DESIGN OF UPSTREAM FISH PASSAGE SYSTEMS

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Sockeye and Summer Chinook Salmon in Fish Viewing Window at Wells Dam, Columbia River

(Photo courtesy of Douglas PUD)

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Section 1.1 - Introduction to Upstream Fish Passage Systems

This portion of fish passage instruction is intended to assist with designing upstream fish passage facilities for fish species that must migrate upstream past passage impediments or barriers to complete their life cycle. The task involved with successful upstream fish passage is a dynamic integration of fish behavior, physiology, and bio-mechanics with hydraulic analysis, hydrologic study, and engineering. All six of these integrated tasks play a specific and important individual role in the design of an upstream fish passage facility. None of these tasks can be ignored, and a fishway design can fail if each task isn't properly assessed and understood. Installing a fish passage structure does not constitute providing satisfactory fish passage unless all of the above components are adequately factored into the design. This instruction is intended to provide the best guidance possible toward achieving safe, timely and efficient upstream fish passage.

<u>Safe, Timely and Efficient Upstream Fish Passage</u>

Safe passage means that active migrants are passed upstream of an impediment with minimal facility induced injury and mortality rates. Depending on the challenges of upstream passage at a site, combined injury and mortality rates at upstream passage sites in the Pacific Northwest are usually less than 2% from fish entry into the project tailrace to fish exit from the project forebay. Many upstream passage facilities for Pacific salmon have survival rates of greater than 99.5%. Some sites, such as Bonneville Dam have active predators (mostly California Sea Lions) in the tailrace below the dam, that often wreak havoc on salmon runs before they are able to reach the relative safety of the fish ladders. Fish Counters have reported rates of up to 40% of the dam count with marine mammal bites or scratches, which can be fatal. Direct observation of Sea Lion predation was measured to be at least 4.2% in the Bonneville Dam tailrace in 2007. This percentage is considered to be a minimum, because many predation events were likely unobserved.

Timely passage occurs when delay time for active upstream migrants is minimized. At some hydro projects in the Pacific Northwest, timely passage has been defined as passage times measured at less than or equal to 24 hours, with no more than 5% of the active migrants taking longer than 1 week to pass. This example of timely passage is for Pacific Salmon at Merwin Dam on the Lewis River, Washington, per agreements made between the fisheries parties and the power utility regarding upstream passage efficiency. Median delay times of less than 24 hours have been demonstrated to be achievable for multiple adult salmonid species at many hydro projects, as documented through radio telemetry studies in the Upper Columbia River and other locations. This parameter is species dependent and possibly site dependent.

Efficient passage means that most or all of the active adult migrants are passed upstream of the dam. Passage success has been measured at greater than 98% for multiple adult salmonid species at many hydro projects in the Pacific Northwest, including the five public utility district operated dams on the upper Columbia River. PIT tag detections from 2003 to 2008 indicate that summer steelhead, spring Chinook and summer Chinook migrating through the Columbia River from Priest Rapids to Wells Dams (5 dams total) pass at minimum rates of 98.2%, 98.1% and 98.3% respectively. These rates are considered to be minimum dam passage efficiency rates because the rates include removal of unknown numbers of tagged fish in the project reservoirs, such as from sport fisheries and other activities.

Upstream Passage Impediments and Barriers

An upstream passage impediment is defined as any structural feature or project operation that causes adult or juvenile fish to be injured, killed, blocked, or delayed in their upstream migration, to a greater degree than in a natural river setting. Artificial impediments require a fish passage design using conservative criteria, because the natural complexity that usually provides fish passage has been substantially altered. Conservative criteria are also required to allow for a range in the physical abilities of multiple life stages and multiple species of fish, as well as variability within specific species and life stages.

It is important to note that no upstream passage facility constructed at an upstream passage impediment can fully compensate for an unimpeded natural channel. As such, additional mitigation measures may be required on a case-by-case basis.

In the context of upstream passage at FERC projects, there are several factors that could influence safe, timely and efficient fish passage. These include (but of course, are not limited to) attraction to a dead end passage route (spillway, turbine flows), fallback through spillways, locks or turbines, reductions in streamflow and the primary factor of a vertical structure in a mostly horizontal river.

The examples listed below do not necessarily imply that passage is completely blocked by the impediment. Rather, this list is comprised of situations where fish passage does not readily occur, in comparison to a natural stream system. Some of the examples in the list do create absolute barriers to fish, depending on the magnitude of the specific example. Examples of passage impediments and barriers include, but are not limited to, the following:

- Permanent or intermittent dams.
- Hydraulic drop over an artificial instream structure in excess of the jumping ability of the weakest species.
- Weirs, aprons, hydraulic jumps or other hydraulic features that produce shallow depth (eg. shallow depths, flow velocity greater than swim burst velocity than 12 ft/s for over 90% of the stream channel cross section.
- Diffused or braided flow that impede the approach to the impediment.
- Project operations that lead upstream migrants into impassable routes.
- Upstream passage facilities that do not satisfy specified design guidelines and criteria.
- Poorly designed headcut control or bank stabilization measures that create impediments such as listed above.
- Insufficient bypass reach flows to allow or induce upstream migrants to move upstream into the bypass reach adjacent to a powerhouse or wasteway return.
- Degraded water quality in a bypass reach, relative to that downstream of the confluence of bypass reach and flow return discharges (e.g., at the confluence of a hydroproject tailrace that returns flow diverted from the river at some upstream location).
- Ramping rates in streams or in bypass reachs that delay or strand fish.

- Discharges to or from the stream that may be detected and entered by fish with no certain means of continuing their migration (e.g., poorly designed spillways, cross-basin water transfers, unscreened diversions).
- Discharges to or from the stream that are attractive to migrating fish (e.g., turbine draft tubes, shallow aprons and flow discharges) that have the potential to cause injury.
- Water diversions that reduce instream flow.

Objectives of Upstream Passage Instruction

In addition to describing the configuration and application of the particular styles of fish ladders, this training manual identifies the process for developing general criteria and guidelines for use in completion of upstream fish passage facility design, and to identify potential pitfalls and advantages for particular types of passage systems given specific site conditions.

In general, NMFS requires volitional passage, as opposed to trap and haul, for all passage facilities. This is primarily due to the risks associated with the handling and transport of migrant salmonids, in combination with the long term uncertainty of funding, maintenance, and operation of the trap and haul program including facility failure. However, there are instances in which trap and haul may be the best viable option for upstream and/or downstream fish passage at a particular site, due to height of the dam, temperature issues in a long ladder, passage through multiple projects or other site- specific issues. The design of trap and haul facilities will be covered in another training session.

The criteria and guidelines included in this document were specifically developed for upstream passage of adult Pacific salmon in “moderately-sized” streams. This description is intentionally vague, because the variability of sites and passage needs within the Pacific Northwest do not lend themselves to a “one size fits all” document specifying stringent criteria for upstream passage systems.

Criteria are specific standards for fishway design, maintenance, or operation that cannot be changed without a written waiver from NMFS. For the purposes of this document, a criterion is preceded by the word “must.” In general, a specific criterion can not be changed unless there is site-specific biological rationale for doing so. An example of biological rationale that could lead to criterion waiver is a determination or confirmation by NMFS biologists that the smallest fry-sized fish will likely not be present at a proposed screen site. Therefore, the juvenile fish screen approach velocity criterion of 0.4 ft/s could be increased to match the smallest life stage expected at the screen site.

A guideline is a range of values or a specific value for fishway design, maintenance or operation that may change when site-specific conditions are factored into the conceptual fishway design. For the purposes of this document guidelines are preceded by the word “should.” Guidelines should be followed in the fishway design until site-specific information indicates that a different value would provide better fish passage conditions or solve site-specific issues. An example of site-specific rationale that could lead to a modified guideline is when the maximum river depth at a site is 3 feet, as compared to the design guideline for a fishway entrance depth of 6 feet. In this example, safe and timely fish passage could be provided by modifying the guideline to match the depth in the river.

It is the responsibility of the applicant to provide compelling evidence in support of any proposed waiver of criteria or modification of a guideline for NMFS approval early in the design process, well in advance of any proposed Federal action.

Take home introductory message

Keep in mind that the criteria and guidelines included in this document are specifically developed for the different species of anadromous Pacific salmon. Use of these criteria and guidelines for other species is not suggested by their use in examples in this fish passage course, and is in fact irresponsible, unless it can be verified that they are suitable for other fish species. The goal of this fishway instruction is to identify a process for fishway design, along with presentation of the role for and design of various components of upstream passage systems, and the integration of components of a passage system to provide a design for an upstream fish passage facility. In this course, the use of criteria and guidelines for pacific salmon are only for demonstration of application of criteria and guidelines.

Section 1.2 - Fish Passage Definitions

Attraction flow - the flow that emanates from a fishway entrance with sufficient velocity and in sufficient quantity and location to attract upstream migrants into the fishway. Attraction flow consists of gravity flow from the fish ladder, plus any auxiliary water system flow added at points within the lower fish ladder.

Auxiliary water system - a hydraulic system that augments fish ladder flow at various points in the upstream passage facility. Typically, large amounts of auxiliary water flow are added in the fishway entrance pool in order to increase the attraction of the fishway entrance.

Backwater - a condition whereby a hydraulic drop is influenced or controlled by a water surface control feature located downstream of the hydraulic drop.

Baffles - physical structures placed in the flow path designed to dissipate energy or to re-direct flow for the purpose of achieving more uniform flow conditions.

Bedload - sand, silt, gravel, or soil and rock debris transported by moving water on or near the streambed.

Bifurcation (Trifurcation) pools - pools where two or three sections of fish ladders divide into separate routes.

Burst speed – A speed that can be maintained by a fish for a duration of only a second or so – also called darting speed.

Bypass reach - the portion of the river between the point of flow diversion and the point of flow return to the river.

Conceptual design - an initial design concept based on the site conditions and biological needs of the species intended for passage. This is also sometimes referred to as preliminary design or functional design.

Cruising speed – a speed that can be maintained by a fish for a several hours.

Diffuser - typically, a set of horizontal or vertical bars designed to introduce flow into a fishway in a nearly uniform fashion. Other means are also available that may accomplish this objective.

Exclusion barriers - upstream passage facilities that prevent upstream migrants from entering areas with no upstream egress, or areas that may lead to fish injury.

Exit control section - the upper portion of an upstream passage facility that serves to provide suitable passage conditions to accommodate varying forebay water surfaces, through means of pool geometry, weir design, and the capability to add or remove flow at specific locations.

False weir - a device that adds vertical flow to a upstream fishway, usually used in conjunction with a distribution flume that routes fish to a specific area for sorting or to continue upstream passage.

Fish ladder - the structural component of an upstream passage facility that dissipates the potential energy into discrete pools, or uniformly dissipates energy with a single baffled chute placed between an entrance pool and an exit pool or with a series of baffled chutes and resting pools.

Fish lift - a mechanical component of an upstream passage system that provides fish passage by lifting fish in a water-filled hopper or other lifting device into a conveyance structure that delivers upstream migrants past the impediment.

Fish lock - a mechanical and hydraulic component of an upstream passage system that provides fish passage by attracting or crowding fish into the lock chamber, activating a closure device to prevent fish from escaping, introducing flow into the enclosed lock, and raising the water surface to forebay level, and then opening a gate to allow the fish to exit.

Fish passage season - the range of dates when a species migrates to the site of an existing or proposed fishway, based on either available data collected for a site, or consistent with the opinion of an assigned NMFS biologist when no data is available.

Fish weir (also called picket weir or fish fence) - a device with closely spaced pickets to allow passage of flow, but preclude upstream passage of adult fish. Normally, this term is applied to the device used to guide fish into an adult fish trap or counting window. This device is not a weir in the hydraulic sense.

Fishway - the set of facilities, structures, devices, measures, and project operations that together constitute, and are essential to the success of, an upstream or downstream fish passage system.

Fishway entrance - the component of an upstream passage facility that discharges attraction flow into the tailrace, where upstream migrating fish enter (and flow exits) the fishway.

Fishway exit - the component of an upstream passage facility where flow from the forebay enters the fishway, and where fish exit into the forebay upstream of the passage impediment.

Fishway entrance pool - the pool immediately upstream of the fishway entrance(s), where fish ladder flow combines with any remaining auxiliary water system flow to form the attraction flow.

Fishway weir - the partition that passes flow between adjacent pools in a fishway.

Flood frequency - the frequency with which a flood of a given river flow has the probability of recurring based on historic flow records. For example, a "100-year" frequency flood refers to a flood flow of a magnitude likely to occur on the average of once every 100 years, or, has a one-percent chance of being exceeded in any year. Although calculation of possible recurrence is often based on historical records, there is no guarantee that a "100-year" flood will occur within the 100-year period or that it will not recur several times.

Flow duration exceedence curve - the plot of the relationship between the magnitude of daily flow and the percentage of the time period for which that flow is likely to be equaled or exceeded. Other time units can be used as well, depending on the intended application of the data.

Flow egress weir - a weir used to route excess flow (without fish) from a fish facility.

Forebay - the water body impounded immediately upstream of a dam.

Freeboard - the height of a structure that extends above the maximum water surface elevation.

Functional design - an initial design concept, based on the site conditions and biological needs of the species intended for passage. This is also sometimes referred to as preliminary design or conceptual design.

Head loss - the loss of energy through a hydraulic structure.

Hopper - a device used to lift fish (in water) from a collection or holding area, for release upstream of the impediment.

Hydraulic drop - the energy difference between an upstream and downstream water surface, considering potential (elevation) and kinetic energy (velocity head), and pressure head. For fishway entrances and fishway weirs, the difference in kinetic energy and pressure head is usually negligible and only water surface elevation differences are considered when estimating hydraulic drop across the structure. As such, staff gages that indicate hydraulic drop over these structures must be suitably located to avoid the drawdown of the water surface due to flow accelerating through the fishway weir or fishway entrance.

Picket leads or Pickets - a set of vertically inclined flat bars or circular slender columns (pickets), designed to exclude fish from a specific point of passage (also, see fish weir).

PIT- tag detector - a device that passively scans a fish for the presence of a passive integrated transponder (PIT) tag that is implanted in a fish and read when activated by an electro-magnetic field generated by the detector.

Plunging flow - flow over a weir that falls into the receiving pool with a water surface elevation below the weir crest elevation. Generally, surface flow in the receiving pool is in the upstream direction, downstream from the point of entry into the receiving pool.

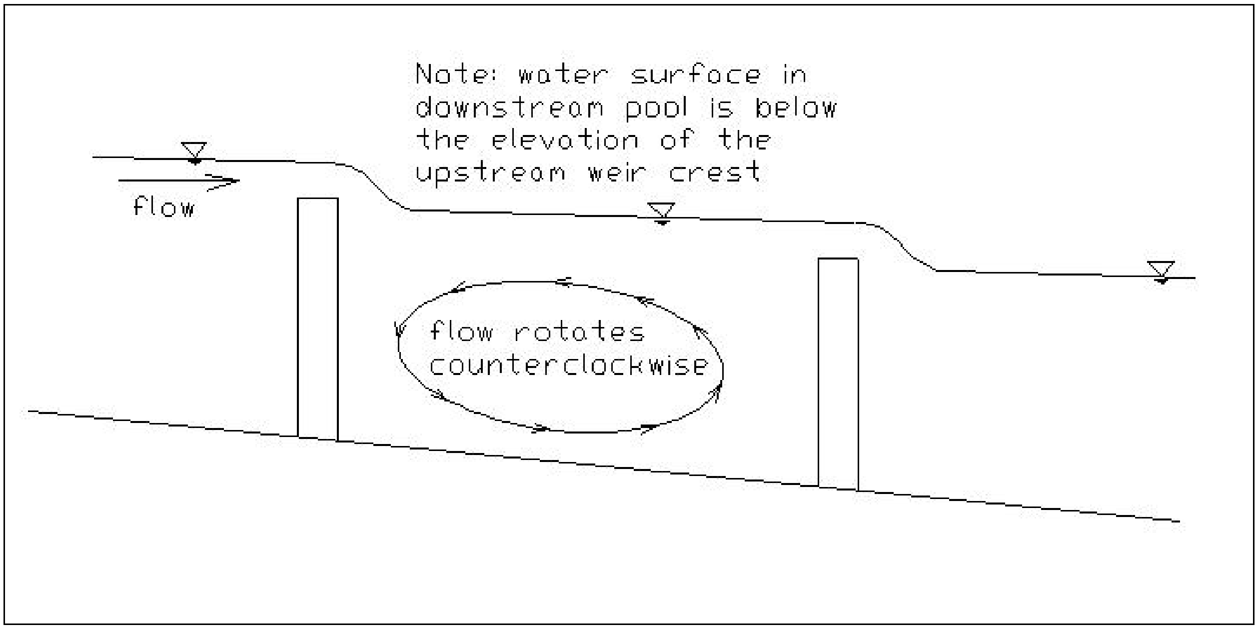

Figure 1.2a - Plunging Flow over Fishway Weir

Porosity - the open area of a mesh, screen, rack or other flow area relative to the entire gross area.

Positive-exclusion - a means of excluding fish by providing a barrier which they can not physically pass through.

Preliminary design - an initial design concept, based on the site conditions and biological needs of the species intended for passage. This is also sometimes referred to as functional design or conceptual design.

Ramping rates - the rate at which (typically inches per hour) a flow is artificially altered to accommodate diversion requirements.

Rating curve - the graphed data depicting the relationship between water surface elevation and flow.

Streaming flow - flow over a weir which falls into a receiving pool with water surface elevation above the weir crest elevation. Generally, surface flow in the receiving pool is in the downstream direction, downstream from the point of entry into the receiving pool.

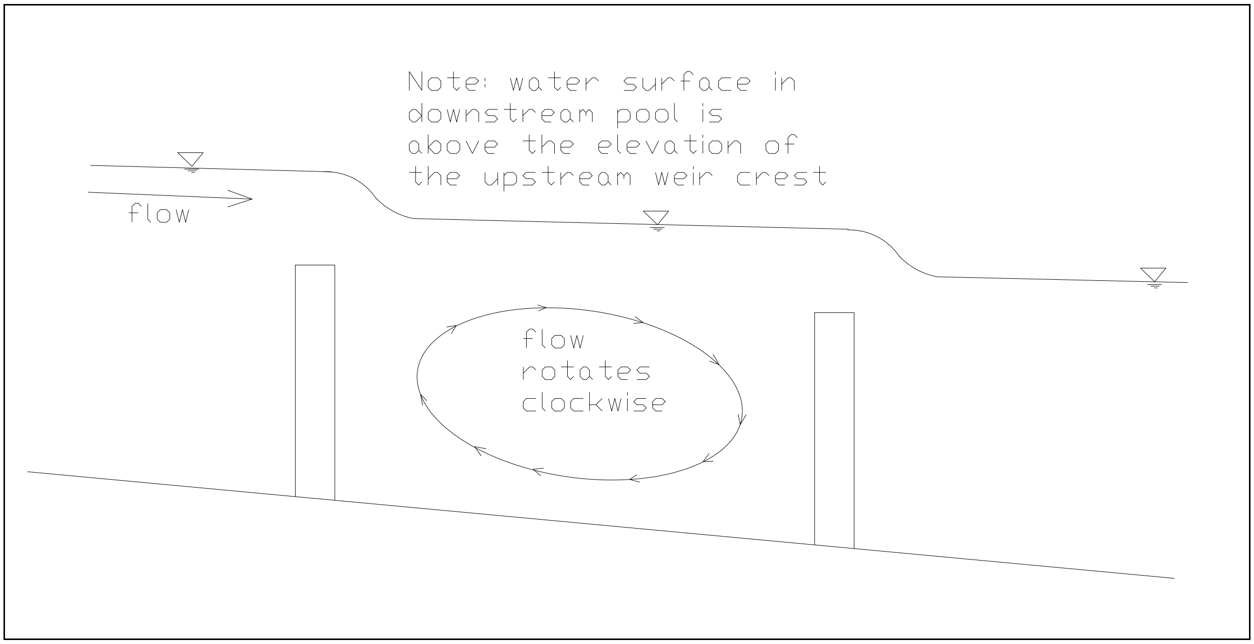

Figure 1.2b - Streaming Flow over Fishway Weir

Sustained Speed – a speed that can be maintained by a fish for a few minutes

Tailrace - the stream immediately downstream of an instream structure.

Tailwater - the body of water that flows below a dam.

Total project head - the difference in water surface elevation from upstream to downstream of an impediment such as a dam. Normally, total project head encompasses a range based on stream flows and/or the operation of flow control devices.

Thalweg - the stream flow path following the deepest parts of a stream channel and contain the highest percentage of streamflow.

Training wall - a physical structure designed to direct flow to a specific location or in a specific direction.

Transport channel - a hydraulic conveyance designed to pass fish between different sections of a fish passage facility.

Transport velocity - the velocity of flow within the migration corridor of a fishway, excluding areas with any hydraulic drops greater than 0.1 feet.

Trap and Haul - a fish passage facility designed to trap fish for upstream or downstream transport to continue their migration.

Trash rack - a rack of vertical bars with spacing designed to catch debris and preclude it from entering the fishway, while providing sufficient opening to allow the passage of fish.

Trash rack, coarse - a rack of vertical bars with spacing designed to catch large debris and preclude it from entering the fishway, while providing sufficient opening to allow the passage of fish.

Trash rack, fine - a rack of vertical bars designed to catch debris and reduce or eliminate entry of fish into the intake of an auxiliary water system.

Upstream fish passage - fish passage relating to upstream migration of adult and/or juvenile fish.

Upstream passage facility - a fishway system designed to pass fish upstream of a passage impediment, either by volitional passage or non-volitional passage.

Velocity head (h_v) - the kinetic energy of flow contained by the water velocity, calculated by the square of the velocity (V) divided by two times the gravitational constant (g) ($h_v = V^2/2g$).

Volitional passage - fish passage made continuously available without trap and transport.

Wasteway - a conveyance which returns water originally diverted from an upstream location back to the diverted stream.

Weir - an obstruction over which water flows.

Section 1.3 - Fish Passage Design Flows

In the Northwest Region, NMFS requires that fishways for upstream passage of anadromous salmonids function at least 90% of the time during the fish passage season, or between the 5% and 95% exceedence flows that occur during the fish passage season. The 5% and 95% are termed the Fish Passage Design High Flow and the Fish Passage Design Low Flow, respectively. The establishment of fish passage design flows between the 5% and 95% is somewhat arbitrary, but it is generally understood that upstream fish passage in many river systems can not occur naturally for all flows. Most streams in the Northwest have sufficient gradient such that high river flows produce velocities and turbulence that temporarily stop passage from occurring. During high flow conditions, fish often seek slower moving stream edges, back eddies or other refuge from higher flows. When streamflows start to recede, upstream migration once again continues. Similarly, when streamflows are low, flow depths and sometimes water quality conditions cause delays in migration until suitable passage conditions occur. Fish often wait in bays and larger rivers until tributary flow increases such that depths and water temperatures are conducive to upstream migration.

Choosing an exceedence flow band for the fish passage design flow range for other species requires specific understanding of under what conditions that species migrates. For some species, the migration flow range or time period may be extremely limited, and for others it may be year round. If the migration period and flow range are unknown, a field study could help to determine this range for a particular site. Minimally, a literature search should be conducted to determine the migration period for a particular species, and field visits could be conducted to get a sense of which flow conditions might be passable for that species.

Recall that the 5% and 95% exceedence flows are flow derived from the relationship between the magnitude of daily average flow and the percentage of the time period for which that flow is likely to be equaled or exceeded. Adding the stipulation that the Fish Passage Design Flows are calculated from the period of record during the fish passage season usually, but not always, truncates the period to be less than annual. If multiple species are to be passed, the migration periods may overlap and the period of record used in calculating the fishway design flows encompasses the total of all migration periods.

Example: Fish Passage Design Flow Calculation

> There are runs of winter steelhead and spring Chinook in the Easycatchum river. Historically in the Easycatchum, per the local biologist, steelhead are known to migrate from December 1 to April 1, and Chinook migrate from May 15 to September 1. A fishway has been identified as the most suitable option and is currently being designed to provide fish upstream passage past the Slowemdown Powerdam.
>
> The USGS gage data for the site contains 24 years of daily flow data. This daily flow data is downloaded into a two column spreadsheet in sequential format, i.e. from earliest date of record to latest date of record, with the corresponding daily average flows in the adjacent column. The entire data set contains about 8,766 (24 years times 365 days) flow records, in theory (some records may be missing or unusable).

> From the passage seasons identified above, the 45 dates between April 1 and May 15 and the 90 dates between September 1 and December 1 are deleted from the data set. When the original data set is reduced by the 3,240 (45 days times 24 years plus 90 days times 24 years) daily records, the resulting data is about 5,526 daily average flow records long.
>
> This data set is then sorted by flow amount from high flow to low flow, making sure to carry the dates along with the flows in the sort. After the sort, the flow corresponding to the 276th record (calculated by 5% of 5,526, or 276 when rounded) represents the Fish Passage Design High Flow, or the 5% exceedence flow during passage season. Similarly, the flow corresponding to the 5,250th record (95% of 5526) represents the Fish Passage Design Low Flow, or the 95% exceedence flow during passage season. The low flow is exceeded 95% of the time during the fish passage season, and the high flow is exceeded only 5% of the time during the fish passage season.

The fish passage design flow range must always be checked against operational conditions at the impediment. If in the example above, 70% of the river flow is diverted into the Slowemdown powerhouse leaving only 30% of the flow in the bypass reach, the flow in this reach must also be assessed for fish passage as well as other habitat conditions. It is beyond the scope of this instruction, but various methods such as Incremental Flow Instream Methodology (IFIM) are available to assess habitat and passage conditions in bypass reaches. In addition, ramping rates should be carefully assessed such that stranding of fish or other migration delay does not occur in the bypass reach. If in the example above, the Slowemdown powerhouse always operates during fish passage season, it can be justified that the passage facility attraction flows (see section 1.10) can be reduced by 70%. However, this must be carefully considered before this decision is made. Could the spillway, powerhouse or individual turbines ever be shut down for periods that overlap into fish passage season, putting a different percentage of flow in the bypass reach? Do spillway flows combine with powerhouse flows such that no attraction flow reduction is warranted? There are many potential scenarios such as these to consider, and the fishway designer must consider each scenario for the design site.

Section 1.4 - Basic Fish Passage Hydraulics

The arithmetic involved in designing fishways is not necessarily complex, and a few basic hydraulic relationships should be understood for fishway design analysis.

<u>Continuity Equation</u>
The basic flow relationship, sometimes called the continuity equation, flow equals average velocity times the cross sectional flow area, or:

(equation 1) $Q = VA$

Where Q equals flow in cubic feet per second (cfs), V equals velocity in feet per second (fps) and A equals cross sectional flow area perpendicular to the average velocity vector, measured in square feet (ft^2).

Example: Open Channel flow in a Pipe

> If water flows 1 foot deep at an average velocity of 4 fps in a circular pipe 2 feet in diameter, what is the flow rate?
>
> Using equation 1, the flow area is half of the area of the 2 foot diameter pipe's area, or 1/2 times pi times the radius squared, or $0.5 \times 3.14 \times 1^2$, or $A = 1.57\ ft^2$. Since V is 4 fps, Q equals 4 x 1.57, or 6.28 cfs (rounded).

This is a simple calculation, but of course, there are complications that occur. It is not possible to directly measure average velocity in a cross section with a flow meter or other device. It must itself be calculated for a complicated cross section such as a stream channel. There are specific points in a flow cross section that do generally represent the average velocity, and these could be used in equation 1 to estimate flow rate. Many hydraulic text books include information on a variety of simple channel shapes with the point of average velocity identified. For example, in a rectangular channel less than 3 feet deep, the average velocity can be approximated by measuring the point velocity in the center of the cross section at 60% of the depth. For rectangular channels greater than 3 feet deep, the average velocity can be estimated by averaging two point velocities taken at the 20% and 80% depths in the center of the cross section.

To estimate average velocity in complex channel cross sections such as a stream channel, a velocity reading must be taken from increments of the cross section, with each incremental cross section representing no more than 5% of the total cross section area – in other words, a minimum of 20 velocities must be measured in sequence across the stream channel. For shallow streams (less than 3 feet deep), the point velocity at 60% of the depth of an incremental cross section is usually considered to be representative of the average velocity at that incremental cross section. For deeper incremental cross sections, the 20% and 80% depth point velocities are averaged to obtain the average velocity for that incremental cross section. To calculate the average velocity for the entire cross section of the stream channel, each point velocity is multiplied by the incremental area it represents to obtain the flow in the incremental area (Q=VA). Then, all of the incremental areas are summed up and all of the incremental flows per each incremental area are summed up. The average velocity for the stream cross section is then calculated by dividing the total flow by the total area. For further guidance, see “Water Measurement Manual”, U.S. Bureau of Reclamation, Denver, Colorado, 1981.

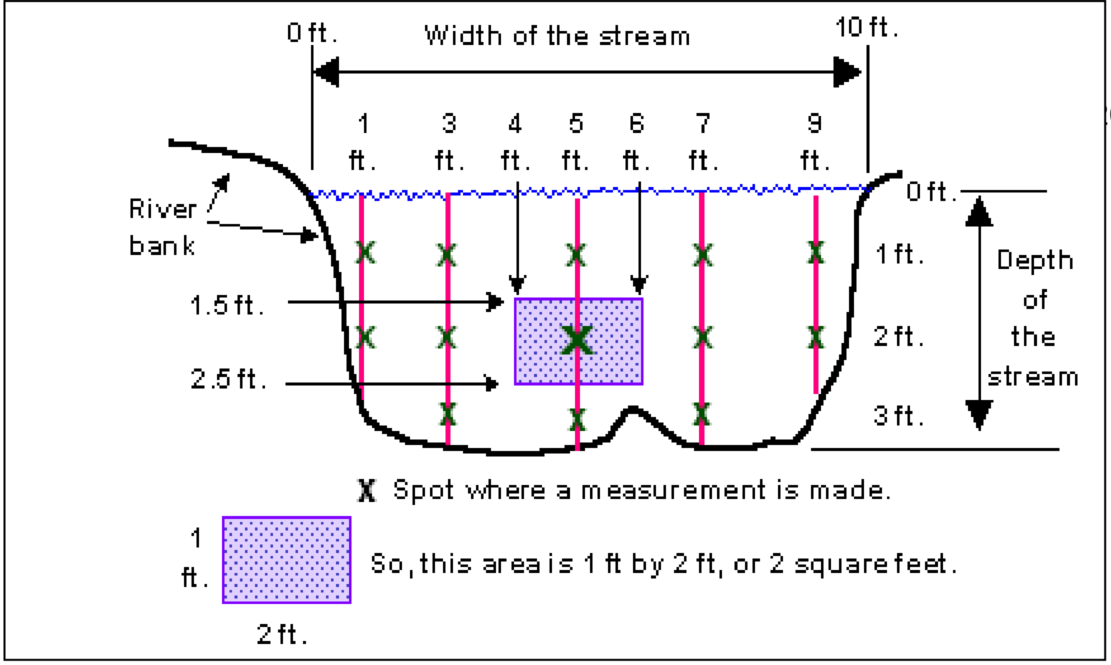

Figure 1.4a - Streamflow Measurement (from U.S. Geological Survey)

Example: Stream flow calculation (from U.S. Geological Survey)

In Figure 1.4a, water depth/velocity measurements are obtained horizontally across the stream at 1, 3, 5, 7, and 9 feet (the vertical lines in the diagram). At each location, measurements of velocity and total depth are obtained. Depending on the depth and flow conditions, one or more velocity reading(s) are obtained in each vertical. For this example, a water depth/velocity measurement is obtained at a point 5 feet from the edge of the stream. The total depth is slightly more than 3 feet and velocity readings are obtained at depths of 1, 2, and 3 feet (the 'X's on the 5-foot vertical line). The purple box represents an area that is midway between this measurement point and the measurement points on either side. The purple area is 2 feet across and one foot high, or 2 square feet. The measured velocity at the big X in the purple box is 2 feet per second. To compute the amount of water flowing in that purple area each second, multiply the area of the purple box times the velocity of the water:

(1) 2 feet wide x 1 foot high = 2 square feet

(2) 2 square feet x 2 feet per second = 4 cubic feet per second.

To compute the total stream streamflow the hydrologist has to create imaginary purple boxes between all of the 'X's and, using the velocity of the water in every box, compute the streamflow for each purple area. Summing the flows for all the purple areas will give the total streamflow. Actually, the example above is a simplified explanation of how streamflow is measured. When an actual measurement is made, the hydrologist takes measurements at about 20 points across the stream. The goal is to have no one vertical cross-section contain more than 5 percent of the total stream discharge.

Velocity Head

When water moves, potential energy is converted to kinetic energy termed velocity head, and is calculated by the relationship identified in equation 2:

(equation 2) $h_v = V^2 / 2g$

where h_v is velocity head, V is velocity, and g is the gravitational constant 32.2 feet per second squared.

Example: calculation of velocity head as flow approaches a weir

An example of transition from potential energy to kinetic energy occurs when flow from a relatively tranquil fishway pool accelerates as it moves toward a fishway weir. In Figure 1.4b, a particle of water near the water surface is traveling very slowly at point A, and accelerates to 4 fps near the weir crest at point B. The velocity head at point B is calculated as:

$h_v = V^2 / 2g = (4 \text{ fps})^2 / (2 \times 32.2 \text{ ft/s}^2) = 16/64.4 = 0.25$ feet

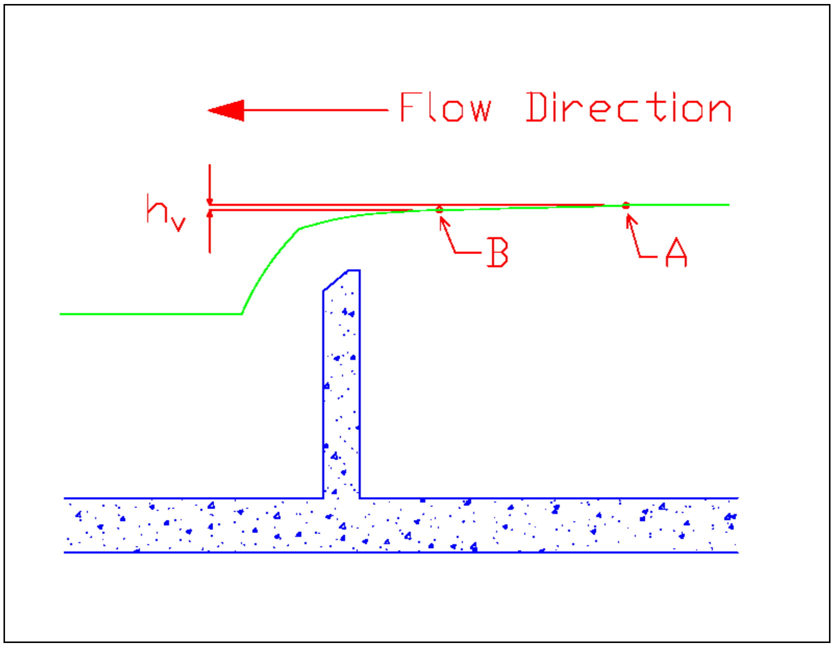

Figure1.4b - Drawdown of water surface at a weir due to velocity head

This example illustrates a point to be considered in design when considering the location of a staff gage to measure water surface elevation at some point in the fishway. The water surface elevation will be reduced as flow approaches a weir and starts to accelerate. For example, if a staff gage is placed too close to a fishway entrance weir that is supposed to record the water surface elevation for the purpose of calculating the fishway entrance head, it will give a misleading (but not wrong) water surface elevation. The water surface elevation will be reduced by a factor proportional to the square of the water velocity. If velocity is low (less than 1 fps), the velocity head is sufficiently low as to not reduce the water surface elevation appreciably.

<u>Weir equation</u>
When water flows over a sharp crested weir, the flow rate can be estimated by equation 3:

> (equation 3) $Q = 3.33 \times L \times H^{1.5}$, where L is the length of the weir in feet and H is the head on the weir in feet and the resulting Q is in cfs.

It is important to note that this equation only applies for a sharp crested weir, with an non-submerged crest with no side contractions. Generally, this equation estimates the maximum flow over a weir. If any of these conditions apply, appropriate coefficients must be applied to estimate flow. For further guidance including calculation of weir coefficients for a variety of weir configurations, see "Water Measurement Manual", U.S. Bureau of Reclamation, Denver, Colorado, 1981.

Example: Weir flow calculation

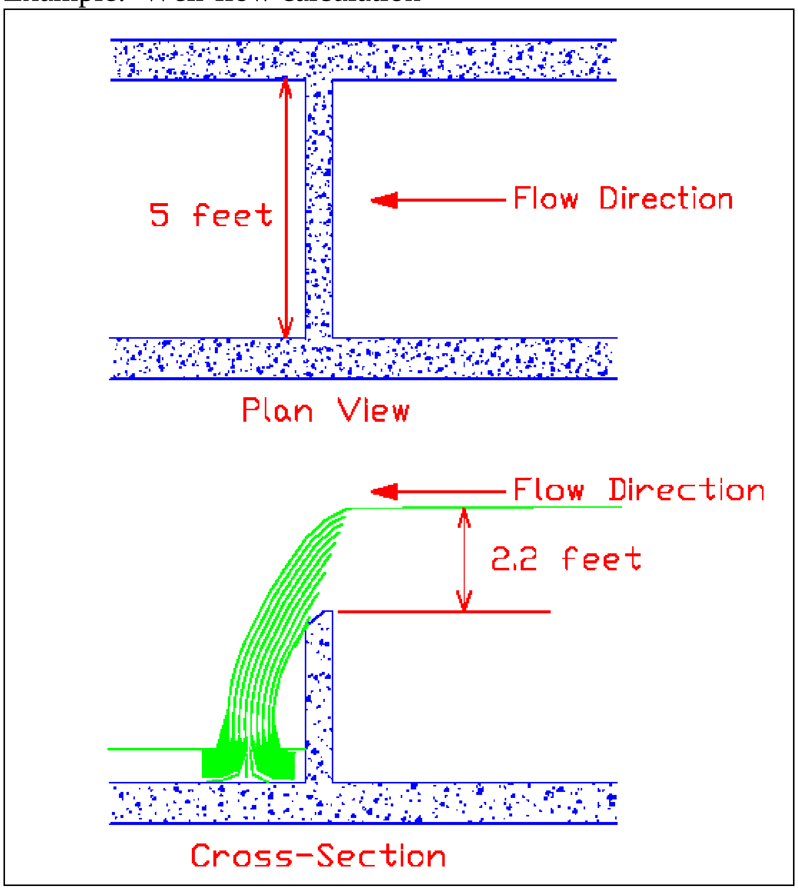

Figure 1.4c - Flow over a sharp-crested weir

A sharp crested weir crest extends across a 5 foot wide rectangular channel, where flow drops into a pool well below the weir crest as shown in Figure 1.4c. The flow depth over the weir crest is 2.2 feet. The flow rate over the weir is calculated by:

$Q = 3.33 \times 5 \text{ feet} \times 2.2^{1.5} = 54.3 \text{ cfs}$

Orifice equation

When water flows through a submerged rectangular orifice such as a head gate for a water diversion, flow can be calculated by equation 4.

(equation 4) $Q = 0.61 \times A \times [2g(H+ h_v)]^{½}$,

where Q is in cfs
A is the area of the orifice in square feet
H is the difference in water surface elevation from upstream to downstream of the orifice
h_v is the velocity head upstream of the orifice, as described by equation 2
g is the gravitational constant of 32.2 ft/s^2.

Once again, many factors can affect the coefficient in front of the variables in this equation. The coefficient of 0.61 is appropriate for a rectangular orifice, and coefficient factors for other shapes of orifice and other flow conditions can be found in “Water Measurement Manual”, U.S. Bureau of Reclamation, Denver, Colorado, 1981.

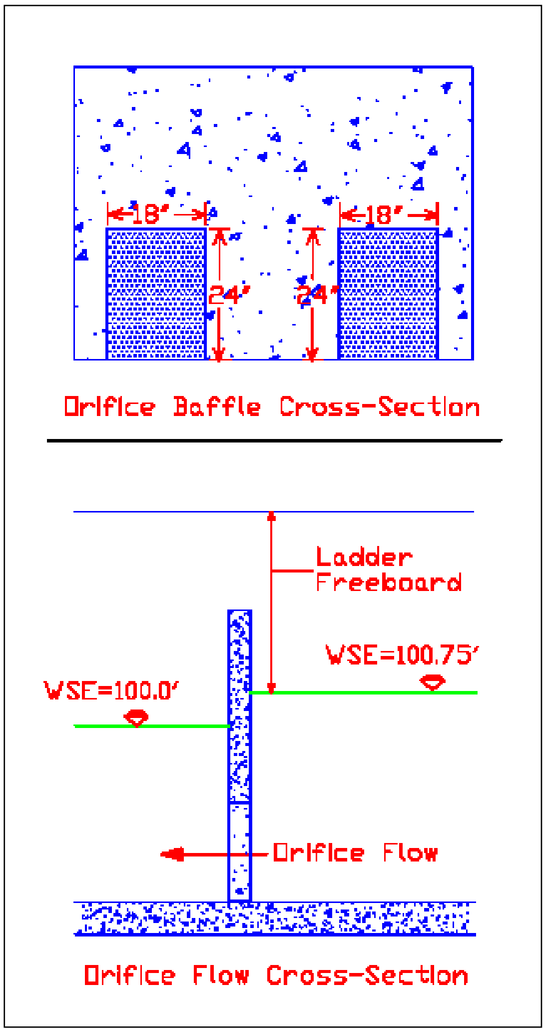

Figure 1.4d - Flow through fishway exit control pool orifices.

Example: Orifice flow calculation

Flow passes through two 18” x 24” orifices located in a fishway baffle between the project forebay and the top exit control fishway pool, with a 9 inch difference in water surface elevation, as shown in Figure 1.4d. The fishway flow passes entirely through these two orifices. The forebay velocity is 0.1 ft/s. The flow through each orifice can be calculated by:

First, calculate the velocity head (equation 2):

$h_v = 0.1^2 / (2 \times 32.2) = .00016$ feet

$Q = 0.61 \times 18/12 \text{ feet} \times 24/12 \text{ feet} \times [2 \times 32.2 \times (9/12 + 0.00016) \text{ feet}]^{½}$

$= 0.61 \times 1.5 \times 2 \times 6.95 = 12.7$ cfs,

Or, 25.4 cfs for both orifices.

Note that in this example, h_v makes no difference in the calculation of flow. Until velocities approaching the orifice exceed 1 ft/s or so, in a practical sense the velocity head is negligible and does not affect the calculated result.

Section 1.5 - Fish Passage Math

Handy Conversions
1 cubic feet per second = 448.8 gallons per minute
1 gallon per minute = 1440 gallons per day
1 cubic meter per second = 35.31 cubic feet per second
1 acre-foot per day = 0.504 cubic feet per second
1 cubic feet = 7.48 gallons
1 cubic feet of water weighs 62.4 pounds
1 gallon of water weighs 8.34 pounds
1 foot per second = 0.3048 meters per second
(degrees Fahrenheit minus 32) times 5/9 = degrees Celsius
1 kilogram = 2.2 pounds
1 foot per second = 1.097 kilometers per hour = 0.682 miles per hour = 16.4 miles per day

Significant Figures and Matching Units
Any top-flight engineering school introductory course will include instruction on a couple basic rules of engineering calculations. The first is to always write down the units of measure along with the numbers used in solving any equation. If the units match on each side of the equation, it's entirely up to your calculator to get the correct answer. If the units don't match, a wrong answer is entirely your fault. Remember, computers and calculators are able to make mistakes at the speed of light. The second rule is, never embarrass yourself by including to many non-zero digits before or after or the decimal point.

Example: Sig Figs and Matching Units

What is the average swimming speed of a fish in feet per second if it swims into a river velocity of 3.0 miles per hour for 7.15 hours and swims 13 miles? The appropriate equation is Distance = Rate x Time, or R = D/T. The upstream migration rate is the net rate of travel of the fish, R.

R (in fps) = [(V_f fps – 3 mile/hour $_x$ 5280 ft/mile/ $_x$ 1 hour/3600 s]
Unit check: fps = fps - mile/hour $_x$ ft/mile $_x$ hour/s
fps = fps - ~~mile~~/~~hour~~ $_x$ ft/~~mile~~ $_x$ ~~hour~~/s
fps = fps – fps (ok)

The velocity V_f of the fish is then:
$R = V_f - 3 = 13/7$
$V_f = 13/7.1 + 3 = 1.83098592 + 3 = 4.83098592$ fps (not ok)
The number that the calculator gives you contains 8 digits after the decimal. However, since the data used to calculate the results contains a minimum of 2 measured digits (3.0 mph or 13 miles), the answer that you give should contain only 2 digits, or 4.8 fps.

Section 1.6 - Fish Passage Physics and Biomechanical Ability

Fish utilize a number of different swimming speeds for the variety of situations that they encounter during their life cycle. As one might expect, these swimming speeds are useful in context of fish passage design. As such, a few definitions of the different modes of swimming speed need to be understood. Some species of fish have been studied fairly extensively in regard to their swimming ability, but unfortunately many have not. If the swimming capability of a species of fish to be passed at a project is unknown, biological investigation is warranted either by conducting swim stamina tests, or potentially by literature research. There are probably a number of ways that swimming performance studies can by conducted, but most involve placing fish in a flow conveyance that has the ability to vary water velocity. Fish are generally tested to fatigue at various velocities, and the time is recorded. There are many resources available that discuss fish swimming speed of various species, including "Fisheries Handbook of Engineering Requirements and Biological Criteria" Milo C. Bell, U.S. Army Corps of Engineers, North Pacific Division, 1990. Also see the Suggested References at the end of this chapter.

<u>Cruising Speed</u>
Cruising speed is the speed normally utilized by a fish in migration mode. Migration speed is determined by the cruising speed capability of a fish and the water velocity that they swim through. For example, if a fish can sustain a swimming speed of 4 fps, and is swimming into a flow velocity of 1 fps, the migration speed is 3 fps, or about 49 miles a day, if this swimming velocity is constantly maintained. However, in the case of Pacific salmon, and possibly for other species as well, migration rates vary over the course of the day, depending on factors such as predator activity, time of day, amount of daylight, passage conditions and many other factors.

Example: Cruising speed

> In 2007, PIT tagged adult Chinook salmon averaged 8.65 days to travel from the Priest Rapids Dam to Wells Dam, passing 118 miles of river and 4 dams in this migration. Using a rule of thumb of 24 hours for passage past a single dam, these Chinook traveled about 25 miles a day through reservoirs where velocities range from near zero up to around 3 or 4 fps. This calculation of daily travel distance matches reasonably well with the known cruising speed range for Chinook from 1 to 4 fps, and the assumption that migration mostly slows or stops during non-daylight hours.

Knowing the cruising speed for a species of fish requiring upstream passage allows determination of the expected migration rate and provides a fish passage specialist with at least a rough framework for assessing the potential effects of delay at a particular passage barrier or a combination of barriers.

<u>Sustained Speed</u>
Sustained speed is the swimming mode that a fish utilizes when challenged by an impediment for a few minutes. As examples, sustained speed is used by a fish when they swim through a lengthy glide in a river, or ascend a few pools in a fishway prior to resting.

Example: Sustained speed – adult salmon passage

The average sustained speed for all species of adult Pacific salmon is something on the order of 8 fps. This means that most or all adult Pacific salmon can jump a height of about 1 foot, at a jump angle of 45° (see equation 5 below), and many salmon can repeat this jump numerous times before requiring rest. Sustained speed forms the basis for design criteria for upstream passage designs. For Pacific salmon, the jump height per fishway pool is one foot, with further provisions that fishway pools contain sufficient volume and pool hydraulics such that each pool contains holding volume, where a fish can recover and continue its migration. However, a word of caution regarding this example – some species of salmon (pink and chum) will not jump to pass a barrier, and most species of salmon show a preference for a passage route that does not require them to jump. As a result, most fishways for salmon include a submerged passage route, such as a deep vertical slot, a roughened chute, an orifice, or a combination of weir and orifice. The take home message – for the species of fish that require passage at a passage impediment, it is of paramount importance to not only understand the range of sustained speed for the species, but understand the behavioral aspects as well.

<u>Burst Speed</u>

Burst speed, also called darting speed, is used by a fish to overcome a swimming challenge that lasts only a second or two, usually to avoid be entrained into passage route that the fish wishes to avoid. Burst speed is also used by fish to jump a vertical barrier of limited height and length to pass upstream. Burst speed can be also be used as the initial attempt to escape predation, with a conversion to sustained speed after the initial escape. Whether the predator goes hungry for the moment or the prey escapes is determined by both of these swim speeds and the capability for the prey to find refuge before the predator catches up. Generally speaking, burst speed is over 5 times the cruising speed in salmonid species.

Example: Cruising, sustained and burst speed – juvenile upstream passage

A stream simulation channel is being designed to pass rearing juvenile salmon upstream, into habitat with superior water quality. The proposed channel is 450 feet long, has a diversity of channel roughness and the average channel velocity based on Manning's equation (consult with an engineer or hydrologist to verify this calculation) is 3.5 fps. If the juvenile salmon have a sustained speed of about 2 fps, is this channel passable?

An excellent question and the answer involves more than a cursory look. At first look, it seems obvious that since the sustained speed of 2 fps is less than the average proposed simulated channel velocity of 3.5 fps, passage is unlikely. Certainly cruising speed, which is generally less than half of sustained speed, could not be used to ascend the 450 foot channel. However, considering that a natural stream channel at a slope of 3% or so is considered to be fairly optimal for coho salmon spawning and rearing, and the average velocity at this stream slope is on the order of 4 to 5 fps, what makes this natural channel work for fish passage? The answer is channel complexity. So long as the channel contains sufficient variety of streambed material, including boulders, cobbles, gravels, sands and silts and each bed material is properly located in the simulated stream channel design, this still has a chance to work for juvenile upstream passage.

At 2 fps sustained swim speed, in one minute a fish can swim 120 feet. At the minimum 0.4 fps cruising speed, in five minutes a fish can travel 120 feet. A two second burst at the darting (burst) speed of 4 feet per second allows a fish to travel only 8 feet.

In assessing the channel design, the design reviewer should consider how a fish could navigate upstream in the proposed channel assuming that the path of migration (migration corridor) begins at either side of the channel. Generally, the stream velocity is maximum in the center of the channel, is reduced on the fringes of the channel, and is near zero behind obstructions such as protruding boulders in the channel. So, if boulders are placed such that they are 8 feet apart, a juvenile fish could dart from boulder to boulder. If longer stretches of lower velocity can verified in the design, a juvenile fish can use these glides to ascend up to about 120 feet, so long as no intermittent turbulence or zones of higher velocity occur in the glide.

As previously discussed, fish passage criteria are developed such that they are intentionally conservative. For a stream simulation channel, this includes consideration of stream velocities and depths at the high and low design flows. In addition, never be so arrogant such that you decide that you can replicate a stream over the course of a construction season that nature takes eons to perfect. Any questionable stream simulation design that is approved should include a monitoring and maintenance program, to verify the design works as intended, and to insure that the design is maintained over time. In particular, flood flows move large debris that can dislodge boulders, move cobble and gravels, and remove sands and silts. If the flood aftermath leaves the simulated channel in non-design conditions, passage corridors need to be re-assessed using the rationale described above. If a stream does not carry bedload of sufficient quantity and size, the simulated streambed will lose its seal, and flow could go sub-surface rendering passage impossible.

Take home message: Stream simulation takes a skilled designer, good understanding of the biomechanical ability of the fish species to be passed, cooperation with nature, and a good monitoring and maintenance plan. Rarely can a stream simulation channel be constructed such that it can be assumed to remain intact. A conservative stream simulation design should not deviate much from the natural stream channel surrounding the constructed channel site, particularly in channel slope and bed material size distribution. Channel lengths should also be conservative, because the longer the length, the more opportunity that a flood flow will disrupt the design migration corridor. For reference, NMFS uses a maximum of 150 feet as a guideline for channel length, and 6% for a maximum stream channel slope. If a design is proposed exceeding this design guidance (as well as a few others – see design guidance below), it will be evaluated based on site constraints and specific evaluation of the proposed migration corridor.

<u>Integrating Biomechanical Ability into Fishway Designs</u>

First, it should be noted that all species of fish will not jump to clear a barrier. Most fishway designs provide a combination of swim-through passage and jump-over passage. In the Pacific Northwest, anadromous salmonid passage is usually provided by a designing a fishway with a combination of sufficiently low fishway velocities and easily passable hydraulic drops such that swimming through the passage corridor utilizing combinations of cruising speed and burst speed is possible. The upper end of the range of sustained speed or burst speed is used to jump weirs or to swim through submerged orifices in a fishway.

Calculating fish jump height

For a fish to successfully jump a barrier, four main components must be in place. First, there must be sufficient room in the downstream pool such that a fish can reach burst velocity and exit the lower pool at a location and on a velocity trajectory that allows a fish to clear the barrier vertically and horizontally. Generally, pool depths that allow this to occur are at least 1.25 times the vertical drop and at least 1.25 times the maximum fish body length. These generalizations assume that burst speed can be nearly instantaneously attained with a stroke or two of the tail fin, as is the case with Pacific salmonids. If this is not the case for species to be passed, these pool depth generalizations should not be used, or should be increased in proportion to the capabilities of the species to be passed. Adequate pool depth must allow a fish to exit the lower pool at burst speed at the appropriate location to clear the barrier. To accomplish this, the fishway designer must have a basic understanding of the hydraulics in the pool, especially where flow from the weir plunges into the lower pool. If flow is aerated, the burst speed of a species is reduced because the water's density is reduced. If the flow contains 50% air, the force of a fish's fin pushing on the water to propel itself is reduced by 50%, which could reduce its burst speed by the same factor. Turbulence at the point of jump exit can also cause a fish to miss its target.

Second, the fish's burst speed must be sufficient such that once it becomes a projectile upon leaving the water surface, it has sufficient velocity to clear the barrier at the apex of the jump. Recall that the difference between speed and velocity is that speed is a scalar quantity (no direction) and velocity is a vector quantity (speed with direction). As discussed above, to be successful, a jump must be made from adequate approach conditions from the pool below in order to leap high enough vertically to clear the barrier. If approach conditions are not adequate, maximum burst speed can't be attained. If the proper jump angle is not made, the projectile velocity of the fish will not launch the fish over the barrier. Keep in mind that once airborne, a fish, like a cannonball or Newton's apple, is subject to only the laws of physics and of these laws, mostly the law of gravity. Other factors can come into play, but are not substantial unless an external force is exerted on any projectile.

Keep in mind that for some species, burst speed may well deteriorate as the condition of the fish deteriorates prior to spawning. In addition, it is certain that all fish of the same species in the same condition do not have the ability to obtain the average burst speed for the species. If this statistical fact is neglected, half of the population will not be able to pass a barrier of average jump height capability for the species. To be conservative, one-half the burst speed might be used for to get a sense of the passibility of a barrier for the entire population that needs to pass. In addition, for fishway design, the designer must never assume that a maximum jump height can be made repeatedly without taking a toll on energy reserves of a fish.

Third, the fish must travel sufficient distance horizontally such that it lands beyond the crest of the barrier in flow with sufficient depth and velocity such that it can continue swimming when it lands.

Fourth, conditions upon landing from a jump must allow fish to continue upstream and not fall back over the barrier. Generally speaking, many salmonid species keep their tail fin moving at burst speed frequency when they are in a jump. If this is the case, it can be expected that they will attain burst speed upon re-entry into the water, but can not maintain this speed for any distance because of their short duration capability at burst speed. Therefore, if they land in water where either the depth is insufficient to mostly submerge their body, or if the water velocity exceeds their sustained swimming speed, fallback over the barrier is likely.

To calculate the jump trajectory upon exiting the jump pool, equations from projectile physics are used.

> (equation 5) Vertical jump height = $(\sin \alpha \times V_b)^2/2g$, Where α is the angle relative to the water surface that a fish exits the water, V_b is the fish's burst velocity, and g is the gravitational constant of 32.2 ft/s^2.
>
> (equation 6) Horizontal jump length at maximum jump height = $(\sin \alpha \times \cos \alpha \times V_b^{2)}/2g$, Where α is the angle relative to the water surface that a fish exits the water, V_b is the fish's burst velocity, and g is the gravitational constant of 32.2 ft/s^2.

Example: Assessing a barrier dam

> A steelhead approaches a dam that drops flow 8 feet into a 12 foot deep pool. The crest of the dam is located 3 feet horizontally from the outside edge of the plunging flow. Water velocity at the crest of the dam is 7 fps, and is 4 inches deep for a distance of a few feet, then deepens and slows to less than 4 fps prior to the flowing over the dam. If the steelhead has a burst velocity of 26 fps and is 30 inches long, assess whether passage is possible.
>
> Step 1: calculate the minimum pool depth = 8 x 1.25 = 10 feet (pool is 12 foot deep, so this is ok)
>
> Step 2: calculate jump height from equation 5. The vertical jump angle is not provided, but a range of possible jump angles can be gleaned from the data. If a fish leaps 90° to the water surface it will achieve the maximum jump height, it will come straight down and re-enters the pool at the exact point of entry, obviously not clearing the barrier. This is how the occasional unwise shooter manages to shoot themselves in the head when shooting a gun in the air. Note that this result comes from equation 6 if the angle α is set to 90° – the cosine of 90° is 0, and the calculated jump length (independent of burst velocity) is zero.
>
> Since we know the fish must jump 3 feet horizontally and 8 feet vertically, the optimal angle α can be calculated from trigonometry. Dividing 8 by 3 and taking the arctangent shows that this optimal jump angle is 69.4°. Using this value for α in equation 5 gives:
>
> Vertical Jump Height = $(\sin \alpha \times V_b)^2/2g = (\sin 69.4° \times 26)^2/(2 \times 32.2) = 9.2$ feet (ok)

Step 3: Calculate horizontal jump distance

Horizontal Jump Length (equation 6) = (sin α x cos α x $V_b^{2)}$/g = (sin 69.4 x cos 69.4 x 26^2)/64.4= 3.5 feet (ok)

It's important to note that this calculated horizontal distance is only to the high point or apex of the jump. If a fish winds up at the same elevation that it started from, the jump length would be twice this result. If a fish clears the barrier by some distance vertically, it will also continue on its parabolic trajectory to attain a greater distance horizontally.

Step 4: A 30 inch long steelhead has a tail that is greater in height than the 4 inch depth at the crest of the dam. In other words, the tail is not entirely submerged so top burst speed can not be assumed. However, since the water velocity is less than one half the maximum burst velocity, this particular fish could probably make it past the dam if it can achieve the jump.

Conclusion: These calculations show that this particular fish could very likely make this jump successfully. However, other factors need to be considered before this falls could be deemed passable for the steelhead run at large, or for other species that may need to pass. For example, if a fish is in poor condition (eg. gravid, far from salt water, injured) or is a less than prime physical specimen (eg. small fish or weak swimmer), the maximum burst speed of 26 fps can not be assumed. If the above calculations are re-done using one half the burst velocity, as is suggested by the literature for fish in poor condition, the jump will not be successful. In addition, if the jump angle is not optimal, the fish will not be able to make the jump. A steelhead is a relentless migrator, so it may make many attempts at the jump, each jump taking a toll on available energy reserves, and each jump potentially causing injury, depending on where it lands. In conclusion, this dam is likely not passable to the steelhead run at large, so the biologist needs to think about an appropriate fish ladder design.

The above example is included here to make a point about why fish passage criteria need to be conservative. Many people have seen a steelhead or salmon make amazing jumps, sometimes nearly 20 feet. Similarly, many people have seen an Olympic high jumper clear nearly 8 feet. But if the continuance of our species counted on mankind being able to make an 8 foot leap in order to propagate our species, a fairly sure wager could be made that our planet would not be experiencing population explosions in most countries around the globe. The average sustained speed for most salmon is about 8 feet per second. In other words, most salmon can for a few minutes using burst speed, and it is not uncommon for radio telemetry studies to show that when are challenged by an impediment beyond their cruising speed, fish will frequently rest for a few minutes after the swimming challenge. An 8 fps sustained speed translates into a jump height of about 1 foot. Since most salmon can make a one foot jump repeatedly (and are willing to do so to propagate their species), the criterion for allowable jump height in a fish ladder is one foot. A related criterion is that ladder pools contain sufficient volume and geometry to provide resting zones of relatively tranquil water, with water velocities in the range of cruising speed of the fish.

Section 1.7 – Upstream Fish Passage Facility Design Phases

Conceptual Design Development - Site Data Requirements

There is quite a bit of information that needs to be accumulated prior to a conceptual fishway design being developed. A conceptual upstream fish passage facility design should minimally identify:

- the general construction footprint of the passage facility relative to the existing project features
- flow distribution into all project components
- how project operations affect operation of fish passage facilities
- fish species present and their run timing
- where design uncertainty needs to be resolved by model studies (physical, hydraulic, and mathematical)
- the major flow features, including the range of flow amounts, of the fishway
- how flow will be distributed throughout the fishway
- the forebay rating curve
- the tailwater rating curve
- high and low fish passage design flows (see Section 1.3)
- project ramping rates
- method of controlling forebay and tailwater changes to maintain fishway design criteria
- style of fish ladder

Generally, the NMFS uses a completed conceptual design as the minimal level of design development for initial fishway design approval. Acceptable conceptual fishway designs are ideal for inclusion as a component of a Section 18 fishway prescription, because they allow the applicant to get a general sense of the cost, and the fisheries agencies a general sense of how the fishway design provides safe, timely and efficient fish passage.

30%, 60%, 90% and 100% Design Review

The NMFS generally requires review and approval of the 30%, 60% and 90% design plans. A 30% design is a refinement of the conceptual design, generally refining such features as fishway weir design, fishway entrance design, diffuser design, auxiliary water system design, and assessment of the migration corridor through the fishway. The 60% design continues to refine these features, but may also reflect fairly significant design changes if certain feature reflected in the 30% design are not feasible, or can be designed more cost effectively. The 90% design is should be pretty close to the final design. The 90% design adds design for features such as control systems and detailed mechanical features. The 100% design is rarely reviewed by NMFS because it generally involves the addition of finishing details – paint, handrails, landscaping. There should be no functional changes in passage features after the 60% design, unless specifically approved by the reviewing fisheries agencies.

Section 1.8 - Features of an Upstream Fish Passage Facility

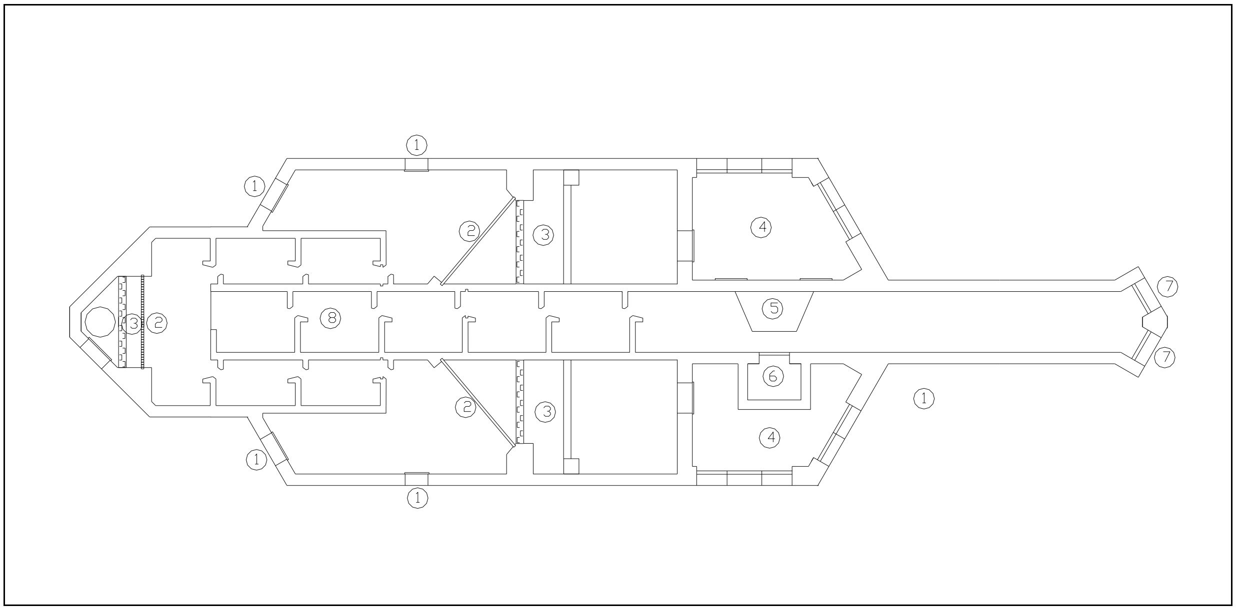

Figure 1.8a. Features of an upstream passage system utilizing a vertical slot fishway (river flow is from right to left)

1 - Fishway Entrances
2 - Add-in AWS Diffusers
3 - Energy Dissipation Features
4 - AWS Supply Pools
5 - Counting station crowder and picket leads
6 - Counting Station
7 - Fishway Exits
8 - Fishway Pool

Figure 1.8a shows an example of a center river fishway, located on the Yakama River in Washington. The river flow is from the right to left side of the drawing. This figure schematically shows many of the features that will be described in detail throughout the remainder of this manual. Regrettably, the dam itself is not shown on this figure, but it is generally located near the center of the ladder (from left to right) and perpendicular to the longer dimension of the upstream passage system. This ladder was chosen for an example because it has most of the features that could be included in an upstream passage system. Additionally, if this center ladder is split in two, each half could be used as a design for passage facility located on the right bank.

Note that there are four separate fishway entrances shown, with two typically operated at a time. A separate fish ladder extends from the pair of entrances on each side of the facility, with flow from a single center ladder splitting flow from the fishway exit into the right side and left side ladders.

Section 1.9 - Fishway Entrance

Description and Purpose - Fishway Entrance

The fishway entrance is a gate or slot through which fishway attraction flow is discharged and through which fish enter the upstream passage facility. The fishway entrance is possibly the most critical component in the design of an upstream passage system. Placing a fishway entrance(s) in the correct location(s) will allow a passage facility to provide a good route of passage throughout the design range of passage flows. The most important aspects of a fishway entrance design are: (1) location of the entrance, (2) shape and amount of flow emanating from the entrance, (3) approach channel immediately downstream of the entrance, and (4) flexibility in operating the entrance flow to accommodate variations in tailrace elevation, stream flow conditions, and project operations.

Criteria and Guidelines – Fishway Entrance

Configuration and Operation: The fishway entrance gate configuration and operation may vary based on site-specific project operations and streamflow characteristics. Entrance gates are usually operated in either a fully open or fully closed position, with the operating entrance dependent on tailrace flow characteristics. Sites with limited tailwater fluctuation may not require an entrance gate to regulate the entrance head. Adjustable weir gates that rise and fall with tailwater elevation may also be ued to regulate the fishway entrance head, while maintaining a constant fishway flow. Other sites may accommodate maintaining proper entrance head by regulating auxiliary water flow through a fixed geometry entrance gate.

Location: Fishway entrances must be located at points where fish can easily locate the attraction flow and enter the fishway. When choosing an entrance location, high velocity and turbulent zones in a powerhouse or spillway tailrace should be avoided in favor of relatively tranquil zones adjacent to these areas. At locations where the tailrace is wide, shallow, and turbulent, excavation to create a deeper, less turbulent holding zone adjacent to the fishway entrance(s) may be required.

Attraction Flow: Attraction flow from the fishway entrance should be between 5% and 10% of fish passage design high flow (see Section 1.3) for streams with mean annual streamflows exceeding 1000 cfs. For smaller streams, when feasible, use larger percentages (up to 100%) of streamflow. Generally speaking, the higher percentages of total river flow used for attraction into the fishway, the more effective the facility will be in providing upstream passage. Some situations may require more than 10% of the passage design high flow, if site features obscure approach routes to the passage facility.

Hydraulic Drop: The fishway entrance hydraulic drop (also called entrance head) must be maintained between 1 and 1.5 feet and designed to operate from 0.5 to 2.0 feet of hydraulic drop for Pacific salmon, but specific criterion should be developed for species present at the site.

Dimensions: The minimum fishway entrance width should be 4 feet, and the entrance depth should be at least 6 feet, although the shape of the entrance is dependent on attraction flow requirements and should be shaped to accommodate site conditions.

Additional Entrances: If the site has multiple zones where fish accumulate, each zone must have a minimum of one entrance. For long powerhouses or dams, additional entrances may be required. Since tailrace hydraulic conditions usually change with project operations and hydrologic events, it is often necessary to provide two or more fishway entrances. Closure gates must be provided to direct flow to the appropriate entrance gate, and gate stems (or other adjustment mechanisms) must not be placed in any potential path of fish migration. Fishway entrances must be equipped with downward-closing slide gates, unless otherwise approved by NMFS.

Types of Entrances: Fishway entrances may be adjustable submerged weirs, vertical slots, orifices, or other shapes. Some species will avoid using orifices, and at these sites, orifices should not be used.

Flow Conditions: The desired flow condition for entrance weir and/or slot discharge jet hydraulics is streaming flow (Section 1.2). Plunging flow (Section 1.2) induces jumping and may cause injuries, and it presents hydraulic condition that some species may not be able to pass. Streaming flow may be accomplished by placing the entrance weir (or invert of the slot) elevation such that flow over the weir falls into a receiving pool with water surface elevation above the weir crest elevation (Katapodis 1992).

Orientation: Generally, low flow entrances should be oriented nearly perpendicular to streamflow, and high flow entrances should be oriented to be more parallel to streamflow. However, you must conduct site-specific assessments to determine entrance location and entrance jet orientation.

Staff Gages: The fishway entrance design must include staff gages to allow for a simple determination of whether entrance head hydraulic drop criterion (as described above) is met. Staff gages must be located in the entrance pool and in the tailwater just outside of the fishway entrance, in an area visible from an easy point of access. Care should be taken when locating staff gages by avoiding placement in turbulent areas and locations where flow is accelerating toward the fishway entrance. Gages should be readily accessible to facilitate in-season cleaning.

Entrance Pools: The fishway entrance pool is at the lowest elevation of the upstream passage system. It discharges flow into the tailrace through the entrance gates for the purpose of attracting upstream migrants. In many fish ladder systems, the entrance pool is the largest and most important pool, in terms of providing proper guidance of fish to the ladder section of the upstream passage facility. It combines ladder flow with auxiliary water system (AWS) flow through diffuser gratings to form entrance attraction flow (see Section 1.9). The entrance pool must be configured to readily guide fish toward ladder weirs or slots.

Transport Velocity: Transport velocities between the fishway entrance and first fishway weir, fishway channels, and over submerged fishway weirs must match the cruising speed of the species to be passed. For salmon, this is between 1.5 and 4.0 ft/s.

Entrance Pool Geometry: The fishway entrance pool geometry must be designed to optimize attraction to the lower fishway weirs. This may be accomplished by angling vertical AWS diffusers toward and terminating near the lowest ladder fishway weir, or by placing primary attraction flows near the lower fishway weir. The pool geometry will normally influence the location of attraction flow diffusers.

Section 1.10 - Auxiliary Water Systems

Description and Purpose – Auxiliary Water Systems

Auxiliary water systems are required when ladder flows from the project forebay are less than the attraction flows specified in Section 1.8. AWS flow is provided by gravity from the forebay or pumped from the tailrace, through a fine trash rack or intake screen, then through a back-set flow control gate, then through an energy dissipation zone consisting of energy baffles and/or diffusers, and finally into the fishway. An AWS provides additional attraction flow from the entrance pool through the fishway entrance, and may also provide flow to an area between fishway weirs that on occasion become back-watered and fail to meet the transport velocity criterion. In addition, the AWS is used to provide make-up flows to various transition pools in the ladder such as bifurcation or trifurcation pools, trap pools, exit control sections, or counting station pools.

Criteria and Guidelines – AWS Diffusers

Vertical diffusers consist of non-corrosive, vertically-oriented diffuser panels of vertically-oriented flat bar stock, and must have a maximum 1-inch clear spacing for Pacific salmon. Similarly, horizontal diffusers consist of non-corrosive, horizontally-oriented diffuser panels of horizontally-oriented flat bar stock, and must have a maximum 1-inch clear spacing. Orientation of flat bar stock must maximize the open area of the diffuser panel. If a smaller species or life stage of fish is present, smaller clear spacing may be required.

Velocity and Orientation: For Pacific salmon, the maximum AWS diffuser velocity must be less than 1.0 ft/s for vertical diffusers and 0.5 ft/s for horizontal diffusers, based on total diffuser panel area. Vertical diffusers should only be used in appropriate orientation to assist in guiding fish within the fishway. Diffuser velocities should be nearly uniform. If designing for other species, the maximum diffuser velocity should probably be less than ½ the minimum cruising speed for the species.

Debris Removal: The AWS design must include access for debris removal from each diffuser, unless the AWS intake is equipped with a juvenile fish screen.

Edges: All flat-bar diffuser edges and surfaces exposed to fish must be rounded or ground smooth to the touch, with all edges aligning in a single smooth plane to reduce the potential for contact injury.

Elevation: Vertical AWS diffusers must have a top elevation at or below the low design entrance pool water surface elevation.

Criteria and Guidelines– AWS Fine Trash Racks

A fine trash rack must be provided at the AWS intake with clear space between the vertical flat bars of $^{7}/_{8}$ inch or less, or always less than the diffuser grating size opening specified above. For

Pacific salmon, the maximum velocity must be less than 1 ft/s, as calculated by dividing the maximum flow by the entire fine trash rack area. For other species, the maximum velocity should be less than ½ the cruising speed of the species present, as a general rule of thumb. The support structure for the fine trash rack must not interfere with cleaning requirements and must provide access for debris raking and removal. The fine trash rack should be installed at a 1:5 (horizontal:vertical) slope (or flatter) for ease of cleaning. The fine trash rack design must allow for easy maintenance, considering access for personnel, travel clearances for manual or automated raking, and removal of debris

Staff Gages and Head Differential: Staff gages must be installed to indicate head differential across the AWS intake fine trash rack, and must be located to facilitate observation and in-season cleaning. Head differential across the AWS intake must not exceed 0.3 feet.

Structural Integrity: AWS intake fine trash racks must be of sufficient structural integrity to avoid the permanent deformation associated with maximum occlusion.

Criteria and Guidelines – AWS Screens

In instances where the AWS poses a risk to passage of juvenile fish (due to high head systems and convoluted flow paths, for example), during the period of juvenile out-migration(s) the AWS intake must be screened for juvenile fish protection. Trip gates or other alternate intakes to the AWS may be included in the design to ensure that AWS flow targets are achieved if the screen reliability is uncertain at higher flows. Debris and sediment issues may preclude the use of juvenile fish screen criteria for AWS intakes at certain sites. Passage risk through an AWS will be assessed by NMFS engineers on a site by site basis to determine whether screening of the AWS is warranted and to determine how to provide the highest reliability possible.

Criteria and Guidelines – AWS Flow Control

AWS flow control may consist of a control gate, turbine intake flow control, or other flow control systems, located sufficiently far away from the AWS intake to ensure uniform flow distribution at the AWS fine trash rack for all AWS flows. AWS flow control is necessary to ensure that the correct quantity of AWS flow is discharged at the appropriate location during a full range of forebay water surface elevations.

Criteria and Guidelines – AWS Excess Energy Dissipation

Excess energy must be dissipated from AWS flow prior to passage through diffusers (Section 1.9). This is necessary to minimize surging and to induce relatively uniform velocity distribution at the diffusers. Surging and non-uniform velocities may cause adult fish jumping and associated injuries or excess migration delay. Examples of methods to dissipate excess AWS flow energy include: (1) routing flow into the pool with adequate volume, then through a baffle system (porosity less than 40%) to reduce surging through entrance pool diffusers; (2) passing

AWS flow through a turbine; (3) passing AWS flow through a series of valves, weirs or orifices; or (4) passing AWS flow through a pipeline with concentric rings or other hydraulic transitions designed to induce headloss.

Energy Dissipation Pool Volume: An energy dissipation pool in an AWS should have a minimum water volume established by the following formula:

$$V = \frac{(\gamma)(Q)(H)}{(16\, ft{-}lbs/s)/\, ft^3}$$

where: V = pool volume, in ft^3
γ = unit weight of water, 62.4 pounds (lb) per ft^3
Q = fish ladder flow, in ft^3/s
H = energy head of pool-to-pool flow, in feet

Note that the pool volumes required for AWS pools are smaller than those required for fishway pools. This is due to the need to provide resting areas in fishway pools, and because AWS systems require additional elements (diffusers, valves, etc.) to dissipate energy, and are not pathways for upstream fish passage.

Criteria and Guidelines – AWS Design (General)

Cleaning: To facilitate cleaning, the AWS must be valved or gated to provide for easy shutoff during maintenance activities, and subsequent easy reset to proper operation.

Bedload Removal Devices: At locations where bedload may cause accumulations at the AWS intake, sluice gates or other simple bedload removal devices should be included in the design.

Section 1.11 - Transport Channels

Description and Purpose – Transport Channels

A transport channel conveys flows between different sectors of the upstream passage facility, providing a route for fish to pass.

Criteria and Guidelines – Transport Channels

Velocity Range: The transport channel velocities should range between 50% and 100% of the minimum cruising speed of the species to be passed, including flow velocity over or between fishway weirs inundated by high tailwater.

Dimensions: The transport channels should be a minimum of 5-feet deep and a minimum of 4-feet wide.

Lighting: Ambient natural lighting should be provided in all transport channels, if possible. Otherwise, acceptable artificial lighting must be used.

Design (General):

- The transport channels must be of open channel design.
- Designs must avoid hydraulic transitions or lighting transitions
- Transport channels must not expose fish to any moving parts.
- Transport channels must be free of exposed edges that protrude from channel walls.

Section 1.12 - Fish Ladder Design

Description and Purpose – Fish Ladder Design

The purpose of a fish ladder is to convert the total project head at the passage impediment into passable increments, and to provide suitable conditions for fish to hold, rest, and ultimately pass upstream. The criteria provided in this section have been developed to provide conditions to pass all anadromous salmonid species upstream with minimal delay and injury.

Fish ladders break an impediment into passable discrete steps, by utilizing a series of fishway weirs to divide the drop into a series of pools with different water surface elevations. Nearly all of the energy from the upstream pool is dissipated in the downstream pool volume, resulting in a series of relatively calm pools that migrating fish may use to rest, stage and ascend upstream. Examples of fish ladders include the vertical slot ladder, the pool and weir ladder, the weir and orifice ladder, and the pool-chute fish ladder.

Vertical Slot Ladder

The vertical slot configuration (see Figures 1.12a,b,c)is a pool type of fish ladder widely used for the passage of salmon and steelhead. The passage corridor typically consists of 1.0 to 1.25 foot-wide vertical slots between fishway pools. However, narrower slots have been used in applications for other fish species and slots may be wider in designs (or two slots may be used per fishway weir) where there is no auxiliary water system. For adult anadromous salmonids, slots should never be less than 1 foot in width. The vertical slot ladder is suitable for passage impediments which have tailrace and forebay water surface elevations that fluctuate. Maximum head differential (typically associated with lowest river flows) establishes the design water surface profile, which is on average parallel to the fishway floor gradient. Vertical slot ladders require fairly intricate forming for concrete placement, so initial construction costs are somewhat higher than for other types of ladders.

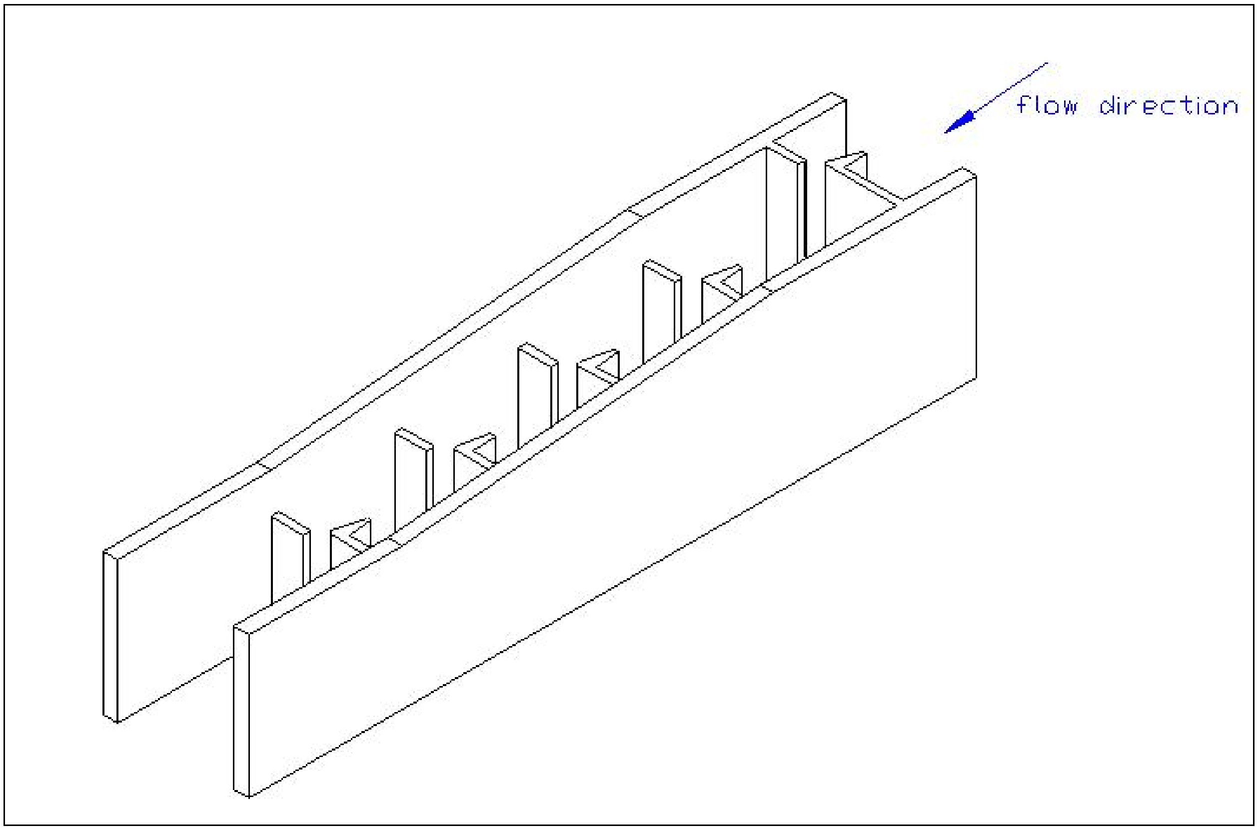

Figure 1.12a - Isometric View of Vertical Slot Fishway.

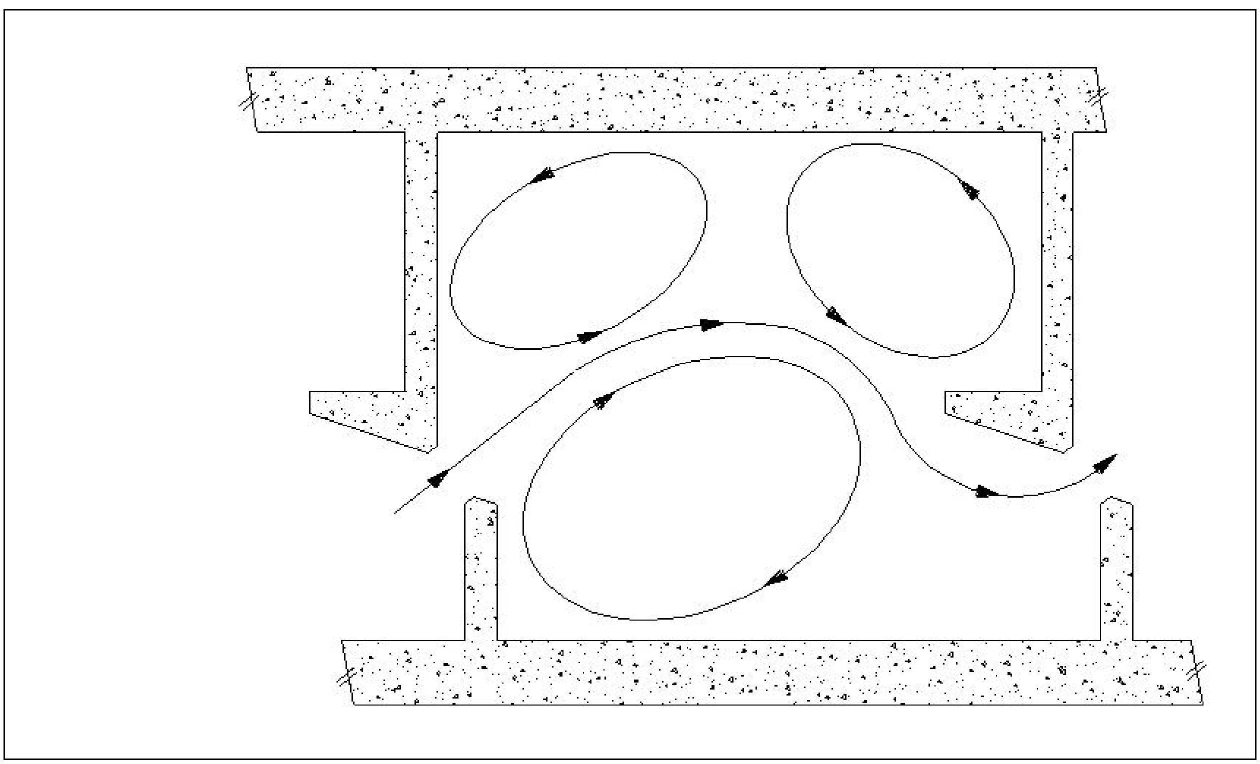

Figure 1.12b - Plan View of Vertical Slot Fishway Showing Generalized Flow Path

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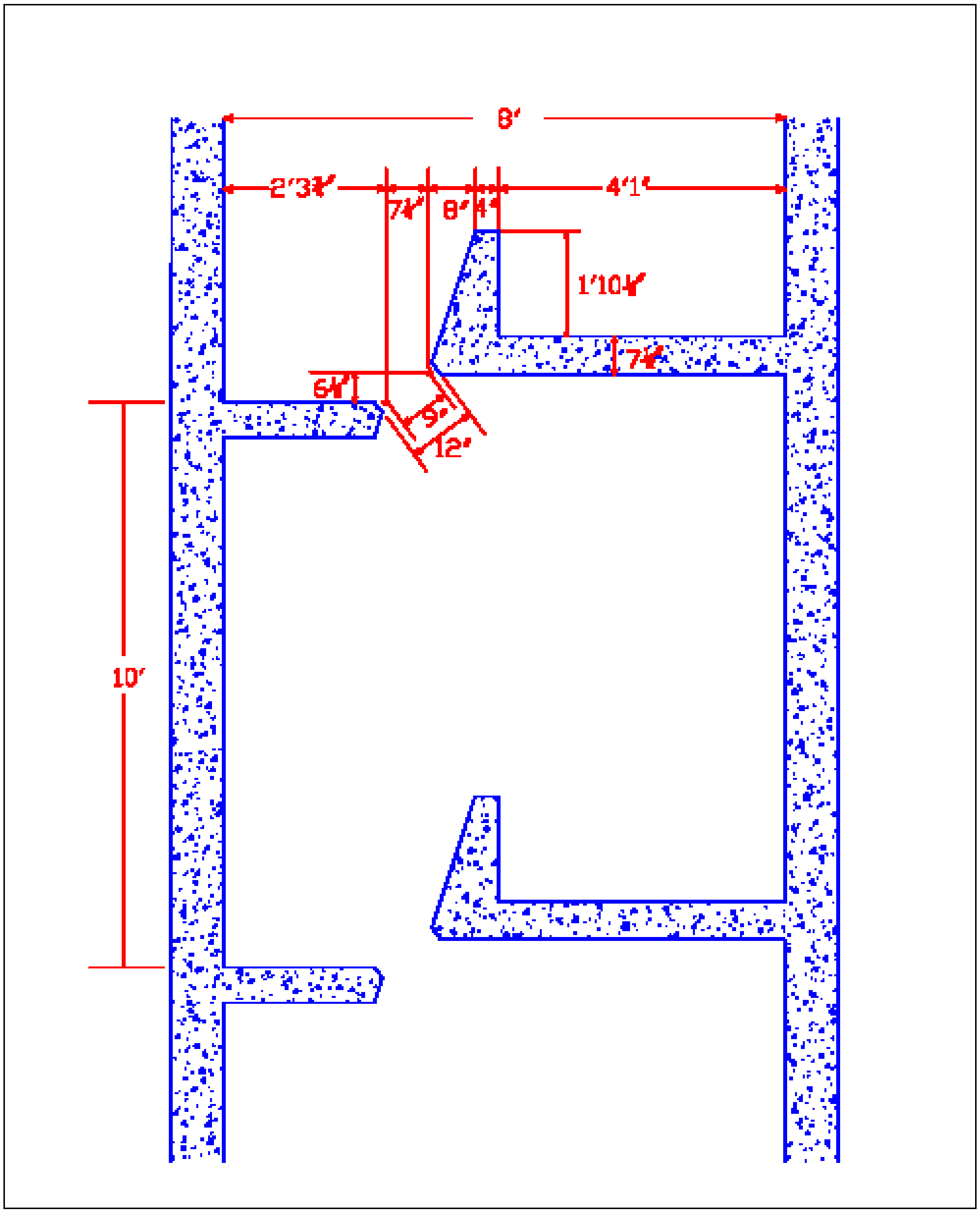

Figure 1.12c - Dimensions of a Typical Vertical Slot.

<u>Pool and Weir Ladder</u>:
The pool and weir fish ladder passes the entire, nearly constant fishway flow through successive fishway pools separated by overflow weirs that break the total project head into passable increments. This design allows fish to ascend to a higher elevation by passing over a weir, and provides resting zones within each pool. Pools are sufficiently sized to allow for the flow energy to be nearly fully dissipated in the form of turbulence within each receiving pool. Pool and weir ladders cannot accommodate much, if any, water surface elevation fluctuation in the forebay pool. When fluctuation of water surface elevation outside of the design elevation occurs, too much or too little flow enters the fishway. When this happens, this flow fluctuation may lead to operation with fishway pools that are excessively turbulent, or provide insufficient flow for

adequate upstream passage. To accommodate forebay fluctuations, this type of fish ladder is often designed with an auxiliary water supply and flow regulation. To accommodate tailwater fluctuations, this type of fish ladder is often designed with an adjustable fishway entrance (i.e., adjustable geometry and/or attraction flow) and additional add-in flow diffusers to meet transport channel velocity criterion.

Weir and Orifice Fish Ladder

The weir and orifice fish ladder (see Figures 1.12d,e,f) passes the fishway flow from the forebay through successive fishway pools connected by overflow weirs and orifices, which divide the total project head into passable increments.

The Ice Harbor ladder is an example of a weir and orifice fish ladder. This ladder design was initially developed for use at Ice Harbor Dam (Lower Snake River), in the middle of the 1960's. The Ice Harbor fishway weir consists of two orifices, centered and directly below two weirs. These orifice and weir combinations are located on each side of the longitudinal centerline of the ladder. Between the two weirs is a slightly higher non-overflow wall, with an upstream projecting flow baffle at each end. An adaptation for lower flow designs is the Half-Ice Harbor ladder design, which consists of one weir, one orifice, and a non-overflow wall between fishway pools.

Weir and orifice ladders cannot accommodate much, if any, water surface elevation fluctuation in the forebay pool. When fluctuation of water surface elevation outside of the design elevation occurs, too much or too little flow enters the fishway. When this happens, this flow fluctuation may lead to operation with fishway pools that are excessively turbulent, or provide insufficient flow for adequate upstream passage. To accommodate forebay fluctuations, this type of fish ladder is often designed with an auxiliary water supply and flow regulating section. To accommodate tailwater fluctuations, this type of fish ladder is often designed with an adjustable fishway entrance (i.e., adjustable geometry and/or attraction flow) and additional add-in flow diffusers to meet transport channel velocity criterion.

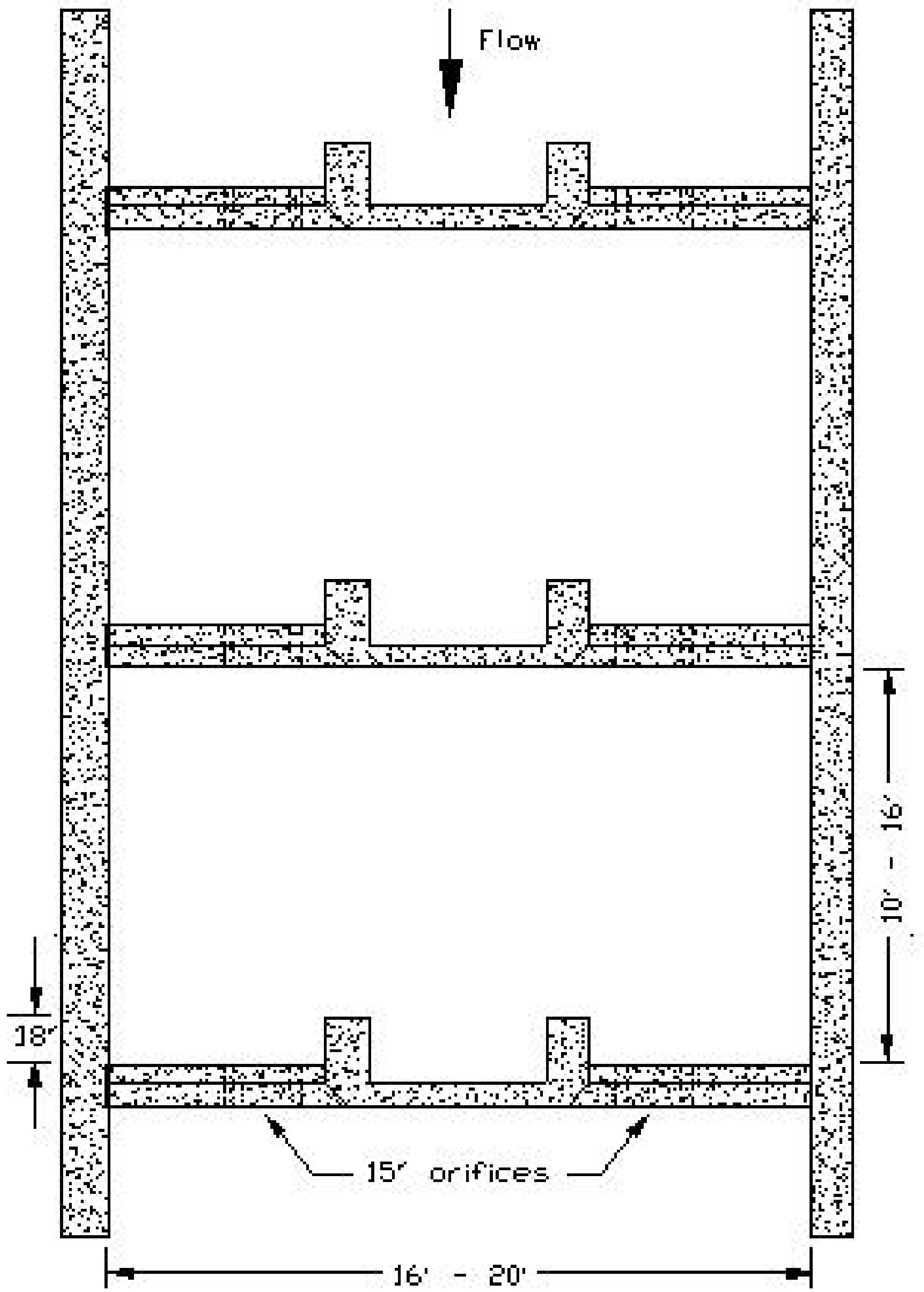

Figure 1.12d. Plan View of an Ice Harbor Type Weir and Orifice Fish Ladder

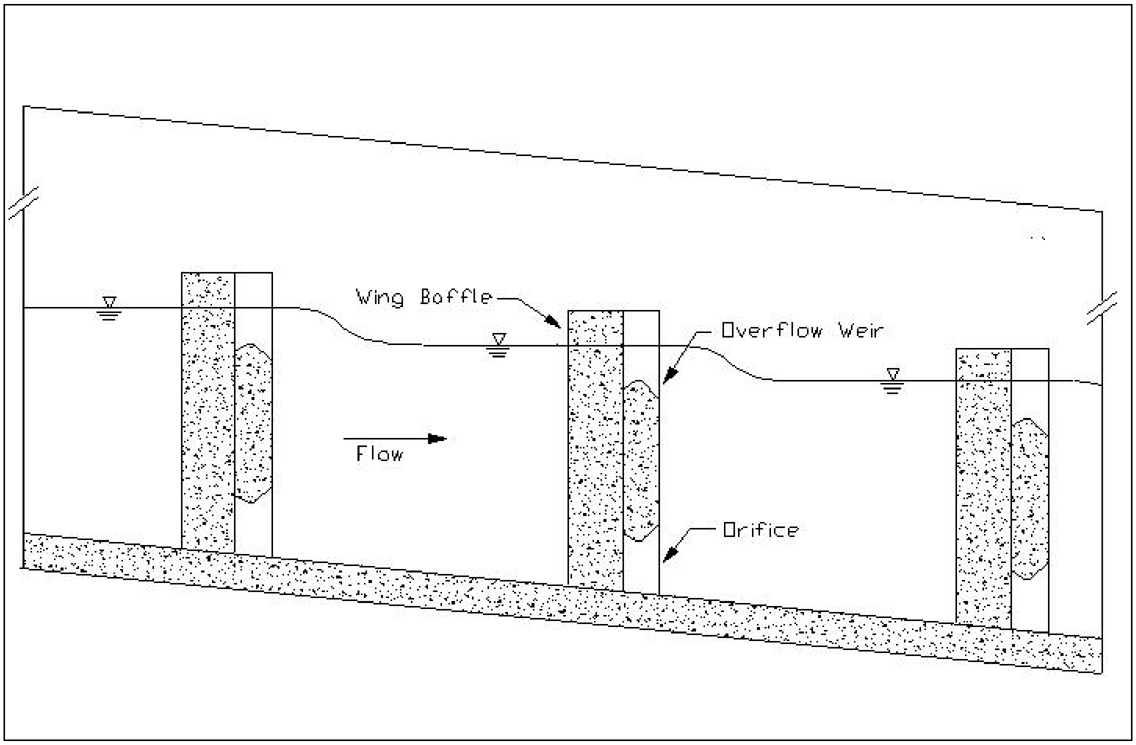

Figure 1.12e - Longitudinal Cross-section of an Ice Harbor Type Weir and Orifice Fish Ladder

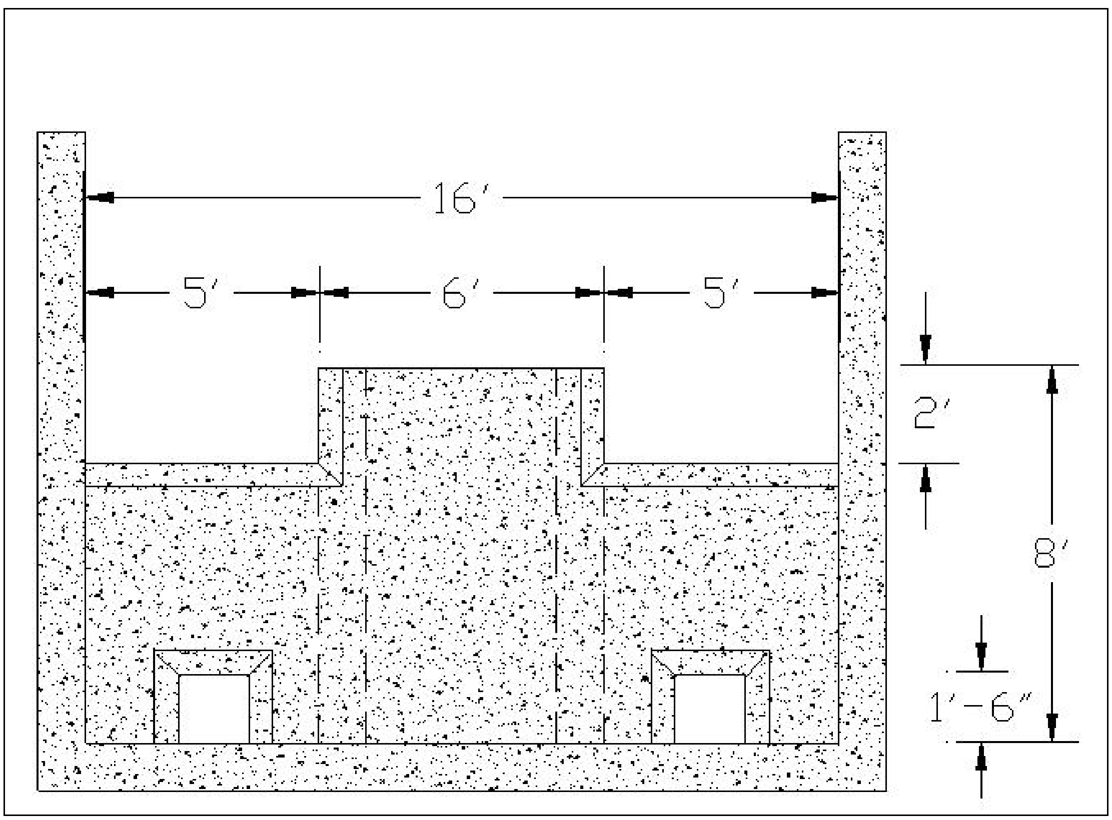

Figure 1.12f - Front View Cross-section of Ice Harbor Fishway Baffle

Pool-Chute Fish Ladder

A pool and chute fishway is a hybrid type of fishway which operates with different flow regimes under different river conditions. This fishway is designed to operate as a pool and weir fishway at low river flows and a baffled chute fishway at higher river flows. This fishway offers an alternative for sites that have fairly low hydraulic drop, and must pass a wide range of stream flows with a minimum of flow control features. Placement of stoplogs, a cumbersome and potentially hazardous operation, is required to optimize operation. However, once suitable flow regimes are established, the need for additional stoplog placement may not be required. Criteria for this type of fishway design are still evolving, and design proposals will be assessed on a site-specific basis.

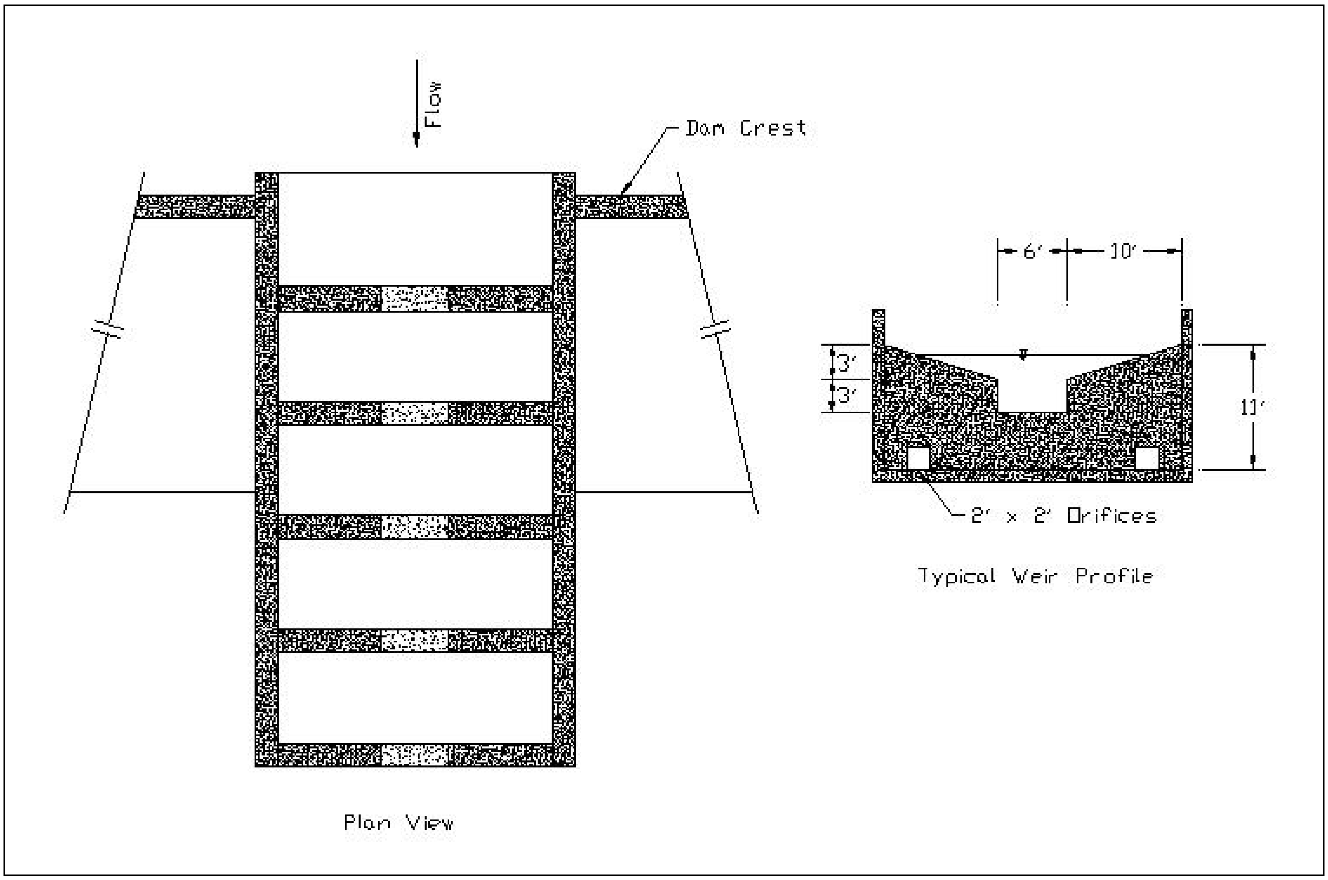

Figure 1.12g. Pool and Chute Fishway

Criteria and Guidelines – Fish Ladder Design

Hydraulic Drop: The maximum hydraulic drop between fish ladder pools must be 1 foot or less for Pacific salmon, and should be less than the velocity head equivalent to the minimum burst speed for other species.

Flow Depth: Fishway overflow weirs should be designed to provide at least 1 foot of flow depth over the weir crest. The depth must be indicated by locating a single staff gage (with the zero reading at the overflow weir crest elevation) in an observable, hydraulically stable location, representative of flow depth throughout the fishway.

Pool Dimensions: The pool dimensions should be a minimum of 8 feet long (upstream to downstream), 6 feet wide, and 5 feet deep. However, specific ladder designs may require pool dimensions that are different than the minimums specified here depending on site conditions and ladder flows.

Turning Pools: Turning pools (i.e., where the fishway bends more than 90°) should be at least double the length of a standard fishway pool, as measured along the centerline of the fishway flow path. The orientation of the upstream weir to the downstream weir must be such that energy from flow over the upstream weir does not affect the hydraulics of the downstream weir. Pool Volume: The fishway pools must be a minimum water volume of:

$$V = \frac{(\gamma)(Q)(H)}{(4\,ft-lbs/s)/ft^3}$$

where: V = pool volume, in ft^3
γ = unit weight of water, 62.4 pounds (lb) per ft^3
Q = fish ladder flow, in ft^3/s
H = energy head of pool-to-pool flow, in feet

This pool volume must be provided under every expected design flow condition, with the entire pool volume having active flow and contributing to energy dissipation.

Freeboard: The freeboard of the ladder pools must be at least 3 feet at high design flow.

Orifice Dimensions: For Pacific salmon, the dimensions of orifices should be at least 15 inches high by 12 inches wide, with the top and sides chamfered 0.75 inches on the upstream side, and chamfered 1.5 inches on the downstream side of the orifice. Orifice dimensions for other species should be developed based on behavioral traits of that species.

Lighting: Ambient lighting is preferred throughout the fishway, and in all cases abrupt lighting changes must be avoided.

Change in Flow Direction: At locations where the flow changes direction more than 60°, 45° vertical miters or a 2 foot vertical radius of curvature must be included at the outside corners of fishway pools.

Section 1.13 - Counting Stations

Description and Purpose – Counting Stations

A counting station provides a location to observe and enumerate fish utilizing the fish passage facility. Although not always required, a typical counting station including a camera or fish count technician, crowder, and counting window is often included in a fishway design to allow fishery managers to assess fish populations, provide observations on fish health, or conduct scientific research. Other types of counting stations (such as submerged cameras, adult PIT-tag detectors, or orifice counting tubes) may be acceptable, but they must not interfere with the normal operation of the ladder or increase fish passage delay.

Criteria and Guidelines – Counting Stations

Location: Counting stations must be located in a hydraulically stable, low velocity (i.e., around 1.5 ft/sec), accessible area of the upstream passage facility.

Downstream/Upstream Pools: The pool downstream of the counting station must extend at least two standard fishway pool lengths from the downstream end of the picket leads. The pool upstream of the counting station must extend at least one standard fishway pool length from the upstream end of the picket leads. Both pools must be straight and in line with the counting station.

Criteria and Guidelines – Counting Window

Design and Material: The counting window must be designed to allow complete, convenient cleaning with sufficient frequency to ensure sustained window visibility and accurate counts and structural viability. The counting window material must be of sufficient abrasion resistance to allow frequent cleaning.

Orientation: Counting windows must be vertically oriented.

Sill: The counting window sill should be positioned to allow full viewing of the passage slot.

Lighting: The counting window design must include sufficient indirect artificial lighting to provide satisfactory fish identification at all hours of operation, without causing passage delay.

Dimensions: The minimum observable width (i.e., upstream to downstream dimension) of the counting window must be 5 feet, and the minimum height (depth) should be full water depth.

Width: The minimum width of the counting station slot between the counting window and back vertical counting window surface should be 18 inches. The design must include an adjustable crowder to move fish closer to the counting window to allow fish counting under turbid water conditions. The counting window slot width should be maximized as water clarity allows, and when not actively counting fish.

Picket Lead: To guide fish into the counting window slot, a downstream picket lead must be included in the design. The downstream picket lead must be oriented at a deflection angle of 45° relative to the direction of fishway flow. An upstream picket lead oriented 45° to the flow direction must also be provided. Picket orientation, picket clearance, and maximum allowable velocity must conform to specifications for diffusers (Section 4.3.2). Picket leads may be comprised of flat stock bars oriented parallel to flow, or other cross-sectional shapes, if approved by NMFS. Combined maximum head differential through both sets of pickets must be less than 0.3 feet. Both upstream and downstream picket leads must be equipped with “witness marks” to verify correct position when picket leads are installed in the fishway. A one foot square opening should be provided in the upstream picket lead to allow escape if smaller fish pass through the downstream picket lead.

Transition Ramps: To minimize flow separations created by head loss that may impede passage and induce fallback behavior at the counting window, transition ramps must be included. These ramps provide gradual transitions between walls, floors and the count window slot. As general guidance, these transitions should be more gradual than 1:8 (vertical:horizontal). A free water surface must exist over a counting window.

Section 1.14 - Fishway Exit Section

Description and Purpose – Fishway Exit Section

The fishway exit section provides a flow channel for fish to egress through the fishway and continue on their upstream migration. The exit section of upstream fish passage facilities may include the following features: add-in auxiliary water valves and/or diffusers, exit pools with varied flow, exit channels, coarse trash rack (for fish passage), and auxiliary water fine trash racks and control gates. One function of the exit section is to attenuate forebay water surface elevation fluctuation, thus maintaining hydraulic conditions suitable for fish passage in ladder pools. Other functions should include minimizing the entrainment of debris and sediment into the fish ladder. Different types of ladder designs require specific fish ladder exit design details.

Criteria and Guidelines – Fishway Exit Section

Hydraulic Drop: For Pacific salmon, the exit control section hydraulic drop per pool should range from 0.25 to 1.0 feet. For other species, the maximum drop should be less than the velocity head calculated by the minimum burst speed of that species.

Length: The length of the exit channel upstream of the exit control section should be a minimum of two standard ladder pools.

Design Requirements: Exit section design must utilize the requirements for auxiliary water diffusers, channel geometry, and energy dissipation as described above.

Location: In most cases, the ladder exit should be located along a shoreline and in a velocity zone of less than the cruising speed of the fish passed, and sufficiently far enough upstream of a spillway, sluiceway or powerhouse to minimize the risk of fish non-volitionally falling back through these routes. Distance of the ladder exit with respect to the hazards depends on bathymetry near the dam spillway or crest, and associated longitudinal river velocities.

Public Access: Public access near the ladder exit should not be allowed.

Section 1.15 - Fishway Exit Sediment and Debris Management

<u>Description and Purpose – Fishway Exit Sediment and Debris Management</u>

For large facilities where maintenance is frequently required and provided, coarse trash racks should be included at the fishway exit, to minimize the entrainment of debris into the fishway. Floating debris may partially block passage corridors, potentially creating hazardous passage zones and/or blocking fish passage. Other types of debris, such as sediment transport into the fishway, may also adversely affect the operation of the facility.

<u>Criteria and Guidelines – Coarse Trash Rack</u>

Velocity: The velocity through the gross area of a clean coarse trash rack should be less than 1.5 ft/s, or less than the cruising speed of the species to be passed.

Depth: The depth of flow through a coarse trash rack should be equal to the pool depth in the fishway.

Maintenance: The coarse trash rack should be installed at 1:5 (horizontal:vertical) slope (or flatter) for ease of cleaning. The coarse trash rack design must allow for easy maintenance, considering access for personnel, travel clearances for manual or automated raking, and removal of debris.

Bar Spacing: The fishway exit coarse trash rack should have a minimum clear space between vertical flat bars of 10 inches if Chinook salmon are present, and 8 inches in all other instances, unless species of fish larger than Chinook are to be passed. Lateral support bar spacing must be a minimum of 24 inches, and must be sufficiently back set of the coarse trash rack face to allow full trash rake tine penetration. Coarse trash racks must extend to the appropriate elevation above water to allow easy removal of raked debris.

Orientation: The fishway exit coarse trash rack must be oriented at a deflection angle greater than 45° relative to the direction of river flow.

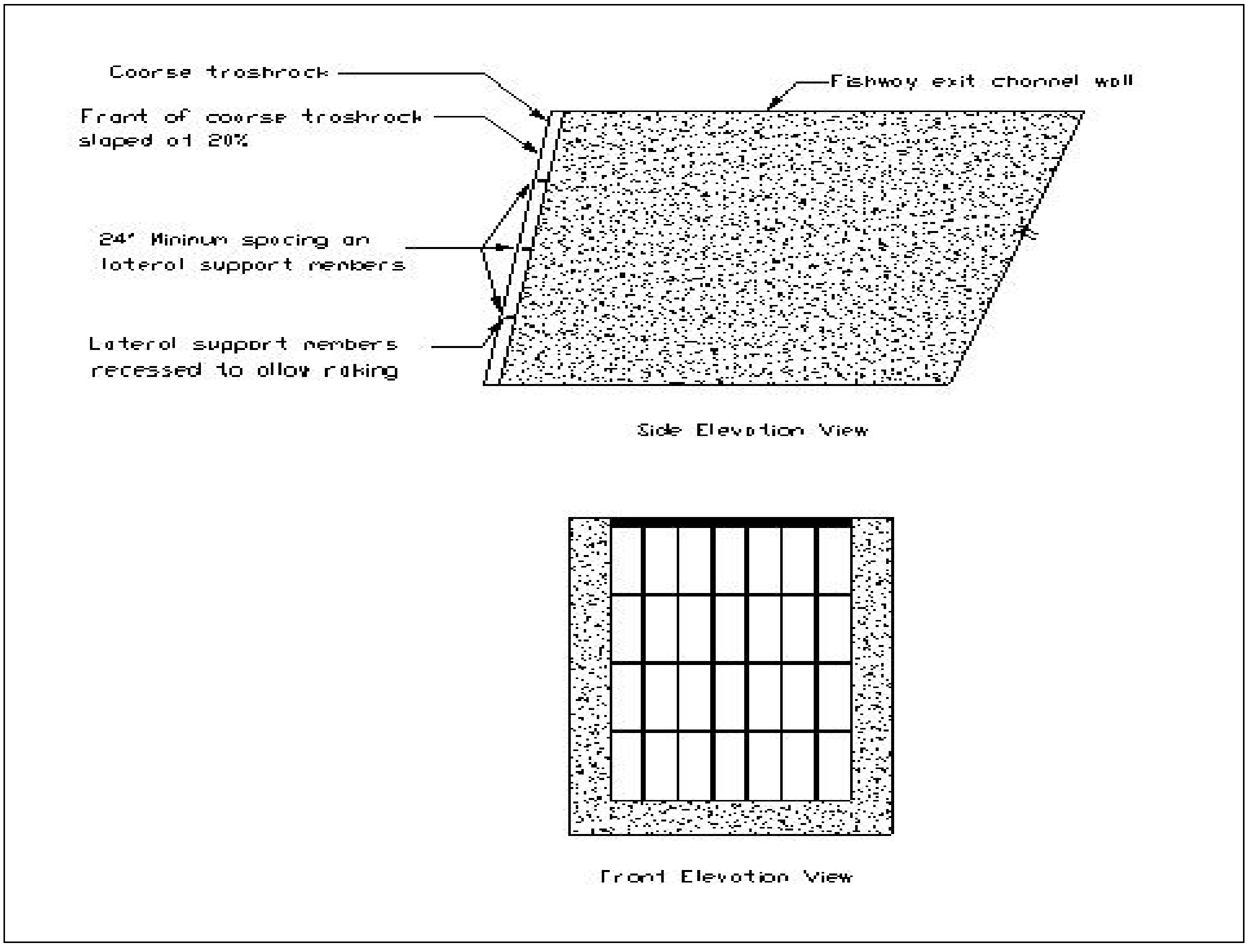

Figure 1.14a. Coarse Trashrack

<u>Criteria and Guidelines – Debris and Sediment Control</u>

Coarse Floating Debris: Debris booms, curtain walls, or other provisions must be included in design if coarse floating debris is expected.

Debris Accumulation: If debris accumulation is expected to be high, the design should include an automated mechanical debris removal system. If debris accumulation potential is unknown, the design should anticipate the need in the future and include features to allow possible retrofit of an automated mechanical debris removal system.

Sediment Entrainment and Accumulation:

- The fishway exit should be designed to minimize entrainment of sediment.
- The facility should be designed such that it does not accumulate sediment or debris during normal operation.

Section 1.16 - Miscellaneous Considerations

<u>Criteria and Guidelines – Miscellaneous</u>

Security: Fishways should be secured to discourage vandalism, preclude poaching opportunity, and to provide public safety.

Lighting: Natural lighting should be consistently provided throughout the fishway. Where this is not possible (such as in tunnels), artificial lighting should be provided in the blue-green spectral range. Lighting must be designed to operate under all environmental conditions at the installation.

Access: Personnel access must be provided to all areas of the fishway, to facilitate operational and maintenance requirements. Walkway grating should allow as much ambient lighting into the fishway as possible.

Edge/Surface Finishes: All metal edges in the flow path used for fish migration must be ground smooth to minimize risk of lacerations. Concrete surfaces must be finished to ensure smooth surfaces, with one-inch wide 45° corner chamfers.

Protrusions: Protrusions (such as valve stems, bolts, gate operators, pipe flanges etc.) must not extend into the flow path of the fishway.

Exposed Control Gates: All control gates exposed to fish (for example, entrances in the fully-open position) must have a shroud or be recessed to minimize or eliminate fish contact.

Maintenance Activities: To ensure fish safety during in-season fishway maintenance activities, all fish ladders must be designed to provide a safe egress route or safe holding areas for fish prior to any temporary (i.e., less than 24 hours) dewatering. Longer periods of fishway dewatering for scheduled ladder maintenance must occur outside of the passage season with safeguards in place to allow evacuation of fish in a safe manner.

Section 1.17 - Roughened Chutes

Description and Purpose – Roughened Chutes

Another general type of fish passage system is the roughened chute, which consists of a hydraulically roughened channel with near continuous energy dissipation throughout its length. Three examples of a roughened chute passage are a baffled chute (including steeppass and Denil fishways), roughened channels or stream simulation, and full width stream weirs.

Types of Roughened Chutes

Baffled Chutes (Denil and Steeppass Fishways): Denil and steeppass fishways are examples of roughened chute fishways and are of similar design philosophy. This type of fishway has excellent fish attraction characteristics when properly sited and provides good passage conditions using relatively low flow amounts. Denil and steeppass fishways are used mainly for sites where the fishway can be closely monitored, such as off-ladder fish trap designs or temporary fishways used during construction of permanent passage facilities. Debris accumulation in any fishway, in combination with turbulent flow, may injure fish or render the fishway impassable. Because of their baffle geometry and narrow flow paths, Denil and steeppass fishways are especially susceptible to debris accumulation. As such, they must not be used in areas where downstream passage occurs, or where even minor amounts of debris are expected.

Denil and steeppass fishways are designed with a sloped channel that has a constant discharge for a given normal depth, chute gradient, and baffle configuration. Energy is dissipated consistently throughout the length of the fishway via channel roughness, and results in an average velocity compatible with the swimming ability of adult salmonids. The passage corridor consists of a chute flow between and through the baffles. There are unique aspects of Denil or steeppass fishways that need to be carefully considered. First, there are no resting locations within a given length of Denil and steeppass fishways. Therefore, once a fish starts to ascend a length of a steeppass or Denil, it must pass all the way upstream and exit the fishway, or risk injury when falling back downstream. If the Denil or steeppass fishway is long, intermediate resting pools may be included in the design, located at intervals determined by the swimming ability of the weakest target species.

The Denil fishway generally is designed with slopes up to 20%, and has higher flow capacity and less roughness than a steeppass fishway. Steeppass fishways may be used at slopes up to 28%. For either fishway, the average chute design velocity should be less than 5 ft/s, or less than the minimum burst speed of the fish. For an upstream passage facility utilizing a Denil or a steeppass ladder, the horizontal distance between resting pools should be less than 25 feet, or less than the distance attainable by a few seconds of minimum burst speed of the species to be passed. Resting pool volumes must adhere to volume requirements. The minimum flow depth in a Denil fishway should be 2 feet, and in a steeppass fishway the minimum flow depth should be 1.5 feet, and depth must be consistent throughout the fishway for all ladder flows. Denil and steeppass fishway exits must be located to minimize the potential for fallback of fish.

Roughened Channels: Another general category of upstream fish passage is termed a roughened channel, where design involves the selection of appropriately sized streambed material placed in such a way as to mimic the configuration in the natural streambed. These are also referred to as stream or streambed simulation, rock channels, or nature-like fishways. By replicating natural stream conditions, a wide variety of life stages and species of fish may be able to utilize the roughened channel for passage. In addition, roughened channels may provide additional benefits to other species such as insects, mollusks, and crustaceans. Roughened channels may not always be the appropriate design choice. This is a relatively new technology without a developed and proven design methodology, and the effectiveness for passing specific species and life stages over a wide flow range, and the long term durability of a wide range of designs has yet to be established. It is expected that through careful engineering and construction techniques, and through monitoring of design uncertainties over time, especially regarding the durability of the roughened channel structure, future design uncertainty can be reduced. If passage conditions in the constructed roughened channel can be achieved that are similar to the downstream passage conditions in the natural stream, there is reason to expect that a properly constructed roughened channel may pass all life stages and species that arrive at the constructed roughened channel.

Designs of roughened channels vary depending on the specific site conditions. Criteria for this type of passage design are evolving, and proposals for this type of ladder assessed on a site-specific basis. In general, roughened channels should only be used when:

- Channel slope using stream simulation is less than 6%.
- Total length of passage is less than 150 feet.
- An appropriate mix of bed materials (from fines to boulder sized material) are used such that flow depths of at least 1 foot can be maintained for upstream adult salmonid passage.
- Sub-surface flow will be minimized by filling voids between larger materials with finer-sized material. Guidance on the mixture of fill material is still evolving, but general guidance is provided in Washington Department of Fish and Wildlife (WDFW) 2003.

The arrangement of bed materials should demonstrate channel complexity similar to the characteristics of the adjacent stream reaches. To minimize the potential for head-cutting to occur, discrete hydraulic drops across the entire width of the roughened channel should be avoided. It should be demonstrated in the design analysis that any scouring of fines from the constructed channel will be refilled by subsequent bedload transport and aggradations. It is noted that if the channel roughness of adjacent stream reaches is heavily influenced by woody debris, it may be difficult to mimic this condition with any sort of constructed roughened channel.

Since this design method is an evolving technology, any site utilizing a constructed roughened channel must include an annual (at a minimum) monitoring plan at least until after a 50-year stream flow event has occurred. Monitoring must include an assessment of passage conditions and/or maintenance of original design conditions, and repaired as necessary to accomplish design passage conditions. The loss of placed bed material after a high flow event will result in loss of flow through the channel substrate, and may render a roughened channel too shallow for fish passage. Criteria for this type of fishway design are still evolving, and design proposals will be assessed on a site-specific basis.

Full Width Stream Weirs: Full width (i.e., full stream width) weirs provide fish passage by incrementally backwatering an impassable barrier or impediment. These structures span the entire width of the stream channel and convey the entire stream flow, breaking the hydraulic drop into passable increments. This is accomplished by incrementally stepping down the water surface elevation from the barrier to intersect the natural stream gradient downstream.

Unlike many of the fishways described herein, these structures are not designed with auxiliary water supply systems, trashracks, or a great deal of operational complexity. Weirs may be constructed from reinforced concrete, or in limited applications, boulders or logs. Since boulders must be large, and usually have unpredictable dimension, a result can be the lack of the desired water surface differential for the range of design streamflows. It is especially difficult to maintain the required water surface elevation differential between weirs (maximum of 1.0 feet) when the design must encompass a wide flow range (tens to thousands of cfs) typical in a Northwest stream. In applications that require precision rock placement for maintenance of hydraulic drop between weirs, for long-term predictability, some applications may require regular maintenance to bring the projects back to design standards. The result is additional instream work that may produce continuing impacts to habitat and fish. These factors must be considered and accommodated before choosing this design for a site.

Design of each weir must concentrate flow into the center of the downstream pool, and/or direct flow toward the downstream thalweg. This concentration is accomplished by providing a slight weir crest elevation decrease from each bank to the center (flow notch). Typically, the flow notch will be designed to pass the minimum instream flow, while higher stream flows pass over the entire weir crest. Natural bedload movement will fill in pools providing a scour pool area below the flow notch, and shallower fringe areas.

Scour is a critical and often underestimated design issue. If sills and weirs are not anchored on bedrock, a means of preventing undermining is required, using embedded anchor boulders or other such means of stabilizing the streambed. If a pool lining technique is selected to prevent undermining of the fishway, a minimum of 4 feet of depth should be provided in each pool and in the tailrace below the fishway. This allows for a fish to stage or hold below each weir before proceeding upstream. In addition, the tailrace area should be protected from scour to prevent lowering of the streambed, and should be monitored after high flows occur to ensure the facility remains passable. Criteria for this type of fishway design are still evolving, and design proposals should be assessed on a site-specific basis.

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