US Army Corps
of Engineers ®
Portland District

75% WILLAMETTE VALLEY HIGH-HEAD BYPASS DESIGN PARAMETERS

U.S. Army Corps of
Engineers Portland District

January 2019

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Acronyms and Abbreviations

CFD	computational fluid dynamics
cm	centimeter
cfs	cubic feet per second
D	diameter
DDR	Design Documentation Report
EDR	Engineering Documentation Report
fps	feet per second
FCRPS	
FL	fork length
mm	millimeter
N	number
NGVD	National Geodetic Vertical Datum
NMFS	National Marine Fisheries Service
psia	pounds per square inch absolute
R	radius
RO	regulating outlet
s	second
SE	standard error
USACE	U.S. Army Corps of Engineers

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1. WILLAMETTE VALLEY HIGH-HEAD BYPASS PROJECT

USACE was directed through the National Marine Fisheries Service (NMFS) 2008 Willamette Project Biological Opinion (2008 BiOp) to address downstream fish passage at dams in the Willamette River Basin. In its Reasonable and Prudent Alternative, NMFS identified measures and timelines for completion that USACE, Bonneville Power Administration, and Bureau of Reclamation (collectively, the Action Agencies) must implement to reduce the Willamette Valley Flood Control Project's effects, including improvements to downstream passage at several dams. All bypass systems developed from recommendations in this report will be evaluated to document post-passage survival and passage success as determined by any established biological performance metrics.

"The Willamette Valley Flood Control Project consists of 13 dams operated by USACE. Most of these dams are "high-head" dams that are over 250 feet tall. The primary purpose of the dams is to provide critical flood damage reduction for the entire Willamette Valley, including the cities of Eugene, Salem and Portland. The projects also provide some hydroelectric generation (about 180 megawatts annually), along with recreational and fishing opportunities, water quality benefits, and municipal and irrigation water." A high-head dam has been defined, within the scope of this study, as any structure that impounds water with a minimum of 150 feet of elevation differential from tailrace to forebay. The height of these dams pose significant challenges to juvenile fish that are traveling downstream to the ocean.

The U.S. Army Corps of Engineers (USACE) Portland District Willamette Valley High-Head Bypass Research Project was initiated in 2015 to investigate the feasibility of volitional fish conveyance for downstream passage at high head dams (see Section 2.3 for more information). The ongoing research project included tests at Green Peter and Cougar Dams. Based on past research and research specific to this project, the Product Delivery Team (PDT) has developed this report to present the findings of this and other applicable research to recommend design parameters to aid in developing successful bypass alternatives at high-head dams.

1.1 OVERVIEW OF DOWNSTREAM FISH PASSAGE AT HIGH-HEAD PROJECTS

There has been a renewed interest in establishing downstream fish passage with volitional bypass for high-head dams, rather than fish collection and transport. This is due to bypass systems potentially providing superior biological performance, and improved operations and maintenance. However, the challenge of passing fish downstream of high-head dams is significant because of the height of the dam, changes in river flows, and fluctuating reservoir elevations of sometimes more than 150 feet in a given year.

Recently, the primary focus for downstream passage at high-head dams has been on the collection of fish (trap and haul) because this is typically the most challenging issue to overcome. The early attempts of conveyance using a bypass met with limited success; see Section 2.1. However, fish, especially of wild origin, are known to be stressed from holding and handling (Barton 2002, Woodward 1987). There has also been recent research showing that some reservoir-reared Chinook salmon are vulnerable to the holding and handling effects of tagging and monitoring (Herron 2017, Monzyk 2015, Beeman 2014, Beeman 2013). Fish passage that reduces or eliminates delay, holding, and handling is the most analogous to a natural system and is biologically preferred. However, the stress associated with high-head bypass, especially those that fall outside of established NMFS criteria (NMFS, 2011), is not well documented, and is a focus of current research. Completed research studies specific to high-head bypass in the Willamette Valley are summarized in Section 2.3.

The application of all NMFS fish passage criteria and design parameters commonly utilized in design of downstream fish passage systems may be challenging when applied to these high-head projects, considering constructability, operability, and cost. The focus of this report is on development of design parameter guidelines for volitional passage systems for downstream fish passage at high-head dams, referred to in this report as high-head bypass, as an alternative to traditional fish collection and transport (trap and haul) with the understanding that some holding/handling may be required for monitoring and sampling activity for a bypass system.

Cougar and Detroit dams are currently in design for downstream passage facilities, with trap and transport as the means of fish conveyance, and they will be the first projects for which alternative studies (Engineering Documentation Reports) will be developed for high-head bypass.

For Cougar Dam, a Design Documentation Report (DDR) has been prepared for the design of a floating screen structure (FSS) to be used to collect fish, with trap and transport for downstream passage. This project is currently in plans and specifications, with a construction award target date of 2020. To accommodate the possibility of a future high-head bypass system at Cougar Dam, flexibility has been incorporated into the design of the FSS to allow for adding a bypass system. For Detroit Dam, DDRs are currently being prepared for the design of a SWS (Selective Withdrawal Structure) and a FSS, with trap and transport for temperature control and downstream fish passage.

1.2 PURPOSE AND NEED

The principal goal of this report is to identify design parameters to inform alternatives development for downstream fish bypass systems at high-head reservoirs, specifically for dams in the Willamette River basin.

The NMFS design criteria (2011), were considered in the development of the design parameters recommended in this report. Recommended design parameters (and corresponding NMFS criteria, where applicable) are presented in Table 2 of this report. This table was developed through examination of existing literature and research, as well as recent research specifically targeted to high-head bypass. Where sufficient information exists, specific design parameter metrics are provided on which conditions are desirable and which need to be avoided.

Designs that fall outside of the recommended parameters, and other established criteria, should consider the use of computer modeling, physical modeling, and testing under the prototype condition to inform risk based decisions. This document is intended to provide guidance, and recognizes that bypass designs must be tailored to address site-specific conditions.

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2. EXISTING KNOWLEDGE

2.1 PRIOR RESEARCH

Research into the best means to safely pass fish around dams has been ongoing since the construction of dams. The first law protecting fish passage in North America was passed in Maryland in 1708, protecting passage for alewives (*Alosa spp*.) (Massachusetts governmental laws, 1887). Other efforts to regulate fish passage followed, but lacked specific criteria and guidance. The result was the installation of many ineffective fish passage systems, and in most cases lack of compliance with fish passage requirements. Scientifically based study into fish passage systems did not begin in earnest until the second half of the 20th century, and initially focused on passage of adult salmon and sturgeon upstream of dams (Katapodis, 2012). The application of a methodical science based approach to solving fish passage issues quickly led to huge improvements in both upstream and downstream fish passage, especially for the dams on the mid and lower Columbia and lower Snake rivers.

Early assumptions about juvenile downstream passage, that passage through hydro-turbines posed little risk to fish, were proven false, especially for high-head dams. Upon this realization, studies began to investigate the use of alternate routes to pass downstream migrants. For high-head dams, the initial studies looked at using surface spillbays as alternatives for fish passage. This was the catalyst for numerous studies from the 1940s through the 1960s, investigating how fish survived prototype conditions and simulated conditions in the laboratory. Areas of greatest focus were physical strike, the relationships between pressure and barotrauma, survival of fish in free fall (both within a column of water and without water), and the injury and mortality of fish exposed to different levels of shear and velocity (see Bell and Delacy 1972 for a synopsis).

Early investigations of survival through the use of direct capture methods showed that the mortality risk varied widely between projects. The projects with the lower mortality rates were spillways where the water discharged through the air and entered the stilling basin without traveling down the face of an ogee (Smith 1938). Based on this information, a series of studies were initiated on the survival of fish in free-fall conditions. These studies showed that fish survival likely depended on the fish’s terminal velocity and if it was contained within a column of water (Regenthal 1955, Schoeneman and Junge 1954). Investigations to quantify the effect of freefall velocity on survival were done by Richey (1956), with the use of wind tunnel experiments to determine the terminal velocity of different sized fish, as well as field experiments dropping fish from different altitudes. The studies determined that if impact velocities of a free-falling fish (not contained in water) were at or above 50 feet per second (fps) there were both internal and external traumatic injuries. The smaller fish reached a lower terminal velocity, so their survival was higher for all altitudes, while larger fish accelerated more quickly and saw mortality increase significantly with altitude.

Studies of low-head mainstem dams on the Columbia and Snake rivers showed relatively high survival through surface routes and spillways. The focus for these projects shifted to fish guidance, in order to pass more fish through these high survival routes (Fields 1957). Though some of the early studies showed promise, efforts to provide surface spill passage at high-head dams, or pass fish utilizing a free-fall conduit for downstream passage, failed to produce viable fish passage alternatives. The design of downstream passage facilities at Cougar dam were based on some of the freefall research, and utilized a vertical freefall conduit as part of the bypass (USACE 1962). Early post-construction tests by Ingrahm and Korn (1969) showed that there was high mortality in this vertical conduit when the facility was operated as designed. It was hypothesized that the fish were being injured and killed at the bottom of the vertical conduit by the dissipation of the energy of the water hitting the sill of the regulating outlet conduit. Operational alternatives to provide a “cushion” of water by almost completely closing the regulating outlet service gate reduced mortality rates in the vertical conduit, but saw equal or greater increases in mortality as fish passed through the narrow regulating outlet gate opening (Ingrahm and Korn 1969).

When it became clear that in many cases guidance would not sufficiently pass fish through safe routes, engineers and fisheries biologists realized that coming to a deep understanding of the mechanisms of fish injury would be important to better understand how to improve passage conditions (Bell and Delacey 1972). These studies tend to categorize fish passage injury types into three categories: mechanical injury, injury from hydraulic shear and turbulence, and barotraumatic injury due to pressure changes. Unsurprisingly, each type of injury is caused by specific types of physical conditions and events (see Cada et al. 1997 for a review).

2.1.1 Mechanical Injuries

Mechanical injuries occur when fish come into contact with structures during passage. Common causes of mechanical injury are: impingement; striking turbine blades, stay vanes and wicket gates, also striking baffle blocks and end-sills in spillway stilling basins, as well as scraping along the concrete as they pass down the spillway ogee, and striking gates and conduit walls in regulating outlets. Mechanical injuries are also common in passage systems where fish are exposed to handling, which includes crowding, brailing, dewatering, netting and handling for research and monitoring. Symptoms of mechanical injury typically present themselves externally as descaling, abrasions, cuts (including complete transection of the body), hemorrhaging or proptosis of the eyes, maceration, and contusions. Traumatic mechanical injuries can also be internal, such as hemorrhaging, organ rupture, and muscular/skeletal injuries, including spinal injuries. The nature and magnitude of the injury is affected by several variables including: the mass of the fish, the speed and angle of the impact, the roughness of the surface of the object, the length of time and frequency of contact, and the surface area of the fish exposed to the object and force.

2.1.2 Injury from Hydraulic Shear and Turbulence

Injuries caused by shear and turbulence can frequently present themselves in a similar manner to some of the more common symptoms of mechanical injuries. This is understandable since the method of injury is similar, with the trauma being caused by abrupt changes in velocity. The most common injuries associated with shear and turbulence are torn opercules and isthumi, decapitation, and internal traumatic injuries, especially spinal injuries. Injury to the opercula and decapitation occur when a fish passes through a severe hydraulic shear plane. The differential in water velocity orient the fish into a negative rheotaxis where the high velocity of the water catches the opercula, causing them to flare out uncontrollably. The force exerted on them will cause the tearing, and if bilateral and severe enough, decapitation. Less severe turbulence is also thought to cause temporary loss of equilibrium, which can make the fish vulnerable to predation.

Studies into the biological effects of shear and turbulence under controlled laboratory conditions began in the late 1960s. At the time, scientists lacked the instrumentation to accurately model or measure velocities at the scale necessary to determine strain forces or rates of acceleration. Because of this, manipulated variables were expressed as velocities (fps) for the jet of water that the fish were traveling within (Groves, 1972) or the velocity of the jet of water that the fish were introduced into (Johnson, 1970).

Testing by Groves (1972) has shown that fish were unaffected when exposed to hydraulic shearing at jet velocities less than 30 fps. In these tests, fish were directly exposed to the shear plane through a release pipe (see Groves 1972, figure 1). When the jet velocity increased to 50 fps, the percent of fish that were disabled rose to 13%, which includes both visible injury (8%) and mortality (2%). The author noted that speeds on the margin of the jet, where the fish first made contact, were slower than the calculated value. However, the orientation and size of the fish had a big influence on the risk of being injured, with smaller fish entering the shear plane head first being at greatest risk.

Groves (1972) also noted that: “Velocity differences are what injure and kill. Thus higher overall velocities produced more damage, because these in turn caused greater differences to be contacted by the fish.”

Richard L. Johnson conducted similar studies detailed in his reports from 1970 (see Johnson 1972, Table 1 for a summary report of all tests). In these studies, the fish were contained within the high velocity jet and discharged into a tank of still water. No injury was observed for the 57.5 fps test, which was the lowest velocity tested. Tests included a variety of species and fish sizes, including juvenile Chinook similar in lengths from 3-9 inches. Consistent with Groves (1972), Johnson observed fish orientation, size, and jet velocity affecting the mortality and injury rates.

The most recent in-depth experiments examining the effects of shear forces on fish is the work done by Department of Energy as part of the Federal Columbia River Power System (FCRPS) Turbine Survival Program (Neitzel et al., 2000, and Deng 2005 & 2010). The methods employed were very similar to both Johnson (1970) and Groves (1972), with the addition of modern instrumentation for fine-scale velocity measurements. These new technologies allowed for the quantification of the strain force experienced by the fish. By changing the velocity of the jet, Neitzel et al. (2000) exposed different species and different sized fish to increasing levels of strain force. Strain rates that caused injury were achieved by exposing the fish to a jet velocity of 30 fps through the apparatus. In general the salmonid species proved more resilient than shad. Deng (2005 & 2010) used the same experimental design with the addition of high-speed motion tracking analysis of video data. This allowed for measurements of acceleration using Kinematic and dynamic parameter analysis. The advantage of this approach is that it allows for measurements of the acceleration forces for each individual fish. This helps overcome issues with variance in the flow field, how the fish experiences that flow field, and variations in fish mass and morphometrics. The results of the study of slow fish entering a high-speed jet showed that fish accelerating at rates less than 100 m/s^2 (328 ft/s^2) had a less than 5% probability of minor injuries (Deng 2005). This was worse than when the fish were entrained in the jet that entered a still body of water (fast fish to slow water), where minor injuries did not occur until accelerations of 319 m/s^2 (Deng 2010). This difference likely had to do with the worst case orientation of the fish to the jet for the 2005 study. The negative rheotaxis of the fish would cause the opercula to be the first part of the body to contact the shear zone as the fish entered the high-speed jet. This acceleration information will allow for more direct application to computational fluid dynamics (CFD) modeling and prototype development.

2.1.3 Barotraumatic Injury Due to Pressure Changes

Salmonids are physotomes (having a direct connection between their swim bladder and esophagus) yet can still be victims of barotrauma associated with dam passage. Typically barotrauma is seen in turbine passed fish where decreases in pressure can occur quickly (<1 second) and range from surface pressure to approximately 50% of surface pressure Brown et al 2014, Čada 2002, Carlson 2010, Cramer and Oligher 1964). Barotrauma related injuries manifest in several distinct symptoms with the two principle mechanisms governed by Henry’s and Boyle’s laws, being the rapid expansion of gas in any gas bearing organs and the decrease in the solubility of gas in the blood and tissues due to decreases in environmental pressure respectively (Brown et al 2012). Since injures are most commonly related to the amount of gas found in fish organs, such as the swimbladder, the depth a fish is acclimated to is a significant factor to the likelihood of injury or mortality. Rapid expansion of gas, especially in the swim bladder, can cause the afflicted organ to expand, and in severe cases burst or rupture, as well as contuse the organ and surrounding tissues. Other symptoms seen in fish exposed to decreases in pressure are emboli and emphysema in the gills, fins and eyes, internal hemorrhaging, hemorrhaging of the eyes and fins, as well as propotosis (also referred to as exopthalmia or eye pop) (Cramer & Oligher 1964, Tsvetkov et al. 1972; Beyer et al. 1976; Rummer and Bennett 2005; Brown et al. 2012).

There are a series of studies dating back to the 1930s that examine the effects of pressure on fish. They have consistently shown that fish that are surface acclimated are not injured by positive pressure exposure (Krietman 1930, Clausen 1934, Holmes 1952, Holmes et. Al 1961, Harvey 1963, Cada 1990, Stephenson, 2010). There have also been numerous studies linking the exposure of depth-acclimated fish to rapid depressurization to sub-atmospheric pressures (< 14 psia) to the likelihood of barotraumatic injuries and mortality (Beyer et al. 1976, Brown et al. 2009, Cramer and Oligher 1964, Holmes et al. 1961, Stephenson 2010). The severity of these injuries also depends on the depth a fish is acclimated to, the rate of pressure change, and the nadir or lowest pressure experienced. Therefore barotrauma related injuries at dams, similar to those in the Ceolumbia and Willamette Rivers, are only likely to occur when a fish that is depth acclimated passes a turbine route and is rapidly decompressed or when passed through deep outlet with a small gate opening.

2.2 EXISTING DOWNSTREAM FISH PASSAGE SYSTEMS IN THE PACIFIC NORTHWEST

The current methods of conveyance for downstream migrants at high-head dams are either trap and transport or trap and bypass. Some high-head projects (e.g., Swift and Pelton Round Butte dams) implement surface collectors and truck transport as a means to pass downstream migrating fish. Other projects (e.g., North Fork and Soda Springs dams) use collectors and bypass pipes.

The following are examples of conveyance strategies that are currently in operation, under consideration, or in development, and those that were constructed but are no longer in operation. The descriptions of projects in this section are not all high-head projects, but rather are intended to provide background on the types of downstream passage systems currently in operation around the Pacific Northwest.

2.2.1 Trap and Transport

Baker River Hydroelectric Project (High Head)

The Baker River Hydroelectric Project is located on the Baker River, Washington, and is owned and operated by Puget Sound Energy. It consists of two dams: Upper Baker Dam (312 feet high) and Lower Baker Dam (285 feet high). Juvenile bypass pipes were constructed with the two dams for downstream migration; however, the pipes were destroyed by landslides and spill events and were never repaired. Fish passage around these two dams is achieved by a trap and haul program. Downstream migrating juvenile fish are collected in a floating surface collector in the forebay of each of the dams and transported and released downstream of the projects.

Cushman Hydroelectric Project (High Head)

The Cushman Hydroelectric Project is located on the North Fork Skokomish River, Washington, and is owned and operated by Tacoma Power. The project consist of two dams: Cushman Dam No. 1 (275 feet high) and Cushman Dam No. 2 (235 feet high). A floating fish collector with guide nets for downstream passage was installed in the forebay of Cushman Dam No. 1 in 2015. Juvenile fish are collected, transported, and released below Cushman Dam No 2.

Cowlitz Falls Dam

Cowlitz Falls Dam is a 140-foot-high project located on the Cowlitz River, Washington, and is owned and operated by Lewis County Public Utility District. Downstream fish passage is achieved by a surface collector in the forebay, which went into operation in

2017. Juvenile fish are collected, transported, and released below Mayfield Dam, downriver of Cowlitz Falls Dam.

Swift Dam (High Head)

Swift Dam is a 512-foot-tall project located on the Lewis River, Washington, and is owned and operated by PacifiCorp. Juvenile fish are collected in a floating surface collector with a guide net system in the forebay and transported and released downstream of Merwin Dam, downriver of Swift Dam.

The Pelton Round Butte Project (High Head)

A Selective Withdrawal Structure (SWS) was constructed in the forebay of Round Butte Dam on the Deschutes River, Oregon, and went into operation in 2010 to facilitate downstream fish passage. Downstream passage around the three dams of the project is achieved by collecting fish in the SWS at Round Butte Dam and transporting and releasing downstream of Pelton Reregulating dam.

After collection, fish are pumped to a higher elevation and go through a series of three separators. Several different dispositions, depending on species and size, are employed, including return to reservoir and downstream transport.

2.2.2 Bypass

North Fork/River Mill (High Head)

The North Fork/River Mill Project is located on the Clackamas River, near Estacada, Oregon, and is owned and operated by Portland General Electric. The project consists of three dams: North Fork Dam (206 feet high), Faraday Dam (approximately 60 feet high), and River Mill Dam (85 feet high, approximately 5 feet of fluctuation). Downstream fish passage around these three dams is primarily achieved by a floating surface collector (FSC) and fixed surface flow outlet (SFO) in the forebay of North Fork Dam, the most upstream dam in the Project. Both passage routes use a common bypass conduit. At the downstream end of the FSC, fish enter a full-flow bypass conduit that connects the FSC to the dam penetration via a flexible pipe. Flow and water levels in the upstream end of the FSC bypass are controlled by manipulation of a flexible section of the bypass conduit on the downstream side of the dam, which has 4 ½ feet of vertical travel, and thus 4 ½ feet of forebay pool fluctuation. From here, fish collected in the FSC continue to traverse the axis of the dam and both the SFO and the FSC bypass conduits outfall into the tertiary screen structure. This structure serves two main purposes: to reduce the combined bypass flow from the FSC (typically 7 cubic feet per second [cfs]) and the SFO (typically 12 cfs) down to 7 cfs for the 7.1-mile-long free surface common bypass conduit (which is called the migrant pipe), and to remove fine debris prior to the migrant pipe entrance. At the downstream end of the migrant pipe, just before the outfall, there is a fish evaluation facility that subsamples the bypass flow to enumerate migrants and allow for the monitoring of fish condition. The injury and mortality rates for the three species tested is presented in Table 1 below. It should be noted that these were calculated for the sampled population, which experience additional holding and handling, and the unsampled population likely has lower rates of injury and mortality.

While there may be aspects of the North Fork/River Mill design that may inform downstream passage solutions at WVP dams, a notable difference is the minor operational reservoir fluctuation that North Fork experiences (approximately 5 feet, basically run of river) compared to reservoir fluctuations at many of the WVP projects.

Table 1. Injury Rates by Species for the North Fork Bypass System (2016-2018)

Species	N	Major Injury	Other Injury	Mortality
Chinook	184	1.1% (0.8%)	3.2% (1.3%)	0.5% (0.5%)
Coho	246	0.8% (0.6%)	2.0% (0.8%)	0.4% (0.4%)
Steelhead	475	0.4% (0.3%)	0.6% (0.4%)	0.2% (0.2%)

NOTE: Shown are the numbers of smolts examined (N) and the estimated injury rate by injury category (Major, Other, Mortality) with standard error (SE) in parentheses (from Ackerman and Pyper 2019, *In Preparation*)

2.3 WILLAMETTE VALLEY HIGH-HEAD BYPASS RESEARCH

2.3.1 Green Peter High Head Bypass Tests

Green Peter Dam is a 380-foot-high multipurpose project located on the Middle Santiam River, Oregon, and is owned and operated by USACE. As part of the Willamette Valley High-Head Bypass research project, biological studies were conducted at the Green Peter Dam juvenile bypass system to evaluate direct injury and direct survival (48-hour survival) of juvenile salmon and steelhead during 2015 to 2017. The tests were conducted using live fish and sensor fish during the late spring of each of the 3 years of the testing period, under three flow treatment conditions: full flow, 75% flow, and 40-50% flow. A knife gate flow control valve on the upstream side of the bypass was used to control flow in the bypass pipe.

The primary goals of these tests were to discern direct (48hr) survival and injury rates at high velocities and at transitions from pressurized to non-pressurized flow in a pipe. Green Peter was selected as a viable test site since it has four existing 12-inch-diameter conduits that run through the dam at four different locations below the maximum conservation reservoir elevation of 1,010 feet. Each of the pipes is 25 feet apart (elevations 910, 935, 960, and 985 feet) and runs through the dam to the downstream face, with the deepest pipe located 100 feet below maximum conservation reservoir elevation. Every pipe has a separate knife gate flow control valve on the upstream interior of the dam. The pipes intersect a 24-inch open conduit that runs down the steep downstream slope of the dam. Fish were released from the forebay deck, via 4-inch flex hose, into one of the 12-inch pipes that penetrate the dam, into the

24-inch pipe and down to an existing evaluation facility at the tailrace. Figure 1 shows a representation of the existing pipe system at Green Peter Dam.

Figure 1. Green Peter Dam Bypass Pipe Elevations (Not to Scale)

Because of reservoir elevations during dry years, the two lowest pipes (elevations 935 and 910 feet) were used for tests for all 3 years of the study, attempting to attain the highest hydrostatic pressures.

Additionally, a study was conducted during 2013 (Normandeau 2014) to evaluate direct injury and direct (48hr) survival of juvenile salmon and steelhead during passage through the steep section of the 24-inch bypass pipe of the Green Peter bypass system. Only the 24-inch pipe was evaluated during this study. Water velocities were calculated at 49 feet per second (fps) with a high survival rate (> 98%) and a low injury rate (< 3%). Sensor fish used in this study experienced the most (23%) significant shear and strike events at the injection system and 24-inch pipe merge. s well, high turbulence in the area of the 24 in. pipe radius and low mean flow depth (2.5 in.) in the 24 inch pipe length related to significant events. Results from the live fish and sensor fish studies are summarized in the following sections.

Live Fish Test Results (2015, 2016, 2017)

Direct injury and direct survival estimates for juvenile fish were as follows:

- Green Peter 24-inch pipe with water velocities @ 49 fp) (Normandeau 2014)
    - Chinook salmon (mean fork length [FL]) 76 millimeters [mm]) = < 3% injury rate; 99.5% survival.
    - Steelhead (mean FL 207 mm) = < 3% injury rate; 98.5% survival.
- Green Peter bypass (12-inch and 24-inch pipes) (Normandeau Associates Inc. 2015, 2017). Elevation differentials tested = 25, 50, 55, and 80 feet. The results were similar for all elevation differentials and all flow conditions tests (full, 75%, and 50% flow); therefore, the results are pooled.
    - Chinook salmon (mean FL 214 mm) = 4% injury rate; 98-100% survival.
    - Steelhead (mean FL 222 mm) = 4% injury rate; 97-100% survival.
    - Young of year steelhead (mean FL 62 mm) = no injuries; 96-100% survival.
    - During 2015, a test was conducted to evaluate flow with the gate valve set for 25% flow (75% closed) and a high rate of injury and mortality was observed, therefore, this treatment test (25% flow) was terminated. It appeared fish were colliding with the knife gate valve obstruction during passage and were severely injured or killed.
- Green Peter bypass (12-inch and 24-inch pipes) (Normandeau Associates Inc. 2018). Elevation differentials tested = 80 and 100 feet. The results were similar for all hydrostatic heads and flow conditions tested (full, 75%, and 50% flow), therefore the results are pooled.
    - Chinook salmon (mean FL 175 mm) = 10% injury rate; 95-100% survival.
    - Larger size Chinook salmon (mean FL 221 mm) = 22% injury rate; 80% survival.
    - Young of year steelhead (mean FL 56 mm) = 6% injury rates; 98-100% survival.

Sensor Fish Studies (2015, 2016, 2017)

The sensor fish studies were conducted in conjunction with live fish releases (Duncan 2013; Deng et al. 2016, 2017, and 2018). Data collected from the sensor fish include pressure, acceleration, and rotation over a time series. During the first 2 years of testing (2015 and 2016), reservoir levels were below normal, which reduced the amount of head the forebay imposed on the passage system. Testing in 2017 saw the highest reservoir levels, which should have provided more relevant test conditions with higher head on the pipes, which theoretically would lead to pressurized conditions in the

12-inch pipes. However, the data using sensor fish showed that the system did not pressurize as expected (Deng et al. 2018). Entrance conditions and characteristics of the release piping system could have been the cause, such as 4-inch flex hose characteristics of actual lengths and friction losses.

Testing in 2016 provided the most valuable results since, though minimal, the system did achieve pressurization in the 12-inch pipe. The results of the 2016 test are summarized below. During the 2016 testing, the forebay range was elevation 989.5 to 991.8 feet.

<u>Flow</u>: Measured flows during testing were between 2.5-3.5 cfs in the 12-inch pipes. As mentioned above, one of the goals was to have a pressurized, or full pipe flow condition, in the 12-inch pipes, with a transition to open channel flow toward the downstream end. The pipes were in reality flowing under open channel conditions, as seen by the pressure measurements, through most of the length of the pipe. Supplemental water from another of the pipes was added to the flow down the steep 24-inch pipe by fully opening one of the upper pipe (elevation 935 feet) valves to achieve 8 cfs total bypass flow at the outfall.

<u>Pressure</u>: The system was slightly pressurized in the 12-inch pipe upstream of the flow control gate valve. When the valve was open 40-50% during the 2016 testing. Pressures of approximately 17 psia were observed upstream of the valve. The pressure immediately went to atmospheric (~ 14 psia) downstream of the valve. The remainder of the system was non-pressurized.

In addition, with the flow control gate valve set at either the full open or 50% closed for all tests, flow was non-pressurized throughout system. The fish releases were from a 4-inch flexible hose from the deck. Full hydraulic head on the pipe was not achieved, which could have been due a combination of losses in the release pipe and conditions in the release system.

<u>Deceleration</u>: A few acceleration “spikes” occurred during the approximately 13 seconds between the slope break at the toe of the dam (flat section of 24-inch pipe) to just upstream of the evaluator during the tests. These few spikes were likely the result of impact of the sensor fish on the pipe walls.

An <u>***average***</u> deceleration of 1.0-1.5 ft/s^2 was observed between the slope break at the toe of the dam to the evaluator.

Relevancy to High-Head Bypass Design Parameters

The tests at the Green Peter bypass system indicate high velocities developed in the steep 24-inch pipe on the downstream face of the dam; approximately 50 fps. The horizontal pipe from the toe of the vertical pipe at the base of the dam to the exit is designed to slow flow and fish from the approximate 50 fps to about 8-9 fps at the exit. Therefore, although fish were traveling down the vertical pipe at approximately 50 fps, deceleration occurred in the horizontal pipe and the velocities were reduced to 8-9 fps before fish exited the pipe.

- In developing design parameters for high-head bypass, a general conclusion shown in these tests is that high velocities are tolerated well by juvenile Chinook salmon and steelhead as long as gradual deceleration occurs prior to fish exiting the bypass.

- The average rate at which high velocities are slowed is a critical factor for safe downstream passage. Deceleration, as discussed above for the Green Peter tests, showed good results at average rates of 1-1.5 ft/s^2.

- Flow depth in high-velocity regions is important, as shallow depth at high velocities lead to a significant chance of collision and strike injuries; established NMFS criteria for depth in open channel conduit should be followed for small conduits that would create shallow flow depths.

2.3.2 Cougar Dam Regulating Outlet Tests

Biological studies were conducted at the regulating outlet (RO) at Cougar Dam to evaluate direct injury and direct survival of juvenile salmon during December 2009 (Duncan 2011, Normandeau 2010) and November 2017 (Deng 2018, Normandeau 2018). The primary goal of both of these tests was to evaluate direct injury and survival of juvenile Chinook salmon passing through the RO under various flow conditions to inform the potential of the regulating outlet or similar pipe as a bypass for downstream fish passage. The service gate of the RO was used to control flow.

For the 2009 study, fish were introduced upstream of RO service gate #1, traveled under the gate, through the RO conduit, then down the steep (70% grade) exit chute to the stilling basin where they were collected. These tests were conducted under two gate openings, 1.5 feet and 3.7 feet, with flows of 440 cfs and 1,040 cfs.

The 2017 study introduced fish downstream of the RO service gate under two gate openings test conditions, 1.3 feet and 2.0 feet, with flows of 480 cfs and 730 cfs, respectively. The forebay elevation for the testing in November 2017 was 1,574 feet.

Live Fish Test Results Summary

The results of the 2009 test indicate overall direct survival was 80.9% for the 1.5-foot gate opening and 88.3% for the 3.7-foot gate opening (Normandeau 2010). However, survival for smaller fish (< 160 mm) was very good, at 97.4%, and 90.8% were malady free under the smaller gate opening. Overall, injury rates were higher (24%) at the smaller gate opening than at the larger gate opening (19%) (Normandeau 2010), so the conclusion is that the larger gate opening provided better conditions for fish passage. The concurrent sensor fish study showed better hydraulic conditions under the larger gate opening.

The results of the 2017 test indicate direct (1hr) survival for juvenile fish at the smaller gate opening (480 cfs) was 97%, while the survival at the larger gate opening (780 cfs) was 88% (Normandeau 2018). The injury rates were 17% and 11% for the two flow conditions, respectively (Normandeau 2018), concluding that although 1-hour survival was higher at the smaller gate opening, injury rates were much higher than at the larger gate opening. Velocity differentials for fish entry from the release pipe into the RO channel were 37.2 fps (1.3-foot gate opening) and 39.7 fps (2.0-foot gate opening) (Deng 2018). The sensor fish data for both tests (2009 and 2017) suggest most of the injuries occurred during passage down the RO chute and not in the RO itself (Duncan 2011, Deng 2018).

Relevance to Design Parameters

- Fish were not depth acclimated for either study, as will likely be the case with surface collection. The 2009 tests showed that with significant pressure changes under the gate to the RO channel, smaller fish (< 160 mm) had a high rate of survival.

- With most injuries occurring on the RO chute, the introduction of fish downstream of the gate, directly into the RO channel, indicates some resilience with significant velocity gradients and high velocities in the RO channel itself.

2.4 HIGH-HEAD BYPASS PROJECTS IN DEVELOPMENT

2.4.1 Cle Elum Dam

Cle Elum Dam is a 165-foot storage dam located on the Cle Elum River, Washington, operated by the Bureau of Reclamation. The dam was not constructed with downstream fish passage structures, and a juvenile fish bypass is currently under construction. The bypass includes a multilevel intake structure in the forebay on the right abutment of the dam that connects to a “helix structure” inside the dam, which then connects to a bypass pipe that exits the dam in the tailrace. The multilevel intake structure has a flow capacity of approximately 400 cfs and will allow the facility to operate under reservoir fluctuation of approximately 100 feet. Several iterations on the design were completed before the final design was decided on. Criteria established for the design (Helix Design for Downstream Passage at Cle Elum Dam, Bureau of Reclamation, November 2015) as follows:

- Minimize impingement of flow and fish.

- Smooth flow conditions.

- Reduce secondary flow rotation to avoid roll-over.

- Minimize turbulence.

- Minimize shear zone and turbulence when merging flows from adjacent inlets.

The Cle Elum bypass project is expected to be completed by 2024.

2.5 DECOMMISSIONED BYPASS PROJECTS

2.5.1 Green Peter Dam

A juvenile fish collection facility with bypass pipes through the dam was constructed with the dam to facilitate downstream migration. The bypass system consisted of a fish well and collection cart in front of the dam and bypass pipes that pass fish through the dam and exited in the tailrace. The bypass was successful at passing juvenile Chinook salmon. However, the bypass facility was decommissioned because of lack of juvenile winter steelhead collection and low return rates of adult fish due to unsuitable tailrace water temperatures. Downstream fish passage currently occurs through the regulating outlets or turbines of the dam. See Section 2.3.1 for research into fish passage at Green Peter Dam.

2.5.2 Cougar Dam

Cougar Dam is a 452-foot-tall multipurpose project located on the South Fork McKenzie River, Oregon, and is owned and operated by USACE. A bypass system was constructed with the dam for downstream fish migration. The bypass system consisted of fish horns at the water intake tower connected to a bypass pipe, which drained vertically into the regulating outlet inside the intake tower. The vertical pipe was approximately 200 feet in length, which meant fish dropped 200 feet vertically with water before landing at the bottom of the regulating outlet. The bypass was decommissioned soon after operation due to high injury and mortality to fish, and currently downstream migrants must pass through the regulating outlet or turbines, located deep in the reservoir.

2.5.3 Fall Creek Dam

Fall Creek Dam is a 205-foot-tall multipurpose project located on Fall Creek, a tributary of the Willamette River, Oregon, and is owned and operated by USACE. A bypass system was constructed with the dam for downstream fish migration. The bypass system consisted of fish horns, located at several positions in the forebay face of the dam, connected to bypass pipes, which exited in the tailrace of the dam. The bypass was decommissioned due to high injury and mortality to fish. Downstream fish passage now occurs through the regulating outlet of the dam. The reservoir is lowered during fall and winter months to a run-of-river elevation, and all water and fish pass the dam though the regulating outlet.

2.5.4 Pelton Round Butte Project

The Pelton Round Butte Project is located on the Deschutes River, Oregon, and is owned and operated by Portland General Electric and the Confederated Tribes of the Warm Springs Reservation of Oregon. The project consists of three dams: Round Butte Dam (440 feet high), Pelton Dam (204 feet high), and Pelton Reregulating Dam (88 feet high). A juvenile fish collection facility and bypass pipes were constructed at Round Butte Dam for downstream migration. However, the facility and bypass pipes were decommissioned in 1966 because of lack of fish attraction to the bypass facility; juvenile fish were not able to easily locate and use the bypass facility.

2.5.5 Upper Baker Dam

Upper Baker Dam, a 312-foot-high dam completed in 1960, and Lower Baker Dam, a 252-foot-high dam completed in 1925, are part of a two-dam system located on the Baker River, Washington, that encompasses the 7.5-mile-long Lake Shannon. Both dams had juvenile fish collection facilities consisting of primitive floating fish screens connected to bypass pipes from 1960 until approximately 2001. The bypass at Upper Baker consisted of a pipe installed diagonally on the downstream face of the dam dropping approximately 290 feet in elevation, with fish exiting the pipe at velocities of at least 40 fps into still water below the dam. The bypass at Lower Baker consisted of a pipe through the reservoir and dam to a level 90 feet below the reservoir surface. Fish traveled through the pipe on the downstream side of the dam and dropped in free fall approximately 160 feet to the river surface. The discharge for both the Upper Baker and Lower Baker bypass pipes was approximately 1-1.5 cfs each.

An estimated 16% stress rate was reported for fish passing through the Lower Baker bypass due to the water column released from the discharge of the pipe imparting velocity on fish, likely to around 50 fps. However, no observed mortality was documented. With reduced flow to eliminate the water column, stress on the fish was eliminated (Bell and Delacey 1972).

Bell and Delacey (1972) also reported that fish were successfully passing through the upper and lower bypass systems based on comparison of downstream collection numbers of fish released above the upper dam, as well as adult returns to the lower dam. However, based on recent conversations with biologists at Puget Sound Energy, subsequent data, including catastrophic drop-offs in adult sockeye and coho returns, showed fish were not successfully passing through both dams. There are a number of possible reasons for the lack of success proposed by Puget Sound Energy biologists, though no contemporary studies on bypass survivability were performed. First, the fish screens had extremely low attraction flow with no nets; 165 cfs and 90 cfs for Upper and Lower Baker dams, respectively, causing few fish to enter into the bypass systems. Second, fish were required to fully navigate Lake Shannon, possibly experiencing high levels of entrainment in the reservoir. Due to the lack of data, estimates of mortality in the bypass systems are also possible.

During the relicensing of the Baker system in 2000, the decision was made to eliminate a bypass system and instead implement a trap and haul system for both dams, for a variety of reasons. Among these was the need to transport fish from above Upper Baker directly below Lower Baker to reduce the likelihood of entrainment in Lake Shannon. Additionally, there were concerns about cost and reliability after a landslide damaged the Lower Baker bypass. Lastly, the decision was made to hold fish in ponds below Lower Baker for approximately 24-48 hours to de-stress and acclimate before volitional release into the river below lower Baker. The logistics of the holding ponds also encouraged a trap and haul system. The decision to decommission the two bypass systems was not due to survivability concerns, but was rather a failure of the collection devices and the nature of a two-dam system.

3. PLANNED RESEARCH, MONITORING & EVALUATION RELATED TO HIGH HEAD BYPASS *(NOTE THIS SECTION TO BE ADDED FOR FINAL DOCUMENTATION OF THE PARAMETER REPORT)*

A growing body of evidence clearly demonstrates juvenile fish that rear in reservoirs have higher than expected mortality rates when captured and handled during field research (Beeman et al 2012;2015, Monzyk et al 2015, Romer 2016, Herron 2018). These fish are often infected with parasitic copepods and it is hypothesized that the parasite has negative effects on the physiology and stress tolerance of juvenile fish, mainly Chinook salmon. The Corps is leading studies with researchers to investigate these effects along with developing protocols to infect test fish for research. Additionally, the Corps is working with researchers to develop methods to study the effects of stress on fish from various conveyances (e.g. trap and haul and piped bypass) at a high head dam.

Information needs are also identified in this document which may be further advanced through the High Head Bypass EDRs for Cougar and Detroit, and objectives will continue to be developed through the annual WATER RM&E development process. These information needs may include biological and bioengineering disciplines, such as hydraulics, structural, mechanical.

4. DESIGN PARAMETERS FOR HIGH-HEAD BYPASS

The parameters described in this section have been identified by the PDT as special concerns for bypassing fish at high-head dams. Table 2 lists these parameters, the NMFS criteria if applicable, and the recommended design parameter guideline for high-head bypass. The table was developed based on review of existing research and the high-head bypass research in the Willamette Valley specific to this project, with consideration of the unique characteristics and operation of high-head projects.

It is important to note that the parameters presented were developed with data which in some cases examined singular aspects of fish passage, and cumulative effects of stresses due to multiple conditions are not necessarily accounted for in the results.

4.1 BYPASS/ENTRANCE PARAMETERS

In general, as stated in the 2011 NMFS criteria: “The screen and bypass must work in tandem to move out-migrating salmonids (including downstream migrant adult salmonids such as steelhead kelts, if present) to the bypass outfall with a minimum of injury or delay.” This general criteria is the overall guidance for any downstream fish passage system and will be the overall goal for any high-head bypass system.

4.1.1 Holding/Handling

Handling includes transfers such as crowding, brailing, sluicing, and netting. Holding is defined as having fish directed to a vessel, tank, raceway, or other area of the facility to delay them for any reason. Holding and handling can cause stress and stress-induced mortality, as well as physical injury and trauma (Schreck 2016, Barton 2002, Pickering 1981). Holding and handling should be avoided; if unavoidable, all steps should be taken to minimize holding and handling.

This parameter is intended to apply to the general population, and it is understood that most systems will require the use of subsampling to monitor for condition issues, and that the sampled fish will be subjected to some degree of holding and handling.

4.1.2 Debris Management and Prevention

Prior to the bypass, all practical means must be taken to remove as much debris as possible, especially larger debris that may cause a blockage. Partial and full debris obstructions within a bypass are a threat to reliable operations and pose a direct risk for fish injury and mortality. It is realistic to assume that multi-stage debris removal strategies will be required at most sites, as they are located in high-elevation reservoirs with significant runoff.

Debris management systems must not pose a threat of injury to fish or delay fish entry. The high-head bypass system design should incorporate debris removal from the area just upstream of the bypass entrance and throughout the bypass system itself.

4.1.3 Access

Where possible, conduits should be open flume to provide maximum access and minimize the potential for debris obstructions. Inspections and monitoring for debris obstructions and monitoring of fish condition and injury must take place frequently to ensure issues are identified as soon as possible, minimizing the risks for fish injury and mortality.

If inspection and debris removal will be through the use of remote equipment, access must be provided at sufficient intervals to allow for effective operations and maintenance. This interval distance will need to be tailored to the specific equipment and operations that are part of the design.

4.1.4 Channel Acceleration and Deceleration

There is established criteria for acceleration in downstream passage to avoid rejection at the bypass entrance, and this criteria would transfer directly to high-head bypass entrances.

The study of fish responses to changes in water velocity has shown that they can use several sensory systems to detect currents, and that they can detect these at velocities as low as 0.03 centimeters per second (Arnold 1974). The established best practice for downstream passage design is that the rate of increase in velocity between any two points in the system should not decrease and should not exceed 0.2 fps per foot of travel. Deceleration at the bypass entrance may require special consideration for monitoring and other evaluation activities.

4.2 BYPASS LAYOUT AND CONDUIT PARAMETERS

4.2.1 Vertical Conduit, Bifurcations, and Merges

Vertical conduit, or free-fall within a pipe or other enclosed conduit in a bypass system, should be avoided if possible. A column of water in a vertical conduit exceeds 50 fps within 42 feet of drop, and would exceed NMFS criteria of 25 fps within 19 feet of drop. Speeds this great are known to injure and kill fish (see shear and velocity parameters below). Additionally, there will likely be turbulent hydraulics in both the conduit and the outfall, further compounding potential risk of injury and mortality. Due to risk and uncertainty, any free-fall may require physical modeling as well as prototype biological testing.

Downwells and convergence/divergence sections must be designed for safe and timely fish passage by proper consideration of turbulence, geometry, and alignment. Turbulence exposes fish to shear forces, as well as recirculation flow patterns.

4.2.2 Pressure

Brown and others (2012) were able to experimentally quantify the factors leading to barotrauma enough to construct a predictive model. They determined that the main factor associated with barotrauma in juvenile Chinook was the ratio between a fish’s depth acclimation and the lowest exposed pressure. Based off of this body of research and the recommendations of Abernathy (2002), the design is recommended to avoid pressures below 7.2 psia or 0.5 atmosphere. It is also recommended to avoid pressure rate changes greater than -500 psi/second. The reader is advised that these values were developed based on the study of salmonids, which are phystomous. The use of these parameter for a bypass where the target species are physoclistic (e.g. members of the orders *Cyprinidae* and *Centrarchidae*) is not advised and may not provide safe passage.

It should be noted that injuries and mortalities observed in these laboratory studies were greatest for depth-acclimated fish. It is unlikely that the fish entering a high-head bypass will be depth-acclimated, since collection systems route fish through free surface conduits that are very shallow (< 2 feet of depth). Physostomes, such as salmon and steelhead, in these conduits should have sufficient time to vent excess gas from their swim bladders before entering a bypass system, which will greatly reduce any risk of barotrauma. It is understood that pressurized flow may be unavoidable in a high-head bypass system due to the large reservoir fluctuations, space constraints, and other operating conditions, but it is safest for fish to travel in an open channel flow condition. Therefore, the design should seek to minimize the length and time fish are exposed to full flow/pressurized conduits, and “u” transitions from free surface to pressurized flow and vice versa should also be avoided in the bypass system.

4.2.3 Conduit Bends

Bends should be minimized in the layout of bypass pipes due to the potential for debris clogging and turbulencAe. Special consideration should be given to bends to minimize supercritical transitions and turbulence. The design should maximize the radius to diameter ratio and consider the conduit shape and canting of the conduit to minimize turbulence and keep fish centered in the water volume.

The ratio of bypass pipe center-line radius of curvature to pipe diameter must be greater than or equal to 5, following NMFS criteria.

4.2.4 Diameter/Geometry

Conduit size and geometry will be determined by hydraulic parameters, including flow, velocity, and minimum depth; however, bypass conduits should be a minimum of 12 inches in diameter/width. Minimum width/diameter is important to avoid debris blockages and to accommodate a range of fish size. Conduit size should be increased as needed to accommodate anticipated debris loads and size, as well as fish size. Smooth transitions throughout the bypass system, including at joints and bends, are required.

4.2.5 Depth of Water in Bypass Conduit

NMFS 2011 criteria states that depth for sub-critical free surface flow in bypass pipes should be greater than or equal to 40% of the pipe diameter. However, for larger pipe diameters, it is possible that depths less than 40% depth to diameter ratio could still provide safe conditions depending on fish size, velocity, alignment, and the roughness of the conduit.

Conduits with supercritical flow may not be able to maintain 40% depth to diameter ratio. Any design falling outside of this criteria would need additional investigation, such as field tests or numerical modeling.

4.2.6 Velocity

Bypass velocities should be greater than or equal to 4 fps to ensure fish are conveyed quickly through the system and to minimize holding and delay. When considering bypass velocities in excess of 12 fps, the design must account for the available cross section of the water and fish size, as well as the conduit itself, due to increased risk of strike, shear, and debris obstructions. The alignment and geometry of the pipe should also be designed to minimize hydraulic transitions and turbulence and to meet the acceleration/deceleration parameter (see Section 4.2.8).

For high-head bypass, there may be a need for velocities to exceed the NMFS guidance for maximum velocity of 12 fps in a bypass. There are numerous examples of fish conveyance structures where fish safely travel at velocities greater than 50 fps (for example, Bonneville Second Powerhouse corner collector, Wanapum Dam bypass, Green Peter bypass conduit, and many spillways and natural fishways). Johnson and others (2003) conducted field and laboratory studies looking at the entry velocity of jets for high-flow outfalls and found that conditions were safe at speeds up to 50 fps.

As discussed in Section 2.1.2, the velocities in themselves are not hazardous; it is the changes in velocity that are the greatest threat to fish safety. The larger your outfall volume, the greater the cross section of your jet, and therefore the lower the risk of fish being exposed to shear planes that could cause injury and mortality. However, high-head bypass conduits will likely not have high rates of discharge (> 100 cfs) or large cross sectional areas for the flow within the conduit. Therefore, the design should keep velocities below 30 fps if possible. For more information on changes in velocity and shear forces, see Section 2.1.2.

The relationship between fish size, available water cross section, and velocity is potentially an area in need of additional study and analysis.

4.2.7 Closure Valves/Flow Control

Regulating the flow into and throughout the bypass will be important in order to maintain safe conditions for fish. This is a particular challenge for systems that experience considerable reservoir pool fluctuations where the conduits between a collector and the bypass system will need to have a variable geometry. In this situation, it may be advantageous to employ a full flow section of bypass conduit, similar to what was installed at the North Fork/River Mill Project (see Section 2.2.2A). Having flow control on the downstream end of a full-flow, gravity-fed conduit could be difficult when the grade of the pipe is steep. Tests at the Green Peter bypass indicate increased injury for fish passing through a 12-inch pipe with a partially closed flow control gate valve (Normandeau 2015, 2018). Under normal operating conditions, a bypass should utilize a fully open cross section, free of flow obstructions.

4.2.8 Conduit Deceleration/Acceleration

Substantial changes in velocity could be necessary for high-head bypass, depending on the layout of the bypass and the existing infrastructure of the project. These velocity changes would occur after the fish enter a bypass conduit and are not likely to be able to exit back upstream. For acceleration and deceleration parameters at the bypass entrance refer to Section 4.1.4.

Changes in velocity are a critical element and must be carefully considered in high-head bypass design. The rate of change in speed of the flow is important and has been shown to affect injury and survival between the bypass and the outfall, especially when fish are being transported at high velocities (greater than 12 fps). A summary of research focused on the effects of shear is presented in Section 2.1.2 of this report. This body of evidence shows consistent results for conditions that cause injury and mortality in juvenile salmonids (as well as other species), especially for velocities in excess of 30 fps.

The speed at which a fish and the body of water that it is traveling in does not in itself injure or kill; however, it exposes the fish to increased risk of dangerous turbulence and shear forces. Bypass designs should try to minimize the potential for both turbulence and shear and try to keep the velocities of fish laden water as uniform as possible. *"Uniform velocities typically present in a stream or artificial conduit do not harm fish. For example, a fish moving 0.3 m/s or 30 m/s (~1.0 or ~100 fps) will not be injured or disoriented if velocities of the water mass in which the fish is traveling are relatively uniform."* Neitzel et al., 2000).

Deng (2005) saw low probabilities of injury when fish acceleration rates were 100 m/s^2 (328 ft/s^2) for fish exposed to a high speed jet (27 fps). This represented the worst case scenario for injury as the fish were exposed to the shear zone head first with a negative rheotaxis. Because the orientation of fish to the bulk flow in a high speed bypass conduit is unknown, the design should ensure that fish accelerations/ decelerations are less than 100 m/s^2 (328 ft/s^2). It should also be noted that these lab studies exposed fish to a single acceleration event. Consideration should be made to reduce the number of acceleration events and try to reduce the acceleration rate as much as possible to reduce the risk of shear injury and passage related stress.

4.2.9 Bypass Outfall

Design should follow NMFS criteria. If deviation is necessary, model or prototype testing would be required.

Table 2. High Head Bypass Design Parameters

Parameter	2011 NMFS Criteria	High Head Bypass Proposed Guideline
General	The screen and bypass must work in tandem to move out-migrating salmonids (including downstream migrant adult salmonids such as steelhead kelts, if present) to the bypass outfall with a minimum of injury or delay.	Same as NMFS.
BYPASS ENTRANCE		
Holding/ Handling		Holding and handling should be avoided; if unavoidable, all steps should be taken to minimize holding and handling.
Debris management and prevention		Before the bypass entrance, all practical means must be used to remove as much debris as possible, especially large debris that may cause blockage. Debris management systems must not pose a threat of injury to fish or delay fish entry.
Access	Access for inspection and debris removal must be provided at locations in the bypass system where debris accumulations may occur.	The entire bypass system must be designed to be dewatered and inspected visually either through direct access (e.g. ports or an open channel) or remote equipment. The system also must be designed to allow for the removal of any debris within the bypass.
Channel Acceleration/ Deceleration	To ensure that fish move quickly through the bypass channel (i.e., the conveyance from the terminus of the screen to the bypass pipe), the rate of increase in velocity between any two points in the bypass channel should not decrease and should not exceed 0.2 fps per foot of travel.	Any increase must be <= 0.2 fps per foot of travel to ensure an acceleration profile that reduces risk of fish rejecting the bypass entrance. Deceleration between the capture point and bypass entrance may be necessary for: • debris removal • transition from free surface to full flow conduit at entrance • Passage monitoring (e.g. PIT detection or Vaki counter) • Additional dewatering upstream of a conduit entrance

Parameter	**2011 NMFS Criteria**	**High Head Bypass Proposed Guideline**
BYPASS LAYOUT and CONDUIT		
Vertical Conduit, Bifurcations, and Merges	Fish should not be pumped within the bypass system. Fish must not be allowed to free-fall within a pipe or other enclosed conduit in a bypass system. Downwells must be designed with a free water surface, and designed for safe and timely fish passage by proper consideration of turbulence, geometry, and alignment.	Free-fall within a pipe or other enclosed conduit in a bypass system should be avoided if possible. Downwells and convergence/divergence sections must be designed for safe and timely fish passage, considering turbulence, geometry, and alignment.
Pressure	In general, bypass flows in any type of conveyance structure should be open channel. If required by site conditions, pressures in the bypass pipe must be equal to or above atmospheric pressures. Pressurized to non-pressurized (or vice-versa) transitions should be avoided within the pipe. Bypass pipes must be designed to allow trapped air to escape.	Pressure in a system should be >= 7.2 psia (~ 0.5 atmosphere) Avoid pressure change rates > -500 psi/sec (Abernathy et Al. 2002).
Pipe Bends	Bends should be avoided in the layout of bypass pipes due to the potential for debris clogging and turbulence. The ratio of bypass pipe centerline radius of curvature to pipe diameter (R/D) must be greater than or equal to 5. Greater R/D may be required for super-critical velocities (see Section 11.9.3.8).	The ratio of bypass pipe center-line radius of curvature to pipe diameter (R/D) >=5. Use of bends should be minimized in the layout of bypass pipes due to the potential for debris clogging and turbulence. R/D ratio should be maximized and consider the conduit shape and canting of the conduit to minimize debris issues, turbulence and keep fish centered in the water volume.
Diameter/ Geometry	The bypass pipe diameter or open channel bypass geometry should generally be a function of the *bypass flow* and slope, and should be chosen based on achieving the velocity and depth criteria in Sections 11.9.3.8 and 11.9.3.9.	Hydraulics and flow will set geometry and diameter. Bypass pipes and flumes diameter or width must be >= 12 inches to reduce risk of debris blockage and accommodate adult sized fish. Maximum diameter/width of bypass conduit<= 30 inches.

Parameter	**2011 NMFS Criteria**	**High Head Bypass Proposed Guideline**
Depth of Water in Bypass Conduit	The design minimum depth of free surface flow in a bypass pipe should be at least 40% of the bypass pipe diameter, unless otherwise approved by NMFS.	Depth for sub-critical free surface flow in bypass pipes >= 40% of the diameter. For larger pipe diameters, depths less than 40% could provide safe conditions depending on fish size, velocity, alignment, and the roughness of the conduit.
Velocity	The design bypass pipe velocity should be between 6 and 12 fps for the entire operational range. If higher velocities are approved, special attention to pipe and joint smoothness must be demonstrated by the design. To reduce silt and sand accumulation in the bypass pipe, pipe velocity must not be less than 2 fps.	Bypass velocities should be >= 4 fps to ensure fish are conveyed quickly through the system and to minimize holding and delay. For high-head bypass design, there may be a need for velocities to exceed the NMFS guidance for maximum velocity (12 fps). Examples of fish conveyance structures where fish safely travel at velocities > 50 fps: Bonneville B2 corner collector, Wanapum Dam bypass, Green Peter bypass conduit, and many spillways and natural fishways. Anytime velocities exceed the established NMFS criteria, designs must consider conduit alignment, risk of shear, how the water and fish are decelerated, and uniformity of flow.
Closure Valves/Flow Control	Closure valves of any type should not be used within the bypass pipe unless specifically approved based on demonstrated fish safety.	Follows NMFS, and consider other means of flow control, such as manipulating pipe elevations or the use of overflow weirs.
Deceleration/ Acceleration	No criteria listed for piped bypass.	Acceleration/Deceleration rate is to be as low as practical and not to exceed 328 ft/s^2. Also it is important to minimize the total number of acceleration/deceleration events.
BYPASS OUTFALL		
		Design should follow NMFS criteria. If deviation is necessary, model/prototype testing would be required.

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