DESIGNING FISH SCREENS
FOR FISH PROTECTION
AT WATER DIVERSIONS

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The following paper should be considered a working document, and its contents will be updated as errors are found and as technology progresses. The contents express the opinions of the author, and not necessarily the National Marine Fisheries Service. Consultation with local fisheries authorities is absolutely required to augment and confirm any information used from this paper.

1.0 -- INTRODUCTION

Protecting the fisheries resources from hydroelectric, irrigation, municipal water supply and industrial water supply developments created the need for design criteria for the construction of juvenile fish screens to protect the fisheries resource from project impacts. This paper discusses a variety of topics involved in the juvenile fish screen design process, in a manner intended for the novice biologist, manager, planner or design engineer.

Screen designs have been improved over the years mostly by the observation and evaluation of existing screens that were constructed based on a little bit of science, a generous dose of intuition and rudimentary understanding of fish behavior. Research in the field of fish passage was historically difficult to finance, and difficult to reach concise conclusions that could lead directly to the establishment of fish passage design criteria. More recently, biological and hydraulic testing of juvenile fish screens, and research specific to the design of juvenile fish screens has lead to further refinement of design criteria. Certain aspects of juvenile fish screen design criteria are now well understood for some species (such as maximum approach velocity and minimum mesh opening for juvenile salmonids), but data for many species is lacking.

There are three basic conceptual types of devices used to exclude juvenile fish from being entrained into a flow diversion: 1) physical barrier screens; 2) behavioral guidance systems; and 3) capture and release systems. A physical barrier screen design works by placing a physical barrier to prevent entrainment. A behavioral guidance system relies on the fish's behavioral response to hydraulic or other conditions produced by the guidance system. A capture and release system attempts to pass fish by collecting fish at points of accumulation in their migration corridor, for release downstream of the project impacts. Each type of system has a variety of designs that have been used over the years, with widely ranging levels of success.

2.0 -- FISH BIOMECHANICS

Of primary interest when establishing design criteria for a juvenile fish screen is the swimming ability of the species and life stage targeted for protection. As one might expect, the swimming capability of as particular species is not constant. Environmental variables such as water temperature, dissolved oxygen level, fish size, stage of development and fish health are major factors that have effects on a fish's ability to swim. Additionally, instream hazards such as a diversion dam or pump intake influence the ability of a juvenile fish to successfully encounter a fish screen and be bypassed back to the river. In the Pacific Northwest when juvenile fish screen criteria was developed by the fisheries agencies, it was decided that the criteria should protect the weakest swimming species in their most vulnerable life stage under adverse environmental conditions. Using this basis for criteria, nearly all fish could be expected to survive an encounter with a diversion and a fish screen.

Fish swimming velocity is usually categorized as either cruising speed, sustained speed or darting speed (see Figure 2-1). Fish can swim at cruising speed for long periods of time (hours) and is the primary speed used for migration. Sustained velocity, also called critical velocity, is a speed that can be maintained for a short period of time (minutes) and is the speed fish swim at when avoiding obstacles such as a fish screen. Darting speed can only be maintained for a short burst period, and is usually only used in panic situations such as predator avoidance.

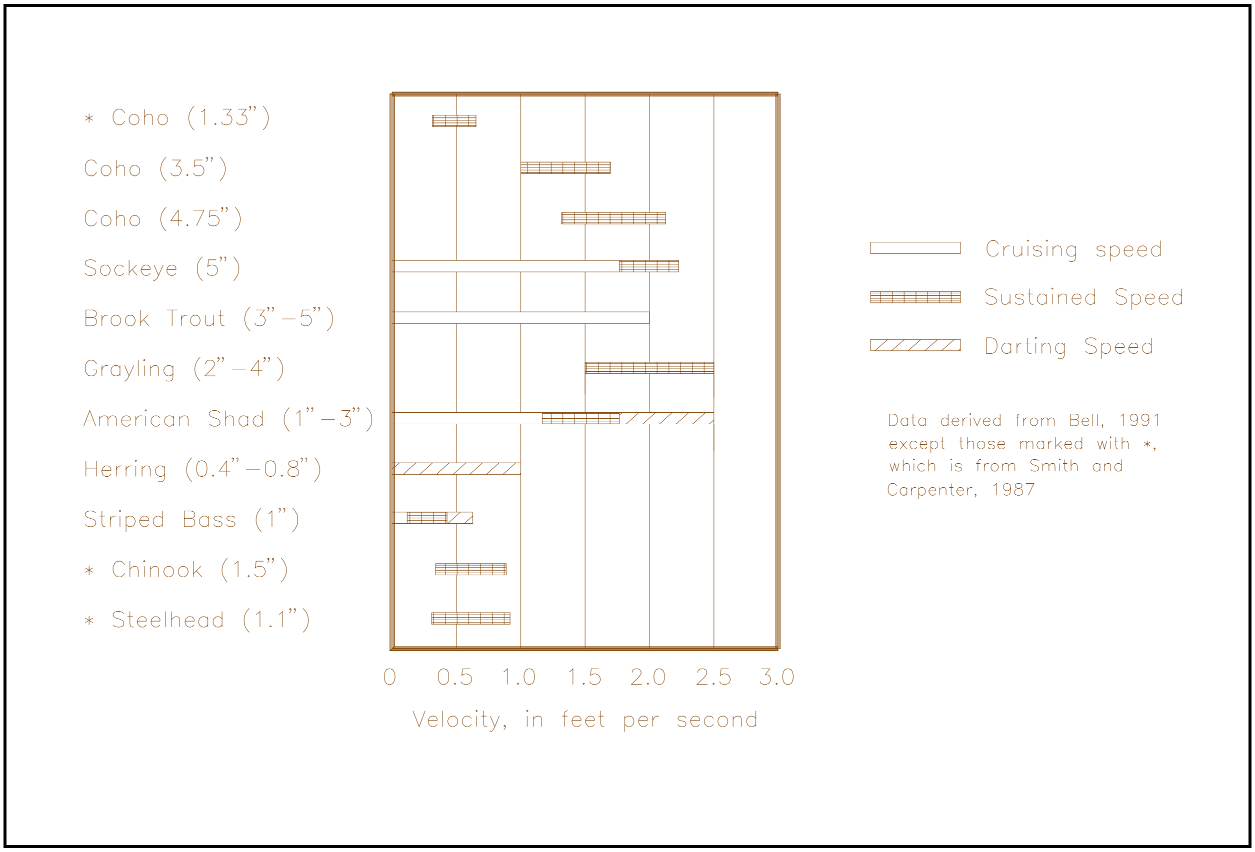

Figure 2-1

The energy expended by fish while swimming is proportional to the square of the water velocity, as shown in Equation 2-1 (Bell 1991). As energy is expended, lactic acid levels may increase to lethal levels, in extreme cases.

Equation 2-1:

$$F = C_D A \mu \frac{V^2}{2g}$$

where :

F =	Force required (pounds)
C_D =	Drag force = about 0.2 (for salmonids)
A =	Cross sectional area of fish (square feet)
μ =	Unit weight of water = 62.4 lbs/ft^3
V =	Relative swimming velocity, in FPS
g =	Gravitational constant, 32.2 ft/sec^2

Fish use their lateral line to sense velocity gradients, and tend to avoid abrupt changes in velocity. Salmonids orient themselves with the current in velocities as low as 0.16 FPS and sense changes of less than 0.33 FPS (Bell 1991). When most juvenile salmonids migrate downstream, their head faces upstream which provides the juvenile fish better control of their motion. When this occurs, the water velocity is of higher magnitude and in the opposite direction of the swimming velocity of juvenile fish, so that the net velocity is downstream. Juvenile salmonid migration past screen sites generally peaks in the late evening, shortly after nightfall, however some migration usually occurs throughout the day. Annual migration periods vary, but for juvenile salmonids, migration generally occurs in the spring time, corresponding with freshet flows. If contact is made with an obstacle, high or low velocity zones, or a boundary layer, the normal response of the fish is to use darting speed to maneuver away from the area. This observed behavior can be put to use in a fish screen design, by providing a screen placed at an angle to the flow. As a fish avoids the screen, the water velocity carries the fish further downstream toward the bypass. If the bypass is sufficiently close (see Section 5-2), successful passage is achieved.

2.1 -- EFFECTS OF WATER TEMPERATURE ON SWIMMING ABILITY

Juvenile salmonid fish screen criteria in the Pacific Northwest has been developed to accommodate the swimming ability of the smallest fish (emergent fry) under the coldest water temperatures possible at a screen site. Figure 2-2 shows how water temperature affected swimming ability of Chinook fry in fry stamina testing done at the University of Washington.

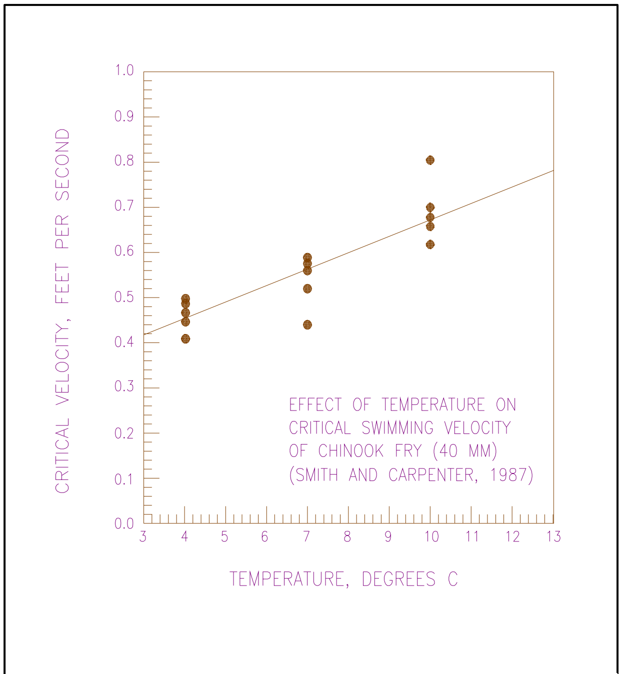

Figure 2-2

Hydrologic conditions vary from year to year, and this can have a significant effect on the species and life stage of fish found at a specific site, especially when coupled with varying water temperatures. For example, low water and warm river temperatures in 1992 on the McKenzie River in Oregon caused fry emergence two to three months earlier than normal. When coupled with a later cold snap that caused water temperatures to approach 32° F, hydrologic conditions in the river tested the limits of juvenile fish to endure conditions encountered at a fish screen. It is not recommended that a screen designer attempt to modify criteria to account for warmer water temperatures, because a single unusual cold weather event that inhibits the swimming ability of fish, could cause high levels of mortality at a juvenile fish screen, possibly placing an entire year class of fish in jeopardy.

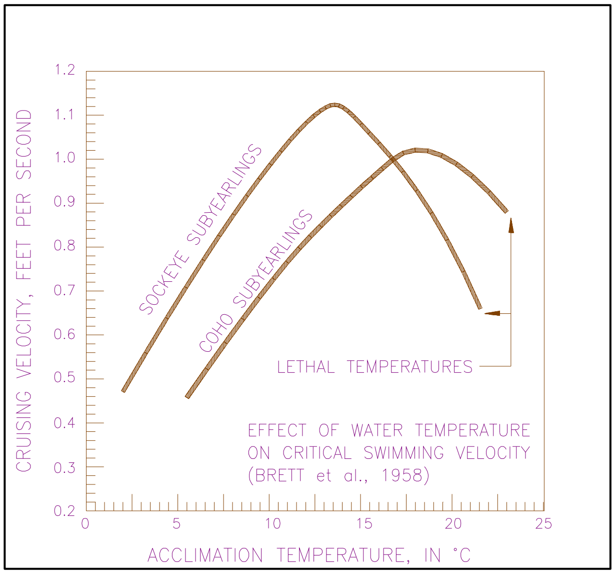

Figure 2-3

High water temperatures can also affect the swimming ability of fish. Figure 2-3 shows how the swimming ability of sub-yearling sockeye and coho was affected over a range, up to temperatures sufficiently high to be considered lethal to juvenile salmonids. If water temperatures are high and other stressors present, such as predators or poor fish facility passage, the potential for significant mortality exists.

Figure 2-3

2.2 -- FISH SIZE AND SWIMMING ABILITY

As one might expect, the size of a fish has an impact on swimming ability. This effect was considered in the development of juvenile fish screen criteria for approach velocity, so that even the smallest fish is able to avoid contact with the screen at the lowest water temperatures. Smaller fish have lower critical swimming velocity, as seen in Figure 2-4. The smallest Chinook fry tend to be in the 38 to 42 mm range, steelhead from 28 to 32 mm, and rainbow from 24 to 30 mm. These sizes correspond to fish newly emerged from spawning beds, and are at their most vulnerable life stage, in regard to swimming ability.

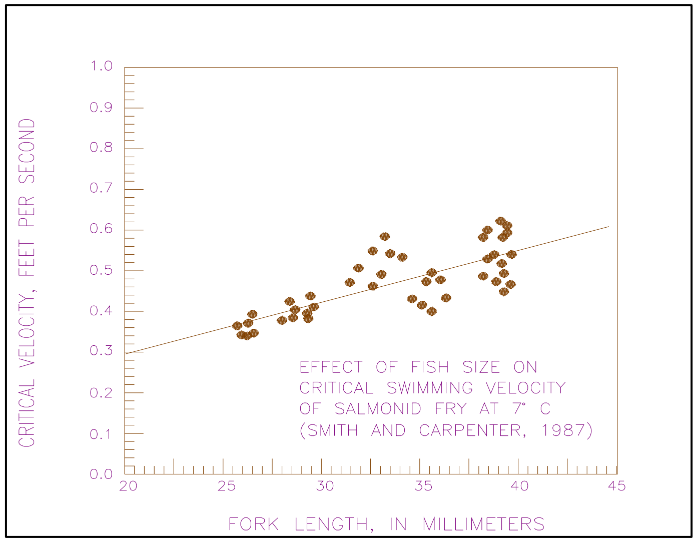

Figure 2-4

2.3 -- DISSOLVED OXYGEN

Swimming speed is affected by dissolved oxygen level, which in turn is related to water temperatures. Swimming speeds may be reduced by as much as 60% at oxygen level at one-third of saturation levels.

3.0 -- PRIORITIZING SCREENING PROJECTS

In some instances, a block of funding may become available to construct a number of juvenile fish screens in a specific area. When this occurs, it is important for managers to develop a system for ranking projects based on the potential for rectifying problems encountered by emigrating juvenile fish. Although many factors must be considered when ranking projects, primary factors influence the ranking process, such as: 1) number of fish entrained with the diverted flow; 2) existing level of fish protection at a specific screen site; 3) presence of endangered or threatened species; and 4) amenable land-owners. Other secondary factors include: 1) proximity to other proposed projects; 2) frequency of diversion; 3) type of diversion; and 4) public education.

Sometimes, the secondary factors listed above may preempt the primary factors. For example, managers may choose to first construct a new fish screen in a prominent location so that local land-owners in need of fish screens might observe a new structure and become informed about the benefits to the resource that the new screen provides, and be set at ease about the potential for adverse impacts on their operations. As another example, sites with endangered or

threatened species usually move quickly to the top of any ranking process.

<u>Example 3-1</u>

Tables 3-1 through 3-5 provide an example of how a manager could prioritize projects, based on two of the primary factors listed above being analyzed by a simple spreadsheet model. In this example, it is assumed that 1,000 juvenile fish enter the upstream project and migrate downstream. It is usually reasonable to assume that the number of fish entering a diversion is directly proportional to the diverted flow percentage. This is not always exactly correct, but lacking site specific information it is a reasonable assumption. In Tables 3-1 through 3-5, the number calculated under the heading "Fish passed per 1000" is the number of fish that manage to get by the project successfully. The heading "Weight Factor" is calculated as the product of the two columns to the left titled "Mortality (%) at Diversion" and "Percent of River Diverted". "Priority ranking" is the priority level based on the weight factor. The column titled "Fish passed per 1000" is calculated by multiplying the number of fish entering the diversion times the estimated mortality times the percentage of flow diverted, and subtracting this product from the number of fish entering the diversion. In this example, the following assumptions are made when prioritizing projects:

- **-- funding is available to construct 3 new fish screens per year.**
- **-- passage improvement is reflected by the change in the "Percent mortality" column.**
- **-- the priority ranking assigned is based only on the "Weight factor".**
- **-- the impact of the screen program can be observed by scanning the "Fish passed per 1000" column.**
- **-- all fish entering an unscreened diversion wind up as mortalities.**

Table 3-1 -- Original condition of fish screening in a hypothetical river basin.

PROJECT (downstream order)	SCREEN CONDITION	PERCENT OF RIVER DIVERTED	MORT-ALITY AT DIVER-SION	WEIGHT FACTOR	PRIORITY RANKING	FISH PASSED PER 1000
Wheaties	very poor	10	30	300	6	970
Salmon Stew	none	85	100	8500	1	145
Bovine Shrine	poor	33	15	495	5	137
Grape Crush	none	2	100	200	7	134
Greedy Gusher	poor	50	15	750	4	123
Water Hog	none	70	100	7000	2	36
Grain Guru	poor	1	15	15	10	35
Habitat Heaven	very poor	5	30	150	8	34
Low Flow Lou	very poor	60	30	1800	3	27
Hay You	fair	20	5	100	9	26

After passing the second diversion (Salmon Stew), which is unscreened and diverts 85% of the river, only 145 fish survive, and 26 out of 1000 survive the gauntlet posed by all of the diversions. The top three priority screens are constructed, and the survival model is applied again (Table 3-2).

Table 3-2 -- Effect of fish screening after year 1 in a hypothetical river basin.

PROJECT (downstream order)	SCREEN CONDITION	PERCENT OF RIVER DIVERTED	MORT-ALITY AT DIVER-SION	WEIGHT FACTOR	PRIORITY RANKING	FISH PASSED PER 1000
Wheaties	very poor	10	30	300	6	970
Salmon Stew	new	85	2	170	--	953
Bovine Shrine	poor	33	15	495	5	905
Grape Crush	none	2	100	200	7	886
Greedy Gusher	poor	50	15	750	4	819
Water Hog	new	70	2	140	--	807
Grain Guru	poor	1	15	15	10	805
Habitat Heaven	very poor	5	30	150	8	792
Low Flow Lou	new	60	2	120	--	782
Hay You	fair	20	5	100	9	774

By fitting three of the most problematic diversions with good quality fish screens, survival out of the basin has increased from 26 fish to 774 fish, a 30-fold survival increase providing a tremendous return to the resource for only treating 30% of the diversions. Now, assume in the second year that three additional diversions are treated with new fish screens (Table 3-3).

Table 3-3 -- Effect of fish screening after year 2 in a hypothetical river basin.

PROJECT (downstream order)	SCREEN CONDITION	PERCENT OF RIVER DIVERTED	MORT-ALITY AT DIVER-SION	WEIGHT FACTOR	PRIORITY RANKING	FISH PASSED PER 1000
Wheaties	new	10	2	20	--	998
Salmon Stew	1 year old	85	2	170	--	981
Bovine Shrine	new	33	2	66	--	974
Grape Crush	none	2	100	200	7	954
Greedy Gusher	new	50	2	100	--	944
Water Hog	1 year old	70	2	140	--	930
Grain Guru	poor	1	15	15	10	928
Habitat Heaven	very poor	5	30	150	8	914
Low Flow Lou	1 year old	60	2	120	--	903
Hay You	fair	20	5	100	9	893

By fitting the next three of the most problematic diversions with good quality fish screens, survival out of the basin has increased from 774 fish to 893 fish, a survival increase of nearly 12%, still a good return to the resource for treating 30% of the diversions. Now, assume in the third year that three additional diversions are treated with new fish screens.

Table 3-4 -- Effect of fish screening after year 3 in a hypothetical river basin.

PROJECT (downstream order)	SCREEN CONDITION	PERCENT OF RIVER DIVERTED	MORT-ALITY AT DIVER-SION	WEIGHT FACTOR	PRIORITY RANKING	FISH PASSED PER 1000
Wheaties	1 year old	10	2	20	--	998
Salmon Stew	2 year old	85	2	170	--	981
Bovine Shrine	1 year old	33	2	66	--	974
Grape Crush	new	2	2	4	--	973
Greedy Gusher	1 year old	50	2	100	--	963
Water Hog	2 year old	70	2	140	--	949
Grain Guru	poor	1	15	15	10	947
Habitat Heaven	new	5	2	10	--	946
Low Flow Lou	2 year old	60	2	120	--	934
Hay You	new	20	2	40	--	930

By fitting the next three of the most problematic diversions with good quality fish screens, survival out of the basin has increased from 893 fish to 930 fish, a survival increase of nearly 3.7%, still a good return to the resource for treating 30% of the diversions. Now, assume in the fourth year that the final screen is constructed (Table 3-5).

Table 3-5 -- Effect of fish screening after year 4 in a hypothetical river basin.

PROJECT (downstream order)	SCREEN CONDITION	PERCENT OF RIVER DIVERTED	MORT-ALITY AT DIVER-SION	WEIGHT FACTOR	PRIORITY RANKING	FISH PASSED PER 1000
Wheaties	2 year old	10	2	20	--	998
Salmon Stew	3 year old	85	2	170	--	981
Bovine Shrine	2 year old	33	2	66	--	974
Grape Crush	1 year old	2	2	4	--	973
Greedy Gusher	2 year old	50	2	100	--	963
Water Hog	3 year old	70	2	140	--	949
Grain Guru	new??	1	2	2	--	948
Habitat Heaven	1 year old	5	2	10	--	947
Low Flow Lou	3 year old	60	2	120	--	935
Hay You	1 year old	20	2	40	--	931

It is interesting to note that building the final screen at site "Grain Guru" produces only 1 additional fish based on the model above. This is largely due to the fact that the last diversion treated only diverted one percent of the total river flow. Similarly, providing a new screen at site "Grape Crush" would not likely have a large impact on survival, since it diverts only two percent of the river flow.

A point of note here is that the size of the diversion is likely less important than the percentage of the flow diverted. A 200 CFS diversion from a 200,000 CFS flow will have less impact on fish survival than would a 12 CFS diversion from a 30 CFS flow, assuming both diversions are similarly located.

Another consideration worth noting when contemplating an array of potential screening projects, is the concept of consolidating diversions. Migration delay and passage problems are obviously reduced if the number of in-river diversions is reduced. It is always worth pursuing the potential for reductions in water usage. Converting from flood irrigation to sprinkler irrigation reduces flow requirements by up to 300%. Either of these actions will result in a less expensive screen and less expense in terms of harm to the fisheries resource.

4.0 - LOCATING THE SCREEN STRUCTURE

Normally, a screen site is chosen based on minimizing the delay of fish encountering the diversion. At some sites, providing that certain conditions can be met, a screen may be placed on the edge of the river so that no bypass is required because fish remain in the river (see Figure 4-1). If river alignment is fairly straight and the water surface elevation fairly constant across the required screen length (see section 5-2), this may be a good alternative for a screen site. However, there are factors that may preclude this option. For example, heavy debris or ice loads in stream may pose structural threat to the screen. At these sites, the screen must either shut down during adverse conditions (protected by heavy stoplogs or a gate), or else a different screen site must be chosen.

For many sites, there is no option for a location of a screen. An example of this might be at an intake in the forebay of a power plant, where a conventional screen should be placed at the

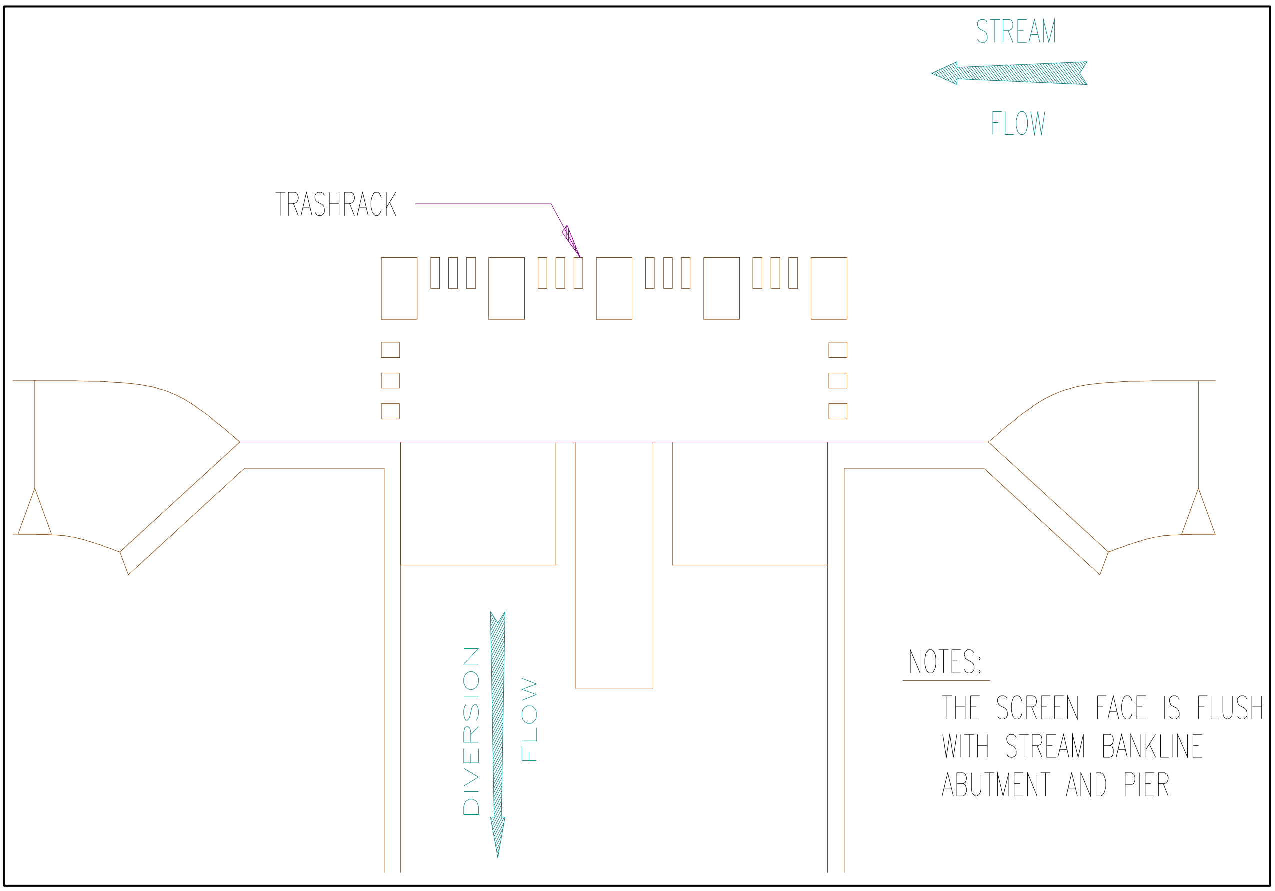

Figure 4-1

inlet. An experimental screen device called an "Eicher screen" have been tested that can be placed inside a penstock, but have not yet been accepted as a viable design option by fisheries

agencies in the Northwest. However, these devices do show promise in adequately protecting some species of fish under certain environmental conditions (Electric Power Research Institute, 1991).

Another constraint on the location of the screen is the hydraulic head available to operate the bypass return pipe. Generally, it requires about two to six feet of head differential between the canal water surface and the river water surface for all combinations of low/high river flows and low/high canal flows. This head differential accounts for:

-- head loss across the screen (a few inches maximum),
-- drop into the bypass well (about 1 foot),
-- headloss through an evaluator (if needed, about 1 foot),
-- velocity head and conveyance loss in the bypass pipe (site specific, but about 1 foot per 100 feet of pipe length per 1000 gallons per minute flow for 10-inch diameter pipe).

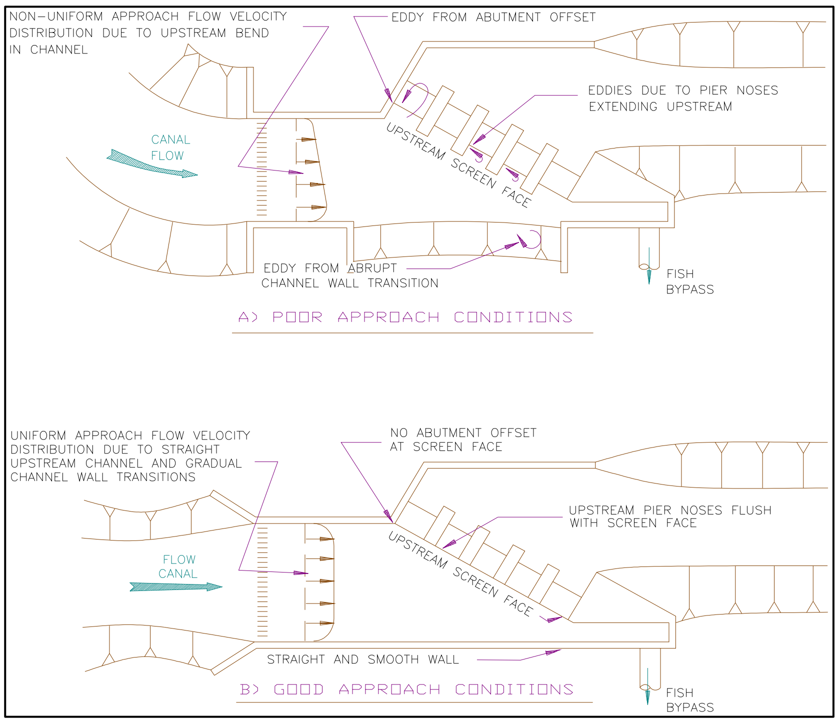

Figure 4-2

Careful bypass return pipe design can reduce some of these headloss components. Hydraulic grade lines should be calculated for each individual design. Shorter bypass pipes may result in a lower requirement for head differential. The available head between the screen site canal water surface and the high water mark (5% exceedence flow) at the bypass outfall needs to be checked to verify that sufficient head exists for the bypass pipe to function correctly (see Appendix A). A straight section of canal that exhibits laminar flow characteristics should be chosen for a screen site, as shown in the lower portion of Figure 4-2. The bank line should also be smooth, without projections or other features that may cause eddies or changes in water velocity.

Figure 4-2

4.1 -- EASEMENTS

Sometimes overlooked in the design process, is the procurement of all the required easements to the proposed screen site. These can be donated to the agency constructing the fish screen, but this is not always the case. When required, easements should be obtained for:

- **the construction staging site,**
- **operations and maintenance access,**
- **the screen site,**
- **the bypass return line,**
- **power lines,**
- **trap boxes.**

It is also important to coordinate construction periods with the water user and with allowable biological in-water work windows. Usually, there are periods of time where it possible for a construction crew to install a screen without affecting operations. If a screen is to be constructed off stream in a canal, in-water work periods may not apply, especially if the screen can be constructed in the dry. It is generally good and usually required protocol to consult with local fish and wildlife agencies to check if there are concerns about the construction schedule, well in advance of construction.

4.2 -- AGENCY COORDINATION

When considering a site for a juvenile fish screen installation, it is important for the designer to ensure that he has contacted all parties that may have interest in or jurisdiction at the site. The list of potential interested agencies can be long, but a few that generally may be interested in water development projects involving fish screens are fish and wildlife protection agencies (such as U.S. Fish and Wildlife Service, National Marine Fisheries Service, State and Tribal Agencies), land use agencies (U.S. Bureau of Land Management, U.S. Forest Service, Natural Resource Conservation Service), water managers and users (U.S. Bureau of Reclamation, water districts, irrigation districts), wetland protection agencies (Environmental Protection Agency, Army Corps of Engineers) and others. It is important to at least touch base with all potential interested agencies to see if they have interest or jurisdiction in a screening project, and also to provide their input as to what other agencies need to be involved. Neglecting the required contact with the appropriate agencies can delay construction due to unanticipated permit requirements. If federal funding is involved, certain processes may be required in the design process, such as Endangered Species Act consultation and National Environmental Policy Act compliance.

4.3 -- SITE SURVEYS

For all juvenile fish screen sites, a minimum level of site recognizance is required before the design process can proceed. The following pages contain a form used in Oregon and Idaho for gathering the required information for the construction of fish screens under the Columbia

River Fishery Development Program. This site survey form contains the minimum level of information required so that a good design can be produced. Explanatory text is listed in small fonts on the form.

JUVENILE FISH SCREEN SITE SURVEY FORM

Surveyed by: **Date:**

I. Description of site (name of diverted stream, type of headgate present, diversion method, ditch dimensions, landowner name, water right etc.)

II. Water Survey Data (indicate method used to determine and estimate a & b based on high water marks, flow records)

1. River water surface elevations (WSE) and streamflow near bypass outfall site

a. High flow = CFS, WSE =

b. Low flow = CFS, WSE =

c. Surveyed water surface = CFS, WSE =

2. River water surface elevation and streamflow at headgate

a. Estimated high flow = CFS, WSE =

b. Estimated low flow = CFS, WSE =

c. Surveyed water surface = CFS, WSE =

3. Head drop through headgate

a. Maximum = feet, CFS =

b. Minimum = feet, CFS =

c. Surveyed water surface =

Estimate a & b based on flow records.

III. Diverted flow and associated canal WSE

1. Maximum diversion = CFS, WSE =

2. Normal diversion = CFS, WSE =

3. Minimum diversion = CFS, WSE =

IV. Recommended screen structure

1. Type of screen: (rotary drum, fixed vertical, etc.)

2. Angle of screen relative to ditch flow:

3. Screen cleaning mechanism: (drum rotation, spray bars, brushes etc.)

4. Screen cleaner powered by: (electric motor, paddlewheel, hydraulic motor etc.)

5. Number and size of drums, or submerged screen area required:

6. For pump intake screens, list minimum river depth at proposed screen location:

7. For pump intake screens, list brand, model, cleaning mechanism, screen dimensions (effective length and width):

V. Recommended bypass return pipe (if applicable)

1. **Pipe diameter =**
2. **Length required (to preferred outfall site) =**
3. **Pipe slope (rise/run) =**
4. **Bypass flow control device (weir length or orifice size):**
5. **Outfall type (submerged, free-fall, open channel):**
6. **Approximate river velocity at outfall =**
7. **Minimum outfall depth =**
8. **Ditch invert elevation =**

VI. Other site constraints (examples: access problems, stream characteristics at bypass outfall site, construction site problems, excessive cut/fill, land owner problems, irrigation season, river flow, construction window, ice jam problems, sedimentation potential, winter operation required for stock water, consolidation potential, irrigation methods that impact indicated water surface elevations, screen location constraints, road/bridge construction required, excessive debris load etc.). If possible, indicate method of coping with constraints.

VII. Site sketch. Include screen/bypass layout, river near screen site and construction constraints.

VIII. Ditch cross sections. Include invert elevations relative to benchmark, distance between cross-sections, and water surface elevation.

IX. Flow measurement data and other available flow information. Indicate water surface elevation relative to local benchmark used in the site survey.

4.4 -- DIVERSION CANAL AS FISH HABITAT

In these times when suitable habitat for fish species is disappearing, some innovative biologists are finding ways to use diversion canals as habitat for salmonids. Sometimes, more water is being diverted than is left instream, thus the potential for off stream habitat in the canal should be investigated. A diversion canal often provides areas of slow velocity in otherwise high gradient streams. If sufficient canal area is available upstream of a screen site, it can sometimes be used for rearing habitat providing proper consideration is given to the details described below. However, it is important to remember that any habitat created in the ditch intended for a specific species, could also become suitable habitat for providing avian (birds) and piscian (fish) predators with a stable food base.

It should always be expected that some method will be used to control riparian growth in the vicinity of the diversion headgate and in the canal. The objective in doing this is to prevent future debris (i.e. riparian cover) from entering the ditch and increasing channel roughness, thereby increasing headloss and reducing flow in the ditch. Leaving bank vegetation in place helps to maintain water temperatures, provides potential forage opportunity (insects) and also can provide cover from avian predators. Effort should be made to encourage leaving this riparian zone intact, especially in the canal upstream from the screen site. Canal maintenance can also include herbicide or pesticide application. Water flow and quality should remain adequate for fish, as is expected for any productive fish habitat. Egress from the off-stream habitat in the canal should be volitional and available whenever downstream migration is underway. Each of these factors should be considered (and perhaps negotiated) before the decision to use the canal as habitat is made final.

4.5 -- DIVERSION OPERATIONS - POTENTIAL PITFALLS

When a new diversion project is in the conceptual stage, there are a certain pitfalls to avoid with diversion operation and its effects on fish. Likewise, when retro-fitting existing diversions, there are factors that affect fish passage that may be beyond the control of the designer of the fish screen, but should at least be discussed with those involved with project operations.

Depending on the specific project, there is often no way to be certain when or how a particular diversion will be operating. Uncoordinated diversion operation can cause fish to be entrained in the canal prior to installation of the fish screen, or trapped in the canal when the diversion is turned off. Good communication with project operators is essential to assure that a fish screen is in good operating condition prior to water diversion, and that fish are out of the canal before the canal is dewatered. XXXXXXX

If a canal is sloped sufficiently and can drain completely, fish can be routed out the bypass providing that the diversion shut down operation is performed adequately. This usually

entails slow rates of closure, sometimes termed as "ramping rates". Often, in hydroelectric projects, a ramping rate of one to two inches per hour is recommended by the resource agencies in the relicensing process (Hunter, 1992). This slow rate of closure will allow juvenile fish to egress from areas where they might become stranded. For hydropower plants, an energy dissipation valve may be required in the event of a load rejection, causing an abrupt shut down of a turbine. The energy dissipation valve allows flow to be routed around the turbine without causing the downstream river to fluctuate beyond allowable rates. In a diversion canal upstream of a fish screen, similar rates could be adopted. It is always a good idea to have a qualified biological team on site to salvage fish during canal shutdown if fish have historically been stranded.

Another potential pitfall involves weed or pest control in a diversion canal by application of herbicides or pesticides. Care must be taken to ensure that there is no possibility for any toxicant to be released into areas where it might come in contact with fish or wildlife. It is prudent to develop in coordination with the diverter, a plan for applying any toxicant. This would involve 1) notifying fish and wildlife authorities before application; 2) salvaging or bypassing fish from a ditch prior to application; and 3) ensuring all gates and valves are closed so no possibility of leakage into the riverine environment is possible.

5.0 PHYSICAL BARRIER SCREENS

The method most widely accepted and most successful method to accomplish juvenile salmonid passage is to provide a physical barrier that safely prevents fish from becoming entrained into a diversion and routes the juvenile fish back to the river. A physical barrier is commonly used for juvenile fish protection in the Pacific Northwest when water is diverted for agriculture, ranching, power production, municipal water supply or other uses. Over 200 physical barrier screens, mostly rotary drum screens, have been constructed since 1992 in Oregon, Idaho and Washington, increasing the chance of survival for endangered salmonid species, as well as other resident fish species.

5.1 SCREEN DESIGN OBJECTIVE – AVOID FISH INJURY AND MORTALITY MECHANISMS

Many mechanisms that cause injury, migrational delay or mortality must be considered when designing a physical barrier screen. These include:

1) physical contact with the screen;
2) impingement onto the screen;
3) entrainment through the screen mesh;
4) predation in the screen forebay;
5) predation at the bypass return pipe and at the outfall in the river;
6) water quality in the ditch;
7) water quantity in the ditch, bypass return pipe and river;

8) debris accumulations in bypass pipes, head gates or trashracks;
9) excessive delay of fish due to poor hydraulic guidance conditions.

5.2 PREVENTING FISH IMPINGEMENT AND CONTACT WITH THE SCREEN MESH

Physical contact with a screen material causes some level of fish injury and/or mortality. In conventional physical barrier designs, the goal is to match the biomechanics and behavior of fish to hydraulic characteristics of the screen and civil works design, in order to minimize or eliminate the probability of contact with the screen. Studies of fish biomechanics have led to hydraulic criteria used for approach velocity (as defined below) in fish screen design (Smith and Carpenter, University of Washington, 1988). In the Pacific Northwest, juvenile fish screen design criteria for salmonid protection has been developed by the National Marine Fisheries Service (see Appendix A), Washington Department of Fish and Wildlife and Oregon Department of Fish and Wildlife. The NMFS juvenile fish screen criteria is now applied regionally for salmonid protection, due to efforts of the Fish Screen Oversight Committee comprised of fisheries personnel from fish and wildlife agencies in Oregon, Washington, Idaho and Montana.

For purposes of definition, the canal velocity vector is broken vectorally into two components, V_a which is the approach velocity, and V_s which is the sweeping or transport velocity. The approach velocity is the component that is perpendicular to the screen face, and must be less than the sustained swimming speed of the juvenile fish that the screen is designed to protect. The sweeping velocity is the velocity component that assists in moving fish along the screen face towards the bypass entrance where the fish is routed back to the river. The sweeping velocity component can be varied by adjusting the angle between the screen face and the direction of canal flow. Steeper angles (i.e. smaller angles) provide a larger sweeping velocity component. NMFS juvenile fish screen criteria calls for sweeping velocity should be between 0.8 to 3.0 FPS. State of Washington juvenile fish screen criteria calls for sweeping velocity to be at least double the approach velocity.

Figure 5-1 and Equation 5-1 show how the flow velocity of the canal, V, is divided vectorally into its two components V_a and V_s.

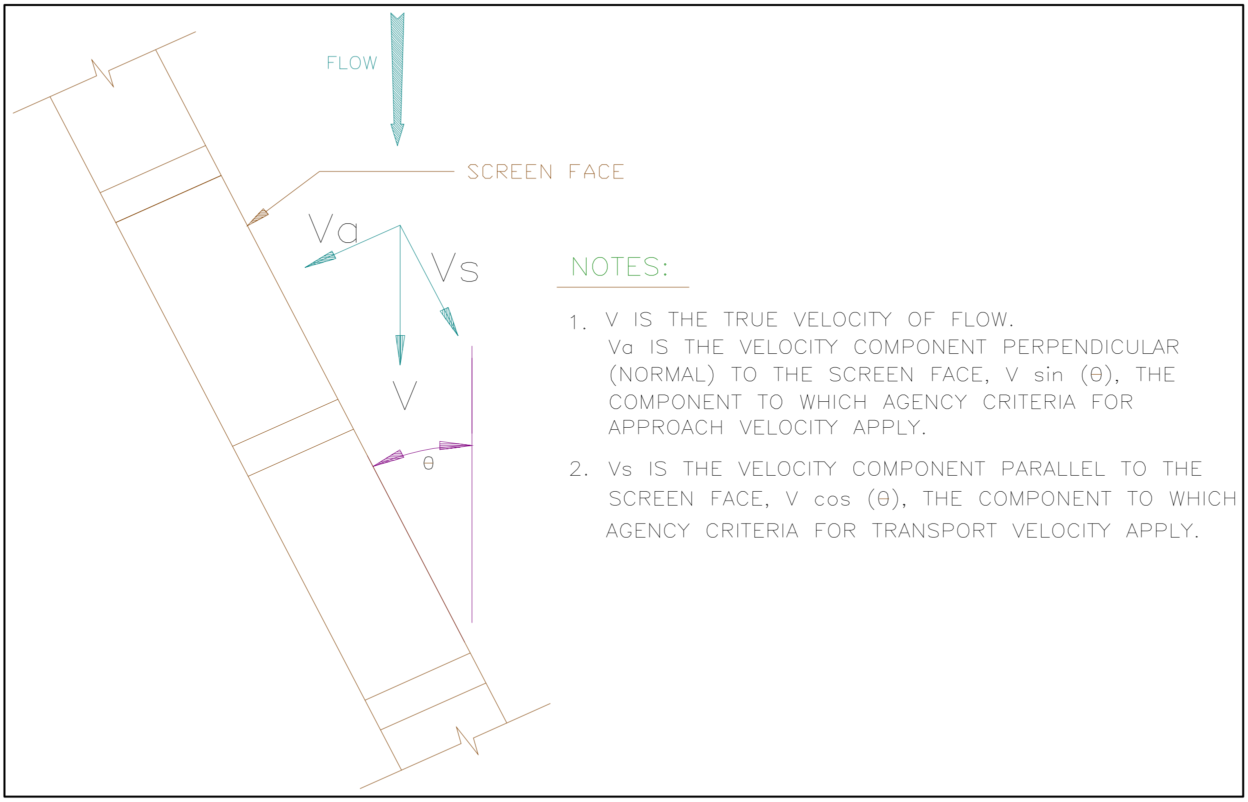

Figure5-1

Equation 5-1: **Approach velocity =** $V_a = V \text{ sine } \theta$

Sweeping velocity = $V_s = V \text{ cosine } \theta$

Where: **V = Canal velocity**

θ = Angle between screen face and canal flow line

Fish impingement onto the screen face can usually be avoided with proper consideration of hydraulic aspects of the design. Juvenile fish screen criteria used in the Northwest specifies that approach velocity must be less than 0.4 feet per second (FPS) to adequately protect salmonid fry. The 0.4 FPS approach velocity was chosen based on the sustainable swimming speed of small juvenile salmonid fry (less than 40 mm fork length), for a particular length of

time when exposed to a screen surface (Smith and Carpenter, 1987). It is usually considered to be the velocity about three inches in front of the screen face, or at the edge of the boundary layer at the screen face. The chosen approach velocity must be conservative, because factors such as fish length, water temperature, injury or disease, and lighting affect swimming ability. In the case of juvenile pacific salmonids, nearly 100% of fry are protected if approach velocity is less than 0.4 FPS. For other species of fish, the sustained swimming speed will vary and it is important to research available literature to determine the appropriate approach velocity for the weakest swimming species that the screen is designed to protect.

To calculate the screen area required to attain the desired approach velocity, divide the maximum diverted flow by the approach velocity, as shown in equation 5-2.

Equation 5-2: $$A_s = \frac{Q_{max}}{V_a}$$

where:

V_a = Approach Velocity
A_s = Screen Area
Q_{max} = Diverted Flow (maximum)

In equation 5-2, it is important to note that the calculated screen area must be entirely submerged when flow is diverted at its maximum rate. The designer should also confirm that an appropriate area of screen surface is submerged throughout the entire range of diverted flows. It may be necessary to elevate the water surface at the screen face by use of downstream stoplogs or control gates, to ensure that sufficient area is wetted to meet the desired approach velocity. For rotating drum screens, it is the vertical projection of the screen area that is used for producing the approach velocity, as opposed to the circumferential screen area.

Example 5-1:
As an example, if 9000 gallons per minute (GPM) is the maximum diversion rate for a given intake, and salmonid fry (sustained swimming speed of 0.4 FPS) are known to inhabit or migrate through the intake vicinity, then the required screen area can be calculated as follows:

$$V_a = 0.4 \text{ FPS (given)}$$
$$Q_{max} = 9000 \text{ GPM} \times \frac{1 \text{ CFS}}{448.831 \text{ GPM}} = 20.05 \text{ CFS}$$

$$A_s = \frac{20.05 \text{ CFS}}{0.4 \text{ FPS}} = \underline{50.13 \text{ Square Feet}}$$

Note that the screen area calculated above is the <u>minimum submerged</u> screen area required to divert the maximum flow rate.

Another hydraulic aspect that must be considered to avoid impingement is the time that a fish is exposed to a screen face. In the NMFS screen criteria, an exposure time of less than one minute is specified in the criteria for juvenile salmonids. Once again, this is based on stamina studies performed at the University of Washington (Smith and Carpenter, 1987) that showed that over 98% of the salmonid fry tested were able to swim for at least one minute at the 0.4 FPS approach velocity. Figure 5-2 and Example 5-2 show how an intermediate bypass

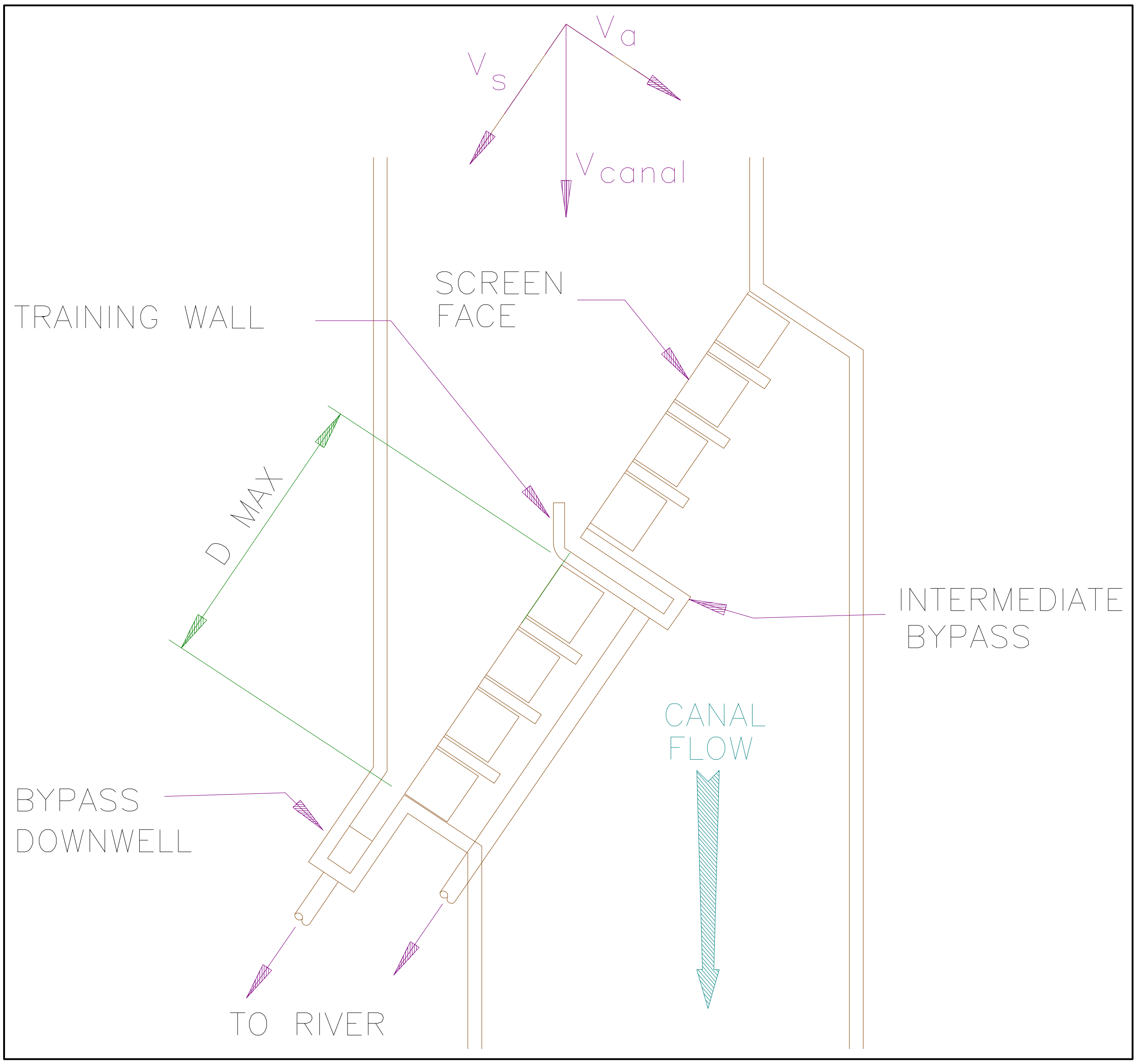

Figure 5-2

entrance can be employed to keep the exposure time within acceptable criteria.

To apply the 60 second exposure time criteria to screen design, the maximum length of screen between bypass return entrances, can be determined by applying equation 5-3:

Equation 5-3: **Maximum length between bypasses = V_s x 60 seconds**

Example 5-2:
Assume that a canal has an average velocity (V) of 2.9 FPS upstream of the proposed fish screen, the maximum canal flow (Q_{max}) is 700 CFS, and the maximum flow depth is 6 feet. Approach velocity (V_a) is 0.4 FPS, and maximum exposure time is 60 seconds.

V = 2.9 FPS
θ = 25°
V_s = 2.9 x cosine 25° = 2.62 FPS (from Equation 5-1)
Maximum length = 2.62 FPS x 60 seconds = <u>158 feet</u>

To check the required screen area, assuming a 6 foot submergence, Equation 5-2 can be used:

$$A_s = Q_{max} \text{ x } V_a = 700 \text{ CFS x } 0.4 \text{ FPS} = 1750 \text{ square feet}$$

Now, dividing the area by the maximum flow depth yields the total required screen length:

Total length required = 1750 square feet x 6 feet = <u>292 feet</u>

For this site an intermediate bypass should be provided as shown in Figure 5-2 at the midpoint of the length of the screen. Dividing the total length required in half gives a 146 foot length between bypass entrances, less than the 158 foot maximum length calculated which provides an exposure time within acceptable criteria.

A third major consideration in juvenile fish screen design to reduce fish impingement probability is careful attention to the alignment of the civil works relative to the screen face. If designed incorrectly, areas of localized high approach velocity (known as "hot spots") will occur. Hot spots on the screen face are usually manifested in debris accumulations at a certain location. If debris is allowed to accumulate at a hot spot location, the effective screen area is reduced, thereby increasing approach velocity, potentially impinging fish on the screen face.

One method that has been used with success to alleviate velocity hot spots, is to provide an

adjustable baffle system downstream of the screen mesh. A baffle system is an array of bars, usually oriented vertically, that have the capability to control flow through the mesh by adjustment of the spacing between baffles. Baffles may be required for the entire length of the screen. If a screen layout is unique for a particular site, it is prudent to incorporate a baffle design, or at least provisions for later baffle installation, into the screen design.

Generally, the designer should assure that the flow is approaching the screen in a laminar mode, with parallel streamlines and uniform velocity. Protrusions that disrupt the flowlines should be avoided. The screen should be located in a straight portion of the canal, for a distance upstream at least equal to the length of the screen civil works. The canal cross section should also be reasonably constant for a similar distance upstream. The downstream canal alignment is not quite as important as the upstream canal alignment, but the designer should ensure that flow can exit the screen structure in a laminar fashion, without constrictions that may create head loss that will result in non-uniform flow through the screen face.

When canal expansions are required to transition into the screen civil works, the designer should follow an 1:8 rule of thumb for expansions. For example, if the average canal width is 20 feet and the civil works provide a 24 foot wide approach canal, then the expansion should begin at least 16 feet upstream of the civil works, allowing for a two foot expansion on each side of the ditch. The rationale behind this rule of thumb is because it is desirable to minimize headloss and turbulence associated with the expansion, and to eliminate the potential for adverse hydraulic conditions at the screen face.

5.3 - SCREEN FACE MATERIAL

For salmonid species, a variety of screen face materials have been tested in regard to preventing fish entrainment. Based on the results of these tests, the agencies have adopted the standards listed in Table 5-1 for screen openings for fry-sized salmonids (less than 60 mm) . These openings represent the minimum screen opening dimension in the narrowest direction.

Perforated Plate Screen	**3/32 inch = 0.09375 inch = 2.38 mm**
Slotted Screen	**0.0689 inch = 1.75 mm**
Woven Wire Screen	**3/32 inch = 0.09375 inch = 2.38 mm**

Table 5-1 - Maximum allowable screen openings for fry-sized salmonids

It is important that the project developer or screen designer to consult with local fish and wildlife agencies to determine what species and size of fish that need to be protected from entrainment into the proposed project. In the Pacific Northwest, most screen locations will

have salmonid fry present at the site under some set of environmental conditions. For example, high flows may displace fry from their normal habitat in the upper watershed to habitat downstream. Another example is when spawning activity is displaced due to temporary or permanent manmade or natural passage barriers in a river system. If specific testing has not been done for particular species of concern in a project, it may be necessary to study the morphology of the life stage/species of concern and make some biological judgement calls to choose an appropriate screen mesh opening size.

Headloss at a fish screen site is usually low for most types of screen mesh material, provided that the approach velocity and the porosity (percent open area) of the screen meet the criteria requirements specified in Appendix A. Generally, a substantial headloss will occur at a screen only if the screen becomes clogged with debris. Normal headloss for a clean screen designed for 0.4 FPS approach velocity and 40% open area should be less than 0.1 foot through the mesh and less than 0.5 feet for the entire screen structure for a worst case scenario with extensive baffling requirements.

Profile bar provides the most structural type of screen face material. It is normally made from stainless steel bars, welded parallel to each other onto structural backing, and is available in a wide variety of openings and porosity. It is also the most expensive material used as a screen mesh. Profile bar can be either oriented vertically or horizontally along the screen face, depending on the operation of the screen cleaning mechanism. However, experience has shown that stringy-type debris tends to move along the screen face more efficiently if the profile bars are vertically oriented. If a brush type cleaning system is to be used for debris removal, it should track in the same direction as the orientation of the length of profile bars. Profile bar is also available in cylindrical or torpedo configurations, for use as a pump intake screen. Profile bar porosity is calculated by dividing the bar opening by the sum of the bar opening plus the bar width.

Perforated plate is made from sheet metal stock, punched with an array of holes in a variety of configurations. It is available in a variety of thicknesses, but care should be taken to account for additional headloss if thick stock is used. Experience has shown perforated plate to be easy to work with, relatively inexpensive, and it seems to handle floating debris very well.

Woven wire mesh is also widely used as a screen face material. As the name implies, it is constructed by a woven mesh of wire, and is available in a wide range of wire gages and opening sizes. Mesh opening and porosity for woven wire mesh can be calculated by using Equations 5-3 and 5-4 below.

Equation 5-3: $M_0 = (1 - ng) \times n$

Equation 5-4: $P_0 = (nM_0)^2 \times 100\%$

where:

M_0 = **Mesh opening (in inches)**

P_0 = **Percent open area**

n = **number of openings per inch**

g = **wire gage (in inches)**

In addition to hydraulic aspects of screen design, the screen face material itself must be smooth, without projections or gaps that could cause de-scaling or other injury. Generally, the three most widely used types of screen face material are perforated plate, profile bar and woven wire screen. Other materials such as monofilament mesh or plastic mesh have been used in some specialized cases. It is important to consider that some screen materials have a rough side and a smooth side, and the smooth side should be on the upstream side in case fish do contact the screen surface. Some sits with algal growth problems may benefit from a mesh that prevents fouling, such as a phosphor-bronze mesh. These details are best addressed by specification in the bid document and assuring quality construction through a thorough inspection process.

5.4 - CHOOSING THE DESIGN FLOW FOR A FISH SCREEN

Depending on the project, it may not be clear as to what the maximum diversion rate will be. For example, in some locations in Oregon, a water right is appropriated as a flow volume, rather than as a flow rate. The implication of this, is that the water user may choose to use his entire water right in one week, or may choose to spread the flow out for the entire summer. Another example is in the Lemhi River basin in Idaho, where a water right is specified as a flow rate, but the water user is authorized under state law to exceed his appropriated flow rate during high flows. In either of these cases, it is difficult for the designer to establish the maximum design flow rate and to proceed with the screen design. If maximum flow rate is in question, a flow study is warranted before design can proceed. For minor projects, this may be a discussion with the water user concerning his irrigation needs. For major projects, a formal flow study may be necessary involving gaging sites, data recorders and flow measurements.

For pump intakes, flow measurements are not always feasible and usually data is not available for choosing a design flow for pump intake screen, especially when the entire irrigation system is under pressurized flow. Some irrigation sprinkler manufacturer's have nomagraphs available that can be used to calculate flow requirements for their specific products. Other methods of calculating flow in a pressurized system are available (such as solving the energy equation by using various methods to estimate system friction and minor losses), but in general these calculations should be left up to a professional engineer. Equation 5-5 is the energy equation rearranged to solve for pump dynamic head.

Equation 5-5: $$H_p = \frac{Q_{max}^2}{2\pi^2 D^2 g} + (z_2 - z_1) + H_f$$

where:

H_p =	Total required pump dynamic head (feet)
Q_{max} =	Maximum flow rate (CFS)
D =	Distribution pipe diameter (feet)
$(z_2 - z_1)$ =	Change in water elevation, from intake to high point (feet)
H_f =	Friction and minor losses (feet)
g =	Gravitational constant, 32.2 ft/sec^2

Usually, the most difficult information to compile is that which is needed to calculate an estimate of the "minor loss" portion of H_f. It is important to note that the term "minor loss" does not necessarily mean that the loss due to the piping configuration is insignificant. Every pipe turn, elbow, junction, coupling, valve, inlet, outlet and any other fixture in the piping system contributes to the minor loss term, and in a complex piping system this term does become important. A hydraulics handbook or pipe manufacturer's literature are sources to consult when determining headloss factors for each component of the distribution network and calculating maximum flow.

Pipe diameter, length and relative roughness are the parameters that determine the magnitude of the friction loss portion of the H_f term. Pipe geometry should be available by observation, and the "relative roughness" of a specific type of pipe material is available from hydraulics manuals or manufacturer's literature. This data is then used to determine the friction factor f, either by using a Moody Diagram or by using curve-fit equations from the Moody Diagram. Discussion of the use of the Moody diagram is beyond the scope of this text, but can be found in a variety of hydraulics or fluid mechanics texts (Chow, 1959 or Janna, 1987).

Since pump energy is usually reported in units of horsepower, rather than in feet, the following Equation 5-6 can be used to convert feet into horsepower.

Equation 5-6: $$whp = \frac{Q\gamma H_p}{550}$$

where:

Q = flow, in CFS
γ = unit weight of water = 62.4 lb/ft^3
H_p = Total required pump dynamic head (feet)
whp = water horsepower

Lacking data and engineering support, and only for the purpose of estimating the screen area required for a <u>small</u> pump intake screen, it may be acceptable to approximate the maximum diversion flow rate using Equation 5-5 and neglecting some of the minor loss part of the term

H_f. Equation 5-7 listed below is derived from Equation 5-5, and only accounts for an inlet loss and not any other minor loss that occurs due to complications in the piping network. Without a complete H_f term, Equation 5-7 should only be used for purposes of determining screen area required for small intake screens only, since it will over estimate the flow rate if the piping system is more complicated.

Equation 5-7:

$$Q_{max} = 1/4\ \pi\ D^2 \times \left[\frac{2g\ (H_p+z_2-z_1)}{2+fL/D} \right]^{1/2}$$

where: H_p, Q_{max}, $(z_2 - z_1)$, g and D are as previously defined
L = Pipe length (feet)
F = friction factor (dimensionless), from Table 5-2

Pipe Diameter (inches)	1	2	3	4	6	8	10	12
f, Friction Factor	0.0195	0.0168	0.0155	0.0146	0.0136	0.0129	0.0124	0.0120

Table 5-2 - Friction factors for plastic pipe of given diameter

For the purposes of designing a small juvenile fish screen (less than 1 or 2 CFS), it can be appropriate to over estimate the maximum flow rate, thereby increasing the required intake screen area. Increasing the screen surface area will likely be less costly than retaining a consultant to calculate or measure flow. Providing additional screen area will lower the approach velocity on the screen face, decreasing the probability of impinging fish, and will also aid the screen cleaning system in serving its function. Flow estimates for larger pump intake systems should be more carefully refined, using good data and a hydraulics expert to determine the maximum flow.

The best method of choosing a maximum design flow level for screen design is to obtain flow records, which are sometimes available from an irrigation or municipal water district. Hydroelectric projects generally are designed for a particular maximum flow level, and there are usually fairly stringent monitoring requirements for federally licensed projects to ensure

that maximum design flows are not exceeded.

If there is sufficient lead time prior to design and construction of a juvenile fish screen, a flow measurement and recording station can be established for a proposed site. This is usually a requirement for large projects where flow amounts are not on record. Usually, a water level recording station (gaging site) is established near the proposed site and data recorded by computer or punched paper tape. A rating curve for the site is established by making repeated flow measurements with a flow meter and measuring tape over a large range of canal flows, and then correlating these with the water level recorder data.

5.5 - HYDRAULIC MODELS

Frequently, it is desirable to examine the site hydraulics under a wide variety of flow conditions in order to make design decisions concerning location and function of fish passage devices. One tool that can be used to achieve this is to construct a scaled replica of the project that has the capability to simulate the desired range of flow conditions. This is termed a physical hydraulic model.

The advantage to constructing a hydraulic model is that design decisions can be reached quickly, without a cumbersome process of data collection at a project. It may take years of physical data collection to understand the project hydraulics under a broad band of conditions. For example, a model can be run under a variety of river flows using a variety of flow splits between a powerhouse and a spillway. Another example of a use of a physical hydraulic model is to study small and large scale hydraulic effects of a particular screen and canal design, and eliminate adverse conditions before the design proceeds.

Since fish passage devices often rely on the interrelation between the project hydraulics and fish behavior, constructing a physical hydraulic model may offer the best chance for success of a passage project. Often times by using a physical hydraulic model, adverse hydraulic conditions can be identified and avoided. These include:

- **eddies that delay migration and may repeatedly subject juvenile fish to predators;**
- **effects of varying water surface elevations on intake and screen hydraulics;**
- **alignment effects;**
- **slow velocity areas that may harbor predators;**
- **uneven velocity distributions on the screen face; and**
- **velocity profiles in the bypass attraction corridor.**

The result of gaining a better understanding the project hydraulics is better protection of the resource, without having to go back and adjust the passage facility hydraulics and hope for success. A model allows the designer to better understand the project operation and hydraulics before design is complete, so that post-construction adjustments are not normally

required. Constructing a physical hydraulic model may also save the project money in the long term, by avoiding the need for costly retrofit of project features. It is strongly recommended that fish passage project designers utilize a physical hydraulic model, especially for a large project that may impact large numbers of fish.

Mathematical hydraulic models have also been used in attempts to fine-tune passage facility designs, with limited success. Using a mathematical model such as a computational fluid dynamic model can yield useful results, if the hydraulics are properly accounted for in the model. However, such models are often difficult to derive and calibrate for even moderately complicated hydraulic systems. As a result, a mathematical model can often miss micro-hydraulics, such as conditions at boundary layers and small eddies that may have significant effects on fish passage.

If a model is not built for a specific project, it is very important that the designer allow for unexpected conditions that may occur at the screen face and in the approach canal upstream of the screens. Including adjustable baffles, water surface elevation control weirs, flow vanes and other hydraulic features often provide sufficient flexibility to hydraulically "tune" the facility after construction. However, it is often difficult to anticipate all adverse conditions that may occur and design accordingly.

6.0 - PREDATION AT AND AROUND THE SCREEN SITE

Many predators exist that may hamper plans to successfully bypass fish around a water development facility. Avian predators will take advantage of concentrations of fish by methods such as:

1) **underwater diving at a bypass outfall or in a screen forebay;**
2) **wading in bypass open channels or at the bypass outfall, or**
3) **picking disoriented or injured fish off of the surface.**

Piscine predators will take advantage of any area in which they can hold near prey concentrations. Because of the tendency for predators to accumulate in areas of prey concentrations, it is important that the designer understand what predators might inhabit the project site and design accordingly to minimize creating new and avoiding existing habitat niches that they may occupy. Note that the word "might" in the previous sentence has special significance, because most water development projects alter the existing habitat in some way. The alteration of habitat can promote the success of predators, both in population numbers and in predation capability, compared to prior to project development. An example of this is where nearly the entire Columbia River system has been changed from a free flowing river into a series of impoundments. The new impounded river system favors many piscine predators that survive and predate better in the slower, warmer water and populations have expanded greatly. Unfortunately for the endangered salmonids occupying or migrating

through the same area, some of these predators are extremely successful in consuming juvenile salmonids. This problem is exacerbated by the fact that the impoundments also delay juvenile salmonid out migration, thus allowing extended windows of opportunity for the predator community.

Assuming that the large scale adverse impacts of a project have been discussed and appropriately mitigated, the principle concept in designing a fish screen to minimize predation potential is fairly simple. The key thought here is that predators are opportunistic, and the idea in screen design is to minimize predation opportunity.

Predation near the diversion intake can be minimized by avoiding structures instream, either existing or proposed, that create predator holding areas. Similarly, predation in an intake canal can usually be avoided if the canal doesn't provide areas where predators can hold. Even small variations in the canal wall surface can create a low-velocity zone where predatory fish can hold and dart into the main flow when a predation opportunity arises.

Locating the fish bypass return pipe into a riverine location where predators can't easily hold provides the bypassed fish an opportunity to escape predation. For screen design in general, it is up to the designer to consult with the appropriate biologists to determine the type of predators present and the type of habitat that they occupy. From this consultation, the bypass outfall should be designed in a manner that minimizes or eliminates habitat niches that predators may occupy. For example, in the Columbia river basin, the Northern Squawfish is a voracious predator of salmonids. The type of habitat preferred by the squawfish is slower moving water with a readily available forage base. Because of this preference, it is desirable to place bypass outfalls in river areas that under all flow regimes exhibit

-- flow velocity greater than 4 FPS;
-- no eddies;
-- fairly laminar flow;
-- sufficient cover depth.

It is also desirable to introduce the fish return flow back to the river such that the velocity vectors of the fish return flow and river flows are nearly parallel.

7.0 - SCREEN OPERATION AND MAINTENANCE

Proper operation and maintenance of a fish screen is equal in importance to a quality screen design. Certain items must be closely monitored in order for a fish screen to adequately serve its function to protect fish. Lack of attention to operational detail has the potential to kill significant numbers of fish that the screen has been designed to protect. It is also equally important to have a good short-term and long-term maintenance punch-list, so that the screen is maintained in optimum condition.

From an operational standpoint, the site should be visited as frequently as environmental conditions dictate. If the river level or diversion flow changes, steps must be taken to ensure that the screen is properly submerged for the amount of flow being diverted. Bypass flow levels may also need to be adjusted for some types of screen design. The bypass pipe entrance and exit should also always be checked during each site visit.

It is a good idea to paint submergence bands at a prominent location that show the proper submergence range for a screen. Providing submergence bands allows water surface elevation to be verified at a glance. Some sites, especially those with large diverted flows, will require staff gages to verify proper water surface elevation and screen submergence.

Dealing with debris at a screen site needs to be addressed on a frequent basis. Trash accumulations on racks can cause significant injury to fish passing through the debris, particularly if the debris is an abrasive material such as tumbleweeds. Debris should be removed from bypass downwells, bypass pipe entrances, trashracks and along the screen face. At times, debris loading is severe enough to warrant removal on a daily basis. At Rocky Reach dam, a prototype surface collector (a capture and bypass fish collection system) being tested collects enough debris to warrant employing a crew to man the screens around the clock. The production model of Rocky Reach's surface collector will have automated screen cleaners. Conversely, small, cold, low-gradient streams with small amounts of bank debris may hardly ever need debris removal. Debris type and quantity varies seasonally, and screen operators need to establish a schedule suitable for their particular site.

Preventive maintenance is as valuable for fish screens as it is for any other piece of mechanical equipment. Components must be greased (with environmentally benign grease) on a regular basis. Screen seals must be checked frequently for wear, and for debris that might be trapped by the seals. Sediment should be removed from the forebay of the screen site before it starts passing through the seals. Some maintenance crews have used a gold dredge to remove sediment from screen forebays, without requiring that the diversion be turned off. Another method employed to remove sediment from a screen forebay is to temporarily reduce flow through the screen and open the bypass return pipe fully, to sluice sediment away from the site.

Winter operation of fish screens brings another set of operational requirements. Ice can quickly clog screens, causing loss of flow to the diversion. Some screen are located in heated enclosures, if the full diversion flow is needed in cold weather situations. Another technique that has been used successfully at rotary drum screen sites to provide small amounts of winter stockwater, is to allow the canal to freeze at full canal flow. Before doing this, the power drive shaft or electric motor gearing needs to be disconnected. After the top of the canal freezes

over with a good solid layer of ice, the canal flow is reduced to lower stockwater levels, and the frozen upper layer remains in place to help insulate the stockwater flow. If fish aren't present in the winter time, or if the ditch flows back into the stream, it may be allowable to remove the fish screen during icing conditions.

Finally, it is a good idea to provide concise operating criteria for a screen site, so that personnel changes don't alter proper operation of the screen. These criteria should include all the items listed above, with information on proper screen submergence, maintenance items, and bypass flow verification. A drawing of the screen showing pertinent features should also be included.

8.0 - FISH SCREEN CLEANERS AND POWER SYSTEMS

All screens should have a reliable, fully functional cleaning system, capable of removing any debris load from the entire screen mesh. Failure to incorporate an adequate mesh cleaning system can cause catastrophic failure of the screen assembly. Project owners have been heavily fined by fish and wildlife agencies for fish mortality because a screen failed due to a faulty cleaning system. It is of paramount importance, both to the fisheries resource and to project viability, that the cleaning system removes debris efficiently, completely and ultimately away from the screen mesh.

In general, manually cleaned (passive) screens can not be relied upon. The idea of an automated screen cleaner is not merely an automated janitorial function - it is essential to maintain hydraulic characteristics at the screen face that directly cause fish injury and mortality when they go awry, and to maintain hydraulic characteristics that allow fish to quickly locate the bypass. A screen that is only partially occluded by a little debris will have localized areas of high velocity that can impinge and kill fish. An adjustable baffle system will be rendered ineffective to its purpose, once any debris gets on the screen face. Criteria is listed in Section 11.10.1.3 of Appendix A that allows for an exception to use a passive screen on very small diversions.

There have been a variety of power systems used to provide energy to cleaning systems for fish screens. These include:

- **electric motors**
- **paddle wheels**
- **hydraulic motors**
- **solar power**

If properly chosen for a particular site, all of these power systems have the ability to be effective, providing that operational checks and routine maintenance is performed on a

regular basis. The selection of the type of power system may be obvious for a particular site. Electric motors work for any site with reasonable access to the power grid, and are used to power drum rotation and traveling screens. Paddle wheels, or water wheels, also work at most sites, providing that there is sufficient minimum water velocity (1-2 FPS) to power the wheel. Hydraulic motors are also powered by a paddle wheel, and have the flexibility to allow the paddle wheel to be placed away from the screen into an area with sufficient water velocity. Hydraulic lines connect the hydraulic motor to the screen. Solar power has also been used to power small drum screens and belt screens. Battery charging systems are available for reasonable costs that allow operations for up to 48 hours without sunlight.

Air-burst cleaning systems are generally used in pump intake screen cleaning systems, and tend to have a variable performance record. At some sites (presumably those sites with out problematic debris) they work pretty well. Other sites with air-burst cleaners have reported that only the upper part of the screen gets cleaned, which might be expected since air bubbles quickly move upwards in a water column. At some sites, air is used to suspend sediment accumulations, to sluice sediment away from critical locations such as screen seals.

Water-jet cleaning systems have been used successfully for fixed plate screens, pump intake screens, vertical traveling screens and as additional cleaners for drum screens at particularly troublesome sites. Jets should cover the entire surface area of the screen. Pressures from 30 to 100 pounds per square inch may be required for proper cleaning action, depending on the screen approach hydraulics and on the type and amount of debris present at the site.

The type of power system for a particular site should be chosen based on the constraints of the site. Some sites may not have electricity available, or, some sites may not have enough hydraulic gradient to power a paddle wheel.

One final note, regardless of the type of cleaning system, a route must be available to pass debris downstream once it is removed from the screen face. Some screen designs incorporate a belt and hopper system, to collect and remove debris form the site. Failure to provide a debris escape route will allow debris to redistribute on the screen mesh, eventually overwhelming the cleaning system.

Trashracks upstream of the screen should be included in the design to catch large debris. The trashrack should be slanted vertically and easily accessible so that debris can be easily removed. Bar spacing on trashracks for juvenile fish screens should be five to six inches for juvenile salmonid fish screens. Spacings smaller than three inches can cause delay or totally block passage of juvenile salmonids.

9.0 - CORROSION CONTROL

A corrosion control system for a fish screen can dramatically increase the life of a facility. Providing isolation of dissimilar metals will prevent the electrolysis process that results in corrosion. Neoprene washers and silicon bolt sleeves should be used when attaching mesh to the structural frame of the screen. Sacrificial anodes are also used at sites with corrosion potential. These are welded directly to the screen frame, and work by providing a more attractive location for electrolysis to occur and produce corrosion. Another potential cause of corrosion occurs when electric motors are grounded to the screen frame. Stray currents produce minute charges in the frame, sometimes increasing the potential for electrolysis to occur.

10.0 - SCREEN TESTING - HYDRAULIC AND BIOLOGICAL

After construction is complete, it is usually recommended that a new screen undergo a series of hydraulic tests, followed by biological testing. Hydraulic tests should include velocity measurements (both magnitude and direction) along the entire screen face, bypass entrance velocity measurements and bypass flow testing. If velocity and bypass flow are not what was designed, adjustment of a baffle system, or installation and adjustment of a baffle system is the next step required. In some instances, upstream flow deflectors can help to correct approach flow problems at a screen face. Placement of these devices is largely trial-and-error, however, an experienced hydraulics expert could make an educated guess as to where to start to correct a hydraulic problem. After any hydraulic adjustment, the same regiment of flow measurements should be taken to see if the objectives were accomplished.

After hydraulic testing is complete and the screen is operating as designed, biological testing should proceed. This may entail marked releases and recapture techniques, releasing fish upstream of the screen and recapturing downstream in the bypass pipe or at the outfall. Periodic biological testing after the initial test period is also recommended, as this will assist in identifying problems with the site as they occur.

11.0 - RESEARCH - PIT TAG DETECTORS, EVALUATORS, TRAPS

A fish screen and bypass pipe provides a concentration of fish, allowing researchers a convenient location to install Passive Integrated Transponder (PIT) tag detectors, trap boxes and other devices for research. A PIT tag detector identifies coding on a PIT tag placed inside of the fish. These are automatically detected and the tag automatically read when passed through a PIT tag detector.

Evaluator structures typically operate by removing fish from a large percentage of the bypass flow by use of a secondary screen. The complexity of evaluator structures vary widely, depending on the biological requirements of a site. Evaluators may have anesthetic equipment, PIT tag or other tag installation stations, holding facilities, loading facilities and other features. Discussion of the design of evaluators is beyond the scope of this text.

Trap boxes are also sometimes used to enumerate out-migrant fish. These are merely a concrete box where the bypass flow enters and fish are retained. An screen system built to the same criteria as the main screen should be used in the trap box. Trap boxes should be checked daily, or even more frequently at the height of the out-migration.

12.0 - TYPES OF POSITIVE BARRIER SCREENS AND THEIR APPLICATION

A variety of different types of positive barrier screen designs have been used for fish protection, with varying degrees of success. Most potential screen sites lend themselves to narrowing the type of screen that might be successful to just a few, based on site specific conditions. The following are types of positive barrier screens that have been used in the Pacific Northwest:

- **rotary drum screens**
- **fixed vertical plate screens**
- **vertical traveling screens (belt and panel)**
- **non-vertical fixed plate screens**
- **horizontal fixed plate screens**
- **Eicher screens**
- **modular inclined screens**
- **pump intake screens**

12.1 - ROTARY DRUM SCREENS

The most commonly used type of physical barrier juvenile fish screen used in the Pacific Northwest is the rotary drum screen. This type of screen has the advantage of providing continuous cleaning action and removes most types of debris away from the screen face. This type of screen has undergone extensive biologically testing, with the results generally showing better than 98% survival of juvenile fish. A rotary drum screen can be used in most open-channel flow situations, providing that the siting criteria previously discussed are followed. Rotary drum screens have been used for diversions up to 3,000 CFS.

A rotary drum screen operates by using a power system (electric motor, paddlewheel, solar drive or hydraulic motor) to rotate the drum. Small floating debris is picked up by the screen mesh and deposited downstream of the screen. Medium-sized debris tends to pass readily down the fish bypass pipe and be removed from the vicinity of the screen. Larger debris generally has to be manually removed from the trash rack or wherever it accumulates in the rotary screen civil structure.

In order for a drum screen to remove debris, it must be properly submerged. Experience has shown that some debris may be picked up at 50% submergence of the drum, but the best cleaning action is noted at 70% to 85% submergence. Exceeding 85% submergence can cause increased probability of fish impingement and subsequent entrainment by being carried over the drum. It is recommended that drum screens be operated between 70% and 85% submergence. Table 12-1 shows allowable flow levels allowing for inactive screen area backed by structural members. Figure 12-1 shows a schematic of a rotary drum screen, and Figure 12-2 shows three drums screens and their civil works. Rotary drum screens do have problems that need to be addressed by vigilant maintenance routine. Since the drum is continually rotating, wear on the side seals and bottom seals must be closely monitored, depending on site conditions. Silt accumulations in front of a rotary drum screen can wear seals quickly, so sometimes a sediment sill is incorporated into the design that allows for a deposition of sediment that can be removed on an annual basis. Mesh must also be regularly inspected for wear. At some sites, filamentous algal growth can cause mesh fouling. Special mesh with growth inhibitor characteristics, such as phosphor bronze, can be used. Additional cleaning mechanisms (internal spray bars) can also be used for sites with algae.

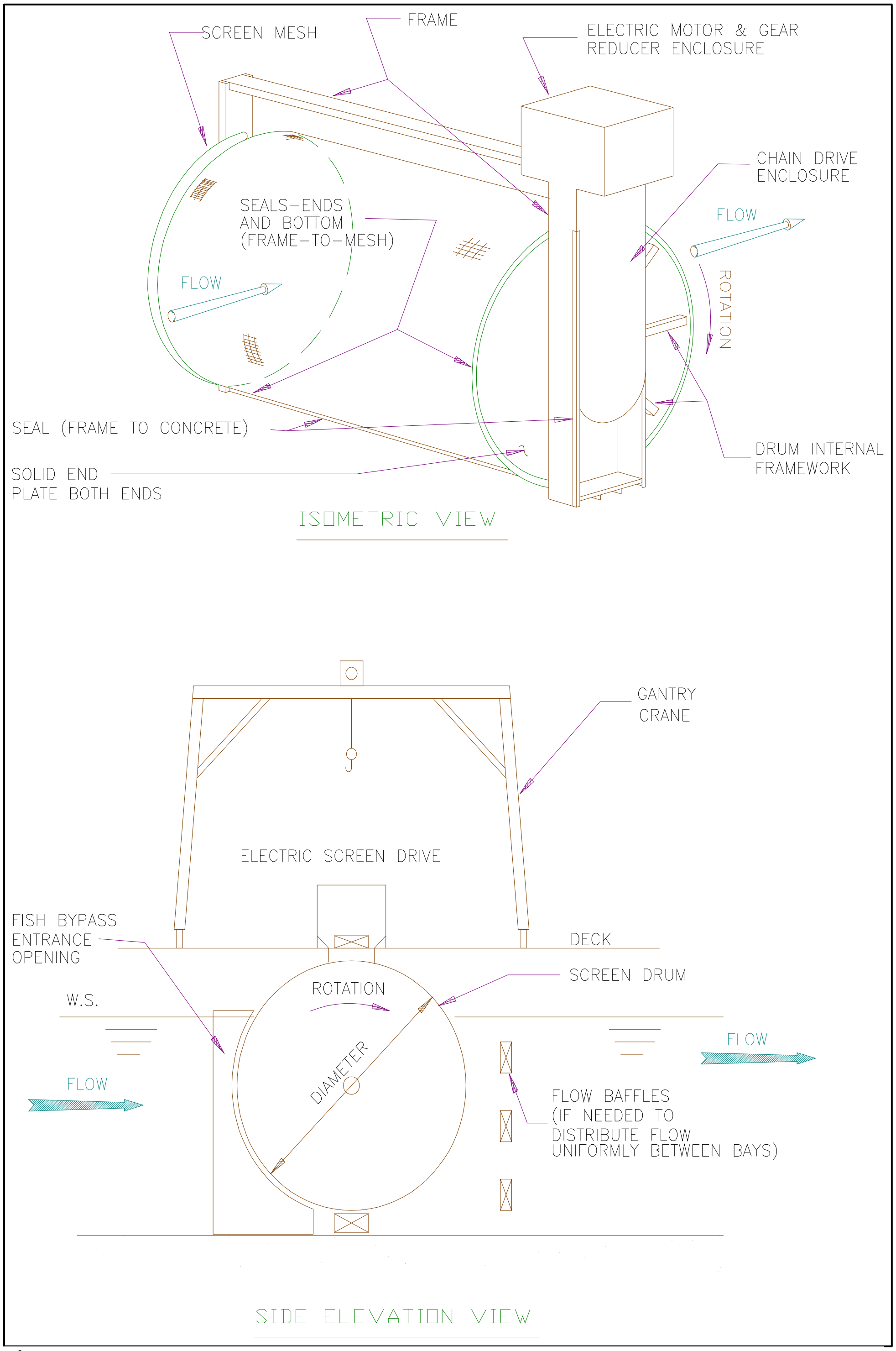
SCREEN MESH
FRAME
ELECTRIC MOTOR & GEAR
REDUCER ENCLOSURE
CHAIN DRIVE
ENCLOSURE
FLOW
SEALS–ENDS
AND BOTTOM
(FRAME–TO–MESH)
FLOW
ROTATION
SEAL (FRAME TO CONCRETE)
DRUM INTERNAL
FRAMEWORK
SOLID END
PLATE BOTH ENDS
ISOMETRIC VIEW
GANTRY
CRANE
ELECTRIC SCREEN DRIVE
FISH BYPASS
ENTRANCE
OPENING
DECK
SCREEN DRUM
ROTATION
W.S.
FLOW
DIAMETER
FLOW
FLOW BAFFLES
(IF NEEDED TO
DISTRIBUTE FLOW
UNIFORMLY BETWEEN BAYS)
SIDE ELEVATION VIEW

Figure 12-1

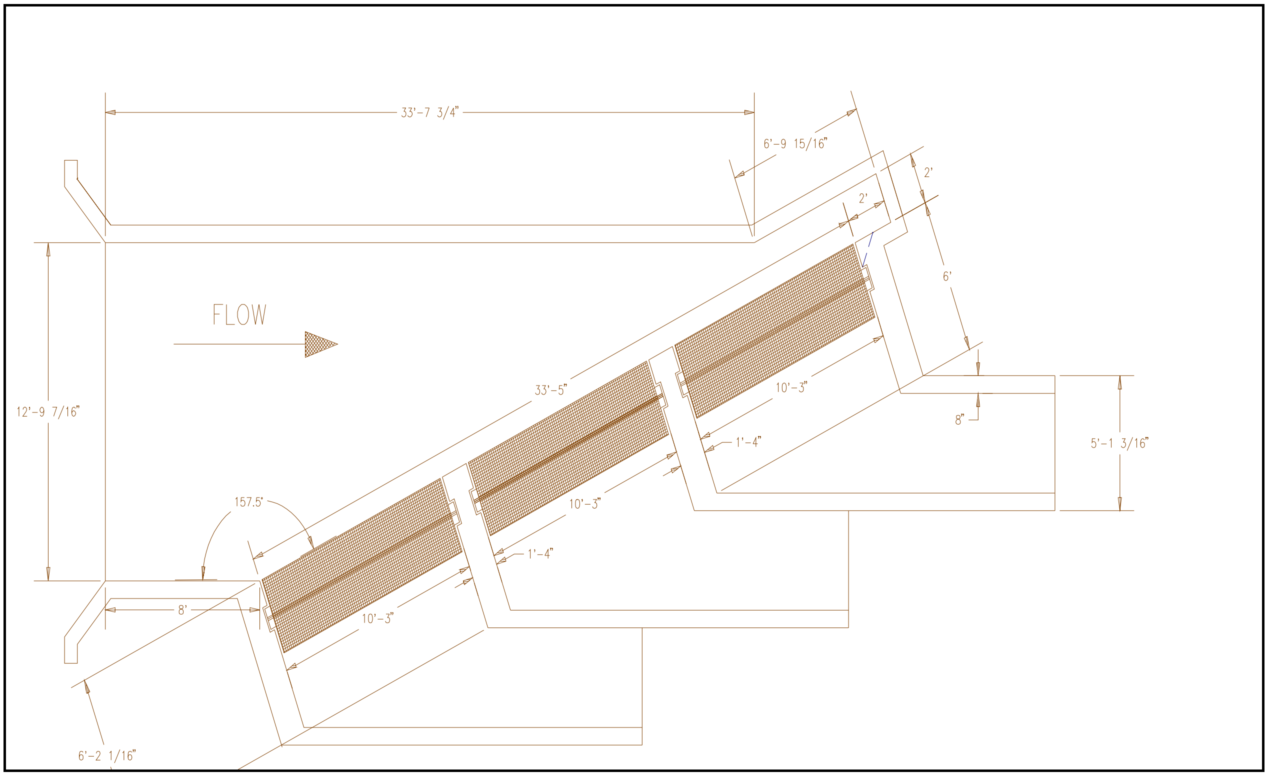

Figure 12-2

Table 12-1 -- Allowable flow amounts for rotary drum screens

Drum Diameter	Submergence	4' Screen Length, allowable CFS	6' Screen Length, allowable CFS	8' Screen Length, allowable CFS	10' Screen Length, allowable CFS
18"	75%	1.52	2.36	3.21	4.05
24"	75%	2.03	3.15	4.28	5.40
30"	75%	2.53	3.94	5.34	6.75
36"	75%	3.04	4.73	6.41	8.1
42"	75%	3.54	5.51	7.48	9.45
48"	75%	4.05	6.30	8.55	10.8
60"	75%	5.06	7.88	10.69	13.50
72"	75%	6.08	9.45	12.83	16.20

12.2 - VERTICAL FIXED PLATE SCREENS

The second most widely used type of positive barrier juvenile fish screen used in the Pacific Northwest is the vertical fixed plate screen. This design of this type of screen lends itself to easy installation of a baffle system, and can usually be hydraulically tuned to achieve fairly uniform approach velocities. Fixed screens are simple to tightly seal since the mesh is fixed to the structural frame, and no wearing surface is produced. A smaller civil works is generally used, as compared to a rotary drum screen site. At some sites, they can be placed directly on the edge of a river, providing that design accounts for icing and debris conditions that may occur. The vertical fixed plate screen system for the Rocky Reach surface collection system dewaters about 6,000 CFS, and is the largest example of this screen type.

Examples of vertical fixed plate screen can be found at:

- **Leaburg canal, McKenzie River, Oregon**
- **Dryden canal, Wenatchee River, Washington**
- **The Dalles Wasco County hydro plant, The Dalles Dam, Columbia River**
- **Rocky Reach hydro project, Columbia River, Washington**
- **Wapatox power canal, Naches River, Washington**

Vertical fixed plate screens must have a mechanical cleaning system for debris removal. Traveling brush cleaners and hydraulic back-spray systems have both been used with some level of success. A reliable mechanical cleaner design is difficult to design, but can be achieved.

Observation reveals that the best brush cleaners produce a small eddy behind the brush as it travels the length of the screen, allowing debris to be suspended until it is passed off the downstream end of the screen. Typically, the cleaning system operation is triggered by either a timing mechanism that operates the cleaner on a specified interval or by head loss detection across the screen mesh, or a combination of both. Regardless of the type of mechanical cleaner, close attention should be paid to the system to assure it is properly functioning. A schematic of the fixed single plate vertical screen at The Dalles Wasco County PUD power plant is shown in Figure 12-3, and a fixed vertical vee screen at Wapatox Canal is shown in Figure 12-4.

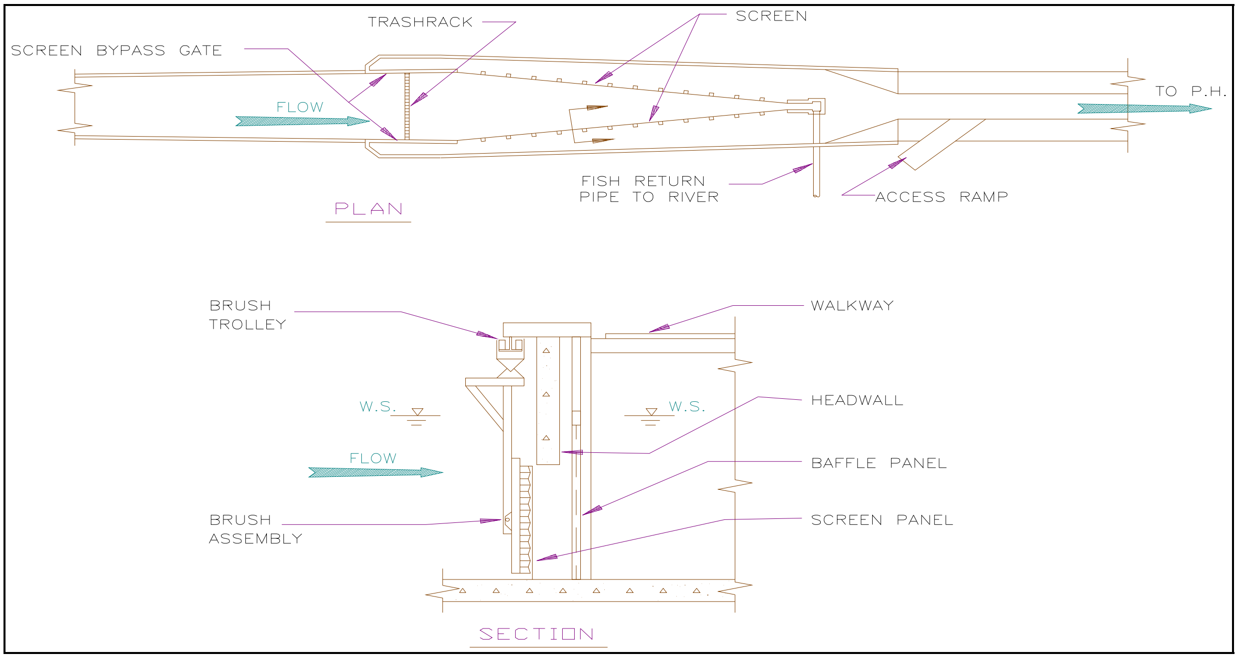

Figure 12-3

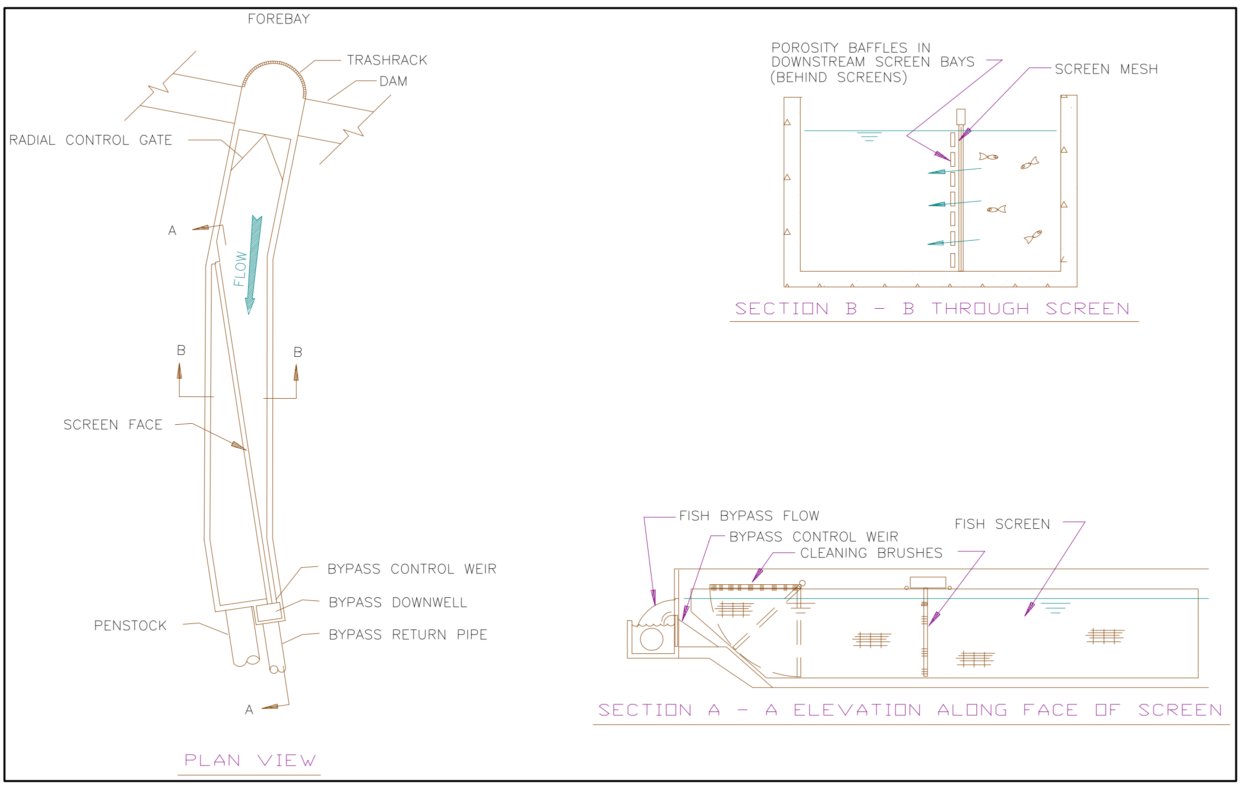

Figure 12-4

12.3 - VERTICAL TRAVELING SCREENS (BELT AND PANEL)

Vertical traveling screens are also widely used in the Pacific Northwest. They have advantages similar to rotary drum screens, in that the mesh rotates to have debris removed on the downstream side. Panel type screens have many discrete mesh panels that rotate around two parallel axis being powered by electric motor. Belt-type vertical traveling screens have a continuous belt mesh, and can be powered by electric motor. A small belt-type vertical traveling screen has been developed by the Oregon Department of Fish and Wildlife that is powered by solar energy.

Many of the panel-type vertical traveling screens are not specifically manufactured for purposes of fish protection, and adapting them for fish protection isn't always successful. Many old installations of these screens show high incidence of impingement and entrainment, due to improper alignment, mesh size and mesh seal problems. Mesh seal problems are hard to identify, since the screen is often located in a sump. Often, these screens are oriented perpendicular to flow, which makes it difficult for out-migrants to locate bypass entrances.

Some example installations of vertical traveling screens can be found at:

-- Lookingglass Hatchery intake, Lookingglass Creek, Oregon

-- Chandler pumpback screens, Chandler canal, Yakima River, Washington

Figures 12-5 and 12-6 show schematics of vertical traveling screens, and a possible layout of the civil works.

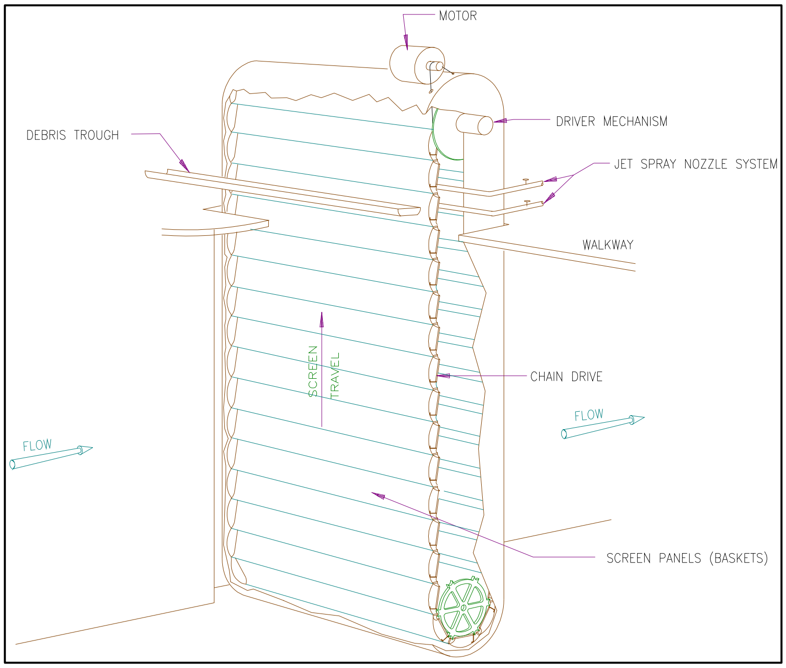

Figure 12-5

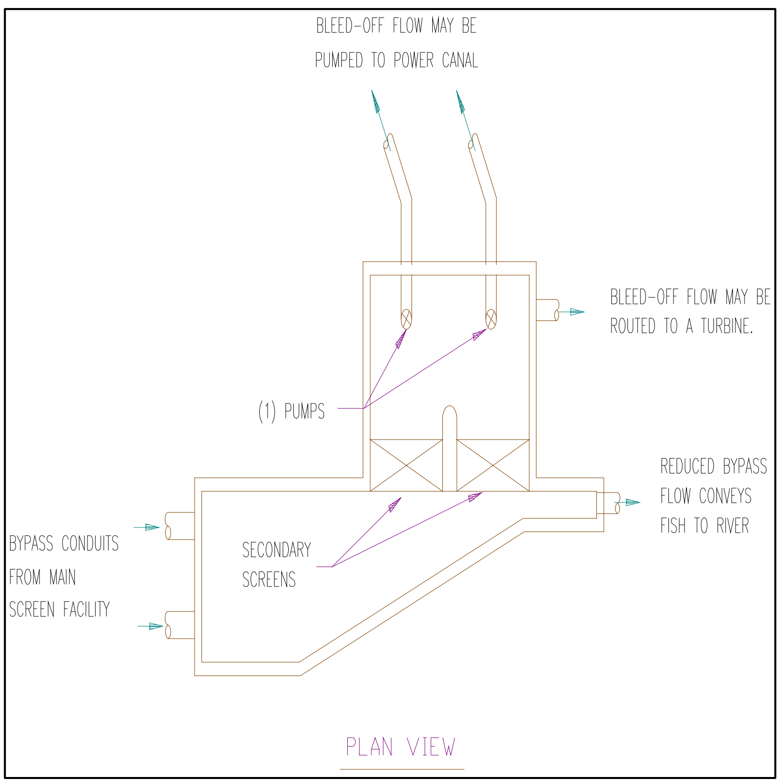

Figure 12-6

12.4 - NON-VERTICAL FIXED PLATE SCREENS

Another category of fixed plate screens is non-vertical screens, such as the Coanda screen shown in Figure 12-7. Coanda screens can work well only if sufficient flow depth exists at the downstream end of the screen. This allows debris to be moved downstream where it won't pose a hazard to fish passing over the screen. Flow drops through the screen, and out a canal where it is routed to its destination.

Coanda screens require several feet of head loss to operate. This requires that an adult fish ladder be constructed to pass adult fish upstream of the screens. These two constraints limit the applicability of this type of screen. Coanda screens are not widely used in the Pacific Northwest, due to lack of sites with proper conditions for installation. A few have been installed in Montana.

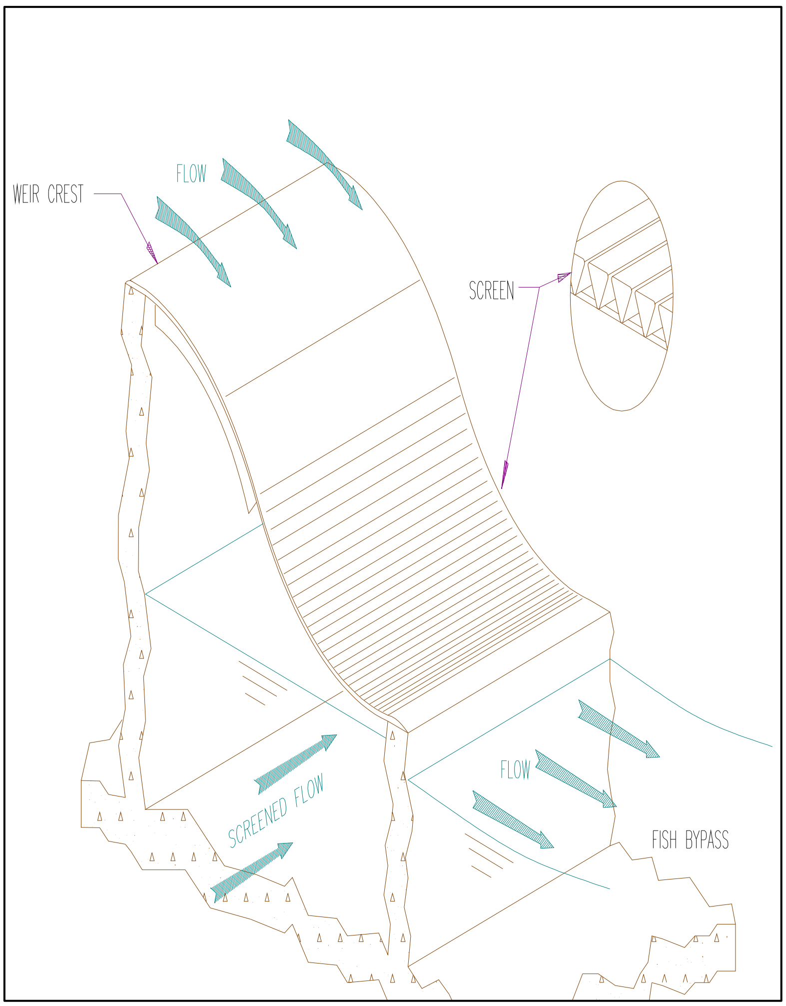

Figure 12-7

12.5 - HORIZONTAL FIXED PLATE SCREENS

Another type of non-vertical fixed plate screen is the horizontal screen. It has limited application and must only be used in streams or canals where flow fluctuations are small. Varying water depth over the screen produces variable approach velocity and the potential for impingement at the screen mesh. A significant structural hazard exists if the cleaning mechanism fails, and the weight of the water overcomes the structural ability of the frame. At some sites, it may be possible to control excessive water depth by use of side overflow water surface control weirs.

12.6 - EICHER SCREENS and MODULAR INCLINED SCREENS

Eicher screens are high approach velocity screens intended for use in powerhouse penstocks. They have been installed at only a couple active sites, the Sullivan Plant operated by Portland General Electric on the Willamette River in Oregon, and the Puntledge Power Plant operated by British Columbia Hydro in British Columbia. To improve juvenile salmonid passage survival, the Sullivan Plant Eicher screen has been augmented with a surface outlet weir near the end of the powerhouse, and with improvements in spillway passage. Eicher screens are still considered experimental, but initial results show promise for some species and life stages of fish. The Electric Power Research Institute (EPRI) has tested a prototype Eicher screen at Elwha Dam, on the Elwha River in Washington (see EPRI, 1991). The reader should consult EPRI 1991, for further information on Eicher screens.

Modular intake screen operate on the same high velocity principle as Eicher screens. The major difference is that these screens can be placed in an open channel, opposed to the closed conduit requirements of the Eicher screen. For both of these screens, cleaning is accomplished by rotating the screen so that it is backwashed by the flow.

12.8 - PUMP INTAKE SCREENS

Pump intake screens are placed on the end of a pump intake in a pressurized system. Many different configurations are commercially available. Figure 12-8 shows how several pump intake screens can be placed on an intake manifold.

Cleaning systems for pump intake screens can be by:

- **fixed spray bar, rotating screen**
- **fixed screen, rotating spray bar**
- **internal air-burst**

Each type of cleaning system can be used successfully, providing that the designer choose the type based on the requirements of the screen site. For example, a fixed jet rotating screen may not work well if placed on a stream bottom with active bedload movement. Air-burst systems generally have problems cleaning the mid to lower portion of the screen surfaces.

Thousands of small irrigation diversions that are currently unscreened are ideal candidates for the small pump intake screens using spray bar cleaning systems.

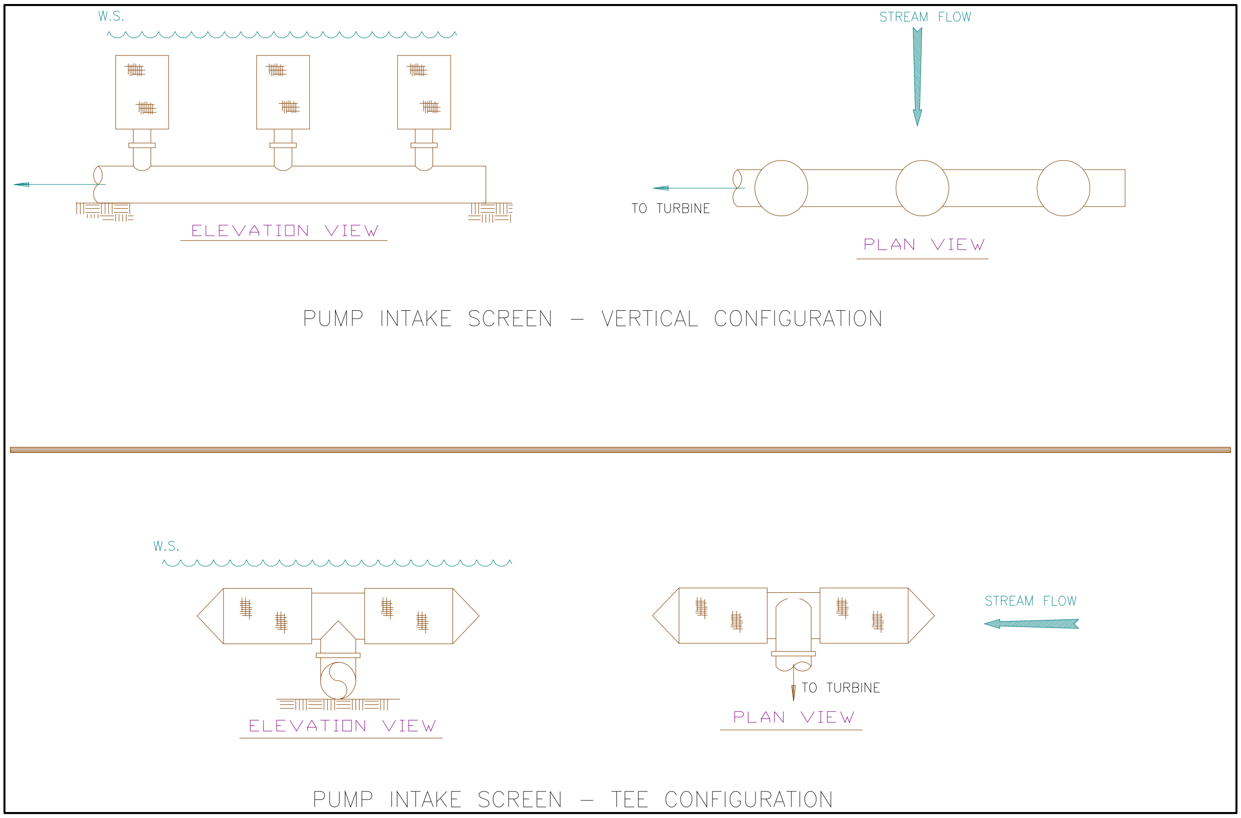

Figure 12-8

13.0 - NON-POSITIVE BARRIERS, COLLECTION DEVICES, ALTERNATIVE TECHNOLOGY

Many types of non-barrier types of technology have been tested over the years, without levels of success that allows their continued use. These include sound barriers, light deterrence systems, louvers, and electric barriers. Most of these devices can be used successfully under certain conditions. However, the main problem with many of these devices is that they fail to account for variable site conditions that most sites exhibit. For example, sound devices may repel fish away from an intake providing the background noise level is low. Light deterrence may work if turbidity is low. Louvers may work well for smolt sized fish, but allow fry to be readily entrained. All of these devices have lesser degree of success when unusual hydraulic conditions occur.

At the Corps of Engineer dams on the Columbia River, guidance screens called submerged traveling screens guide fish away from the turbine intakes, up a gatewell, through an orifice

and into a juvenile bypass channel leading below the project. A great deal of research has been performed on the operation of theses systems, and results vary with season and species. The design of these screens is quite involved and beyond the scope of this document.

Another type of juvenile passage system is termed a surface collector system. These systems are generally specifically designed for a site, and the process for designing surface collection systems is beyond the scope of this paper. These systems are currently being evaluated at:

- **-- Rocky Reach Dam, Chelan County PUD on the Columbia River**
- **-- Wanapum and Priest Rapids Dams, Grant County PUD on the Columbia River, and**
- **-- Corps of Engineers, Columbia and Lower Snake Rivers**
- **-- Baker Dam, Baker River, Washington.**

Results of a type of surface collector system at Wells Dam, a hydro-combine operated by Douglas County PUD on the Columbia River, have shown good success when compared to other types of guidance systems. Juvenile fish survival has been tested to be over 95-98% at Wells Dam.

Spillway passage is another means of juvenile passage being used at various projects in the Pacific Northwest. Generally, survival rates are around 98% for fish passed via spillways. However, high levels of spill can cause gas supersaturation which can be lethal to fish.

APPENDIX A – 2008 NMFS JUVENILE SALMONID FISH SCREEN CRITERIA

11. FISH SCREEN AND BYPASS FACILITIES

11.1 Introduction – Fish Screen and Bypass Facilities

This section provides criteria and guidelines to be used in the development of designs of downstream migrant fish screen facilities for hydroelectric, irrigation, and other water withdrawal projects. The design guidance provided in this section applies to *fishway* designs after a decision to provide a passage facility has been made. Unless directly specified herein, this guidance is not intended for use in evaluation of existing facilities, nor does it provide guidance on the application of the design for any particular site. Sections 1, 2, 3, and the Foreword of this document also apply to the guidelines and criteria listed in this section.

In designing an effective fish screen facility, the swimming ability of the fish is a primary consideration. Research has shown that swimming ability of fish varies and may depend upon a number of factors relating to the physiology of the fish, including species, size, duration of swimming time required, behavioral aspects, migrational stage, physical condition and others, in addition to water quality parameters such as dissolved oxygen concentrations, water temperature, lighting conditions, and others. For this reason, screen criteria must be expressed in general terms.

Several categories of screen designs are in use but are still considered as experimental technology by NMFS. These include Eicher screens, modular inclined screens, coanda screens, and horizontal screens. The process to evaluate experimental technology is described in Section 16. Several of these experimental screen types have completed part or all of the experimental technology process, and may be used in specific instances when site conditions allow. Design of these screens, or new conceptual types of experimental screens, may be developed through discussions with NMFS engineers on a case-by-case basis.

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 a proposed Federal action. After a decision to provide passage at a particular site has been made, the following design criteria and guidelines are applicable, in addition to those described throughout Section 3.

11.2 Functional Screen Design

A *functional screen design* should be developed that defines type, location, size, hydraulic capacity, method of operation, and other pertinent juvenile fish screen facility characteristics. In the case of applications to be submitted to FERC and for consultations under the ESA, a *functional design* for juvenile (and adult) fish passage facilities must be developed and submitted as part of the FERC License Application or as part of the Biological Assessment for the facility. It must reflect NMFS input and design criteria and be acceptable to NMFS. *Functional design* drawings must show all pertinent hydraulic information, including water surface elevations and flows through various areas of the structures. *Functional design* drawings must show general structural sizes, cross-sectional shapes, and elevations. Types of materials must be identified where they may directly affect fish. The final detailed design must be based on the *functional design*, unless changes are agreed to by NMFS.

11.3 Site Conditions

To minimize risks to anadromous fish at some locations, NMFS may require investigation (by the project sponsors) of important and poorly defined site-specific variables that are deemed critical to development of the screen and bypass design. This investigation may include factors such as fish behavioral response to hydraulic conditions, weather conditions (ice, wind, flooding, etc.), river stage/flow relationships, seasonal operational variability, potential for sediment and debris problems, resident fish populations, potential for creating predation opportunity, and other information. The life stage and size of juvenile salmonids present at a potential screen site usually is not known, and may change from year to year based on flow and temperature conditions. Thus, adequate data to describe the size-time relationship requires substantial sampling efforts over a number of years. For the purpose of designing juvenile fish screens, NMFS will assume that *fry*-sized salmonids and low water temperatures are present at all sites and apply the appropriate criteria listed below, unless adequate biological investigation proves otherwise. The burden-of-proof is the responsibility of the owner of the diversion facility.

11.4 Existing Screens

11.4.1 Acceptance Criteria and Guidelines for Existing Screens

If a fish screen was constructed prior the establishment of these criteria, but constructed to NMFS criteria established August 21, 1989, or later, approval of these screens may be considered providing that all six of the following conditions are met:

11.4.1.1 The entire screen facility must function as designed.

11.4.1.2 The entire screen facility has been maintained and is in good working condition.

11.4.1.3 When the *screen material* wears out, it must be replaced with *screen material* meeting the current criterion stated in this document. To comply with this condition, structural modifications may be required to retrofit an existing facility with new *screen material.*

11.4.1.4 No mortality, injury, entrainment, impingement, migrational delay, or other harm to anadromous fish has been noted that is being caused by the facility;

11.4.1.5 No emergent *fry* are likely to be located in the vicinity of the screen, as agreed to by NMFS biologists familiar with the site.

11.4.1.6 When biological uncertainty exists, access to the diversion site by NMFS is permitted by the diverter for verification of the above criteria.

11.5 Structure Placement

11.5.1 Specific Criteria and Guidelines – Structure Placement: Streams and Rivers

11.5.1.1 Instream Installation: Where physically practical and biologically desirable, the screen should be constructed at the point of diversion with the screen face generally parallel to river flow. However, physical factors may preclude screen construction at the diversion entrance. Among these factors are excess river gradient, potential for damage by large debris, access for maintenance, operation and repair, and potential for heavy sedimentation. For screens constructed at the bankline, the screen face must be aligned with the adjacent bankline and the bankline must be shaped to smoothly match the face of the screen structure to minimize turbulence and eddying in front, upstream, and downstream of the screen. Adverse alterations to riverine habitat must be minimized.

11.5.1.2 Canal Installation: Where installation of fish screens at the diversion entrance is not desirable or impractical, the screens may be installed in the canal downstream of the entrance at a suitable location. All screens installed downstream from the diversion entrance must be provided with an effective *bypass system*, as described in Sections 11.9 through 11.12, designed to collect and transport fish safely back to the river with minimum delay. The screen location must be chosen to minimize the effects of the diversion on instream flows by placing the bypass outfall as close as biologically feasible (i.e., considering minimizing length and optimizing the hydraulics of the bypass pipe) and practically feasible to the point of diversion.

11.5.1.3 Functionality: All screen facilities must be designed to function properly through the full range of stream hydraulic conditions as defined in Section 3 and in the diversion conveyance, and must account for debris and sedimentation conditions which may occur.

11.5.2 Specific Criteria and Guidelines – Structure Placement: Lakes, Reservoirs, and Tidal Areas

11.5.2.1 Intake Locations: Intakes must be located offshore where feasible to minimize fish contact with the facility. When possible, intakes must be located in areas with sufficient ambient velocity to minimize sediment accumulation in or around the screen and to facilitate debris removal and fish movement away from the screen face. Intakes in reservoirs should be as deep as practical, to reduce the numbers of juvenile salmonids that encounter the intake.

11.5.2.2 Surface Outlets: If a reservoir outlet is used to pass fish from a reservoir, the intake must be designed to withdraw water from the most appropriate elevation based on providing the best juvenile fish attraction and appropriate water temperature control downstream of the project. The entire range of *forebay* fluctuation must be accommodated in design. Since surface outlet designs must consider a wide spectrum of site-specific hydraulic and fish behavioral conditions, NMFS engineers and biologists must be involved in developing an acceptable conceptual design for any surface outlet fish passage system before the design proceeds.

11.6 Screen Hydraulics – Rotating Drum Screens, Vertical Screens, and Inclined Screens

11.6.1 Specific Criteria and Guidelines – Screen Hydraulics

11.6.1.1 Approach Velocity: The *approach velocity* must not exceed 0.40 ft/s for *active screens*, or 0.20 ft/s for *passive screens*. Using these approach velocities will minimize screen contact and/or impingement of juvenile fish. For screen design, *approach velocity* is calculated by dividing the maximum screened flow amount by the vertical projection of the *effective screen area*. An exception may be made to this definition of *approach* *velocity* for screen where a clear egress route minimizes the potential for impingement. If this exception is approved be NMFS, the *approach velocity* is calculated using the entire *effective screen area*, and not a vertical projection. For measurement of approach velocity, see Section 15.2.

11.6.1.2 Effective Screen Area: The minimum *effective screen area* must be calculated by dividing the maximum screened flow by the allowable *approach velocity*.

11.6.1.3 Submergence: For rotating drum screens, the design submergence must not exceed 85%, nor be less than 65% of drum diameter. Submergence over 85% of the screen diameter increases the possibility of entrainment over the top of the screen (if entirely submerged), and increases the chance for impingement with subsequent entrainment if fish are caught in the narrow wedge of water above the 85% submergence mark. Submerging rotating drum screens less than 65% may reduce the self-cleaning capability of the screen. In many cases, stop logs may be installed downstream of the screens to achieve proper submergence. If stop logs are used, they should be located at least two drum diameters downstream of the back of the drum.

11.6.1.4 Flow Distribution: The screen design must provide for nearly uniform flow distribution (see Section 15.2) over the screen surface, thereby minimizing *approach velocity* over the entire screen face. The screen designer must show how uniform flow distribution is to be achieved. Providing adjustable *porosity* control on the downstream side of screens, and/or flow *training wall*s may be required. Large facilities may require hydraulic modeling to identify and correct areas of concern. Uniform flow distribution avoids localized areas of high velocity, which have the potential to impinge fish.

11.6.1.5 Screens Longer Than Six Feet:

- Screens longer than 6 feet must be angled and must have *sweeping velocity* greater than the *approach velocity*. This angle may be dictated by site-specific geometry, hydraulic, and sediment conditions. Optimally, *sweeping velocity* should be at least 0.8 ft/s and less than 3 ft/s.
- For screens longer than 6 feet, *sweeping velocity* must not decrease along the length of the screen.

11.6.1.6 Inclined Screen Face: An inclined screen face must be oriented less than 45° vertically with the screen length (upstream to downstream) oriented parallel to flow, unless the inclined screen is placed in line with riverbank and reasonably matching the slope of the riverbank.

11.6.1.7 Horizontal Screens: Horizontal screens have been evaluated as an experimental technology, and may only be considered if the majority of flow passes over the end of the screen at a minimum depth of 1 foot, and positive downstream *sweeping velocity* in excess of the approach velocity exists for the entire length of screen. Post construction monitoring of the facility must occur. Since site-specific design conditions are required, NMFS engineers must be consulted throughout the development and evaluation of the design.

11.7 Screen Material

11.7.1 Specific Criteria and Guidelines – Screen Material

11.7.1.1 Circular Screens: Circular screen face openings must not exceed $^{3}/_{32}$ inch in diameter. Perforated plate must be smooth to the touch with openings punched through in the direction of approaching flow.

11.7.1.2 Slotted Screens: Slotted screen face openings must not exceed 1.75 mm (approximately $^{1}/_{16}$ inch) in the narrow direction.

11.7.1.3 Square Screens: Square screen face openings must not exceed $^{3}/_{32}$ inch on a diagonal.

11.7.1.4 Material: The *screen material* must be corrosion resistant and sufficiently durable to maintain a smooth uniform surface with long term use.

11.7.1.5 Other Components: Other components of the screen facility (such as seals) must not include gaps greater than the maximum screen opening defined above.

11.7.1.6 Open Area: The percent open area for any *screen material* must be at least 27%.

11.8 Civil Works and Structural Features

11.8.1 Specific Criteria and Guidelines – Civil Works and Structural Features

11.8.1.1 Placement of Screen Surfaces: The face of all screen surfaces must be placed flush (to the extent possible) with any adjacent screen bay, pier noses, and walls to allow fish unimpeded movement parallel to the screen face and ready access to bypass routes.

11.8.1.2 Structural Features: Structural features must be provided to protect the integrity of the fish screens from large debris, and to protect the facility from damage if overtopped by flood flows. A *trash rack*, log boom, sediment sluice, and other measures may be required.

11.8.1.3 Civil Works: The civil works must be designed in a manner that prevents undesirable hydraulic effects (such as eddies and stagnant flow zones) that may delay or injure fish or provide predator habitat or predator access.

11.9 Bypass Facilities

11.9.1 Specific Criteria and Guidelines – Bypass Layout

11.9.1.1 Bypass Location:

- The screen and bypass must work in tandem to move out-migrating salmonids (including downstream migrant adult salmonids such as steelhead *kelts*, if present) to the bypass outfall with a minimum of injury or delay.
- The bypass entrance must be located so that it may easily be located by out-migrants.
- The bypass entrance and all components of the *bypass system* must be of sufficient size and hydraulic capacity to minimize the potential for debris blockage.
- Screens greater than or equal to 6 feet in length must be constructed with the downstream end of the screen terminating at a bypass entrance. Screens less than or equal to 6 feet in length may be constructed perpendicular to flow with a bypass entrance at either or both ends of the screen, or may be constructed at an angle to flow, with the downstream end terminating at the bypass entrance.
- Some screen systems do not require a bypass system. For example, an end of pipe screen located in a river, lake, or reservoir does not require a bypass system because fish are not removed from their habitat. A second example is a river bank screen with sufficient hydraulic conditions to move fish past the screen face.

11.9.1.2 Multiple Entrances: Multiple bypass entrances should be used if the *sweeping velocity* may not move fish to the bypass within 60 seconds, assuming fish are transported along the length of the screen face at a rate equaling *sweeping velocity*.

11.9.1.3 Training Wall: A *training wall* must be located at an angle to the screen face, with the bypass entrance at the apex and downstream-most point. For many facilities, the wall of the civil works opposite to the screen face may serve as a *training wall*. For single or multiple *vee screen* configurations, *training wall*s are not required, unless an intermediate bypass must be used.

11.9.1.4 Secondary Screen: In cases where there is insufficient flow available to satisfy hydraulic requirements at the bypass entrance for the primary screens, a secondary screen may be required within the primary bypass. The secondary *bypass flow* conveys fish to the bypass outfall location or other destination, and returns secondary screened flow for water use.

11.9.1.5 Bypass Access: Access for inspection and debris removal must be provided at locations in the *bypass system* where debris accumulations may occur.

11.9.1.6 Trash Racks: If *trash racks* are used, sufficient hydraulic gradient must be provided to route juvenile fish from between the *trash rack* and screens to the bypass.

11.9.1.7 Canal Dewatering: The floor of the screen civil works must be designed to allow fish to be routed back to the river safely when the canal is dewatered. This may entail using a small gate and drain pipe, or similar provisions, to drain all flow and fish back to the river. If this cannot be accomplished, an acceptable fish salvage plan must be developed in consultation with NMFS and included in the operation and maintenance plan.

11.9.1.8 Bypass Channel Velocity: To ensure that fish move quickly through the bypass channel (i.e., the conveyance from the terminus of the screen to the bypass pipe), the rate of increase in velocity between any two points in the bypass channel should not decrease and should not exceed 0.2 ft/s per foot of travel.

11.9.1.9 Natural Channels: Natural channels may be used as a bypass upon approval by NMFS engineers. A consideration for utilizing natural channels as a bypass is the provision of off-stream habitat. Requirements for natural channels include adequate depth and velocity, sufficient flow volume, protection from predation, and good water quality.

11.9.2 Specific Criteria and Guidelines – Bypass Entrance

11.9.2.1 Flow Control: Each bypass entrance must be provided with independent flow-control capability.

11.9.2.2. Minimum Velocity: The minimum bypass entrance flow velocity should be greater than 110% of the maximum canal velocity upstream of the bypass entrance. At no point must flow decelerate along the screen face or in the bypass channel. *Bypass flow* amounts should be of sufficient quantity to ensure these hydraulic conditions are achieved for all operations throughout the *smolt* out-migration period.

11.9.2.3 Lighting: Ambient lighting conditions must be included upstream of the bypass entrance and should extend to the *bypass flow* control device. Where lighting transitions cannot be avoided, they should be gradual, or should occur at a point in the *bypass system* where fish cannot escape the bypass and return to the canal (i.e., when bypass velocity exceeds swimming ability).

11.9.2.4 Dimensions: For diversions greater than 3 cfs, the bypass entrance must extend from the floor to the canal water surface, and should be a minimum of 18 inches wide. For diversions of 3 cfs or less, the bypass entrance must be a minimum of 12 inches wide. In any case, the bypass entrance must be sized to accommodate the entire range of *bypass flow*, utilizing the criteria and guidelines listed throughout Section 11.9.

11.9.2.5 Weirs: For diversions greater than 25 cfs, *weir*s used in *bypass system*s should maintain a *weir* depth of at least 1 foot throughout the *smolt* out-migration period.

11.9.3 Specific Criteria and Guidelines – Bypass Conduit and System Design

11.9.3.1 General: Bypass pipes and joints must have smooth surfaces to provide conditions that minimize turbulence, the risk of catching debris, and the potential for fish injury. Pipe joints may be subject to inspection and approval by NMFS prior to implementation of the bypass. Every effort should be made to minimize the length of the bypass pipe, while maintaining hydraulic criteria listed below.

11.9.3.2 Bypass Flow Transitions: Fish should not be pumped within the bypass system. Fish must not be allowed to free-fall within a pipe or other enclosed conduit in a bypass system. Downwells must be designed with a free water surface, and designed for safe and timely fish passage by proper consideration of turbulence, geometry, and alignment.

11.9.3.3 Flows and Pressure: In general, *bypass flow*s in any type of conveyance structure should be open channel. If required by site conditions, pressures in the bypass pipe must be equal to or above atmospheric pressures. Pressurized to non-pressurized (or vice-versa) transitions should be avoided within the pipe. Bypass pipes must be designed to allow trapped air to escape.

11.9.3.4 Bends: Bends should be avoided in the layout of bypass pipes due to the potential for debris clogging and turbulence. The ratio of bypass pipe center-line radius of curvature to pipe diameter (R/D) must be greater than or equal to 5. Greater R/D may be required for super-critical velocities (see Section 11.9.3.8).

11.9.3.5 Access: Bypass pipes or open channels must be designed to minimize debris clogging and sediment deposition and to facilitate inspection and cleaning as necessary. Long bypass designs (eg. greater than 150 feet) may include access ports provided at appropriate spacing to allow for detection and removal of debris. Alternate means of providing for bypass pipe inspection and debris removal may be acceptable as well.

11.9.3.6 Diameter/Geometry: The bypass pipe diameter or open channel bypass geometry should generally be a function of the *bypass flow* and slope, and should be chosen based on achieving the velocity and depth criteria in Sections 11.9.3.8 and 11.9.3.9.

Table 11-1 provides examples for selecting the diameter of a bypass pipe based on diverted flow amount, assuming 1) bypass pipe slope of 1.3%; 2) Manning's roughness of 0.009; and 3) other bypass pipe criteria (Section 11.9) are met. Bypass pipe hydraulics should be calculated for a given design to determine a suitable pipe diameter if the design deviates from the assumptions used to calculate pipe diameters in Table 11-1.

Table 11-1. Bypass Design Examples

Diverted Flow (cfs)	*Bypass flow* (cfs)	Bypass Pipe Diameter (in)	*Bypass flow* Depth (in)
< 6	5% of diverted flow	10	2 ½
6 - 25	5% of diverted flow	10	4
40	2.00	12	4 ¾
75	3.75	15	6
125	6.25	18	7 ¼
175	8.75	21	8 ½
250	12.5	24	9 ½
500	25.0	30	12
750	37.5	36	14
> 1000	design with direct NMFS engineering involvement		

11.9.3.7 Flow: Design *bypass flow* should be about 5% of the total diverted flow amount, unless otherwise approved by NMFS. Regardless of the *bypass flow* amount, hydraulic guidelines and criteria in Sections 11.9.3.8 and 11.9.3.9 apply.

11.9.3.8 Velocity: The design bypass pipe velocity should be between 6 and 12 ft/s for the entire operational range. If higher velocities are approved, special attention to pipe and joint smoothness must be demonstrated by the design. To reduce silt and sand accumulation in the bypass pipe, pipe velocity must not be less than 2 ft/s.

11.9.3.9 Depth: The design minimum depth of free surface flow in a bypass pipe should be at least 40% of the bypass pipe diameter, unless otherwise approved by NMFS.

11.9.3.10 Closure Valves: Closure valves of any type should not be used within the bypass pipe unless specifically approved based on demonstrated fish safety.

11.9.3.11 Sampling Facilities: Sampling facilities installed in the bypass conduit must not in any way impair operation of the facility during non-sampling operations.

11.9.3.12 Hydraulic Jump: There should not be a hydraulic jump within the pipe.

11.9.3.13 Spillways: Spillways upstream of the screen facility also act as a *bypass system*. These facilities should also be designed to provide a safe passage route back to the stream, adhering to the bypass design principles described throughout Section 11.9

11.9.4 Specific Criteria and Guidelines – Bypass Outfall

11.9.4.1 Location:

- Bypass outfalls must be located to minimize predation by selecting an outfall location free of eddies, reverse flow, or known predator habitat. The point of impact for bypass outfalls should be located where ambient river velocities are greater than 4.0 ft/s during the *smolt* out-migration. Predator control systems may be required in areas with high avian predation potential. Bypass outfalls should be located to provide good egress conditions for downstream migrants.
- Bypass outfalls must be located where the receiving water is of sufficient depth (depending on the impact velocity and quantity of *bypass flow*) to ensure that fish injuries are avoided at all river and *bypass flow*s. The *bypass flow* must not impact the river bottom or other physical features at any stage of river flow.

11.9.4.2 Impact Velocity: Maximum bypass outfall impact velocity (i.e., the velocity of *bypass flow* entering the river) including vertical and horizontal velocity components should be less than 25.0 ft/s.

11.9.4.3 Discharge and Attraction of Adult Fish: The bypass outfall discharge into the receiving water must be designed to avoid attraction of adult fish thereby reducing the potential for jumping injuries and false attraction. The bypass outfall design must allow for the potential attraction of adult fish, by provision of a safe landing zone if attraction to the outfall flow can potentially occur.

11.10 Debris Management

11.10.1 Specific Criteria and Guidelines – Debris Management

11.10.1.1 Inspection and Maintenance: A reliable, ongoing inspection, preventative maintenance, and repair program is necessary to ensure facilities are kept free of debris and that screen media, seals, drive units, and other components are functioning correctly during the outmigration period. A written plan should be completed and submitted for approval with the screen design.

11.10.1.2 Screen Cleaning (Active Screens): *Active screens* must be automatically cleaned to prevent accumulation of debris. The screen cleaner design should allow for complete debris removal at least every 5 minutes, and operated as required to prevent accumulation of debris. The head differential to trigger screen cleaning for intermittent type cleaning systems must be a maximum of 0.1 feet over clean screen conditions or as agreed to by NMFS. A variable timing interval trigger must also be used for intermittent type cleaning systems as the primary trigger for a cleaning cycle. The cleaning system and protocol must be effective, reliable, and satisfactory to NMFS.

11.10.1.3 Passive Screens: A *passive screen* should only be used when all of the following criteria are met:

- The site is not suitable for an *active screen*, due to adverse site conditions.
- Uniform approach velocity conditions must exist at the screen face, as demonstrated by laboratory analysis or field verification.
- The debris load must be low.
- The combined rate of flow at the diversion site must be less than 3 cfs.
- Sufficient ambient river velocity must exist to carry debris away from the screen face.
- A maintenance program must be approved by NMFS and implemented by the water user.
- The screen must be frequently inspected with debris accumulations removed, as site conditions dictate.
- Sufficient stream depth must exist at the screen site to provide for a water column of at least one screen radius around the screen face.
- The screen must be designed to allow easy removal for maintenance, and to protect from flooding.

11.10.1.4 Intakes: Intakes must include a *trash rack* in the screen facility design which must be kept free of debris. In certain cases, a satisfactory profile bar screen design may substitute for a *trash rack*. Based on biological requirements at the screen site, *trash rack* spacing may be specified that reduces the probability of entraining adult fish.

11.10.1.5 Inspection: The completed screen and bypass facility must be made available for inspection by NMFS, to verify that the screen is being operated consistent with the design criteria.

11.10.1.6 Evaluation: At some sites, screen and bypass facilities may be evaluated for biological effectiveness and to verify that hydraulic design objectives are achieved. At the discretion of NMFS, this may entail a complete biological evaluation especially if waivers to screen and bypass criteria are granted, or merely a visual inspection of the operation if screen and bypass criteria is met in total.

11.10.1.7 Sediment: Provision must be made to limit the build-up of sediment, where it may impact screen operations.

11.11 End of Pipe Screens (including pump intake screens)

11.11.1 Specific Criteria and Guidelines – End of Pipe Screens

11.11.1.1 Location: *End of pipe screens* must be placed in locations with sufficient ambient velocity to sweep away debris removed from the screen face, or designed in a manner to prevent debris re-impingement and provide for debris removal.

11.11.1.2 Submergence: *End of pipe screens* must be submerged to a depth of at least one screen radius below the minimum water surface, with a minimum of one screen radius clearance between screen surfaces and natural or constructed features. For *approach velocity* calculations, the entire submerged *effective screen area* may be used.

11.11.1.3 Escape Route: A clear escape route should exist for fish that approach the intake volitionally or otherwise. For example, if a pump intake is located off of the river (such as in an intake lagoon), a conventional open channel screen should be placed in the intake channel or at the edge of the river to prevent fish from entering a lagoon.

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