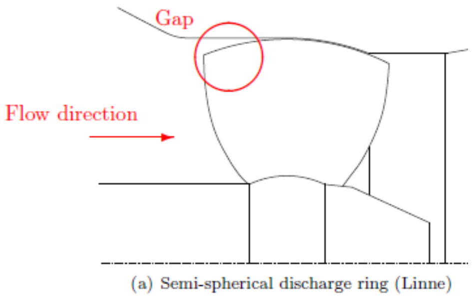
Nadir pressure probability distribution - CFD vs. sensor fish[8]

[7] "John Day Dam – General Information", *Hydroelectric Information for Columbia and Snake River Projects*, http://www.cbr.washington.edu/crisp/hydro/jda.html
[8] Figure adapted from: **Ebner, Laurie L. and Kiel, James D.** "*John Day CFD Nadir pressure Analysis*", paper presented at EPRI Conference, Washington, D.C., 2011

Fish Friendly Turbine Design Concepts

Example: Borgharen

- Horizontal bulb turbines at Borgharen (Meuse river, Netherlands, 2011)
  - Focus on eel and juvenile salmonid survival
  - Blade impact and grinding identified as prominent injuries
- Mortality estimation by means of strike-probability equation
  - Calibration of empirical coefficient λ based on field-monitoring data for similar power plant (Linne)
  - Positive effect of reduction in runner gaps modeled by reduction of λ
- Effects of relevant layout parameters on fish survival:
  - ↑ Number of runner blades ➔↓ fish survival
  - ↑ runner speed ➔ ↓ fish survival
  - ↑ flow rate (determined by operating scheme of power plant) ➔ ↑ fish survival



Gap between runner and semi-spherical discharge ring at Linne
(from Andritz internal report)

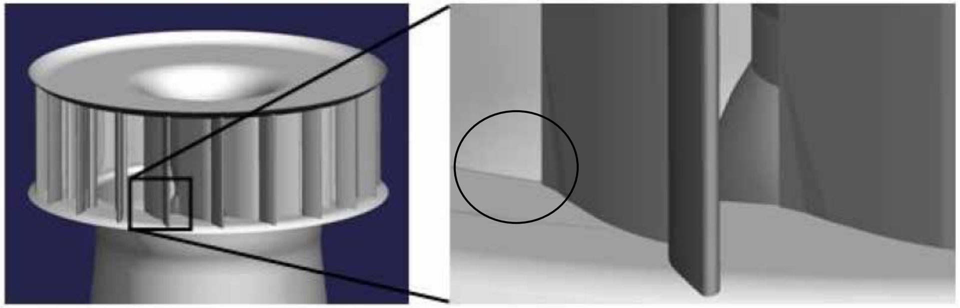
ANDRITZ Hydro

Fish Friendly Turbine Design Concepts

Example: Rock Island

- **Rehabilitation of 5 Kaplan turbines (22.5 MW) at Rock Island power plant (Columbia River, WA, 2006)**
  - **Special attention to fish-friendliness during design process**
- **Approach: Inclusion of design features known or assumed to increase fish survival**
  - **Distributor: Stay vane-guide vane alignment, sharpened guide vane TE (overhang reduction)**
  - **Runner: gap reduction at LE and TE, go from 5 to 4 blades, blunt blade LE**
  - **Draft tube: horizontal splitter vane to reduce turbulence**

Rock Island power plant[18]



Sharpened Guide Vane TE[19]

[18] "Hydroelectric Plants in Washington", *Power Plants around the World*, Photograph courtesy of U.S. Environmental Protection Agency, 07/10/2007. http://www.industcards.com/hydro-usa-wa.htm

[19] **Grafenberger, Peter, Schmidt, Stephen, Bickford, Brett M**.: "*Rehabilitation of the Rock Island Project*", HydroVision 2006

Fish Friendly Turbine Design Concepts

Example: Priest Rapid - Reduced Gap Runner

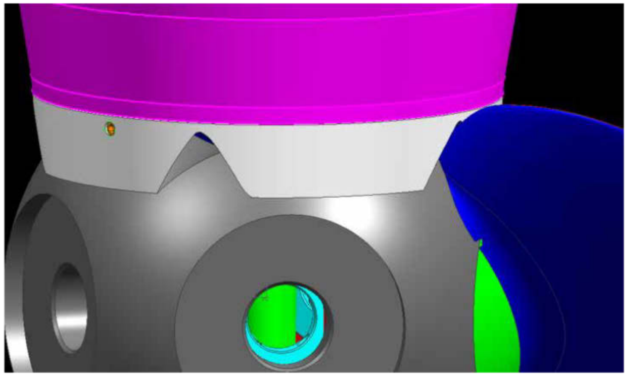
- **Model tests in context of Priest Rapids Refurbishment (vertical Kaplan turbine,** Columbia River, WA, USA) **)**

Kaplan runner design incorporating fish-friendly design features

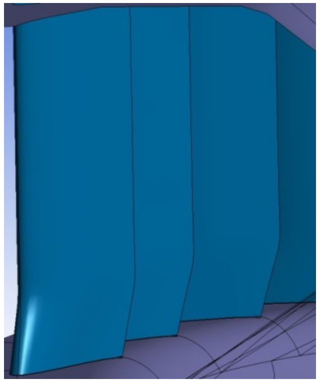
- **Fully spherical discharge ring → minimize blade tip gap**
- **Spherical hub with "pockets" → minimize hub gap**
- **Runner: gap reduction at LE and TE, change from 6 to 5 blades**

The BioPA tool was used to evaluate the overall performance indicator which makes it easy to compare proposed turbine geometries and layouts to the existing design. The performance indicator of fish mortality, shows a dramatic improvement of fish survival for the fish friendly runner design, compared to the existing turbine.

Priest Rapids Dam



Runner hub pockets



Reduced guide vane overhang

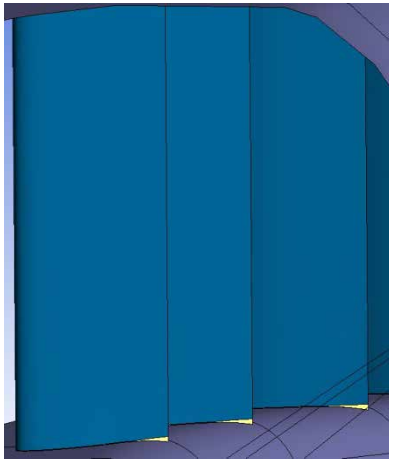
ANDRITZ Hydro

Fish Friendly Turbine Design Concepts

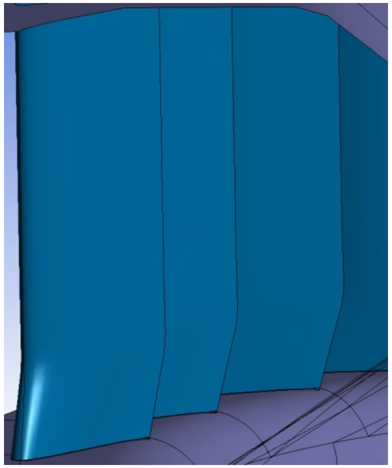
Example: Xayaburi (EGAT)

- **7 Kaplan turbines (Ø 8.6 m, 186.6 MW) at Xayaburi Power plant (Mekong River, Laos)**
  - **Special attention to fish-friendliness during design process**
- **Approach: Inclusion of design features known or assumed to increase fish survival**
  - **Distributor: guide vane overhang reduction**
  - **Runner: reduced number of blades - 5 instead of 6 as initially proposed**
  - **Runner hub: Oil free**

Schematic overview of power plant [XAYABURI Power Company Limited]



“normal" guide vane design



Minimum guide vane overhang

ANDRITZ Hydro

Fish Friendly Turbine Design Concepts

Example: McNary Model Development

- **Model tests in context of McNary Refurbishment Project (Diagonal turbine, Columbia River, WA / OR, 2008)**
  - **Runner model sent to USACE ERDC lab in Vicksburg for fish-friendliness evaluation**
- **Evaluation consisted of visual analysis of beads passing through hydraulic passages**
  - **Neutral buoyancy beads as juvenile fish**
  - **Bead paths ranked by severity of disturbances (impacts & direction changes)**

Relative size of plastic beads used for fish simulation

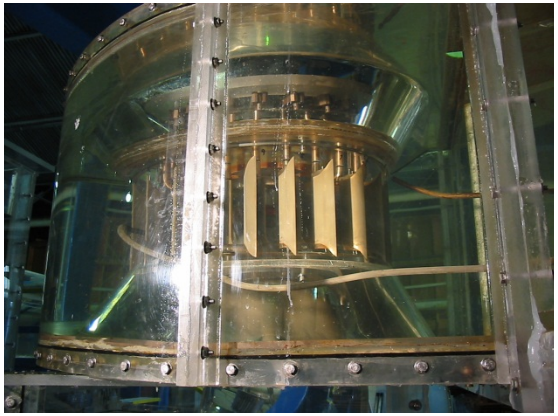
Beads in model distributor (from high speed video)[20]

[20] **Weiland, M.A., Mueller, R.P., Carlson, T.J., Deng, Z.D. and McKinstry, C.A.** *"Characterization of Bead Trajectories through the Draft Tube of a Turbine Physical Model",* Pacific Northwest National Laboratory, 2005

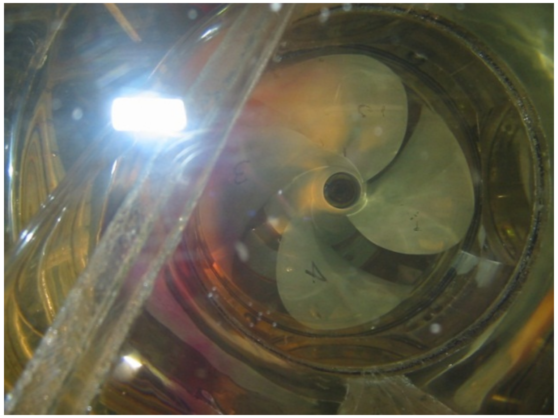
Fish Friendly Turbine Design Concepts

Example: McNary Model Development

- **Result: proposed Andritz Hydro runner model favorably compared to original McNary model results**
  - **Smooth flow coming off runner and transition through throat and elbow**
  - **↓ severe bead contacts, ↓ sudden direction changes**
  - **↓ hydraulic shear below runner**
  - **From USACE evaluation of proposal: *"The proposed runner performs exceptionally well. (…)This runner would appear to provide significantly improved fish passage conditions as compared to the existing runner and was noted as providing a "snow flake" effect because the beads appeared to smoothly drift down from the runner into the draft-tubes."*** [21]



Andritz Hydro model casing in Plexiglas stand



Andritz Hydro model runner in Plexiglas stand

[21] *"Proposal Strengths, Deficiencies, and Weaknesses , Factor 1 - Fish Passage Environment",* USACE evaluation of GE Hydro proposal, 2008

Concluding Remarks

- **Fish survival assessment is a complex task:**
  - **Wide problem scope**
  - **Relatively few studies of turbine-related injuries**
  - **CFD modeling of fish still in early stage**
    - **Andritz Hydro takes an active role on this**

- **Current state of the art allow comparative fish survival assessment**
  - **e.g. between different design layouts or between an original and replacement turbine**
- **Andritz Hydro will continue to take an leading role regarding fish-friendliness**

ANDRITZ HYDRO GmbH

Non-disclosure statement