Keeyask Generation Project

Environmental Impact Statement

Supporting Volume

Aquatic Environment

KEEYASK
Hydropower Limited Partnership

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ATTACHMENT 1: REFERENCE DOCUMENT FOR KEEYASK EIS: PARAMETERS CONSIDERED IN THE SELECTION AND DEVELOPMENT OF TURBINES FOR KEEYASK GS TO INCREASE FISH PASSAGE SURVIVAL

Manitoba Hydro Interoffice Memorandum

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Introduction

The Keeyask GS turbines are the first turbines for which Manitoba Hydro has considered a number of variables affecting fish passage survival in the selection and development processes. Although there are many variables to consider beyond those specifically relevant for fish survival (particularly efficiency and cost), a general objective for the Keeyask GS turbine selection and development is to achieve a minimum survival rate of 90% for fish as large as 500 mm. The following principal features were considered in the selection and will also be considered in the further development of the turbine design: number of blades; thickness and shape of leading and trailing edge of blades: turbine rotation rate; turbine runner diameter and blade speed (impact velocity): stay vane and wicket gate number, alignment and shape, clearance at wicket gates, wicket gate overhang, and low absolute pressure (nadir).

Stay Vane/Wicket Number, Alignment, and Shape

The number and shape of both the stay vanes and wicket gates can affect the condition of fish when they encounter these flow directing structures just upstream of the turbine runner. Additionally, the alignment and distance between the stay vane and wicket gate may also affect the condition of fish that contact the upstream edge and/or pass between these structures. The primary cause of injuries would be due to direct contact, and possible shear forces between the trailing edge of a stay vane and leading edge of a wicket gate. Generally direct contact should inflict only minimal injuries at strike velocities of less than 6.1 m/s (Bell 1991). Few direct survival/injuries studies have been designed to evaluate the condition of fish after encountering the stay vanes and wicket gates. Normandeau et al. (1999) did obtain survival/injury on HI-Z tagged juvenile salmon (average length 154 mm) that were released from three pipes mounted on stay vanes and another pipe mounted 5.5 m directly upstream of the stay vane. The percentage of recaptured fish alive 48 h after turbine passage at the McNary Project (Tables 1 and 2) for fish that potentially encountered the stay vanes/wicket gates (92.4%) was similar to the fish that were released downstream of the stay vanes/wicket gates (90.9–92.7%). Injury rates were actually slightly less for fish that potentially encountered the stay vanes/wicket gates; 3% versus 3.8–5.1% for fish released downstream of the stay vanes/wicket gates.

The turbine selected for Keeyask GS has wicket gates with rounded upstream edges which will minimize direct contact injuries. The extended length and profile design of the stay vanes of the selected turbine design improves the flow conditions in the vicinity of the stay vanes and wicket gates, which reduces turbulence and flow separation. These features should improve passage conditions for fish, particularly through the minimization of the shear and turbulent zones that can injure and disorient fish.

Clearance at Wicket Gates and Runner

Minimizing gaps at the wicket is beneficial for fish, particularly if water accelerates sufficiently enough through these openings to cause shear and/or strike induced injuries to entrained fish. The primary gap areas of potential entrainment are between the trailing edge of the stay vanes and leading edges of the downstream wicket gates; between the top of a wicket gate and the head cover; and between the bottom of the wicket gates and the bottom ring. Laboratory studies on juvenile salmon indicate that shear induced injuries generally begin to occur when areas of contrasting flows produce strain rates >900 cm/s/cm (Neitzel *et al.* 2000); while direct contacts begin to elicit injuries at ≥6.1 m/s (Bell 1991).

The gaps at the bottom and top of the wicket gates of the selected turbine design have been sufficiently minimized to eliminate the chance of fish (except possibly larval fish) being drawn into these areas that have a higher risk of injury/mortality. Gaps between the runner and discharge ring, and the runner and head cover are also sufficiently small in the selected turbine design to minimize the risk of fish being drawn into these areas where they could incur injuries.

Wicket Gate Overhang

The lower edge of a wicket gate guide vane typically over hangs the bottom ring for most conventional turbine designs, depending on turbine load. Depending on the extent of this overhang a zone of turbulent flow can set up downstream of this protrusion point. Each turbulent zone is generally not very extensive but under certain wicket gate openings a turbulent zone can develop at the bottom trailing edge of each wicket gate.

The turbine design selected for Keeyask GS has minimized or eliminated (depending on load) the wicket gate overhang, such that the development of turbulent zones at the trailing edge of the wicket gates is avoided.

Number of Blades

Strike inflicted injuries due to blade contact are the dominant injuries observed in most direct survival/injury studies conducted using HI-Z tag fish recapture method. Therefore, minimizing the number of blades will likely have the greatest effect on reducing fish injury and mortality. Blade number minimization is most beneficial for larger fish, at propeller type turbines, provided good flow characteristics can be maintained through the turbine blades. Examination of the survival/injury results from HI-Z tag turbine passage evaluations conducted on large size turbines (6–8 m diameter) similar to those proposed for Keeyask GS indicate that five-bladed units generally had higher survival (median of 96.2%) and lower injury rates (median of 2.1%) than six-bladed units (medians of 94.8% and 3.6 %, respectively) for juvenile fish (114–184 mm mean length range, Table 2). The trend for higher survival and lower injury rates for turbines with fewer blades persisted whether the turbine had fish friendly features or not. The best example of this was an extensive study (more than 8,000 fish) conducted at Wanapum Dam to evaluate a conventional Kaplan turbine and a new advanced hydro turbine system (AHTS) (Dresser *et al.* 2006 a, b; Normandeau *et al.* 2006; and Table 2). The AHTS had many fish friendly features including, minimal gaps at the hub and blade tip, alignment of stay vanes and wicket gates and minimized wicket gate overhang; however, the AHTS had six blades versus five for the conventional Kaplan Unit. Fish directed towards the hub had slightly higher survival rate for the AHTS (98.5 %) compared to the conventional Kaplan unit (97.9%); however, fish directed towards the mid blade had a higher survival rate at the conventional turbine (97.1%) compared to the AHTS (95.4%).The same trend was observed when recaptured fish were examined for injuries with fewer hub directed fish injured at the AHTS (0.9%) than the conventional Kaplan unit (1.8%) but the opposite for mid blade directed fish (3.3% for AHTS, 2.5% for conventional).

The effects of the number of blades at large units is more pronounced for larger fish (Table 2). This is based on four HI-Z tag fish recapture studies conducted on adult eels (690–1,020 mm), two studies on adult northern pike (595–661 mm), adult walleye (431–447 mm), and adult American shad (423–425 mm) (Table 2) Average survival of the eels decreased with increasing blade number and was 92.4 and 93.0% for the four bladed units, but only 79.9% and 73.5% for five and six bladed units respectively. The corresponding injury rate also increased (6.536.7 %) with an increase in blade number. The average survival of adult northern pike and adult walleye was higher in a five bladed unit (75.6% and 87.7%, respectively) compared to a six bladed unit (65.9% and 80.4%, respectively). Survival of adult American shad passed through a five bladed Kaplan unit was higher (88.2%) than for adult American shad passed through a seven bladed mixed flow unit (84.3%).

The turbine design selected for Keeyask GS has five blades. The selection of a turbine design with a low number of blades will significantly improve the survival of fish and reduce injuries.

Blade Leading Edge Thickness

The shape, thickness, and speed of the leading edge of the turbine blades can affect both survival and injury rate of fish that make direct contact. Generally, the risk of blunt force injury and/or lacerations is reduced with a thicker and rounder leading edge and a slower blade speed. However, a blade leading edge that is too thick can reduce turbine efficiency. The size of the fish, its orientation to the blade and area of the body that makes blade contact affect the extent, type, severity of injuries. Laboratory studies conducted by Amaral *et al.* (2008, 2011) evaluated the effects of fish species, length, and orientation and blade impact speed, and blade thickness on fish mortality. Blade speed and fish length to the thickness of the leading edge of the blade were the primary factors affecting survival of fish encountering the upstream edge of a turbine blade. The length of the fish to the thickness of the leading edge of the blade was designated as L/t.

Empirical field data collected on HI-Z tagged adult walleye and northern pike also demonstrate the effects of narrow leading edge blades on rate and type of fish injuries. North/South Consultants and Normandeau Associates (2009) reported that survival rates were higher for a five bladed unit than for a six bladed unit for both walleye (87.7% and 80.4%, respectively) and northern pike (75.6% versus 65.9%) at the Kelsey Generating Station in Manitoba. However, the rate of injured fish did not show a corresponding decrease (Table 2). The percentage of injured walleye did not decrease with the decrease in blade number and were close to 32% for both the five and six bladed units. The corresponding injury rate for the northern pike was higher for the five bladed unit (61.7%) than the six bladed unit (53.4%). The lack of a decrease in injury rate with a decrease in blade number was attributed to the considerably thinner (sharper) leading blade edge design of the five bladed turbine (Figure 1). Some injured specimens from the five bladed unit also displayed a patch of scales and skin removed from the side of a fish with a distinct line where the fish was initially struck (Figure 2). Specific information on leading edge blade thickness and shape is not readily available for most of the HI-Z tag studies conducted on smaller fish (<200 mm) presented in Table 2.

The selected turbine design allows for an option to increase the thickness of the leading edge blade, and this will be examined and evaluated in the further development of the turbine design, to reduce the risk of injury and mortality of fish due to contact with the blade.

Blade Trailing Edge

The impact of the shape and thickness of the trailing edge of a turbine blade on fish injury has not been extensively evaluated, but eliminating turbulence and wake at the blade's trailing edge is beneficial for both turbine performance and fish that pass close to the trailing edge of a blade.

Without completing extensive testing (that would require working models), it is difficult to estimate whether the blade trailing edge of the selected turbine design would produce minimal or no turbulence zones. In the further development of the turbine design, Manitoba Hydro will strive to reduce turbulence and wake at the blade trailing edge (both for benefit to fish, and for turbine performance). Rounding the edges may also be considered, to reduce the effect of fish directly contacting the trailing edge of the blade.

Rotation Rate, Runner Diameter and Blade Speed

Higher rotation rates of turbine runners can affect the survival of fish by increasing the probability of fish contacting a blade and also increasing the speed at which the leading blade edge could contact a fish. Rotation rate is influenced greatly by runner diameter, with larger units generally having slower rotation rates. If runners are of similar size with the same number of blades, a higher rotation rate would likely make the unit less fish friendly. The large turbine runners (6-8 m diameter) where HI-Z tag tests have been conducted had rotation rates ranging from75–120 rpm (Table 2). Because of the interaction of number of blades, runner diameter, operating head and other factors the direct effects of rpm on fish survival/injury was not always obvious. Juvenile salmon passed through Bonneville turbines with the slowest rpm (75) did have some of the higher survival rates, at 98 and 99% for hub passed fish; however these units also had five blades and a relatively low head (17.4 m). Survival rates for juvenile salmon were lower (all ≤96.1%) at the higher 90 rpm units (Ice Harbor, John Day, Lower Granite, and Rocky Reach); however, these were also all six bladed units and had a higher head (close to 30 m).

The detrimental effects of higher rotational rate (300 rpm), higher head (55 m) and numerous blades (13) was demonstrated at a HI-Z tag test conducted at the Arrowrock Station (Normandeau Associates 2011). Survival of smaller (mean length of 284 mm) and larger (mean length of 457 mm) salmon was only 11.1% and 0.0%, respectively. The unit tested was a Francis type turbine and was also quite small (1.7 m diameter).

The design selected for Keeyask GS is a large diameter turbine runner, with a slower rotation rate (75 rpm), and a low number of blades (five). Based on these parameters, the survival of fish will be very good, particularly when compared to turbines with higher rotation rates and a higher number of blades.

Low Absolute Pressure (Nadir)

Fish passing through a turbine experience pressure changes over a short period of time. In a conventional hydroelectric facility pressure increases as a fish descends to the upstream side of the runner, drops rapidly upon passing the runner, increases in the draft tube, and then returns to near atmospheric pressure at the surface of the tailrace, or greater pressures if the fish swims to deeper water (Figure 3). Low absolute pressure that a fish may experience upon passing the turbine runner can cause decompression injuries (barotraumas) to fish that are acclimated to different depths prior to turbine entrainment. The lowest pressure a fish encounters (nadir pressure), and the depth to which it is acclimated appear to be the primary factors affecting mortality (Figure 4) and the rate, severity, and type of injury. Injuries associated with sudden decompression trauma include ruptured air bladder, ruptured blood vessels, air bubbles in the internal organs and in fins. Many of these injuries result in death. Among fish with swim bladders, the response to rapid pressure changes encountered within a turbine is affected by whether the fish is physostomous or physoclistous. Physostomous fish (*e.g.*, salmon, eels, shad, sturgeon, whitefish and catfish) have a pneumatic duct that connects the swim bladder with the esophagus. Gas can be quickly taken into or vented from the swim bladder through the mouth and pneumatic duct, so that adjustment to changing water pressures can take place rapidly, often on the order of seconds. Physoclistous fish (*e.g.,* sunfishes, basses, perch and walleye) lack a direct connection between the swim bladder and the esophagus. In these fish the contents and pressures within the swim bladder must be adjusted by diffusion into the blood, a process measured on the order of hours.

For both physoclistous and physostomous fish, the depth of acclimation prior to decompression relative to the pressure of exposure influences the magnitude of barotraumas. Laboratory studies indicate that the highest mortalities occur when the pressure reduction was greatest, i.e., when the exposure pressure was a relatively small fraction of the acclimation pressure. Figure 5 shows percent mortality for physoclistous and physostomous fishes following exposure in the laboratory to rapid and brief pressure reductions. Note that all the fish in a laboratory chamber were exposed to large pressure changes, in contrast to a field situation where only a fraction of the fish population may be exposed to large pressure changes. The data were taken from studies that included fish held at a pressures associated with different depths long enough to become acclimated. The fish were then exposed to a rapid and brief pressure drop in order to simulate the duration of low pressure exposure within a turbine. The data suggest that: 1) decompression is more detrimental for physoclistous species compared to physostomous species, and 2) overall mortality is low when the minimum pressure is 40% of the acclimation pressure. The principal species of concern for Keeyask GS are sturgeon, white fish, walleye, and northern pike, of which walleye is the only physoclistous species.

Although controlled laboratory studies have been conducted to assess the effect of sudden decreased pressure on fish; no known controlled field studies were found. The pressure decreases that fish experience within the runner occur rapidly and may be large. The nadir, or lowest pressure a fish may be exposed to depends on where the fish passes the turbine. The lowest pressure occurs on the suction side versus the pressure side of the turbine blade. A device called the Sensor Fish has been used to determine the pressures present in some turbines, primarily Kaplan, on the Columbia River to which fish are exposed during turbine passage (Deng *et al.* 2007; Carlson *et al.* 2008). In some Sensor Fish examples, nadirs below vapour pressure were measured (Carlson *et al.* 2008), but most ranged between 35 and 200 kPa (5 and 29 psi).

Although thousands of HI-Z tagged fish have been passed through turbines with a wide range of nadirs very few (<1%) of the recaptured fish have displayed injuries that could be attributed to sudden decompression trauma. Because the HI-Z tagged fish are held in water less than 40 cm deep prior to turbine passage these test fish are not acclimated to depths that a portion of naturally entrained fish would be. However, it has been very obvious from the HI-Z tag tests that there is little evidence that a sudden increase or decrease in pressure has any substantial negative effects on near surface acclimated fish.

Based on the parameters of the selected turbine design, it is anticipated that fish passing through the Keeyask GS turbines will be not be exposed to sudden increases or decreases in pressure that would have substantial negative effects on the fish.

Predicted Survival: Franke Formula

An analysis of turbine parameters can be used to estimate survival using a formula developed by Franke *et al.* (1997). The formula grew out of efforts by the U.S. Department of Energy (DOE) to design more “fish-friendly” turbines. The formula calculates the probability (P) of blade strike by relating such turbine parameters as the number of blades, runner diameter, and runner rotation rate to fish length and operating condition. Fish length and available passage space are the principal drivers of the output. In developing the formula, Franke *et al.* (1997) considered previous works that calculated turbine strike probability and new information developed by the authors. Existing empirical data were used to validate the model for conventional hydro projects. A thorough discussion of the derivation and application of the formulas is provided in Franke *et al.* (1997).

Based on this formula, the turbine design selected for Keeyask GS will have an estimated survival over 90%. This generalized estimate includes fish up to 500 mm, at a single discharge condition (maximum), three passage locations (near hub, mid blade and tip) and a blade strike correlation factors (0.1 and 0.2). The blade strike correlation factor designated lambda (λ) is used to account for variability in strike potential resulting in mortal injuries and also to relate the output to empirical data available to the Franke study. The value of lambda in the range of 0.1 to 0.2 was determined by Franke *et al.* (1997) from Kaplan survival tests. Although the formula calculates a probability, in the present context it is more conventionally used in the formula Survival (S) = 1 – P, with results expressed as a survival percentage.

Summary

A number of variables were considered in the selection and development of turbines for the Keeyask GS to minimize the risk of injury and mortality of fish as they pass downstream. These variables include the number, alignment, and shape of stay vanes and wicket gates, clearance at the wicket gates and runners, wicket gate overhang, number of blades, blade leading edge thickness, blade trailing edge (related to turbulence), rotation rate, runner diameter, blade speed, and absolute lowest pressure.

The use of a fixed blade vertical shaft turbine design for Keeyask GS results in several advantages for fish passage survivability compared to other turbine styles. The fixed blade pitch of the vertical shaft units allows for the gap between the runner blades and the discharge ring to be minimized, reducing the likelihood of fish impingement and injury. The low rotational speeds associated with large diameter vertical shaft turbines also result in greater fish survivability. To reduce the risk of striking or impingement injuries; runner blades incorporate a thicker rounder leading edge, the gaps between wicket gates and both the head ring and head cover were minimized, and the wicket gate overhang was also minimized. To reduce turbulence levels experienced by fish passing through the turbines, the runner blades incorporate a thinner trailing edge, and the shape of the draft tubes incorporate large sweeping radii. These are all known to improve the probability of a fish passing through a turbine without incurring significant injury or mortality.

This is the first time that Manitoba Hydro has included these variables relevant for fish survival as part of the evaluation in the initial turbine design selection process, and as a priority for further turbine design development. Although there are many variables to consider beyond those relevant for fish survival (particularly efficiency and cost), the objective for the Keeyask GS turbines is to achieve a minimum survival rate of 90% for fish as large as 500 mm.

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Table 1: Summary of turbine passage evaluations conducted utilizing the HI-Z Tag recapture technique (Heisey *et al.* 1992) (Summarized by P. Heisey of Normandeau Associates Inc.)

Number of Clients/Utilities	Number of Projects	Number of Fish Species*
32	48	21

Turbine Types

Propeller	Kaplan	Bulb (Horizontal Kaplan)	Francis	Hydrokinetic
16	26	4	15	1

*Species included: striped bass, rainbow trout, largemouth bass, chinook salmon, European eel, American eel, American shad, smallmouth bass, coho salmon, steelhead, Atlantic salmon, yellow perch, brown bullhead, channel catfish, bigmouth buffalo, white sucker, bluegill, northern pike, walleye, lake whitefish

Table 2: **Summary of physical and hydraulic characteristics of hydroelectric turbines similar in type and size to those proposed for the Keeyask Project and HI-Z tag acquired fish survival/injury data (Summarized by P. Heisey of Normandeau Associates Inc.)**

Station	Species	Average Size (mm)	Turbine Type	Blade Passage Vicinity[1]	No. of Blades	Runner Speed (rpm)	Dia. (m)	Peripheral Velocity (mps)	Test Discharge (cms)	Project Head (m)	Sample Size	48 d Survival	Visible Injury (%)
Bonneville	salmon	165	Kaplan	T[2]	5	75	7.11	27.9	176-340	17.4	966	0.933	3.9
Bonneville	salmon	166	Kaplan MGR	T[2]	5	75	7.11	27.9	176-340	17.4	963	0.952	1.9
Bonneville	salmon	165	Kaplan	M[2]	5	75	7.11	27.9	176-340	17.4	911	0.961	2.3
Bonneville	salmon	166	Kaplan MGR	M[2]	5	75	7.11	27.9	176-340	17.4	903	0.963	1.0
Bonneville	salmon	165	Kaplan	H[2]	5	75	7.11	27.9	176-340	17.4	681	0.992	0.7
Bonneville	salmon	166	Kaplan MGR	H[2]	5	75	7.11	27.9	176-340	17.4	681	0.980	1.0
McNary Dam	salmon	153-155	Kaplan	H[2]	6	86	7.11	31.9	351	21.6–22.9	330	0.927 [4]	4.1
McNary Dam	salmon	153-156	Kaplan	M[2]	6	86	7.11	31.9	351	21.6–22.9	310	0.916 [4]	3.8
McNary Dam	salmon	153-156	Kaplan	T[2]	6	86	7.11	31.9	351	21.6–22.9	309	0.909 [4]	5.1
McNary Dam	salmon	153-157	Kaplan	WG[2]	6	86	7.11	31.9	351	21.6–22.9	315	0.924 [4]	3.0
McNary Dam	salmon	140-158	Kaplan	M	6	86	7.11	31.9	218	21.6–22.3	2121	0.951	2.6
Wanapum	salmon	154	Kaplan	H&M	5	85.7	7.20	32.3	255-481	22.9	1278	0.943	2.6
Wanapum	salmon	169	Kaplan[5]	H	5	85.7	7.20	32.3	255-481	23.5	1829	0.979	1.8
Wanapum	salmon	169	Kaplan[5]	M	5	85.7	7.20	32.3	255-481	23.5	1829	0.971	2.5
Wanapum	salmon	169	AHT Kaplan[5]	H	6	85.7	7.72	34.7	255-481	23.5	1833	0.985	0.9
Wanapum	salmon	169	AHT Kaplan[5]	M	6	85.7	7.72	34.7	255-481	23.5	1834	0.954	3.3
Ice Harbor	salmon	139	Kaplan	M	6	90	7.11	33.5	246	29.1	2698	0.961	3.4
John Day	salmon	136	Kaplan	M	6	90	7.92	37.4	334-564	31.2	1630	0.947	2.6
Lower Granite	salmon	149	Kaplan	H&M	6	90	7.92	37.4	510	29.9	1830	0.949	3.5
Priest Rapids	salmon	155	Kaplan	M	6	86	7.21	32.4	255	23.8	1239	0.963	3.6
Rock Island	salmon	179	Propeller	H&M	6	100	5.74	30.1	227	12.2–12.8	279	0.932	5.5
Rock Island	salmon	179	Kaplan	H&M	6	100	5.74	30.1	227	12.2–12.5	281	0.961	3.6
Rock Island	salmon	179	Bulb	T&M	4	86	7.01	31.5	481	11.0–12.5	280	0.957	3.6
Rocky Reach	salmon	114	Propeller	H	5	86	7.89	35.4	130 MW	28.0	265	0.961	5.8
Rocky Reach	salmon	161-184	Kaplan	H&M	6	90	7.11	33.5	227-454	29.0	1076	0.949	4.7
Rocky Reach	salmon	185	Imp. Kaplan	H	6	90	7.11	33.5	227-453	28.0	985	0.950	3.1
Conowingo	shad	125	Mixed Flow	H	6	120	5.72	35.9	227	27.4	108	0.929	4.2
Safe Harbor	shad	119	Mixed Flow	H	7	76.6	6.10	24.4	261	16.8	199	0.979	4.85

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Station	Species	Average Size (mm)	Turbine Type	Blade Passage Vicinity[1]	No. of Blades	Runner Speed (rpm)	Dia. (m)	Peripheral Velocity (mps)	Test Discharge (cms)	Project Head (m)	Sample Size	48 d Survival	Visible Injury (%)
Safe Harbor	shad	118	Kaplan	H	5	109.1	5.60	31.9	235	16.8	100	0.970	3.1
Safe Harbor	shad	423	Kaplan	H	5	109.1	5.60	31.9	235	16.8	98	0.882	9.8
Safe Harbor	shad	425	Mixed Flow	H	7	76.6	6.10	24.4	261	16.8	100	0.843	11.3
Kelsey	walleye	431	Propeller	T, M&H	5	102.9	7.92	42.7	312	17.1	91	0.877	31.6
Kelsey	walleye	447	Propeller	T, M&H	6	102.9	7.92	42.7	227	17.1	99	0.804	31.8
Kelsey	pike	595	Propeller	T, M&H	5	102.9	7.92	42.7	312	17.1	95	0.756	61.7
Kelsey	pike	661	Propeller	T, M&H	6	102.9	7.92	42.7	227	17.1	88	0.659	53.4
Beaucaire	eel	690	Bulb	M/T	4	94	6.24	30.7	313	13.7	275	0.93	6.5
Fessenheim	eel	704	Kaplan	H/M/T	4	88	6.67	30.8	362	15.2	281	0.924	11.5
Ottmarsheim	eel	750	Kaplan	H/M/T	5	94	6.25	30.7	316	15.6	300	0.799	26.5
Robert Moses	eel	1020	Propeller	M	6	99	6.10	31.7	244-272	25.0	240	73.5 (88h)	36.7

1. H = near hub, M = near mid-blade, and T = near tip.
2. Fish released at stay vanes and passage directed toward specific areas of turbine blades.
3. Fish released just upstream and directed toward stay vanes/wicket gates.
4. No adjustment for control fish (none released).
5. Tests conducted concurrently under same hydraulic conditions.

Figure 1: **Comparison of leading edge shape and thickness of blades for a 6 (A) and 5 (B) bladed turbine at Manitoba Hydro's Kelsey Generating Station**

Figure 2: **Unique injury observed on some fish passed through a new 5 bladed turbine at Manitoba Hydro's Kelsey Generating Station attributed to leading edge of blades being thin**

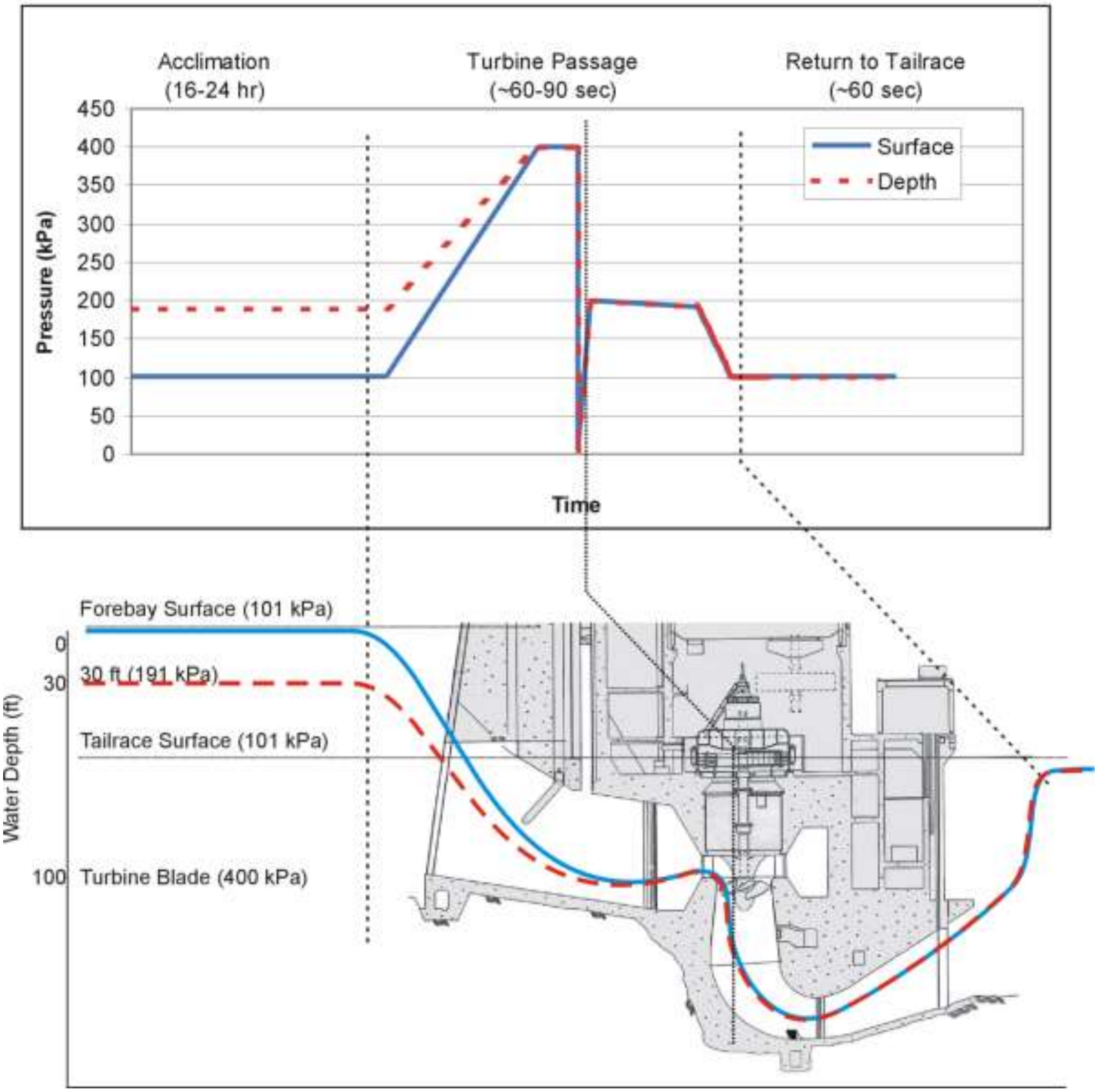

Figure 3: **Laboratory simulated Surface (101 kPa) and 30 ft depth (191 kPa) acclimation and pressure profile for a fish passing a conventional Kaplan turbine. Pressure increases as the fish's depth increases. Pressure spike occurs as fish pass the turbine blades. Pressures then return to surface pressure as fish pass through the draft tube and enter the tailrace. (Source: Abernethy *et al.* 2001)**

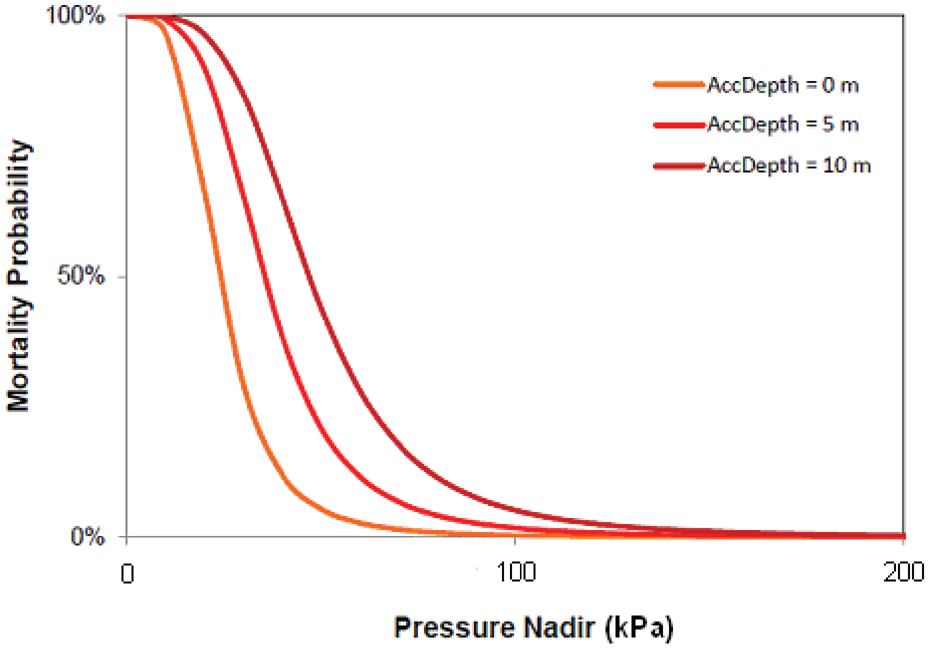

Figure 4: **Relationship between barotrauma induced mortality at depth fish are acclimated to when exposed to sudden decrease in pressure (Source: Brown *et al*. 2009)**

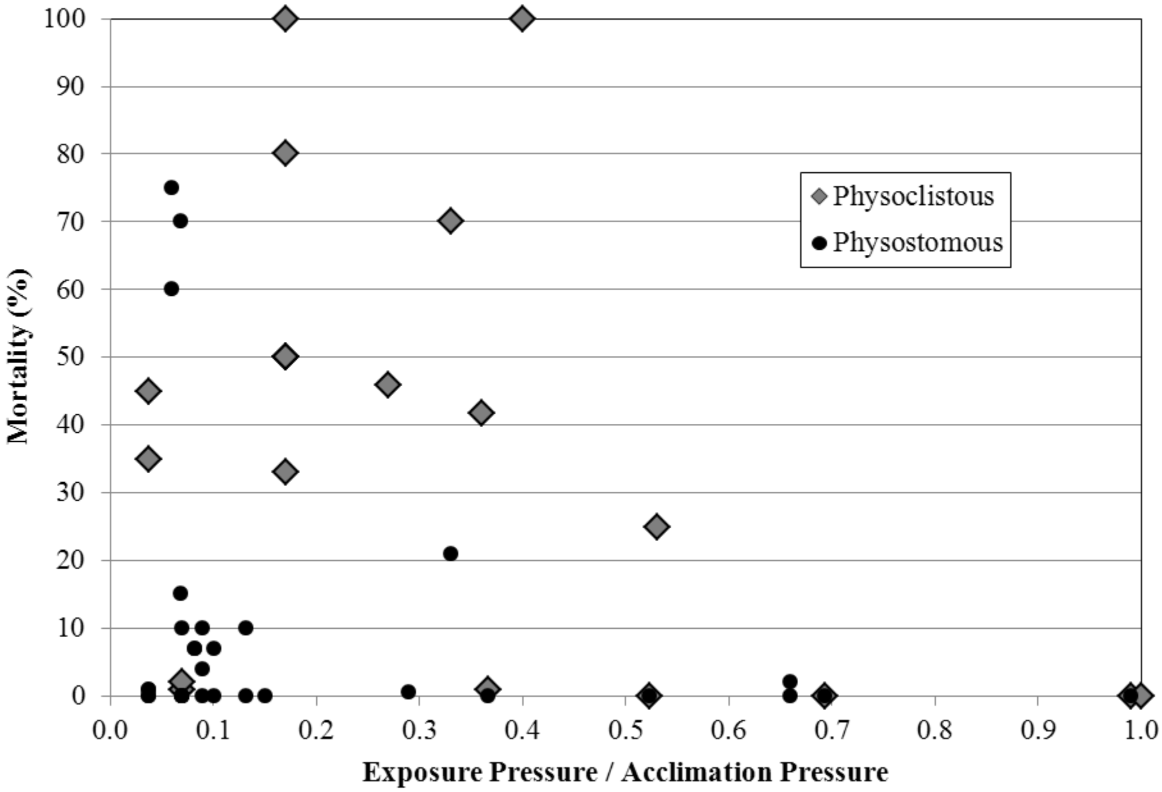

Figure 5: **Graphic representation of fish mortalities following exposure to brief and rapid pressure reductions in laboratory test chambers**

ATTACHMENT 2: TRASH RACK SPACING AND EFFECTS TO FISH

Introduction

Although trash racks are primarily installed to hold back large debris and ice, they can also act as behavioural and mechanical barriers for fish. Temporary and permanent impingement of fish on the racks is possible. Mainly for these reason trash racks are often perceived by operators of hydroelectric generating stations as mechanical barriers for fish of species of domestic, commercial, or regulatory importance. However, the degree to which trash racks can become a fish hazard or exclusion device varies considerably between trash rack design (mainly bar spacing), fish species and local site conditions (Hadderingh and Bakker 1998; Odeh and Orvis 1998). The current design clear bar spacing for the proposed Keeyask GS is 16.75 cm (KGS ACRES Ltd. 2011).

The following sections establish the primary species and size classes of fish to be considered in an ecological evaluation of trash racks at the Keeyask GS and provide information on fish swimming behaviour and performance relevant to trash rack encounter, the likelihood and consequences of fish impingement, and the use of trash racks for fish exclusion and guidance.

Fish Species and Size

Thirty-seven fish species have been recorded from aquatic habitats close to the proposed Keeyask GS. However, only 17 species are regularly captured within the mainstem of the Nelson River and contribute notably to the fish community in terms of either numbers or biomass (AE SV). All fish species are vulnerable to entrainment but the relative frequencies and magnitudes of entrainment will be largely species specific and be affected by factors such as habitat use, life stage, spawning season, and swimming capacity. For example, extrapolating from drift net catches of ten to hundreds of thousand fish over approximately two- to four-week long periods in early summer and that sampled only a very small portion of the Nelson River cross-sectional area (Pisiak 2005; Bretecher *et al.* 2007; MacDonald 2007), it can be assumed that millions of fish pass downstream over Gull Rapids annually. However, the vast majority of these fish are larvae and juveniles of catostomids (likely white sucker) and, less so, freshwater drum, sculpins, rainbow smelt, emerald shiner, and trout-perch. Downstream movements over Gull Rapids of adults of large bodied species such as lake whitefish, northern pike, walleye, and lake sturgeon have been confirmed in tagging and telemetry studies (AE SV), but this type of data are of limited use for assessing the potential frequencies of entrainment into a powerhouse flow. Qualitative data on fish entrainment frequencies are available from another GS in the Manitoba Hydro system. Based on the results of recent studies applying detection and imaging (*i.e.*, DIDSON) sonar technologies at Manitoba Hydro's Great Falls GS on the Winnipeg River (North/South Consultants Inc. [NSC] *et al.* 2012, 2011; Murray 2012), entrainment rates during summer and early fall were in the order of a few thousands of fish per day, with the vast majority (80%) consisting of fish <15 cm estimated total length[1].

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[1] The trash racks at Great Falls GS are positioned downstream of the turbine intake gates, have 14.0 cm bar spacing (Malenchak *pers. comm.* 2011) and water velocities immediately upstream of the racks range from 0.73–1.03 m/s (Backhouse and Malenchak *pers. comm.* 2011). Except for lake whitefish, the fish species at Great Falls comprised all target species of the Keeyask Project and most of the other species known to occur in the lower Nelson River.

Species identification is difficult with hydroacoustic techniques. By incorporating independent data on the species composition in the Great Falls Forebay during the time of sonar monitoring, NSC *et al.* (2012) suggested that the fish species most susceptible to entrainment were yellow perch, emerald shiner, and walleye or sauger. Because of physical design requirements it is unlikely that trash rack bar spacing can be reduced to physically exclude small bodied (*i.e.*, <15 cm total length) species from passing the racks. Therefore, fish impingement and exclusion will mainly be an issue for the large-bodied species.

In addition to mainly biological parameters, such as the likelihood and frequency of entrainment into the powerhouse flow, other criteria are important when deciding on which species should be considered as the main drivers for trash rack design criteria for the Keeyask GS. Four species (lake sturgeon, lake whitefish, northern pike, and walleye) have been identified as Valued Environmental Components (AE SV). These species were selected as target species for the evaluation of trash racks because of their ecological importance, representation of different fish passage (*i.e.*, swimming performance and behaviour) guilds, and because they are of particular relevance to resource users and regulators. It can be assumed that an assessment of trash rack design options for the target species will also be directly applicable to several other species such as suckers (Catostomidae), yellow perch, sauger, and mooneye.

Except for lake sturgeon, (male) individuals of the other target species first recruit into the spawning population at a length of approximately 200 mm. This length also represents a size of fish that pass through hydroelectric GSs in numbers that can be feasibly monitored by imaging sonar (Murray 2012). For these reasons, a fork length of 200 mm will also be used as the lower bound of the fish size range for the current evaluation. The upper bound is represented by the maximum length expected for the target species in the Keeyask area. These lengths are 170 cm for lake sturgeon, 110 cm for northern pike, 70 cm for walleye, and 60 cm for lake whitefish.

Swimming Behaviour and Performance of Target Fish Species

Two main aspects of fish swimming are relevant when assessing trash rack design in view of fish protection: fish behaviour and fish swimming performance. Behaviour includes the vertical and horizontal position of fish in the water column and their response to sudden changes in water velocity and turbulence, whereas swimming performance refers to a fish's ability to swim against water currents of various velocities.

Swimming Behaviour

Little information exists on the fine-scale behaviour in forebays and near hydroelectric dams of potamodromous fish (*i.e.*, species that migrate entirely within freshwater environments), including the five target species.

The location of a fish in the forebay water column is important for trash rack encounter and dam passage. Coutant and Whitney (2000) have argued that "non-migratory" fish are entrained accidentally, and the likelihood of such events is related to the degree to which these fish use habitats closest to the powerhouse. The powerhouse intake channel at the Keeyask GS is designed for equal flow distribution parallel to the walls of the channel and minimal surface roughness, resulting in approximately equal discharge into each turbine bay. These engineering design criteria translate into a generally structureless, relative high velocity, deep water environment. Because of the consequent lack of, for example, fine sediments and other attractive substrates for invertebrate filterers and grazers, physical shelter, still water resting areas, and visual orientation, the intake channel will not provide suitable habitat for most fish species. Nevertheless, some fish may enter the intake channel due to migratory behaviour or density dependent movements. Larger fish motivated to migrate downstream may initially be deterred by the flow conditions near the trash racks, will search for alternative passage routes, potentially returning to the trash racks repeatedly. Based on the results of the studies at Manitoba Hydro's Great Falls GS on the Winnipeg River (NSC *et al.* 2011, 2012; Murray 2012), entrainment rates during summer and early fall are in the order of a few thousand fish per day, with less than 10% consisting of fish >20 cm estimated total length.

There is evidence that the spatial distribution of larger-bodied potamodromous species moving towards and through hydroelectric plants differs from the surface oriented pattern for downstream moving salmonid smolts. These differences may be partially related to the fact that downstream migration behaviour, including swimming depth, may change during fish ontogeny. For example, Michaud and Taft (2000) found that "small" fish approached the dam of a Wisconsin hydroelectric GS in the surface (<0.5 m depth) waters. Furthermore, walleye larvae mainly drifted in the upper portion of the water column of some small (Franzin and Harbicht 1992) and mid-size (D'Amours *et al.* 2001) Canadian streams. In contrast, the vertical distribution of older walleye does not seem to follow a distinct pattern. Summarizing the results from a review of 45 turbine entrainment monitoring studies at small hydropower sites in the eastern USA dominated by non-salmonid species, Coutant and Whitney (2000) state that the vertical distribution of adult fish, including walleye, yellow perch, and white sucker was rather uniform throughout the water column near the turbine intakes. Similar, although not species-specific results were obtained from a hydroacoustic study at Manitoba Hydro's Great Falls GS on the Winnipeg River that included most species relevant to the Keeyask Project. Although water depths of <4 m could not be assessed and some minor differences existed in the percentage of fish passage at 1-m depth intervals (starting at 4 m depth) in front of the six intake gates, the vertical distribution of fish at each unit (excluding one unit with debris accumulation problems) was quite uniform, with a mean passage depth of 8-10 m (NSC *et al.* 2011, 2012).

Further, indirect support for a relatively uniform depth distribution of older individuals of some of the Keeyask target species during their approach of trash racks comes from telemetry studies on the vertical distribution of fish in forebays and large rivers. Lahti (2003) found pikeperch (*Sander lucioperca*), the Eurasian ecological equivalent of walleye, to use a large range in water depth (1.2–30.8 m) in a Finnish hydroelectric reservoir during the summer. However, the vertical distribution of pikeperch differed seasonally with water temperature and between the sexes, indicating that particularly female fish moved from surface waters into deeper, colder (<10ºC) water in late July. Northern pike are often considered to be surface-orientated, preferring shallow vegetated areas in lakes, although habitat selection can be more versatile (Casselman and Lewis 1996). One of the few studies of pike movements in a large regulated river (up to 19.5 m deep) confirms that pike generally occupy relatively shallow water (<5 m), but that some individuals are regularly found at larger depths (Vehanen *et al.* 2006).

The vertical distribution of lakes sturgeon likely differs from the other target species in that individuals spend most of their time on or near the bottom (*e.g.*, Barth *et al.* 2009). This spatial habitat preference suggests that lake sturgeon will likely approach turbine intakes low in the water column.

In contrast to the lack of a clear vertical distribution pattern, Coutant and Whitney (2000) reported distinct horizontal patterns in fish distribution, indicating that many species, including walleye, yellow perch, and white sucker approach power stations mainly along the shoreline or other physical structures. This hypothesis is supported by data from Johnson *et al.* (1989) showing that fish approached the dam at the Vanceburg GS (three bulb units, 329 cms flow each) on the Ohio River mainly from one shore and that the turbine unit closest to this shore consistently entrained the largest number of fish (43%). These authors also found that between 83% (spring) to 96% (summer) of the fish detected by hydroacoustics immediately in front of the trash racks were actually entrained through the turbines (based on Fyke net captures in front of the turbine). However, only 0.3% of the entrained fish were larger game fish (sauger, channel catfish, white bass [*Morone chrysops*]), whereas 8% and 9% of the approximately 4,200 fish captured by gillnetting and electrofishing in the forebay were sauger and white bass, respectively (Johnson *et al.* 1989).

The hydroacoustic studies at the Great Falls GS on the Winnipeg River also have documented substantial differences in fish entrainment among turbine units, indicative of shore-biased fish approach trajectories (NSC *et al.* 2012, 2011). However, this bias was not entirely consistent between the two study years and may have been affected by station operations. In 2012, Unit 6 closest to the north shore had the second highest discharge of all units over the study period and entrained more fish than the other five units combined. In 2011, when the discharge through Unit 6 was near average, Units 1 and 2 closest to the south shore entrained almost half of all fish.

Slower (0.1–0.4 m/s) than maximum surface and depth-averaged (0.6–0.7 m/s) intake channel water velocities are expected to exist near the shorelines south and, particularly north of the channel upstream of the Kelsey powerhouse and near the bottom of the channel as it slopes down to a depth of approximately 32 m and before it forms a 50 m long, 3 m deep rock trap below the turbine intakes. Thus, it can be expected that most fish volitionally approaching the powerhouse area will primarily be moving within the relatively slow near-shore or bottom currents.

Swimming Performance

Fish approaching trash racks at turbine gates experience an accelerating flow field. For the proposed configuration of the Keeyask powerhouse and intake channel and with the reservoir at full supply level, surface (0.5 m depth) water velocities within the intake channel will increase from 0.56–0.69 m/s to a maximum of 1.25 m/s over the last approximately 15 m upstream of the trash racks. The average flow velocity through the trash racks of each unit ranges from 1.14–1.25 m/s over most of its height, with lower velocities near the bottom. Fish entrained into the flow immediately upstream of the trash racks, including impingement on the trash racks must be able to swim against such velocities long enough to first escape the steep velocity gradient followed by a section of the steady, fast flowing areas of the intake channel until they reach areas where maintaining position poses no problem and they can repay the oxygen debt (*i.e.*, reduce elevated blood and tissue concentrations of anaerobic pathways metabolites; Brett 1964; Beamish 1978) accumulated during burst swimming (see below).

The swimming performance or ability of fish has been categorized into three main types (Beamish 1978):

- Sustained swimming speed: occurs at relatively low velocities and can be maintained for long periods (>200 min) using energy derived from aerobic processes only without resulting in muscular fatigue;
- Burst swimming speed: highest speed of which a fish is capable; the speed can be maintained for a short time (<20 seconds) and is fuelled by energy derived entirely from anaerobic processes; and
- Prolonged swimming speed: covers the spectrum between sustained and burst speed and ends in fatigue.

Because swimming speeds of fish in the wild are difficult to measure and fatigue can rarely be assessed, swim chambers have been developed in which fish are forced to swim in a small tube against uniform current velocities (see reviews in Beamish 1978; Castro-Santos and Haro 2010). One of the key metrics of swimming capacity developed in conjunction with the swimming chambers is the so-called critical swimming speed (CSS), measured by gradually increasing current speeds by approximately 10 cm/s every 60 minutes until the fish fatigue (Brett 1964). Originally designed to measure sustained speed, the time step has subsequently been reduced and CSS should be considered a comparative performance index (Castros-Santos and Haro 2010) or a special category of prolonged swimming. The following section summarizes literature data on the swimming performance of the Keeyask target species (TL= total length; FL= fork length).

Lake Sturgeon

- Information on lake sturgeon swimming performance has mainly been generated from hatchery-reared fish, which likely have lesser swimming ability.
- CSS range from 0.39 m/s at 15°C for juveniles of 15.7 cm mean TL (Webb 1986) to 0.97 m/s at 14°C for fish >120 cm TL (Peake *et al.* 1997).
- Burst speeds have been measured at 0.9 m/s for fish of 23–55 cm TL and at 1.8 m/s for fish 106-132 cm TL (Peake *et al.* 1997; the test temperature was 14°C).
- Maximum sustained speeds of fish of 23–55 cm TL increased from 0.12 m/s at 7°C to 0.26 m/s at 21°C (Peake *et al.* 1997). The temperature effect decreased with increased swimming speeds, such that burst speeds were almost independent of temperature.
- Exercised fish (108 cm mean TL) of hatchery origin volitionally ascended a 38 m long experimental fishway at mean speeds of 1.9–2.4 m/s (range 0.94–3.3 m/s) without an obvious effect of temperature in the range of 11.4–20.6°C (Kynard *et al.* 2011).

Lake Whitefish

- Only one study on lake whitefish swimming performance could be located, no information on burst speeds is available.
- Bernatchez and Dobson (1985) measured CSS of 0.63–0.75 m/s at 5–17°C for fish of 10–39 cm TL.
- Lake whitefish morphology and muscle structure is indicative of relatively strong swimming capabilities, at least compared to non-salmonid species; this species is known to pass rapids of a

length and mean current speed either too long or too high for passage based on critical swimming speeds (Bernatchez and Dobson 1985).

Northern Pike

- Based on regression equations published in Jones *et al.* (1974) CSS of fish of 12–62 cm FL can be calculated as 0.19–0.47 m/s; the test temperature was 12°C.
- Burst speeds (<1 s) of 2.8–3.4 m/s for fish with a mean FL of 41.2 cm and at water temperatures between 8–12ºC (Frith and Blake 1995).

Walleye

- Based on regression equations published in Jones *et al.* (1974) CSS of fish of 8 – 38 cm FL can be calculated as 0.38–0.84 m/s; the test temperature was 19°C.
- Peake *et al.* (2000) measured burst speeds of 1.6–2.6 m/s for fish of 8–67 cm FL at temperatures of 6–21ºC.
- Fish of approximately 32 cm FL could maintain burst speeds of up to 4.0 m/s for approximately 11 seconds (Castro-Santos 2005).

The above values from swimming performance tests do not necessarily reflect the true swimming capacity of the target species. Swimming speeds obtained in forced performance tests inside of small laboratory swimming chamber do not adequately represent the performance of unrestricted fish in the wild, because the laboratory tests limit the range of potential swimming behaviours (*e.g.*, Tudorache *et al.* 2007, 2010). Therefore it is not surprising that free-swimming fish allowed to enter the swimming test arena within large flumes volitionally, consistently exhibit swimming speeds and stamina well in excess of those confined to a chamber and subjected to artificial stimulation (Haro *et al.* 2004; Peake 2004a; 2008; Castro-Santos 2005; see last bullet for walleye).

It should also be noted that most swimming performance tests are conducted at temperatures known to be near the performance optimum for the species. Fish swimming capacity can be compromised at suboptimal temperatures, as has been shown for lake whitefish (Bernatchez and Dodson 1985) and lake sturgeon (Kynard *et al.* 2003). It can be assumed that adults of the target species mainly move, and potentially encounter the trash racks during times when water temperatures will not substantially affect their swimming capacity.

In summary, current speeds that are expected to exist at and near the Keeyask trash racks are unlikely to impose velocity barriers or traps for healthy, adult fish of the target species, particularly considering the likely bottom oriented approach of the relatively weaker swimmer, lake sturgeon.

Fish Exclusion by Trash Racks

Trash racks can also act as behavioural barriers to fish. Trash rack bar dimensions, spacing, and orientation affect water flow characteristics (Katopodis *et al.* 2011) which in turn cause fish behavioural responses as has been demonstrated in laboratory experiments (Hanson and Li 1983; Floyd *et al.* 2007; Enders *et al.* 2009; Russon *et al.* 2010; Silva *et al.* 2011). However, information relevant to realistic flow-conditions found at hydroelectric GS is lacking or speculative (McKinstry *et al.* 2005; Jansen *et al.* 2007). Altered behaviours, such as changes in head-tail orientation (Hanson and Li 1983), aggregation (Floyd *et al.* 2007), searching and upstream escapement (Calles *et al.* 2010) may lead to migratory delays or render fish more vulnerable to predation (Neitzel *et al.* 1990, cited in Baumgartner 2005), but will not permanently exclude motivated fish from moving downstream. However, if these fish are physically unable to pass the openings between the bars, they will be excluded from moving into the turbine flow or, if no alternative passage route exists, from moving downstream of the GS.

A recent study by Dale Wrubleski (Research Scientist, Wetlands Institute for Wetland and Waterfowl Research, Ducks Unlimited Canada) who monitored the movement of fish trying to enter Delta Marsh (Lake Manitoba) provides relationships of body length to body width for some target species. These length-width relationships are presented in Table 1.

From the data provided in Table 1 it is apparent that, based on physical dimensions alone, none of the target species except lake sturgeon grow to a size that would result in their physical exclusion during a head on approach of the Keeyask trash racks. Up to 5% of the number of adult lake sturgeon captured in large mesh gill nets in the Keeyask area would be physically excluded by a 16.75 cm clear bar spacing. However, a clear spacing of as small as 11 cm would not exclude even the largest individuals of the other four target species from the turbine flow.

Assuming that most fish approach the racks from a position close to the shore and/or will exhibit a behavioural avoidance response to the accelerating flow field within the immediate area in front of the racks, they may not face the bars head on but at an oblique angle. In that case or if adult individuals of the target species are unable to maintain rheotactic orientation immediately in front of the trash rack, they could suffer lateral impingement. Considering the prevailing water velocities at the trash racks and the swimming capacities of the target species, permanent lateral impingement is unlikely to occur.

Fish Impingement on Trash Racks

Three alternative outcomes have been documented for fish approaching trash racks: upstream escapement, passage through the racks, and impingement on the racks (Calles *et al.* 2010). For fish motivated to migrate downstream such as European eel (*Anguilla anguilla*), escapement often is not permanent and at a Swedish hydroelectric GS approximately half of the initial escapees died as a result of impingement at the last attempt (Calles *et al.* 2010). The degree to which trash racks can become a fish hazard varies considerably between rack design (mainly bar spacing), fish species and local site conditions (Hadderingh and Bakker 1998; Odeh and Orvis 1998). Based on their swimming capacity and physical dimensions relative to the trash rack openings it is unlikely that individuals of the target (or any other) species will become permanently impinged on the Keeyask trash racks at the currently proposed rack spacing of 16.75 cm. However, because trash rack spacing may be subject to review and because impingement can represent a source of fish mortality at hydroelectric GSs (Calles *et al.* 2010), fish impingement and its consequences will be briefly discussed.

There exists little data regarding water velocities that cause injury/mortality to fish due to impingement on trash racks (and similar physical barriers), or for minimum speeds required for fish to swim off such structures. Furthermore, most of the few existing studies are on small-bodied fish, species not present at

Keeyask, or juveniles of species considered useful surrogates of target species. For example, a narrative account of early (1952) laboratory experiments by Montén (1964) indicates that 5 cm-long European minnows (*Phoxinus* sp.) were trapped against a metal mesh screen (no dimensions given) at current speeds of 0.8 m/s. Current had to be reduced to 0.3 m/s for these fish to swim off the screen, and fish pressed against the screen for ~2 min at velocities of 1.8 m/s suffered serious gill injuries (Montén 1964). Peake (2004b) examined the ability of juvenile (3–7 cm fork length) northern pike to avoid impingement on irrigation intake screens. Pike never became impinged on screens (mesh size 0.25 cm^2) at approach velocities of 0.15 m/s or less, impingement observed at 0.25 m/s did not result in injuries or mortality, and velocities of >0.35 m/s resulted in injury or death of at least 10% of the individuals. In laboratory experiments that primarily evaluated the efficiency of a bottom bypass in passing shortnose sturgeon (*Acipenser brevirostris*) past a trash rack with 5.1 cm spacing, Hogan *et al.* (2008) demonstrated that 1 year-old fish were able to maintain swimming after contact with the rack at approach velocities of up to 0.61 m/s. A laboratory study specifically designed to evaluate the response of adult European eel to bar racks (1.2 cm spacing), indicated that eels did not show avoidance behaviour prior to encountering the racks and reacted only after physical contact with the racks (Russon *et al.* 2010). These authors also found that eels did not get impinged or passed through vertical racks angled relative to the flow and leading to a bypass, whereas impingement and passage was frequent for horizontally inclined racks facing the flow and without a bypass. Frequency of impingement was higher under low discharge (0.13 m^3/s) while passage through the upright rack was common under high discharge (0.28 m^3/s), and impinged eels could swim off the rack at water velocities of 0.9 m/s (Russon *et al.* 2010). A companion telemetry study at a hydroelectric GS (turbine discharge of approximately 65 m^3/s) found that tagged eels could escape upstream from approach velocities at the trash racks (2.0 cm clear bar spacing) of 0.87–1.04 m/s, but that all fish (19 out of 35 attempting passage) that became impinged, died (Calles *et al.* 2010). Substantial impingement mortality was further indicated by the more than 240 untagged eels that were retrieved from the trash racks during the four-week long study.

Conclusions

The currently proposed 16.75 cm clear bar spacing of the Keeyask trash racks will likely not prevent or interfere with the downstream movement of the vast majority of fish approaching the racks. Depending on their approach trajectory and orientation, some of the largest fish of the target species may get initially impinged on the racks. Most of these fish should have the capacity to swim off the racks and move upstream. Some of the impinged fish, particularly if their swimming capacity is compromised may be pushed through the bar spaces by the current when trying to move off the rack. A few fish may not be able to swim off the racks and, consequently, suffer severe injuries resulting in death. As a large proportion of the fish that may get impinged on the trash racks can expected to be mature individuals actively moving downstream, these fish likely make repeated attempts at passing the Keeyask GS. A reduction of the currently proposed bar spacing may result in a reduction in the numbers of fish closely approaching the bar racks (increased behavioural exclusion) and an increase in both the number/proportion of fish being unable to swim off the rack after initial impingement and becoming permanently impinged on the racks or forced through the racks (increased mechanical exclusion, potential increase in approach velocities). Overall, less fish will likely be entrained into the turbine flow than under the currently planned bar spacing. Due to the lack of baseline data, suspected non-linear relationships between, for example, bar spacing and impingement rate, the relative frequencies of the different outcomes of trash rack encounter are difficult to predict. For example, there is evidence that trash rack spacing close to the mean body width of individuals of a target species/population results in high impingement mortality (Calles *et al.* 2010). When trying to evaluate design options for a hydroelectric GS to minimize fish mortality, individual passage routes should not be considered in isolation, but potential rates of injury and mortality have to be compared for each passage route including exclusion and bypass devises, to guide decisions on which option(s) will provide the best solution for a specific location.

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Table 1: **Regression equation, coefficient of determination (r^2), number of fish, and length range of fish for the relationship between fork length (Lth) and body width (Wd) for target species. Max Lth represents the (theoretical) maximum length of a fish expected to fit through a clear bar spacing of 16.75 cm**

Species	Regression equation	r^2	n	Lth range (mm)	Max Lth (mm)	Source
Cisco	Wd = -7.432 + 0.127 Lth	0.76	59	185–300	1375	Wrubleski *pers. comm.* 2010
Northern pike	Wd = -7.392 + 0.105 Lth	0.91	211	230–815	1665	Wrubleski *pers. comm.* 2010
Walleye	Wd = -18.55 + 0.179 Lth	0.83	76	298–740	1040	Wrubleski *pers. comm.* 2010
White sturgeon	$Wd = (0.2765\ Lth^{1.07})/\pi$	-	-	-	1350	Jager (2006)