Whooshh Fish Transport System

Compilation of Whooshh studies through 2017

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Introduction

Whooshh Innovations is an innovative engineering company focused on addressing the challenge of fish passage. Traditional fish passage solutions are costly, requiring years to install, and in the end, are only minimally adaptable and often do not provide adequate passage for all fish species found in a waterway. Given the obstacles, new, cost-efficient, modular and adaptable fish passage options are needed. The Whooshh fish passage system was designed using novel, innovative ecotechnology to allow autonomous, selective, volitional upstream fish passage over low and high head dams. The technology provides fish passage through the application of air pressure differentials to glide the fish rapidly through a soft, flexible tube, with controlled deceleration and smooth exit. This provides safe, timely, efficient and effective fish transport through the near-frictionless, soft flexible tubes using a light water mist which lubricates the tube and maintains fish gill hydration. Upon exiting a tube, the fish then swim on continuing their migration unharmed with no negative passage-related impact. The Whooshh Fish Transport System (WFTS) facilitates passage of all targeted species of adult fish through size-appropriate Whooshh tubes. The scanning/sorting capabilities of the system seamlessly assess the fish dimensions and apply tube size-sorting decisions in real-time without handling, detaining or delaying the fish as it slides through the system. The Whooshh system has emerged as a rapidly deployable, adaptable and superior technology that differentiates itself by promising to be the only modular, cost-effective fish passage solution that does not require large amounts of water, labor, or capital to meet or exceed regulatory fish passage requirements. The WFTS is intended to move fish at dams, hatcheries, farm sites, and processing plants.

The adaptable, flexible nature of the WFTS extends its versatility to various fish passage applications and locations. The complete WFTS allows for migratory species of fish to volitionally enter the system, eliminating fish handling and associated passage delay (Fast, Johnson, Bosch, & Bryan, 2017; Hansen, 2015; NWTT, 2015; Whooshh, 2015a, 2016d). An alternate WFTS model has been designed to accommodate hand-loading the fish into the system, an attribute often desired in hatchery and rescue scenarios (Earthfixmedia, 2014; Whooshh, 2014b, 2014c, 2015b). The Whooshh system can be used to pass fish over a barrier or dam and directly back into the river, or to augment trap and haul and bypass channel practices by transporting fish from a river or trap into a hatchery truck or raceway. The tube length is custom fitted to the location needs and the tube diameter fitted to the size of the species to be transported. The modular capabilities of the system ensure a straightforward path to system expansion, addressing design needs for multiple tubes to accommodate a larger range of fish sizes and(or) to increase the throughput of fish passing through the system. With the addition of the scanning/sorting components, the WFTS has the added potential to be used to selectively pass only targeted species while preventing passage of invasive species.

How it Works

The WFTS utilizes a patented pneumatic technology platform that takes advantage of pressure differentials to rapidly, directionally, move objects gently over distance. The pressure differential introduced creates a motive force that push/pulls objects from a higher-pressure region to a lower pressure region. Unlike traditional upstream fish passage solutions which are water-based and thus limited by the weight of water and high pressure, this system uses very minimal amounts of water in the form of a mist to mildly lubricate the flexible, smooth, near-frictionless tube providing the fish a comfortable differential air-pressure driven glide (Whooshh, 2018). The Whooshh system is *linear;* it can move multiple objects in line one at a time, it is *asymmetric;* it can move objects of differing size and shape, it is *atraumatic*; it moves objects gently so as not to injure or damage, and this is accomplished via passage through a flexible tube at high speed such that objects are propelled at a controlled but rapid rate. The physics of movement through the system involves forces on a single fish (friction, gravity and pressure drop) independent of height or length. Thus, the Whooshh fish passage system is an innovative technology that is well-suited to address the challenges of low and high-head dam fish passage. Smart engineering and materials together with well-designed modular components are additional areas of innovation which enable versatility, limit the environmental footprint and provide time and economic savings in installation and operation.

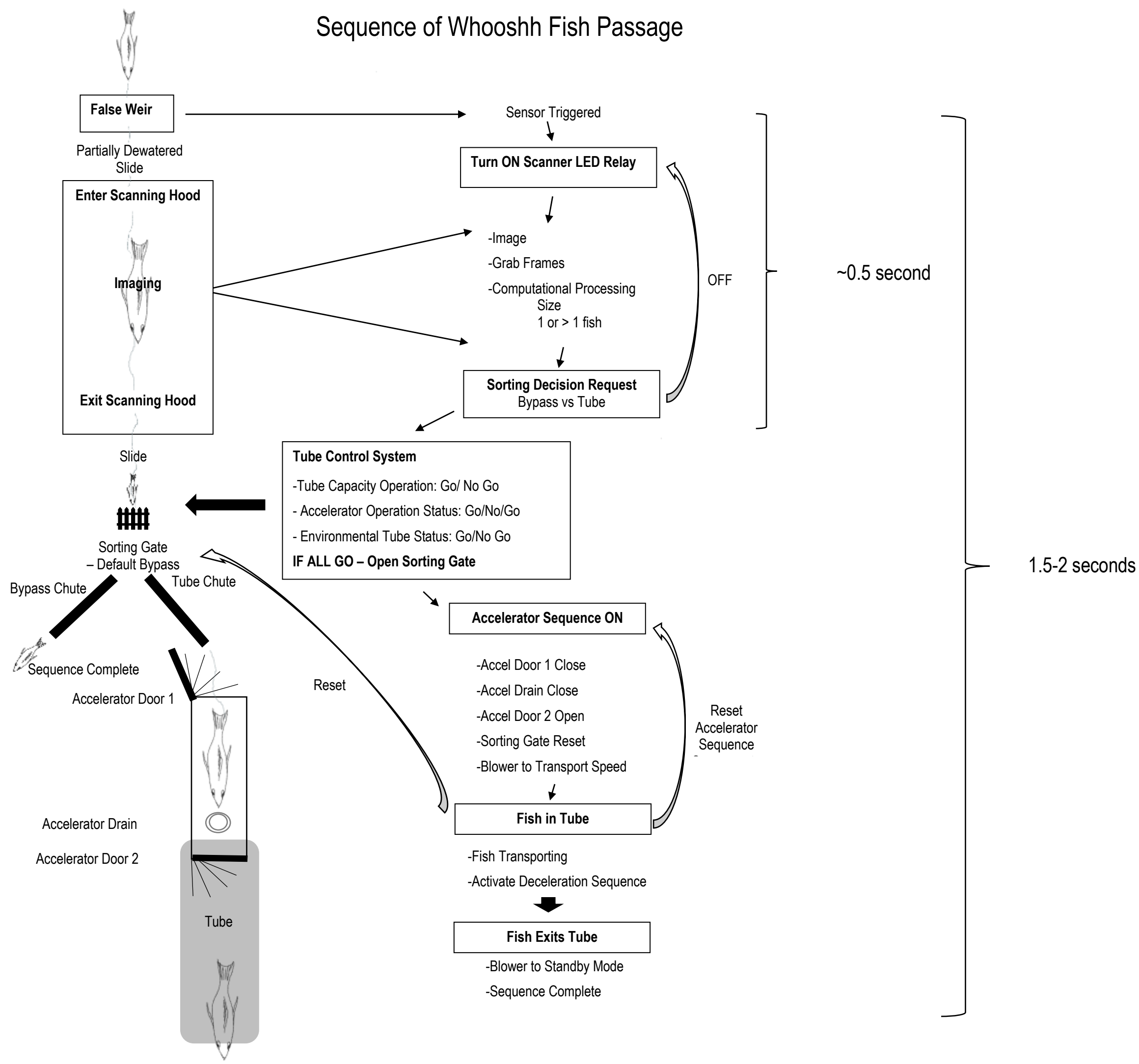

Figure 1. Sequence of Whooshh Fish Passage from entry over the false weir to the glide through the Whooshh tube.

WFTS Evaluations: Species and Distances

Multiple studies have been conducted to evaluate efficiency, mechanisms, versatility, and performance of the Whooshh fish passage system (Appendix A). A range of species have been successfully transported including: fall and spring Chinook, Tule Chinook, Sockeye, Pink and Coho salmon, Rainbow trout, Steelhead, Sturgeon, Atlantic salmon, Gizzard shad, Largemouth bass, Northern pike, Common white sucker, Longnose sucker, Walleye and American shad (Amaral, Grant, Dearden, Pyatskowit, & Jacobson, 2016; Mesa, Gee, Weiland, & Christansen, 2013; Miehls, Zielinski, Hrodey, Dearden, & Johnson, 2017; NWTT, 2015; Stette, 2014; Summerfelt, May, Crouse, McKnight, & Bryan, 2015; Whooshh, 2014a, 2014b, 2014c, 2015a, 2016b). These studies have provided evidence of successful live fish transport through the WFTS with tube distances ranging from a short ~40 ft tube to a long tube of 1,100 and an installation of multiple tubes placed in series to achieve a transport distance of 1700 ft. In addition, tube transport has been evaluated at various distances including tubes of 100, 250, and 500 ft length (Table 1). The WFTS has been deployed in locations requiring relatively horizontal transport as well as locations requiring passage with a vertical rise of up to 180 ft (Fast et al., 2017; Geist, Colotelo, Linley, Wagner, & Miracle, 2016; Whooshh, 2014a, 2016a). As discussed, the physics of movement through the WFTS is independent of a specific site required height or length. Thus, the only defining limitation of height or length is that of the dam structure itself. The WFTS has transported live species from water level on rivers, up their embankments, over and across hatchery raceways, up and over both earthen and concrete dam structures, and in processing plant applications. WFTS has transported gutted fish across processing plant ceilings, around corners and through limited open spaces in walls and tunnels (Fryer, 2017; Hansen, 2015; HDR Engineering, 2017; NWTT, 2015; Stette, 2014; Whooshh, 2016a, 2016c).

Table 1. Selected examples of fish species, distances and WFTS mean passage times.

Live Species	Tube	Distance	Height	Mean Time
Chinook n=294[1]	T147	40 ft	8 ft	3 sec
Pinks n=500[2]	T123	80 ft	30 ft	2-3 sec
Atlantics n=40[3]	T195	100 ft	<6 ft	6 sec
Chinook n=289[4]	T185*	100 ft	10 ft	5 sec
Sockeye n=797[5]	T123	100 ft	6 ft	5 sec
Tule Chinook n=52,000[6]	T195	120 ft	25 ft	6 sec
Sockeye n=54[5]	T123	140 ft	40 ft	8 sec
Amer. Shad n=41[7]	T123	175 ft	30 ft	10 sec
Chinook n=39[4]	T195	250 ft	<6 ft	13 sec
Steelhead n=18[4]	T147	250 ft	<6 ft	13 sec
Atlantics n=1000[8]	T195	459 ft	25 ft	16 sec
Chinook n=58[1]	T147	1100 ft	100 ft	35 sec
Sockeye n=126[9]	T123	1700 ft	180 ft	57 sec

*Modified 195

[1] YN &USBR, [2] PIT, [3] SINTEF, [4] PNNL, [5] CRITFC, [6] WDFW (WA), [7] Brookfield, HDR (ME), [8] Grieg Seafood (Norway), [9] YN, USBR & USGS

Recently key thought leaders have begun raising questions as to the nature, utility, or lack thereof, of the current standards and means of evaluating fish passage installations (Castro-Santos, Cotel, & Webb, 2009; Castro-Santos & Haro, 2010; Cooke & Hinch, 2013; Roscoe & Hinch, 2010; Silva et al., 2017). Roscoe et al., reviewed all published fish passage effectiveness monitoring studies from 1960-2008. Remarkably, in nearly 50 years, only 96 peer-reviewed articles have been published on the topic. The number alone highlights the need to take a better look at fish passage effectiveness monitoring and to redefine what the critical fish passage evaluations should be. They should include meaningful assessments that characterize the impact of fish passage systems in terms of the sustainability of fish species and river ecosystem connectivity broadly categorized in evaluations of efficiency, mechanism, consequences, and physiology (Roscoe & Hinch, 2010).

WFTS Studies

Since its inception in 2011, Whooshh Innovations has collaborated with state and federal government agencies, US national laboratories, tribal nations, academic institutions, conservation groups, public utility districts, hydropower energy companies and private industries to further advance engineering ecotechnology and the science of upstream fish passage. In addition, these collaborators have contributed to studies designed as comparative evaluations of the biological consequences of fish passage through the WFTS verses passage through conventional fish passage approaches. To date, eighteen studies have been performed (Figure 2), three have been published in peer review journals (Geist et al., 2016; Mesa et al., 2013; Summerfelt et al., 2015), one additional manuscript is anticipated from a recent study, and the outcomes of other studies have been presented at conferences (Amaral et al., 2016; Fast et al., 2017) and(or) are available as Open Access reports drafted by independent third parties and government agencies (Erikson, Tveit, & Schei, 2016; Fryer, 2017; HDR Engineering, 2017; Kock et al., 2018). Links to these, along with links to internal summary reports and videos, are available on the Whooshh web page (https://www.whooshh.com/studies.html).

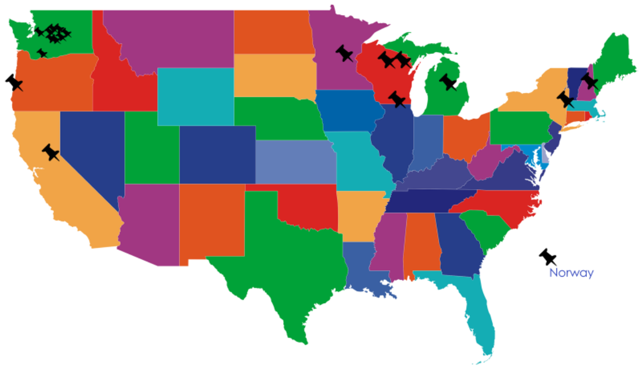

Figure 2. Pinpoints indicate approximate locations of collaborative fish passage studies and demonstrations performed with various partners. The studies have evaluated the performance of WFTS and consequences to fish. More than 15 different fish species have been used in WFTS studies.

Survival: Short-term

The scope of these studies has addressed the National Maine Fisheries Service (NMFS) named areas of interest with respect to fish passage system performance evaluation: Survival, Migration, Passage Delay, Egg Viability, Injury, Homing, Disease Transmission, Behavior, and Durability through passage studies involving a range of species. Table 2 lists a collection of the short-term survival evaluation outcomes from six studies in which ten different species were assessed (Amaral et al., 2016; Erikson et al., 2016; HDR Engineering, 2017; Miehls et al., 2017; Whooshh, 2014c, 2016b). Fish behavior immediately after exiting the WFTS has been consistently observed as that of normal swim with typical upright orientation and free-range of motion to turn as desired. Survival outcome assessments of 24 hr. and 1 week required containment of the fish post-passage. Containment is a known stress inducer to migrating fish. The negative impact of containment not-withstanding, the short-term survival rates observed were nearly 100%.

Table 2. WFTS fish passage short-term survival assessment

Species	Immediate	24 hr	1 wk	WFTS Distance
Atlantic Salmon broodstock	100%	100%	100%	WFTS-100 ft
American Shad	100%	>90%*	ND	WFTS-175 ft
Sturgeon	100%	100%	ND	WFTS- 50 ft
Gizzard Shad	100%	ND	ND	WFTS-175 ft
Northern Pike	100%	ND	ND	WFTS-175 ft
Rainbow Trout	100%	ND	ND	WFTS-175 ft
Common White Sucker	100%	ND	ND	WFTS-175 ft
Walleye	100%	ND	ND	WFTS-175 ft
Steelhead	100%	ND	ND	WFTS-250 ft
Atlantic Salmon broodstock	100%	100%	100%	WFTS-459 ft

*Study setup operation/containment mortalities specifically-associated with study execution restrictions
ND – Not Done
Collaborators: [1]SINTEF (Norway), [2]Brookfield & HDR (ME),[3]Alden Labs (WI), [4]USGS &GLFC (MI), [5]WDFW (WA), [6] Grieg Seafood (Norway)

Survival: Long-term

Survival until spawning after fish passage can encompass a period of ~1-4 months. WFTS fish passage evaluation studies of adult survival until spawning have been performed in two settings. The first, referred to as the Roza study, involved passage to a hatchery truck of Chinook salmon after PIT-tagging and condition assessment at the Roza Adult Monitoring Facility (RAMF). RAMF is run by the Yakama Nation, supported by the US Bureau of Reclamation (USBR), and is located on the Yakima river, a tributary of the Columbia river in Washington state. The study Chinook were truck transported for approximately one hour to the Cle Elum hatchery facility where they were released into the hatchery raceways to reside until reproductive maturation was complete. The second study was designed as a migration study conducted by the Columbia River Inter-Tribal Fish Commission (CRITFC), assisted by the Yakama Nation. In this study, referred to as the Priest Rapids study, sockeye salmon were PIT-tagged at the Priest Rapids dam off-ladder adult fish trap (OLAFT), and subsequently either hand-carried to a calm water channel to volitionally return to the fish ladder and continue upstream migration or they were hand-loaded into a 100 ft WFTS which exited into the same calm water channel for continued volitional return to the fish ladder. The treatment of all study fish was the same aside from the WFTS passage evaluation fish which had the additional WFTS passage experience. OLAFT is located at Columbia river kilometer (rKm) 639. The migrations of the tagged fish were tracked for several months, by way of the PIT antennas present at various dams located 10s-100s of rKms upstream on the Columbia, Wenatchee and Okanogan rivers.

Survival Long-term: Hatchery setting

The Roza study was conducted over three consecutive years. The Chinook were either hand-carried to the transport truck or hand-loaded into a WFTS with a 40 ft tube exiting directly into the hatchery truck. To ensure hatchery required quotas, only ~15% of the Chinook were allotted to the WFTS passage group. As the fish could be identified by their PIT-tags, fish of both the treatment and control groups were housed together. The Cle Elum hatchery outdoor cement raceways are continuously supplied with fresh Cle Elum river water. Table 3 shows the adult survival until spawning percentages of the Chinook that passed through the WFTS tube and those hand-carried. The survival rates between the control and treatment groups are comparable. It is interesting to note the difference in survival observed between years. It is presumed that the environmental conditions experienced within a given year (most notably temperature) attributed most significantly to the across-years survival variability observed. In the hatchery containment setting, WFTS passage had no negative impact on long-term survival until spawning.

Table 3. Long-term survival until spawning in a hatchery setting show comparative reproducible rates across three years.

	2014	2015	2016
Total Study	N=468	N=562	N=550
Non-WFTS	90%	73%	85%
WFTS – 40 ft	94%	77%	86%
	Cool/Normal Yr	Extremely Hot Yr	Hot Yr

In 2016 there was an opportunity to examine if the distance traveled through a Whooshh tube might influence survival until spawning in the hatchery setting. The Chinook run arrive at Roza from May to July. The WFTS passage treatment fish were subdivided with the early allocated treatment fish (May 16–June 9th) hand-loaded into the 40 ft WFTS system and the later arriving allocated treatment fish (June 10-July 6th) hand-loaded into a 1,100 ft WFTS system which included a 100 ft vertical climb (Top and bottom right photos on report cover). Control, hand-carried, Chinook were collected across the run. A 95% confidence interval (*) was calculated for the control (Non-WFTS) group as it had the largest sample number and therefore defined the tightest confidence interval. The data clearly indicate that the proportion of Chinook that survived until spawning all fall within the 95% confidence interval indicating no statistical difference between the groups (Table 4). Thus, passage through the WFTS has no negative impact on long-term survival until spawning in a hatchery setting. In addition, the proportion that survives until spawning is independent of the Whooshh tube distance traveled. The average time for passage through the 40ft WFTS was 2-3 seconds whereas the average 1,100ft WFTS passage time was 35 seconds (Table 1).

Table 4. Long-term survival until spawning in a hatchery setting is independent of WFTS tube distance traveled.

	Non-WFTS	WFTS-40 ft	WFTS –1100 ft
Sample size	N=382	N=110	N=58
Survival	85% (81-88%)*	86%	82%

Survival Long-term: River Migration

In the same year, 2016, the Priest Rapids study was conducted. The sockeye salmon that arrive at Priest Rapids dam are of two origins: the Wenatchee and the Okanogan. The Wenatchee sockeye swim an additional 115 rKm upstream in the Columbia river to the Wenatchee river confluence and then continue migrating up the Wenatchee river to spawn. The Okanogan sockeye continue an additional 220 rKms up the Columbia river to the Okanogan river confluence and then continue migrating up the Okanogan river to spawn. Genetics of sampled sockeye can determine the sockeye origin, however, as the origin of the sockeye was not known at the time of sampling the fish were randomized switching between treatment groups every five fish. The following is a link to a brief video showing the 100ft WFTS passage (https://1drv.ms/v/s!Ak8mNDpAR2geinsYc-bdQ9EzyrPo) to the calm water channel shown in the middle panel of Figure 3 below.

Figure 3. Priest Rapids Study: Middle panel is a photograph of the calm water channel where sampled fish recovered prior to continuing ladder swim. The left panel is a map of the Columbia river, tributaries and dams. The right panel is a photograph of the remaining 15.5 vertical feet of the ladder the sockeye climbed at Priest Rapids dam after sampling, PIT-tagging, and +/- passing through a 100ft WFTS at OLAFT. The green arrow indicates the location where the calm water channel connects to the fish ladder.

The comparative Priest Rapids study was designed to introduce the variable, passage through a 100 ft WFTS system, as the only intended difference between the control group and the treatment group. The impact of passage through a 100ft WFTS on survival, migration, and passage time were directly evaluated and aberrant homing, abnormal behavior or potential disease transmission were indirectly assessed. The 785 PIT-tagged sockeye were tracked across approximately four months, multiple dams and hundreds of river kilometers. Table 5 sequentially lists the various upstream PIT antenna arrays the study sockeye encountered and their distances from Priest Rapids dam. Wenatchee origin sockeye migrate past the Rock Island and Tumwater antennae where-as the Okanogan sockeye migration path runs past the Rock Island, Rocky Reach, Wells, Zosel and the Okanogan river confluence antennae. The control group, 395 sockeye, and the treatment group, 391 sockeye, had comparable survival rates to the various migration detection points. There was a small difference noted in the distribution of Wenatchee verses Okanogan origin sockeye in the two groups which is evident in the percentages that reached Rocky Reach and Wells/Tumwater. Many factors the influence long-term survival in a river setting. In this study, the potential of those factors, passage through a100ft WFTS not-withstanding, to impact migration efficiencies was a constant distributed across all groups. When considering the treatment variable, passage through a 100ft

WFTS, the outcome differences were not remarkable. No differences in survival, migration, passage time, homing, behavior or disease transmission were identified when comparing study groups.

Safety and Welfare

Assessing safety and welfare associated with passage through the WFTS has been addressed in several studies. The first study was completed in 2011 wherein the US Geological Survey conducted a physiology study of Whooshh transported rainbow trout originating from a hatchery employing a prototype transport tube. The published study details the physiological stress measures evaluated and found Whooshh transported fish exhibited no overt injuries or excessive stress indications when compare to net haul transported control fish (Mesa et al., 2013).

Table 5. Priest Rapids Study: Percentage of control (Full ladder) and treatment (Full ladder with WFTS-100ft passage) sockeye detected at various upstream migration locations. The Wells and Tumwater detections were combined to capture the percentage of study fish reaching a distance migration of 165-191 rKm regardless of sockeye Wenatchee or Okanogan origin.

	Priest Rapids	Rock Island	Rocky Reach	Wells/ Tumwater	Zosel	OKC
Distance		91 rKm	124 rKm	191/165 rKm	351 rKm	368 rKm
Full Ladder N=395	93%	83%	61%	65%	44%	25%
Full Ladder with WFTS-100ft N=391	94%	84%	56%	70%	43%	25%

The outcomes of a study of Atlantic salmon by the Conservation Fund Freshwater Institute at their recirculating aquaculture system (RAS) facility in West Virginia were published in 2015 (Summerfelt et al., 2015). This study investigated the effect of travel through the Whooshh tube. Atlantic salmon were transported either head first or tail first through the WFTS tube. The salmon exited the tube into a holding tank and were held for observation to evaluate swim behavior and signs of injury or scale loss. It was reported that using the WFTS provided water usage savings. The outcomes of the study indicated the WFTS provided safe transport of the fish regardless of entry orientation and that the quick and adaptable WFTS installation provided many operational efficiency benefits.

Mechanisms and Efficiencies

In 2014, the Washington Department of Fish & Wildlife (WDFW) began using a Whooshh system for the first time to transport live migratory fall Chinook at a separation weir located along the Washougal river in Washington State. The system was used to transport hatchery salmon approximately 120 ft from the river, up the embankment, with a total rise of approximately 25 ft, exiting directly into a waiting hatchery truck. No overt injuries or welfare issues have been noted. Over an eight-week period, WDFW successfully transported more than 10,000 salmon in 2014 and more than 16,000 salmon in 2015. To date, they have transported more than 52,000 Chinook through the WFTS which provided strong evidence of mechanism utility and durability and the benefits of WFTS increased efficiencies. Prior to 2014 WDFW hand carried the hatchery salmon in a boot or tote from the middle of the river, up the embankment and dumped the fish into the hatchery truck. The 6 seconds per WFTS fish passage provides substantial efficiencies in time savings and labor. In addition, using the WFTS provided safety benefits to both fish (reduced handling and dropping risk) and to WDFW staff (removal of slip, fall and muscle fatigue hazards associated with carrying the fish through water and up the embankment to the hatchery truck) (Earthfixmedia, 2014; Whooshh, 2014c, 2016b).

Physiology and Consequences

Five additional studies, completed before 2017, have extended the scope of physiology examination and consequences of fish passage. Applying the definitions of Roscoe and Hinch (Roscoe & Hinch, 2010) physiology considers the physiological implications of passage including metabolites, hormones, and energy expenditure and consequences refers to the impact to the fish associated with passage such as injury, delayed mortality and reproductive success. The Pacific Northwest National Laboratory (PNNL) conducted a comparative assessment that included physical examination, epithelial injury assessment (fluorescein), internal stress (cortisol levels), adult mortality, productive spawning, and egg viability post transport. The study contained a net transferred control group, a trap and haul group and two WFTS groups transported via a tube of 40 ft or 250 ft in length. The Geist et al., publication states that there were no observed mortalities or obvious signs of injury to the fish due to passage through the WFTS. The immune responses and egg survival were similar among the WFTS 40 ft, WFTS 250 ft, and trap and haul study groups, with WFTS being slightly better (Geist et al., 2016; PNNL, 2015). Overall, the results of the PNNL study suggest that WFTS passage does not negatively impact fish physiology and that the consequences of passage through the WFTS on adult fall Chinook salmon, regardless of transport distance, were comparable or better to that of the trap and haul method.

Reproduction

The Roza long-terms survival until spawning study described above provided additional data on the reproductive potential of the spawned Chinook across the three years of study (Fast et al., 2017). Egg viability is routinely quantified by the Yakama Nation at the eyed-egg stage. Table 6 provides the percentage of viable eggs assessed approximately 4 months after spawning. The data suggests there is no negative reproductive consequence associated with WFTS passage of 40 ft or 1,100 ft. It is interesting to note that the environmental conditions of a given year which impacted that adult long-term survival rates until spawning (Table 3) had no bearing on the viability of the eggs produced from the adults that survived and spawned. Egg viability percentages were consistently reproduced across the three years of study.

Table 6. Percentage of viable Chinook eggs measured at the eyed-egg stage.

	2014	2015	2016
Non-WFTS	95.1%	94.6%	94.6%
WFTS-40 ft	93.0%	92.8%	92.9%
WFTS-1100 ft	ND	ND	96.8%

ND = Not Done

Evaluation of the physiology and consequences of passing large, broodstock Atlantic salmon through a 100 ft WFTS was conducted by SINTEF at AquaGen in Norway (Erikson et al., 2016). The value of these broodstock populations are considerable. The assessment was a comparative evaluation of stress, behavior, welfare, mortality and other irregularities. Blood chemistries (cortisol, chloride, glucose, and lactate) and white muscle biochemistry (pH and temperature) were collected at specific time intervals prior and post fish transfer. Transferring fish between tanks as they mature is a routine occurrence in broodstock settings. Maintaining fish welfare and a low-stress environment is critical to ensuring high fecundity. Figure 4 shows the study setup. There were no mortalities, no injuries, no signs of abnormal behavior or other irregularities observed. The blood chemistries indicated the WFTS transported broodstock maintained low stress levels and provided good fish welfare. In addition, the authors described several benefits, WFTS "reduced the fish exposure time to air compared with the traditional hand carry method…(and) transfer of fish by WFTS was quicker, safer (lower risk of dropping the fish) and less labor intensive than by hand carry (traditional method)"(Erikson et al., 2016).

Figure 4. The WFTS set-up at AquaGen's broodstock facilities. Left photo: handloading Atlantic salmon into the WFTS. Middle photo: WFTS entry side next to the holding tank. Right photo: WFTS exit into the observation tank.

Energetics

Insight into energetic costs of fish passage, a physiology parameter, was gained through the head to head fish passage sub-study performed on a single day as part of the Priest Rapids study. As described above, sockeye salmon were sampled and PIT-tagged as they came through the OLAFT facility at Priest Rapids dam. On the last day of the 2016 study, permissions were granted to alter the WFTS configuration such that the WFTS fish passage sockeye would bypass swimming through the remaining fish ladder section and pass through a 180 ft Whooshh tube up a rise of ~40 ft over the dam crest and exit directly into the forebay. The control sockeye would be released after sampling into the calm water channel where they would recover from sedation before volitionally swimming up the remaining 15.5 ft vertical climb up the fish ladder to reach the forebay (Fryer, 2017; Whooshh, 2016c). Thus, this single day sub-study was a comparative fish passage analysis of the impact of swimming just the last 15.5 ft of the Priest Rapids fish ladder verses WFTS fish passage gliding over the dam. 110 sockeye were evaluated (Fish ladder controls n=56 and WFTS passage n=54). Figure 5 photographs illustrate the head to head fish passage routes of the sockeye at Priest Rapids Dam.


Figure 5. Left panel is the last 15.5 vertical feet of the Priest Rapids fish ladder. The green arrow indicates the location through which control fish pass from the calm water channel to enter the fish ladder. Right panel is a portion of the 180 ft long WFTS tube with the 40 ft climb used in the head to head sub-study. The WFTS was temporarily installed, used and removed all within 8 hrs. on a single study day.

The sockeye were sedated with Aqui-S during tagging and sampling. Typically, they recovered from sedation in 2-3 minutes once they were returned to fresh water. The WFTS group recovered from sedation in a tote prior to passage through the WFTS. Passage timing from OLAFT to the forebay was initiated just after PIT-tagging when the placement of the tag was confirmed by the hand wand PIT-tag reader. Therefore, the passage time included sedation recovery time. The passage time, for the control sockeye to swim the 15.5 vertical feet up the fish ladder, the median was 2.9 hours and the mean was 23 hours. The passage time, for the WFTS sockeye to glide through the 180 ft Whooshh tube and up 40 ft, median and mean were 2.6 minutes. The actual tube travel time was noted to be ~ 8 seconds. The travel times from Priest Rapids upriver 91 rKm to Rock Island dam and 124 rKm to Rocky Reach dam are shown in Table 7. A Mann Whitney U test was used to compare the treatment population means of travel times to upstream sites. A p value ≤ 0.05 was considered statistically significant. The WFTS fish passage group traveled faster, further upstream than the control fish ladder swim group. The energy costs of just 15.5 ft of vertical fish ladder climb putatively depleted the energy reserves of the control group such that over the course of 91-124 rKm river travel, the energy costs equated to from a half to more than a full day. Upstream beyond Rocky Reach the differences in travel times remained evident, however, detection sample sizes became too small to indicate statistical significance. The ability of the WFTS passage fish to travel further faster indirectly suggests that the physiological implications of WFTS fish passage are more energetically favorable for the fish than fish ladder swim. Thus, less depleted, the WFTS group had the energy resources to more efficiently migrate upstream.

Table 7. Travel times reflect energetic costs of fish passage

	Rock Island Sockeye number	Median Travel Time	Mean Travel Time	**Rocky Reach** Sockeye number	Median Travel Time	Mean Travel Time
Distance	91 rKm			124 rKm		
Controls: last 15.5 ft ladder swim	n=46	4.07 d	5.39 d	n=21	5.61 d	6.58 d
WFTS: 180ft over the dam glide	n=44	3.48 d	3.89 d	n=33	4.82 d	5.36 d
Mann Whitney U test*			p<0.01			p=0.03

Volitional Entry Versatility

The WFTS is a highly adaptable, versatile, modular fish passage technology. For river connectivity, volitional passage settings, the WFTS can be fitted to various conventional guidance and attraction systems which facilitate access to the WFTS false weir entry (Hansen, 2015). The selection of guidance and attraction system utilized will be site dependent, dictated primarily upon the fish species requiring fish passage. Four WFTS volitional entry studies performed at different locations are described.

Water Flow Attraction and Guidance

In 2015, the City of Newport, OR sponsored a demonstration study whereby adult rainbow trout broodstock were attracted to a WFTS using water flow, entered on their own, and were transported over an earthen dam crest (Whooshh, 2015c). In this study, the false weir was positioned just above water level with enough flow to encourage upstream movement interest. Rainbow trout swam effortlessly over the false weir and directly entered the WFTS accelerator for fish passage (Figure 6A &B).

Pool and Weir Attraction and Guidance

A second study was conducted on the White river in Buckley, WA in collaboration with state and federal agencies, tribal nations, and fish and water industry partners (NWTT, 2015; Whooshh, 2015a, 2016d). A multistep pool and weir system was constructed a short distance upstream within the side rock channel that branches off the White river. The side rock channel is located downstream of the USACE Buckley fish trap. Chinook and pink salmon migrate up the White River. A bar grate was positioned to prevent Chinook from passing up through the pool and weir system. The pinks swam through the bar grate easily and readily passed through the pools and over the small weirs directly into the WFTS (Figure 6 C &

Figure 6. A&B City of Newport, OR water flow attracted Rainbow trout for volitional entry with false weir just above the surface level. C&D White river pool and weir steps providing pink salmon with false weir access for volitional WFTS entry. E&F Prosser hatchery steeppass in a stream of the Yakima river combined with a study WFTS with the prototype scanning sorting component. Chinook and Coho volitionally entered WFTS. G&H Ringold Springs Alaskan steeppass and flow box facilitated volitional WFTS entry of Columbia river Chinook and steelhead.

D). Approximately 500 pink salmon were transported through an 80 ft Whooshh tube which ran up an embankment at an angle of ~35 degrees and exited directly into a hatchery truck to be driven miles upstream above two sequential dams.

Alaskan Steeppass Attraction and Guidance

In the fall of 2016, the WFTS was fitted to the top of the Prosser hatchery steeppass operated by the Yakama Nation and owned by the USBR (Figure 6E & F). Hatchery fall Chinook and Coho migrate up a small side stream off the Yakima river where the hatchery operation is located. The fish typically volitionally swim up the steeppass and slide down a pipe to holding tank wherein they are netted and hand-sorted. For the study, the WFTS false weir was positioned at the top of the steeppass, the fish were partially dewatered as they swam over the false weir and then slid down a 10-degree angle through the prototype WFTS scanning/sorting component. The scanning/sorting component collected images in real time as the fish slid through without fish detainment or handling. The system directed the Chinook down a chute to a large Whooshh tube for passage to a hatchery raceway and the Coho were directed down a second chute to a smaller Whooshh tube that exited into a new hatchery holding tank. Both of the tubes were roughly 300 ft in length. The Prosser study extends the number of species and the length of Whooshh tube passage via WFTS volitional entry.

Pacific Northwest National Laboratories (PNNL) investigators conducted a fourth volitional entry study of the WFTS in the fall of 2017, at Ringold Springs hatchery in Mesa, WA. Hatchery Chinook and steelhead volitionally swim up Spring Creek off the Columbia river and through a creek-wide V-trap into a holding pool fed by natural spring water. A 30 ft Alaskan steeppass and flow box were fitted to the WFTS false weir entry and positioned with the 5 cfs of flow and the terminal end of the steeppass located within the holding pool (Figure 6 G&H). The Ringold study focused on volitional entry and scanning and sorting to distinguish fish by size. The Chinook were identified by size and directed to the Whooshh tube for 100ft passage to a holding pool and condition assessment. The smaller steelhead were identified by size and directed to the bypass chute and back to the holding pool. The study provided the opportunity to optimize attraction flow parameters for the species present and to demonstrate the autonomous, volitional, selective capabilities of the WFTS. Three hundred and sixty-seven Chinook volitionally entered and were selectively passed through the WFTS. Chinook were netted from the holding pool and condition assessments performed as a non-passage control group. A few minor hemorrhaging injuries were reported in the study but the WFTS passage group rates were slightly lower than those observed in the non-passage, dip-netted control Chinook group (Garavelli et al., 2018). These studies demonstrated volitional fish passage, successful attraction and safe transport of live species without human handling.

Figure 7. Fish Passage study categories to evaluate Safe, Timely, Effective and Efficient passage.

Adaptive Optimization Management

The 2017 Whooshh upstream fish passage project at Cle Elum dam was designed to showcase the modular, cost-efficient, and rapid deployment of our novel fish passage solution. The project was supported by the United States Bureau of Reclamation (USBR) and the Yakama Nation (YN). Whooshh installed two tubes in series with a booster accelerator to create a 1700 ft long and 180 ft high fish passage path, in less than 3 months. The Whooshh system requires no forebay-water use, was designed to accommodate varying forebay water levels and was constructed to minimize the environmental, land-use footprint. Engineering and installing a fish passage system of this size in such a restricted timeframe has never been attempted or accomplished before. The installation was designed to address the features required of volitional fish passage as illustrated in Figure 7.

To fully shake down, calibrate and quality check the functional operation of the system required the ability to run the system with live trial run "test" fish while observing system performance and adjusting calibration features for optimal performance. Unfortunately, 2017 was an extremely low run sockeye year which contributed to a study design changing outcome. With only one-fourth of the needed shake down test fish available prior to commencement of the study and the study change which reduced the study to just ~25% the original study size and limited the fish to just trucked, out-planted sockeye. The new study was limited to only four days of sockeye collection, trucking and fish passage which occurred concurrently with adaptive optimization management of the system. Substantial adaptive modifications of the Whooshh fish passage system were implemented throughout the four days of study from sensor alignment to calibration of coding sequence timing. The most significant shakedown finding was discovered after the second study day. A manufacturing defect which prevented the misting water to gain entry into the tube, was identified resulting in insufficient tube lubrication. A misting corrective action was put in place and operational by the fourth day of study. The adaptive operational management adjustments increased the survival until spawning estimates calculated by USGS by ~40% from day 1 to day 4. By day 4 the survival until spawning estimates of the outplanted sockeye group that underwent fish passage were statistically equivalent to the no-passage outplanted sockeye group which was delivered directly to Cle Elum reservoir (Kock, 2018). Traditional fish passage structures lack the versatility to enact adaptive operational optimization on a time scale of hours to days. Typically, one to multiple seasons are required to identify, plan and implement an adaptive improvement which then requires an additional season(s) to assess the effectiveness of the adaptive management. The ability to rapidly assess WFTS performance and adapt operational settings based on unique engineering specification performance parameters in a timeframe of hours to days, rather than across seasons, both accelerates and focuses the capacity to problem-solve to achieve maximum operational benefits in the present term rather than at some potential future date.

As a USBR sponsor requirement, all sockeye, regardless of size, were required to be transported through the fish passage system. The study, however, only supported the installation of a single Whooshh tube of a specific size. The T123 tube was selected however, in addition to small run numbers, the majority of the sockeye encountered were substantially smaller than anticipated, falling below the WFTS specifications for T123 tube transport. To fulfilling the USBR requirement to transport all sockeye, the Whooshh scanning/sorting system bypass function was deactivated such that all sized fish, regardless of specifications, were sent to the forebay through the Whooshh tube. The tube transport size specifications, although ignored in this study, have been established based upon then system relationships between tube cross-sectional occlusion and the ability to create an air pressure differential to safely glide the fish through the tube. Figure 8 clearly shows a positive correlation between the size of fish passing through the tube and survival, reinforcing the importance of the Whooshh tube design specifications for fish size associated with a given Whooshh tube size and safe passage. The mean travel time from below the Cle Elum dam tailrace over the dam and to the forebay was less than one minute.

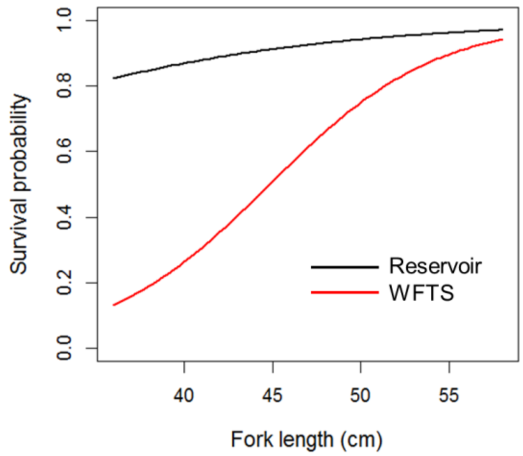

Figure 8. Effect of fork length (in centimeters [cm]) on survival probability estimates of adult sockeye salmon passed through a Whooshh Fish Transport System (WFTS) or released at a reservoir release site (Reservoir) in Cle Elum Reservoir, Washington, July 19, 2017 (release day 4) (Kock, 2018).

Evaluation Outcomes

The results of the Whooshh studies have attracted the interest of a number of dam owners and operators seeking an affordable, safe, timely, efficient and effective fish passage solution. Traditional fish passage designs have capital costs in the tens of millions of dollars. Whooshh fish passage solutions are designed to be deployed and operational in a few months rather than the typical multiyear timeline for new fish passage ladder design and construction. The Whooshh fish passage solutions are consistently much less expensive (typically 75% less than the cost of a fish ladder), can be deployed years earlier and provide data driven opportunity for sustainable fish population fish passage. Further, because Whooshh does not require water from the forebay for passage, up to 10% more water may be available for power generation or water management purposes.

The Whooshh fish transport system is the first technology breakthrough for fish passage in decades. Old passage methods cannot provide new and better results. The conventional fish passage methods have been tried for decades and have revealed their limitations. Whooshh Innovations designed and incorporated solutions into the WFTS to address the limitations of conventional fish passage. The innovative WFTS ecotechnology is the fish passage solution that provides benefits to fish, fisheries managers, dam operators and hydropower producers. The WFTS provides real hope that dams and fish can each co-exist and even thrive in the future. Fish runs can recover. There is no longer the need to waste water filling fish ladders. The WFTS fish passage is safe, timely, effective and efficient. There is no more promising fish passage system in the world today.

Conclusions

The Whooshh fish transport system provides safe, timely, efficient and effective fish passage. It is an innovative ecotechnology for fish passage that provides benefits for both fish and water management. The WFTS can address fish passage challenges of low and high head dams easily as it is not restrained by water flow and water pressure constraints. Moving fish rapidly, gently directing them through a smooth, flexible, misted tube via a small air pressure differential provides a passage path that is safe, does not cause fish stress nor tax the migratory energy reserves of the fish. The scope of WFTS studies conducted span passage considerations across a range of species and distances, in addition to survival, river migration, physiology, reproduction, and energetic-associated impacts. The outcomes have been reproducible and highly favorable. The challenges to fish passage today include additional features such as the influence of climate change and invasive species management which conventional fish passage device have not been designed to address. Solutions to these challenges have been incorporated into the WFTS safe, timely, effective and efficient fish passage system via the versatility of the system scanning technology that enables real-time selective sorting and fish passage with no-spill water requirements. The versatile design and comprehensive incorporation of solutions to all known challenges to upstream fish passage have made the WFTS the first and most complete selective, autonomous, volitional and economical upstream fish passage system available.

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Appendix A: Matrix of Whooshh Studies

Study	Species	Date	Survival	Migration	Passage Delay	Egg Viability	Injury	Homing	Disease Transmission	Behavior	Durability/ Maintenance	No. Interest Areas Evaluated/
Whooshh labs	Rainbow Trout Tilapia Atlantic Salmon		3				3				3	**3**
USGS	Rainbow Trout	2011	1				1				1	**3**
WDFW/USGS Kalama Study	Steelhead	2014	1				1				1	**3**
WDFW Washougal	Tule Chinook	2014-2017	1			1	1			1	1	**5**
Yakama Nation Roza Dam	Spring Chinook	2014	1			1	1		1	1	1	**6**
PacifiC NW Labs/DOE	Fall Chinook	2014	1			1	1					**3**
Puyallup Buckley Study	Pink Salmon	2015	1	1							1	**3**
Yakama Nation Roza Dam	Spring Chinook	2015	1			1	1		1	1	1	**6**
Alden Labs/Memonimee/EPRI	Sturgeon	2015	1				1			1		**3**
Freshwater Institute	Atlantic Salmon	2015	1				1			1		**3**
CRITFC Priest Rapids Study	Sockeye	2016	1	1	1			1	1	1		**6**
Yakama Nation/USBR Roza Dam	Spring Chinook	2016	1			1	1		1	1	1	**6**
SINTEF AquaGen Norway Study	Atlantic Salmon	2016	1			1	1			1		**4**
Yakama/USBR Prosser Study	Coho Fall Chinook	2016	2			2	2		2	2	2	**12**
USGS Great Lakes Fisheries	Gizzard Shad Largemouth Bass Northern Pike Rainbow Trout Common White Sucker Longnose Sucker Walleye	2017	7				7			7		**21**
Brookfield Cataract Dam	American Shad	2017	1				1			1		**3**
USBR Cle Elum	Sockeye	2017	1	1				1		1		**4**
Pacific NW Labs SBV DOE	Fall Chinook Steelhead	2017	2		2		2			2	2	**10**
Total Number of Test Evaluations/Species			**28**	**3**	**3**	**8**	**25**	**2**	**6**	**21**	**14**	**104**