DOWNSTREAM PASSAGE FOR SALMON AT HYDROELECTRIC PROJECTS IN THE COLUMBIA RIVER BASIN: DEVELOPMENT, INSTALLATION, AND EVALUATION

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EXECUTIVE SUMMARY

From 1933 to 1975, development of the hydroelectric system on the mainstem Columbia and Snake rivers involved construction of a series of major dams. Of these dams, Grand Coulee Dam blocked the Canadian portion of the mainstem, and Hells Canyon Dam blocked the upper Snake River to migrations of adult salmon (Figure 1). In the portions of the mainstem and Snake that are not blocked, there are 13 dams with fish ladders that provide passage for adult salmon. These include four on the lower mainstem Columbia reach, five in the mid-Columbia reach, and four in the Snake River. 70 dams located on tributaries in the basin are also part of the coordinated hydroelectric system. Some of these, such as those on the Cowlitz River, are not passable by salmon, and others, such as those above Hells Canyon Dam, lie above impassable dams. Juvenile salmon migrating downstream past those projects with fish passage facilities may use several routes. They either pass through the turbines, spillways, turbine intake bypass systems, navigation locks or ice and trash sluiceways. A few juvenile salmon may pass by way of fish ladders designed for adult passage, but these are not designed, located or operated in ways that will attract juveniles. Full development of the hydroelectric system included provisions for storage of spring runoff by dams in the upper tributaries. These storage operations distributed flow over the year and reduced the volume of spill available for passage of juvenile salmon in the spring, forcing more juveniles to pass through the turbines.

The first measurement of mortality of juvenile salmon in passing through turbines came in the early 1950's by Harlan Holmes. He recorded recovery of marked adult salmon that had been marked as juveniles and released in two groups, one that passed through the turbines and the other that was released below the turbines. Numerous studies since then have recorded measurements of mortality between 2.3 and 19 percent at various projects, averaging about 11 percent overall. With this rate of loss in passing through turbines, fewer than half of the fish migrating downstream from above the uppermost projects in the Snake River or upper Columbia River would survive to below Bonneville Dam without spill or other passage routes. Mortality in spill averages less than 2 percent at projects where losses due to concentrations of predators below the spillway are not a factor.

Numerous methods have been investigated for their potential in diverting the juvenile salmon away from the turbine intakes and into a safe passage route. We summarize those efforts in the text. They include efforts to improve effectiveness of spill, barrier nets, fish "gulpers", salvage from gatewells, electric fields, sound, lights, louvers, ice and trash sluiceways, turbine intake screens, and surface collectors. Of these mechanical devices, only turbine intake screens and surface collectors have proven effective enough to justify full installation.

Spill is effective as an interim measure or as a supplement to a mechanical bypass. Effectiveness of spill is measured in terms of the percentage of fish approaching the dam that is diverted into spill. Spill effectiveness varies from project to project. Application of spill is limited by water quality standards that limit the amount of spill because of concern about production by spill of high gas saturation levels that can kill fish. Several studies suggest that the effectiveness of spill in passing juvenile salmon can be improved. The standard spill gates at projects in the basin are fitted with tainter gates that open from below, usually at a depth of around 50 feet below the surface. Provision of spill from the surface increases the effectiveness of a given volume of water in passing juvenile salmon by a factor of two or more. It has also been learned that spreading spill of a given total volume of water (in acre feet) over a 24 hour period passes more than twice as many fish as the same number of acre feet of water spilled over a 12 hour period.

Tests of prototype turbine intake diversion devices have led to the development, construction and operation of bypass systems at all of the projects on the mainstem Columbia River and in the Snake River except The Dalles, Rocky Reach, Rock Island, Wanapum and Priest Rapids dams. In Appendix A, we document the requirements of the Federal Energy Regulatory Commission (FERC), the Northwest Power Planning Council (NPPC), and the National Marine Fisheries Service (NMFS/NOAA) for installation of bypass systems at each project. We also provide information on the status of those bypass facilities and future installation schedules at each of the 13 projects. Future installation is scheduled at The Dalles, Wanapum and Priest Rapids Dams, and is under study at Rocky Reach and Rock Island dams. Meanwhile, The Dalles Dam uses the ice and trash sluiceway to pass at least 40 percent of the juvenile salmon approaching the dam and more when spill is added. Turbine intake screens have been the primary choice by the Corps of Engineers (Corps) at their projects. The Corps has a schedule for replacement of standard length screens with extended-length screens at all eight of their projects, including The Dalles. As an example of the cost of these measures, in 1992 the Corps budgeted $32 million for development and installation of intake diversion screens. This program has been ongoing since the 1960's (Corps, 1992).

Effectiveness of turbine intake screens is measured by fish guidance efficiency (FGE), which is the percentage of fish approaching the turbine intakes that is diverted by screens. Measured fish guidance efficiency differs from project to project and with respect to other factors, which include the design of the screen, the species of salmon, degree of smoltification, time of day, and progress of the season. Extended length screens have achieved higher measured fish guidance efficiency than standard length screens. Fish guidance efficiency of extended length intake screens, although at times reaching values as high as 93 percent for steelhead and coho and 88 percent for chinook yearlings, are for the most part below 50 percent for subyearling chinook and sockeye. Fish that are not guided will pass through the turbines. Fish guidance efficiency appears to have reached an upper limit that is less than the surface collector at Wells Dam. Intake screens are unlikely to prove 100 percent effective in diverting juvenile salmon (Office of Technology Assessment, 1995, p.127). The 1987 Fish and Wildlife Program of the NPPC set a standard of 90 percent fish guidance efficiency for intake screens - “if it can be achieved." It appears that this standard can not be achieved.

Fish that are successfully guided by the screens into the bypass conduits are subject to injury at the screen and within the bypass system. The Fish and Wildlife Program of 1994 specified a criterion of 98 percent smolt survival within bypass and collection systems from the screen to the end of the outfall. This standard appears to be attainable. However, losses due to predation at the outfalls and in the tailraces can be substantial in some situations.

While fish guidance efficiency focuses on measurement of effectiveness of mechanical devices in diverting fish away from turbine intakes, fish passage effectiveness (FPE) is a measurement of the total percentage of fish that pass a project by routes other than the turbines. Passage can be through spill, the ice and trash sluiceway, or through the intake bypass system with the aid of screen diversion. In other words fish passage efficiency focuses on fish that are diverted away from the turbine intakes and into a safer passage route. Both NMFS/NOAA and the NPPC have established goals of 80 percent fish passage which includes all salmon species in both spring and summer.

The most successful bypass system in the basin is at Wells Dam where a surface collector passes an estimated 89 percent of the juvenile salmon in both spring and summer. Thus, it is the one project in the basin with a bypass that can achieve the 80 percent fish passage goal. Feasibility of using surface collectors at other projects is being investigated by the Corps, and by Chelan and Grant County Public Utility Districts.

In Appendix B, we compare the goals for fish passage of FERC, NPPC, and NMFS/NOAA with what was achieved in 1995. Experience in that year serves as an example illustrating that, except at Wells Dam, the NPPC and NMFS/NOAA goals of 80 percent fish passage can not be achieved without the addition of spill, due to limitations of performance of turbine intake screens or ice and trash sluiceways that are present. Furthermore, the amounts of spill required to meet the goals can not be provided due to gas saturation limits required by water quality standards.

To compare the performance of the fish passage measures as required in the NMFS/NOAA Proposed Recovery Plan with what was actually achieved, estimates of fish passage achieved at each of the Snake River and lower Columbia River projects in 1995 were produced by the Fish Passage Center (1995). (See Appendix B.) Under the NMFS/NOAA requirements, highest fish passage, 78 percent, was achieved at The Dalles Dam (Fish Passage Center, 1995). With the exception of Bonneville Dam at 55 to 62 percent, all of the lower river projects achieved fish passages in the 70 percent range. Snake River projects, with the exception of Ice Harbor Dam, achieved fish passages between 50 to 60 percent. Ice Harbor Dam achieved an estimated 79 to 84 percent fish passage, but with excessive spill.

Therefore, the 80 percent fish passage goals of NMFS/NOAA or the NPPC can not be achieved in the river reaches where endangered Snake River fish are present. The fish passage goals were achieved at Ice Harbor Dam in 1995 but only because turbine outages led to inadvertent spill in amounts that caused gas saturation to exceed limits.

With respect to FERC requirements, which apply in the mid-Columbia reach, the fish passage requirements at Wells Dam of 70 percent in spring and 50 percent in summer were exceeded by the 89 percent measured. The FERC requirement of 50 percent fish passage at Priest Rapids Dam in summer was met (62 percent) by provision of spill alone. Fish passage requirements by FERC at Wanapum Dam and at Priest Rapids Dam in summer could not be met because of limitations on spill due to gas saturation limits for water quality. FERC requirements were met at Rocky Reach and Rock Island dams, as they are specified in terms of spill amounts, not fish passage. The NPPC fish passage requirement of 80 percent, which applies as well as FERC requirements in the mid-Columbia reach, was met only at Wells Dam.

Calculation of the amount of spill required to achieve the 80 percent fish passage goal in the Snake River and lower Columbia River is complicated, requiring assumptions that go beyond available data. Decisions on the appropriate fish guidance efficiency to use depend upon predictions of the mix of species and other factors. Spill effectiveness curves are lacking for most of the Corps projects, requiring an assumption of a 1:1

relationship between percentage of flow that is spilled and the percentage of fish passed. This assumption is not met where adequate data are available for analysis, such as at John Day and The Dalles dams.

The calculated spill amounts in the Detailed Fishery Operating Plan depend upon an assumption (or conclusion) that there is an advantage to spilling 12 hours at night versus 24 hours a day as a benefit to power production. We question this assumption. We believe a more detailed analysis of costs and benefits to fish and power would be warranted. In any case, the spill amounts calculated for use by NMFS/NOAA can not be provided in practice due to limitations on gas saturation levels. This in spite of the fact that for the duration of the juvenile migration period water quality standards were expanded to permit 120 percent saturation. In addition, by 1995, five of the eight federal mainstem and Snake River projects were at least partially equipped with flip lip spillway deflectors designed to reduce gas saturation levels. (See Appendix A.) The NMFS/NOAA Proposed Recovery Plan specifies an upper limit of 115 percent gas saturation in the forebays of the projects. This standard can not be met at all during normal spring runoff.

Analysis by the Fish Passage Center indicated that survival of PIT tagged juvenile chinook salmon was not adversely affected by gas saturation levels experienced in 1995, which were 130 percent to 138 percent from May 25 to June 8 at Ice Harbor Dam (Fish Passage Center, 1995). Further studies are needed of juvenile salmon survival in natural river situations where gas saturation levels are high.

Future developments of juvenile bypass are expected to be in surface collectors, ice and trash sluiceways, and surface spill, all of which take advantage of a natural surface orientation of juveniles. Measures are needed to reduce gas saturation levels associated with spill levels that are required to meet fish passage goals.

INTRODUCTION

Development of the hydroelectric system in the Columbia River Basin began in the late nineteenth century on the tributaries. The first dam on the mainstem Columbia River was Rock Island Dam, completed in 1933, Figure 1, followed soon by Bonneville Dam in 1938 and Grand Coulee Dam in 1941, Table 1. Grand Coulee Dam blocked the Canadian portion of the upper Columbia River to migrating adult salmon. Hells Canyon Dam, completed in 1967, blocked the upper Snake River to salmon passage (Petersen, 1995). There are now thirteen dams on the mainstem Columbia and Snake Rivers that are passable by salmon. Additional hydroelectric projects on the tributaries bring the total to 211 dams in the Columbia River Basin of which 83 are part of the coordinated power system (Interagency Team, 1991; Logie, 1993). Some of these are impassable to salmon or are above dams that are impassable. In 1964, the United States and Canada agreed to a treaty that established the goal to develop the potential of the Columbia River and its tributaries to the mutual advantage of both countries (Bonneville Power Administration, 1980). As a result of the treaty, two Canadian mainstem dams, three Canadian tributary dams, and two Montana projects were built. Hydroelectric power generation, flood control, and irrigation were the benefits identified by the U. S. Army Corps of Engineers and the Bureau of Reclamation (Logie, 1993).

By 1976, the Bonneville Power Administration (BPA)(1980) could say that the Columbia River was fully developed for hydroelectric generation. The Hanford Reach, the one remaining undammed portion of the river, was debatable as a potential site, due to the potential for flooding of underground storage facilities for atomic wastes at the Hanford Reservation. Average annual discharge from Bonneville Dam, lowermost dam on the river, is 183,300 cfs (Interagency Team, 1991). Total storage capacity of the reservoirs in the system amounts to 55.3 million acre feet (68.2 billion m^3), which is about 25 percent of the basin's average total annual runoff (Logie, 1993; Thomas, 1997). This capacity is used to store a portion of the spring freshet for the benefit of later power production, and drawdown in late winter and early spring for the benefit of downstream flood control and other purposes (Logie, 1993). As a comparison, storage capacity in the Colorado River is about four times the average annual runoff in that system (Thomas, 1997).

Figure 1. Major Northwest Dams
(Source: Interagency Team, 1991)

Table 1. Dates of Closure of Dams on the Columbia and Snake Rivers (Source: Interagency Team, 1991)

Project Name	Columbia	Snake
Swan Falls		1901
Lower Salmon Falls		1907
Upper Salmon Falls		1932
Rock Island	1933	
Bonneville	1938	
Grand Coulee	1941	
Bliss		1948
C. J. Strike		1952
McNary	1954	
Chief Joseph	1955	
Brownlee		1958
The Dalles	1959	
Priest Rapids	1959	
Rocky Reach	1961	
Oxbow		1961
Ice Harbor		1961
Wanapum	1963	
Wells	1967	
Hells Canyon		1967
John Day	1968	
Keenlyside	1968	
Lower Monumental		1969
Little Goose		1970
Mica	1973	
Lower Granite		1975
Revelstoke	1983	

Figure 2. Diagram of a typical hydroelectric dam in the Columbia River Basin that shows the spillway (A and inset B), the powerhouse to the right of the spillway, powerhouse cross section (area F in the circular inset), and the navigational lock (E) to the left of the spillway (not present in mid-Columbia dams). In the powerhouse cross section, fish are shown moving up into a bypass inside the powerhouse, while the water continues on through the turbine. The diagram also shows the powerhouse tailrace (D), the adult fish ladder exit and entrance (E on the right), and navigability (G).

DAMS AS OBSTACLES TO MIGRATIONS OF SALMON

As the nearest large river to the north, the Fraser River stands as an example where experience with salmon is useful for comparison with experience in the Columbia. In 1960 at the behest of the International Pacific Salmon Fisheries Commission, Andrew and Geen undertook an analysis of the probable effects of hydroelectric development in the Fraser River, British Columbia on salmon production in the Fraser system. The proposed development would have involved construction of 18 dams on the mainstem and 44 on tributaries. They concluded that,

> "Dam construction presents a serious threat to the continued expansion - and indeed the very existence - of the commercial and recreational value of the Fraser River fisheries resource.... Although the fish-dam problem has existed for centuries in many countries, no practical solutions have yet been found that afford complete protection for anadromous fish in rivers obstructed and altered by large dams." (Andrew and Geen, 1960, p 2).

Largely on the basis of their conclusions, the Fraser River mainstem remains undammed to this date. Although their study was completed 37 years ago, their conclusion that no practical solution to the fish-dam problem has yet been found still applies, as borne out by experience in the Columbia River which is summarized below.

The typical mainstem dam on the Columbia River presents challenges to the migrations of both juvenile and adult anadromous fishes. The mainstem dams are for the most part around 100 feet high, although Rock Island Dam is about 50 feet high, while Grand Coulee and Hells Canyon dams are over 300 feet high and are impassable to fish. Juvenile emigrants, moving downstream in the direction from left to right in Figure 2, may pass the project by one of four basic routes: the powerhouse, the spillway, the navigation channel, or the fish ladders. As seen in a cross section of the powerhouse (inset Circle, Figure 2), when following the flow of the water onto the upstream face of the powerhouse, juveniles are forced to dive in order to follow the water flow (Arrows below point F in the inset) into the entrance to the turbine gallery. (Some projects, such as The Dalles Dam, have an ice and trash sluiceway adjacent to the powerhouse which passes some juveniles.) If the project has a bypass, the juveniles may encounter a screen which sends them upward in gatewells toward the upper deck of the powerhouse (Up Arrow, below Point F) and into a series of passages connecting the gatewells that will bring them out of the powerhouse to below the dam in the vicinity of Area D (Figure 2). Juveniles that miss the screen continue on through the turbine and exit near the downstream side of the powerhouse in the vicinity of Point D (the Tailrace). Note that point D describes the same basic area in both the circular inset and the main drawing. Fish ladders are provided for adults moving upstream and are not used by juveniles to a significant degree. Most likely, the relatively small volume of water in the ladders and their location make it difficult for the juveniles to find them. The five projects in the mid-Columbia reach do not have navigation channels.

Compensation for losses of salmonids due to construction and operation of the hydroelectric system has been attempted primarily by hatchery production, and to a much lesser extent by habitat improvement, which is considered to be in its developmental stages. Mitigation at the projects of mortalities experienced by juveniles migrating downstream has been attempted primarily by construction of bypass systems for juvenile salmon at the dams, and by provision of a "water budget" for facilitating movement of juvenile salmon out of the system (NPPC, 1984). Transportation of juvenile salmon by truck and by barge is in fact part of the bypass system because it depends upon the bypass system for collection of fish moving in the river. This report deals with the subject of development and operation of bypass systems. This report does not address other subjects, including the water budget or transportation of juveniles.

The significance of bypass facilities for juvenile salmonids can perhaps be judged by the fact that the Corps of Engineers budgeted $32 million in 1992 for development and installation of diversion facilities, a program that has been ongoing since the 1960's (Corps, 1992).

DEVELOPMENT OF BYPASS SYSTEMS IN THE COLUMBIA BASIN

ADULT FISH PASSAGE

Federal law, dating from 1906, authorizes the United States Departments of Commerce (and/or Interior now) to require fishways at all federally licensed dams (Office of Technology Assessment, 1995). Accordingly, passage for adult salmon was provided at the time of construction at the five dams licensed by the FERC in the mid-Columbia reach. In addition, when Congress authorized the non-federally licensed dams, those constructed and operated by federal agencies (U.S. Army Corps of Engineers and U.S. Bureau of Reclamation), they required adult fish ladders at the time of construction at all except Grand Coulee Dam and Chief Joseph Dam. Those dams were thought to be too high to have effective ladders. In addition, Grand Coulee Dam was planned for irrigation and flood control, both of which require extensive fluctuations in pool elevation that was considered to make a fish ladder (of standard design) unfeasible. Hells Canyon Dam, constructed by Idaho Power Company on the Snake River included provision for fish passage that was not successful (Petersen, 1995). In the basin, impassable dams have blocked salmon from about 35 percent of their former habitat (NPPC, 1987).

While in general adult passage facilities are considered to be effective in design and operation, questions remain about possible delays in movement of adults approaching and passing through the ladders (Mighetto and Ebel, 1995). Chapman, et al. (1994) concluded that, while the analysis is complicated by fall-back of fish that are counted twice, the best estimate is a 5 percent loss of adult chinook between dams. This loss is due to several factors including harvest, mainstem spawning, fish turning into tributaries, and fish not locating ladder entrances. Bjornn and Peery (1993) reviewed the literature relating to factors affecting movement of adult salmon through dams and reservoirs on the lower Sanke River. Studies have shown that levels of spill can lead either to reduced time spent in passage at a dam with low spill levels relative to no spill or increased time spent with high spill levels relative to low spill. (Also see Dauble and Mueller, 1993). Mendel, et al. (1993) discuss factors affecting upstream migrations of adults into the Snake River. Recent advancements in the technology of tracking radio tagged adults has made it possible to closely track individual adult salmon as they approach and transit dams and fish ladders (e.g. Stuehrenberg, et al., 1995, Swan, et al., 1994). Studies are under way or in the process of interpretation. It is hoped that they will lead to identification and correction of any problems in adult passage that might exist at particular projects.

MORTALITY OF JUVENILE SALMON IN TURBINES

While the need for adult passage was obvious, the need to provide downstream passage for juvenile salmon was questioned by some (Office of Technology Assessment, 1995; Petersen, 1995). That the contrary point of view was given some attention is shown by the fact that four downstream migrant bypass facilities were provided at Bonneville Dam when it was built in 1938 (Andrew and Geen, 1960; Bell, et al., 1967). Although we can find no description of them, they were apparently surface collection devices used in conjunction with screened water intakes. They were placed at the north end of the spillway and south end of the powerhouse where it was hoped they would attract juvenile migrants away from the turbines or spillway (Mighetto and Ebel, 1995). They were found to be ineffective for that purpose by the Corps of Engineers' biologist, Ivan Donaldson (Mighetto and Ebel, 1995), and by the 1950s were being used primarily to obtain samples of fish moving past the project (Anas and Gauley, 1956).

The need to provide passage for juvenile salmon was first established as a result of a set of experiments conducted by Harlan Holmes at Bonneville Dam from 1938 to 1948. These experiments showed a loss of 11 to 14 percent of juveniles in passing through the turbines (Bell, et al., 1967). Holmes used juvenile fish in paired groups, one released below the dam as a control and the other released into the turbine intake. He then compared the relative rates of return of the adults from those groups. Some Corps officials at that time were skeptical of the results (Petersen, 1995, p.110), but there is no longer any doubt that turbines cause loss of fish in passage. However, some may question the values Holmes measured. More information on that point is provided below.

Once Holmes had established a reference point, it was then possible to proceed with methods using recovery nets in the tailrace and other techniques that did not require waiting years for the adults to return. Verification by other investigators soon followed (Schoeneman and Junge 1954, 1959; Schoeneman, 1956; Schoeneman, et al., 1961). Available estimates of mortality of salmonids in turbines range from 2.3 to 19 percent (see Table 2). There is considerable variability in survival estimates from one project to another. This variability should be taken into account in modeling survival of juvenile salmon in downstream passage.

Table 2. Estimated mortality of juvenile salmon and steelhead associated with passage through turbines at hydroelectric projects in the Columbia River (Sources: Bell, et al., 1967; DeHart, 1987: Others, more recent, are named in the table.

Dam	**Mortality**	**Year**	**Authors**	**Species**
Bonneville I (1993)	11% to 15%	1938-1948	Holmes (1952), per Mighetto and Ebel, 1995)	Chinook Subyearlings
	4%	1954	Weber (1954, See Iwamoto and Williams, 1993)	Chinook Subyearlings
Bonneville II	2.3% or 9.5%*	1988-1990	Gilbreath, et al. (1993)	Chinook Subyearlings
John Day	13%	1980	Raymond and Sims (1980)	Chinook Yearlings
McNary	11% **	1955; 1956	Schoeneman, et al., (1961)	Chinook Subyearlings
Ice Harbor	10% to 19%	1968	Long (1968)	Coho “fingerlings”
Lower Monumental	16%	1975	Long, et al., (1975)	Coho (20-22/ lb)
	3.5%	1994	Muir, et al., (1995A)	Chinook Yearlings
Lower Granite	16.9% ***	1987	Giorgi and Stuehrenberg, (1988)	Chinook Yearlings
Little Goose	8%	1993	Iwamoto, et al., (1994)	Chinook Yearlings
Wells	16%	1980	Weitkamp, et al., (1980)	Steelhead
Rock Island No. 2 (Bulb Turbines)	5.7% or 13%****	1979	Olson and Kaczynski (1980)	Coho and Steelhead
Big Cliff (North Santiam River; Tributary to the Willamette River)	11% **	1957	Schoeneman, et al., (1961)	Chinook (Yearlings and Subyearlings)
	13.5%	1957	Oligher and Donaldson (1965)	Chinook Yearlings
	11.8%	1964	Oligher and Donaldson (1966)	Chinook Yearlings
	8.6%	1966	Oligher and Donaldson (1966)	Chinook Yearlings

Estimates using radio tagged salmon recovered immediately in the tailrace (HI-Z Turb'n Tag, Heisey, et al., 1992).

Dam	Mortality	Year	Author	Species
Rocky Reach Dam				
Variable blades	7%	1994	RMC Env. Serv. and Skalski (1994)	Chinook Yearlings
Fixed blades	3.9%	1994	RMC Env. Serv. and Skalski (1994)	Chinook Yearlings
Lower Granite Dam	5.2%	1995	Normandeau Associates, et al., (1995)	Chinook Yearlings

*Gilbreath, et al. (1993) provide data that produce a weighted average estimate of 2.3 percent mortality over three years of study, if fish released in the tailrace are used as reference controls. If fish released near the Hamilton Island Boat Launch downstream are used as the reference controls, the estimate is 9.5 percent. Their data show that, in the two years for which there are comparisons, fish released in the tailrace experienced an additional 6.8 percent mortality relative to the downstream release. In 1989, fish were released in the spillway. They survived at a higher rate than the fish released in the tailrace and at the same rate as the fish released downstream. Therefore, the difference between the two estimates of mortality in turbines can be explained by the fact that the higher estimate includes an element of mortality in the tailrace. Fish passing through the spillway were not exposed to this source of mortality. It appears that in the tailrace at Bonneville Dam there are peculiar back eddies or shore areas where there may be concentrations of predators (Ledgerwood, et al., 1994).

**Schoeneman, et al. (1961) found no significant difference between the 1955 estimate of 13 percent and the 1956 estimate of 8 percent mortality at McNary Dam, and combined them to get the 11 percent estimate. Similarly, they combined estimates at Big Cliff for yearlings and subyearlings.

***Giorgi and Stuehrenberg (1988) felt that their estimate was on the high side due to failure of test and control fish to mix at recovery sites, as required by the experimental protocol. However, their estimate agrees with the later one of Iwamoto, et al. (1994).

****There was a dispute over the results of this study at Rock Island. The point estimate was 5.7 percent mortality, but an ad hoc committee appointed to review the study found that there was no significant difference between that estimate and the estimates at Big Cliff and McNary dams, (Chapman, et al., 1980). Nevertheless, the administrative law judge for FERC found in favor of the 5.7 percent estimate, but ordered development of a bypass system, (Rock Island Project, 34 FERC 63,044 at 665,167.]

While oversimplifying the situation, an overview can be useful for the purposes of this report. The average of the first group of 18 estimates that used comparable study methods is 10.9 percent mortality. Estimates from three studies that used a radio tagging system that allowed quick recovery of marked fish in the tailrace are lower than most of the others. Estimates for these three ranged from 3.9 percent to 7 percent (RMC Environmental Services, Inc. and Skalski, 1994 and Normandeau Assoc., et al., 1995) and averaged 5.5 percent. The lower estimates most likely estimate mortality directly associated with turbine passage, while the others probably include factors beyond the turbine.

It is apparent that a portion of the mortality measured in some of the studies occurred in the tailrace or downstream, rather than in the turbines themselves. For example, see the Table 2 footnote that is a review of data from a study by Gilbreath, et al. (1993) at the Bonneville Dam Powerhouse II. In addition to losses of juvenile salmon in direct turbine passage, losses have been identified in intake and discharge structures, the tailrace, or reservoir, and losses due to predation as an incidental effect of turbine passage or other losses not directly assignable to turbine effects, (Long, et al., 1975). Other factors that affect mortality of salmonids in turbines will be discussed below.

MORTALITY OF JUVENILE SALMON IN RIVER REACHES

Studies designed to measure mortality of juvenile salmon in river reaches are summarized in Table 3. A set of studies conducted over three different years in the mid-Columbia found an average of about 15 to 16 percent mortality from one project to the next for juvenile chinook salmon passing each of the five projects in the mid-Columbia. This included mortality in the turbine, tailrace, and reservoir (Chapman and McKenzie, 1980; McKenzie,, et al., 1982; McKenzie, et al., 1983).[1] Similar system-wide mortality estimates of 20 to 25 percent per project were derived for the Snake River and lower Columbia (Raymond 1979; Sims, et al. 1984). Steward (1994), and Williams and Mathews (1994) have questioned the validity of the early series of Snake River and lower Columbia River estimates. On the other hand, Giorgi and Stuehrenberg (1978) estimated mortality of chinook in the reach through the reservoir at Lower Granite Dam to the tailrace at Lower Granite Dam to be 18 percent in 1978.

In any case, these estimates are no doubt higher than in today's system with improved bypass systems in place at all of the dams (NMFS/NOAA, 1995 p V-2-3; NRC, 1995). Bypass system improvements include construction of bypass facilities at Lower Granite and Ice Harbor dams, modifications of bypass facilities at Little Goose and Lower Monumental dams, removal of debris from collection systems, installation of flip-lips in spillways to reduce gas supersaturation, changes in turbine operations, and implementation of the water budget. The conclusion that survival is now higher is supported by the studies of Iwamoto, et al. (1993) and Muir, et al. (1995). The “PIT Tag” (Prentice, et al., 1992) is a new technology that has made possible studies such as the latter two that can provide estimates of survivals through given “reaches” or segments

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[1] The 1980 study produced a higher estimate (20 percent), but there were difficulties in execution of the study design, which called for release groups to arrive at downstream recovery sites at near the same time, which they did not do (Chapman and McKenzie, 1980).

of the river, where detectors are located at both ends. The proposed procedure for developing such estimates in the Columbia Basin, based on a concept referred to as the Cormack-Jolly-Seber concept (See Burnham, et al., 1987) was first outlined in a document prepared by Skalski and Giorgi (1992). This resulted in the Snake River studies by NMFS and the University of Washington in 1993 and 1994 (Iwamoto, et al., 1993; Muir, et al., 1995A).[2] Their estimates of mortality of juvenile chinook in passing through reservoir to tailrace of three projects in the Snake River in 1993 and 1994 ranged from 8 to 22 percent per project and are probably site specific, Table 3. In 1994, mortality of naturally produced chinook in passing through the full length of the reach from the reservoir at Lower Granite to the tailrace at Lower Monumental Dam was estimated to be 27 percent (Muir, et al., 1995A). On a per project basis, mortality would amount to a little less than 10 percent, which is in the range of their other estimates.

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[2] The estimation method employed by Iwamoto, et al. (1994) and Muir, et al. (1995) had been questioned, but at the request of the NWPPC the ISG supervised a review (Independent Scientific Group, 1996). The ISG report concluded that the procedure was the best available method for estimating survival rate in reaches.

Table 3. Estimated Mortality of Juvenile Salmon and Steelhead in Passing Through Reaches of River
(Sources: Originals as cited, and Bevan, et al., 1994)

For Hatchery Chinook

River Reach	Mortality	Years/Author
Mid-Columbia	15%-16% per project (five projects)	Chapman and McKenzie (1980); McKenzie, et al. (1982); McKenzie, et al. (1983)
Through Lower Granite Reservoir from Asotin	18%	Giorgi and Stuehrenberg (1978)
Lower Granite Reservoir from Asotin to Various Downstream Locations	10%	Iwamoto, et al. (1994)*
To tailrace at Lower Granite	8%	Muir, et al. (1995)
From Lower Granite to tailrace Little Goose	14%	Iwamoto, et al. (1994)*
	21%	Muir, et al. (1995)
From Little Goose to tailrace Lower Monumental	11%	Muir, et al. (1995)

For Hatchery Steelhead

Lower Granite Reservoir from Asotin to various downstream locations

To tailrace at Lower Granite	10%	Muir, et al. (1995)
From Lower Granite to tailrace Little Goose	22%	Muir, et al. (1995)
From Little Goose to tailrace Lower Monumental	17%	Muir, et al. (1995)

For Naturally Produced Chinook

From Lower Granite Reservoir to Lower Monumental tailrace	27%	Muir, et al. (1995)

Table 3 (Continued) Estimated Mortality of Juvenile Salmon and Steelhead in Passing Through Reaches of River

(Sources: Originals as cited, and Bevan, et al., 1994)

For Naturally Produced and Hatchery Chinook.

[The following figures are taken from the Draft Snake River Salmon Recovery Plan (Bevan, et al., 1994). They have been criticized by Steward, (1994), Williams and Mathews, (1994), and NRC, (1995, p. 201) who concluded that system and average project mortalities were overestimated. For the purposes of the Draft recovery plan and our purposes here, they should be viewed as relative values that provide a comparison of survival before and after Little Goose and Lower Monumental dams were added to the system. In any case they are not relevant to the system as it now exists, as explained in the text.]

From Salmon River to Ice Harbor Dam: Before and after Little Goose and Lower Monumental Dams Were Built

Years	**Estimated Mortality**	**Author**
Before 1970	11%	Raymond (1979)
After 1970	67%	Raymond (1979)

From Lower Granite to The Dalles Before and After Little Goose, Lower Monumental and Ice Harbor Were Built

Before	37%	Raymond (1979)
After	80%	Raymond (1979); Sims, et al. (1984)

* This study was designed to test the method and associated assumptions, not to produce survival estimates. Nevertheless, the resulting estimates are close to those in the later study.

Conditions in the mid-Columbia reach have also improved since the studies of Chapman and McKenzie (1980) and McKenzie, et al. (1982, 1983) were conducted. Wells Dam has a fully functioning bypass system, as well as new turbines with higher efficiency ratings, and the other mid-Columbia projects have added spill amounts as bypass routes for juvenile salmon. These factors are discussed in more detail below.

The new estimates of mortality in turbines and the estimates of survival in reaches of the river have brought into focus the need to be able to separate direct mortality induced upon juvenile salmon in the turbines from mortality experienced as an indirect result of turbine passage or from other causes. The ability to separate is necessary because the solutions will differ. There have been several attempts to separate mortality estimates into components for the reservoir and tailrace. Iwamoto, et al. (1993) developed a specific estimate for mortality in the reservoir above Lower Granite Dam, which was based on a series of reach survival estimates applying from a point above Lower Granite Dam to the tailrace at little Goose Dam. Iwamoto, et al. also developed estimates of survival in turbines at both dams. The study produced an estimate of zero mortality for yearling chinook in the reservoir above Lower Granite Dam in 1993. Muir, et al. (1995A) developed an estimate of steelhead smolt mortality from the forebay at Lower Monumental Dam to the tailrace, amounting to 42 percent, a surprisingly large number. Unfortunately, there seems to be no estimate of mortality of steelhead in turbines for Lower Monumental Dam. However, even assuming the worst, say 20 percent mortality in the turbines, the result indicates a high loss of juvenile steelhead in the forebay. At Bonneville Dam, mortality of subyearling chinook in the tailrace downstream to the Hamilton Island Boat Launch was estimated to be 10.5 percent (Dawley, et al., 1989). The data of Johnsen and Dawley (1974) can be used to estimate a 54.5 percent loss of juvenile salmon from the tailrace at Bonneville Dam to Rainier Beach, Oregon. These studies indicate that in some instances losses of juvenile salmon in the forebay and tailrace exceed the losses in turbines.

Studies of predation by squawfish also indicate that the highest losses occur in the forebays and tailraces of the dams (Gadomski and Poe, 1993). Birds are particularly troublesome in the tailrace. Predation losses are discussed in a separate section of Return to the River (Williams, et al., 1996). As an example, Gadomski and Poe (1993) estimated a loss of 1.4 million juvenile salmon in John Day reservoir due to squawfish predation in 1993.

SOURCES OF MORTALITY IN TURBINES

Existing physical models of turbine facilities were used in studies designed to explore the factors responsible for the smolt mortality associated with turbine passage, such as those of Cramer (1960, 1965), and Cramer and Oligher (1960, 1961). Further extensive, pertinent literature on the subject is summarized by Bell, et al. (1981); Turbak, et al. (1981); Lucas (1981); Bell (1991); and Cada, et al. (1997).

Bell, et al. (1981) and Bell (1991) summarized the findings as follows. Fish survival is related to the efficiency curve of propeller type turbines. Highest survival occurs at highest efficiency. All of the Columbia River and Snake River Powerhouses on the portion of the river passable by salmon are equipped with propeller type turbines. Turbines with negative pressure within the draft tube have a higher kill rate than those with positive pressure, pointing to the importance of maintaining an optimum tailwater elevation. Clearances between the runners and their surroundings are a potential source of mortality.

Remedies to the turbine passage problem were sought through the decades of the 1960's and 1970's (Mighetto and Ebel, 1995). Best turbine operating criteria were defined, i.e. - operate at the upper end of the turbine efficiency curve. Design characteristics were analyzed - minimize negative pressures in the draft tube, and avoid clearances around runner blades that could impact fish (Bell, et al., 1967). At the same time, efforts were continued to develop methods for diverting fish away from the turbine intakes.

SMOLT BEHAVIOR AS IT AFFECTS THEIR BYPASS AT DAMS

The preponderance of evidence demonstrates that juvenile salmon migrating downstream are oriented to the upper portion of the water column. Giorgi and Stevenson (1995) reviewed much of the evidence at Corps projects. Johnson (1995) reviewed the evidence from salmon literature world-wide. When juvenile salmon encounter a dam, they prefer surface outlets, when available, and are reluctant to sound. Raymond and Sims (1980) found that juvenile salmon passing through gates with surface spill were as likely to pass in the day as at night. In comparison, juvenile salmon sampled from the turbine intakes, the ceilings of which were located at about the same depth as the bottoms of the unlogged spill bays, showed a strong peak at night. This finding suggested that juvenile salmon approaching the dam delayed sounding to the intakes until after dark, and that they more readily passed through surface spill.

The number of juvenile salmon in the ice and trash sluiceway at The Dalles Dam peaked around mid-day (Nichols, 1979; Nichols and Ransom, 1980, 1981; Steig and Johnson, 1986; and Johnson, et al., 1987). At Bonneville Dam, the number also peaked at mid-day (Willis and Uremovich, 1981). (All as summarized by Giorgi and Stevenson, 1995.) This is in contrast to turbine intakes where the number of juvenile salmon reaches a peak at night (Giorgi and Stevenson, 1995 summarize Long, 1968; Magne, et al., 1983; Steig and Johnson, 1986; and Johnson, et al., 1987). Observations in the mid-Columbia generally agree with the summary of Giorgi and Stevenson, although occasional differences raise questions regarding the possibility of differences for sockeye and perhaps coho. (Findings of the mid-Columbia Coordinating Committee annually for the years 1980-1993.)

Further evidence of the surface orientation of juvenile salmon comes from the fact that juveniles are observed to accumulate in gatewells of unscreened turbine intakes, as first noted in the early 1960's by Cliff Long and George Snyder (Mighetto and Ebel, 1995). In addition, juveniles generally sound to significant depths only when no alternative is presented (Wagner and Ingram, 1973; Dunn, 1978). Numerous hydroacoustic studies that were undertaken at each of the five mid-Columbia projects showed that juvenile salmon were concentrated in the upper portion of the water column, generally in the upper one-third. (Biosonics, numerous - see references. e.g. Ransom, et al. (1988) found that fish approaching Rock Island Dam were surface oriented.) Juvenile salmon have been sampled in the Wells forebay with purse seines, a fishing method that operates at the surface (Findings of the mid-Columbia Coordinating Committee, 1989).

In the forebay at lower Granite Dam, 92 percent of the juvenile salmon were found to be in the upper 36 feet of the water column (Smith, 1976). The turbine intake screen technology depends upon the fact that juvenile salmon are concentrated near the ceiling of the intake as they pass through. Numerous examples exist (e.g. Long, 1968). Fyke net sampling at each of the mid-Columbia projects showed that 75-80 percent of the juvenile salmon were in the upper portion of the intakes (e.g. Hays, 1984).

Eicher (1988) reviewed studies of passage efficiency at deep intakes. The studies of Regenthal and Rees (1957) were particularly informative. They showed 55 percent of chinook would exit the reservoir when the only route was 118 feet deep or less, 48 percent when it was at 146 feet, and 8 percent when it was 160 feet (as summarized in Eicher, 1988). Eicher concluded that "…. it has been accepted that fish [salmonids] sound to great depths as a last resort, and if an alternative, such as an artificial outlet, is available, they will use it preferentially and can be collected in that way." (Eicher, 1988).

SPILL AS A MEANS OF BYPASS FOR JUVENILE SALMON

Normal Spill

Depending upon the hydraulic capacity of the individual projects and the river flow in the particular year, there will normally be spill during the spring freshet when the largest numbers of juvenile salmon are moving downstream.

Studies of mortality in spill have been conducted at six projects, resulting in 13 estimates, Table 4. Five of the thirteen separate estimates were of zero mortality in spill. Five others were of 2 percent or less. Studies revealed a potential for added mortality from predation below the spillway.[3] One unusually high estimate of 27.5 percent at Lower Granite Dam was probably associated either with high predation by squawfish or other adverse conditions below the dam, such as were described for Little Goose Dam in 1994 (Muir, et al., 1995A).

Spillway design affects the rate of injury and survival, with free-fall being the least injurious (Bell and DeLacy, 1972; Stone and Webster, 1986). Back-roll may be created with certain designs and spill levels, which can trap fish in turbulence, adding to the potential for predation and other causes of mortality (Stone and Webster, 1986)

Sims and Ossiander (1981) reported that spill increased survival more than flow did. Their analysis suggested that the first 10 percent of spill increased survival by 28 percent, while the first 10 percent increase in flow added 13 percent survival.

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[3] Some references state that mortality of juvenile salmon in spill ranges from 0 to 4 percent (Fish Passage Center, 1994), or 0 to 3 percent (NMFS/NOAA Proposed Recovery Plan, 1995). However, close scrutiny of the studies upon which these numbers are based leads us to conclude that 0 to 2 percent is the more likely range for standard spill bays. In addition, local conditions such as back eddies or other situations that may favor the presence of predators may lead to higher numbers (e.g. such as those Muir, et al. (1995) suggested may have occurred below Little Goose Dam in 1994.)

Table 4. Estimates of Mortality of Juvenile Salmon and Steelhead in spill.

Mortality	Species	Location	Reference
2%	chinook	McNary Dam	Schoeneman, et al. (1961)
2.2%	steelhead	Lower Monumental Dam	Long, et al. (1975) [For spill bays with deflectors]
27.5%*	steelhead	Lower Monumental Dam	Long, et al. (1975) [For spill bays without deflectors]
4%**	chinook	Lower Monumental Dam	Muir, et al. (1995B) [For combined bays]
1.5%	chinook	Lower Monumental Dam	Muir, et al. (1995B) [For spill bay without deflector.]
7%	chinook	Lower Monumental Dam	Muir, et al. (1995B) [For spill bay with deflector.]
0%***	steelhead	Wells Dam	Weitkamp, et al. (1980) [Confidence interval included 0]
1%	coho	Rocky Reach Dam	Heinle and Olson (1981)
0%	chinook	Bonneville Dam	Ledgerwood, et al. (1990)
0%	chinook	Bonneville Dam	Johnsen and Dawley (1974) [For spill bay with deflector]
0%	chinook	Bonneville Dam	Johnsen and Dawley (1974) [For bay without deflector]
1%	chinook	John Day Dam	Raymond and Sims (1980) [Authors concluded that the point estimate did not differ from 0]
0%	chinook	Little Goose Dam	Iwamoto, et al. (1994)

* This unusually high estimate at Lower Granite Dam was probably associated either with high predation by squawfish or other adverse conditions below the dam, such as were described for Little Goose Dam in 1994 (Muir, et al. 1995A). See next footnote.
** Muir, et al. (1995B) found no statistically significant difference between the survival estimates for spill bays with and without deflectors, in spite of what the point estimates might suggest.
*** The mid-Columbia Coordinating Committee agreed that the estimate was zero (mid-Columbia Coordinating Committee, 1985)

Spill Deflectors – Perforated Bulkheads and “Flip-Lip” Spillways

A problem encountered with high spill amounts is gas supersaturation, leading to a condition in fish similar to the divers “bends”, in which gas bubbles appear in the blood stream and other tissues, which can lead to death (Ebel, 1969; Ebel, et al., 1975; Bouck, 1980). The subject is discussed in more detail in Return to the River (ISAB 96-6). The condition of supersaturation is brought about by the plunging of water from the spillway, carrying air with it and putting it under pressure in the pool below. As the pressure is removed, the bubbles appear.

Perforated Bulkheads in Turbine Intakes

In an effort to reduce nitrogen supersaturation, slotted bulkheads were installed by the Corps in 27 of the empty turbine bays in the lower Snake River projects in 1971 (Long, et al., 1972). Prototype tests at Little Goose Dam had shown that water could be run through the slotted bulkheads with little increase in nitrogen saturation. However, the mortality rate of smolts passing through the slotted bulkheads was measured at 50 percent at Lower Monumental Dam, which led to their abandonment (Long, et al., 1972).

Spill Deflector - "Flip Lip" Spillway Design

A remedy that has been adopted is a spill deflector (“flip lip”) design for the spillway, which directs the spill in a horizontal direction, rather than vertical (Smith, H.A. Jr., 1974). At flows of 123 to 169 kcfs, the spill deflectors at Little Goose Dam were shown to reduce gas saturation levels downstream by about 10 percent, relative to levels before the deflectors were installed. Saturation was measured at 128 percent with spill of 46 to 59 percent of flow (Park, et al., 1977). At Lower Monumental and Lower Granite dams, also equipped with spill deflectors, they found gas saturation levels to be 2 to 8 percent lower than at Little Goose, under the same flow conditions. These lower levels were probably due to the greater depth of the stilling basin below Little Goose Dam and smaller deflectors there, 8 feet in length compared to 12 feet at the others. At McNary Dam, they found gas saturation was lower by 16 to 20 percent with the spill deflectors in place than it had been before (Park, et al. 1977).

In a more thorough analysis, Johnsen and Dawley (1974) developed curves showing the relationship of gas saturation levels below the spillway with forebay gas levels, spill discharges, water temperatures, tailwater elevations and effects of deflectors at Bonneville Dam. With forebay gas levels of 110 percent and tailrace elevations of 24 feet, the deflectors generally reduced gas saturation levels by about 10 percent (130 percent reduced to 120 percent). But at higher discharge rates (thus tailrace elevations) the difference lessened, to the extent that it appeared the deflectors might be disadvantageous at spill discharges above 14 kcfs per bay.

Implementation of Flip-lip Spillway Design

The demonstrated success of spill deflectors in reducing levels of gas saturation has led to installation of these devices at several Corps dams, and a call by NMFS/NOAA for improved devices at Ice Harbor and John Day dams. Additional information on installation at specific projects is provided in Appendix A. Only Lower Granite Dam is fully equipped with flip-lip spillbays across the spillway. Four of the eight Corps projects in the Snake River and lower Columbia River, namely Little Goose, Lower Monumental, McNary and Bonneville dams are partially equipped with spill deflectors. They are being planned for installation at Ice Harbor in 1997 and John Day in1998 (NMFS/NOAA, 1995; Bruce, 1995; Fishery Agencies and Tribes, 1993). (See Appendix A.)

Effectiveness of Spill

In evaluating the effectiveness of various passage routes for juvenile salmon migrating downstream, reference to Figure 2 is useful for explaining several terms that will appear later in the text. Fish passage efficiency (FPE), or simply fish passage, is the percentage of total fish approaching a project that are passed by routes other than the turbines. Fish guidance efficiency (fish guidance efficiency) is the percentage of fish approaching a turbine intake that are successfully diverted, usually by screens, into a bypass system. Similarly, spill effectiveness and effectiveness of the ice and trash sluiceways are evaluated in terms of the percentages of total fish that are diverted into spill or the sluiceways. Thus, fish passage efficiency is the total of fish guidance efficiency added to spill effectiveness and effectiveness of the ice and trash sluiceways. In other words, fish passage, as the term is used, includes all the fish except those that continue their passage through the turbines. In each route, there may be associated injury or mortality of fish. An additional standard of fish survival is therefore applied to those fish that are successfully passed away from the turbines by each route, i.e. survival in the bypass system, survival in spill, and survival in the ice and trash sluiceway.

In the 1980's, studies of spill effectiveness were done that used hydroacoustic technology at each of the mid-Columbia projects. These studies revealed that the relationship between the percentage of juvenile salmon passed in spill and the spill volume relative to total river flow is complex and varies from project to project (Raemhild, et al. 1984; Biosonics, 1983A; Biosonics 1983D; Biosonics 1984). For the studies, spill percentage relative to river flow was maintained for a week at each of four levels: 20, 40, 60 and 80 percent (85 percent at one project). Curves were developed that described the relationship for each project. As an example of the non-linear relationship often found, at Wanapum Dam in the spring of 1983, night-time spill of 20 percent of the instantaneous flow passed on the average about 45 percent of the fish, while spill of 50 percent passed 60 percent of the fish (Biosonics, 1983 D). On the other hand, at Rocky Reach Dam during the spring of 1983, night-time spill that amounted to 20 percent of the instantaneous river flow was estimated to pass about 16 percent of the fish. Spill of 50 percent passed about 30 percent of the fish, and spill of 80 percent passed about 55 percent of the fish (Biosonics, 1984).

Experience in 1995 at Priest Rapids and Wanapum Dams showed that spreading the spill of a given total volume of water (a certain number of acre feet) over a 24 hour period doubled the percentage of fish passed in spill, as compared to spilling the same volume over a 12 hour period at night. These two situations might have been expected to pass the same percentage of fish or less, given the volume for volume comparison. In fact, at Priest Rapids Dam in 1995, 17 percent spill for 24 hours for 60 days during the summer achieved 62 percent fish passage. Whereas in the summer of 1994, spill of 40 percent for 12 hours per night for 34 nights only achieved an estimated 33 percent fish passage (Hammond, 1995).

As for the Corps projects, in the late 1970’s NMFS/NOAA investigators were seeking ways to increase the passage rate of juvenile salmon over the spillways (Giorgi and Stevenson, 1995). Spill effectiveness has been studied, using hydroacoustic technology, at John Day Dam annually since 1983 (Magne, et al., 1987A, 1987B; Kuehl, 1986; Johnson and Wright, 1987; McFadden and Hedgepeth, 1990; Ouellete, 1988; all as summarized by Giorgi and Stevenson, 1995). Magne, et al. (1987) focused on developing an overall ratio of percentage fish passage to percentage spill for a range of values from 37 to 66 percent spill, for the spring and summer seasons. They found spill effectiveness ratios of 1.3 in 1987, 1.4 in 1989, and 1.1 in summer, 1988. Analysis of the spring observations is hampered by a paucity of observations at spill levels other than around 50 percent. Only three observations were below 45 percent spill (four counting the intercept). This leads to caution in drawing inferences. Although our analysis suggests there is a difference between spring and summer, we believe it best to combine the data for both seasons until a wider range of spill values may be available. The relationship then falls short of 1.0. The combined data would estimate 50 percent fish passage in 60 percent spill at John Day Dam. Obviously, spill effectiveness must improve at some spill level beyond the observations, since 100 percent spill must include 100 percent of the fish.

Willis (1982), using marked coho, estimated effectiveness of the ice and trash sluiceway at The Dalles Dam in passing fish at various levels of spill from about 10 percent to about 60 percent of the river flow. He was able, using equations developed from regression analysis of the data, to calculate the percentage of fish that must pass through spill at given flow levels. These calculations revealed spill effectiveness estimates of about 30 percent fish passage at 10 percent spill, and 75 percent fish passage at 40 percent spill (Willis, 1982). This high effectiveness of spill and of the ice and trash sluiceway is not surprising, considering the configuration of The Dalles Dam. The dam's spillway is at right angles to the natural course of the river, the powerhouse is nearly parallel to the natural course of the river, and the sluiceway is at the downstream end of the powerhouse. (See Giorgi and Stevenson, 1995, Figure 11.)

Surface Spill

On the basis of a study at John Day Dam, Raymond and Sims (1980) suggested that surface spill would be more effective in passing fish than standard spill. The standard spill gates in the Columbia River projects are designed to open from the bottom of the spillbay, typically at depths near 50 feet; (47-58 feet below normal operating pool at John Day Dam, for example, according to Giorgi and Stevenson, (1995)). Raymond and Sims placed stop logs in the spillbay to create surface spill. They found that juvenile salmon passing through the bays with surface spill were as likely to pass in the day as at night. In comparison, samples of juvenile salmon from the turbine intakes, the ceilings of which were located at about the same depth as the bottoms of the unlogged spill bays, showed a strong peak at night. This finding suggested that juvenile salmon approaching the dam delayed sounding to the intakes until after dark, and that they more readily passed through surface spill. Giorgi and Stevenson (1995) observed that surface spill remains to be adequately evaluated at Corps projects. The Corps has begun studies on effectiveness of surface spill.

Some projects are fitted with sluiceway spill gates that open from the top. Wanapum and Priest Rapids dams are each equipped with one such gate that is located closest to the powerhouse in the array of spill gates, Figure 3. They are smaller spill bays, being designed for passage of debris rather than control of water elevation in the forebay. It was thought that spill at these sluiceways might be especially effective in passing juvenile salmon because of their proximity to the powerhouse, where flow is normally concentrated. Hydroacoustic evaluations confirmed this hypothesis, Table 5 (Ransom and Malone, 1990; McFadden, et al., 1992, Ransom, 1995).

Table 5. Sluiceway (Surface Spill) Effectiveness in Passing Fish.

Project	Season	% Fish Passed	% River Flow Spilled	Spill Duration
Priest Rapids	Spring	3.0%	1.3%	12h (night)
		1.6%	0.3%	24h
	Summer	4%	2%	12h (night)
		2.1%	0.6%	24h
Spill in the sluiceway was judged to be twice as effective as spill in the spillway.				
Wanapum Dam				
	Spring	4%	0.5%	24h

The spillway at Rock Island Dam is equipped with several gates that open from below, but at a depth of about 35 feet, as compared to another set of gates that opens from a depth of about 55 feet. There, when spill was split 50:50 between deep and shallow spill gates, the shallow spill gates passed 87 percent of the fish passing in spill (Ransom, et al., 1988).

Figure 3. Cross sectional diagrams of the Wanapum Dam sluiceway and spillway. The spillway diagram shows the "tainter" gate which opens from the bottom upward to control the flow of water. Both are equipped with such gates. (Modified from Ransom and Malone, 1990)

Effectiveness of Surface Spill

Current thinking is that these sluiceways at Wanapum and Priest Rapids dams are more effective than the standard spill gates, not simply because they are located closest to the powerhouse, but because they operate in the upper portion of the water column where the fish prefer to be. Accordingly, Grant County Public Utility District modified a standard spill gate at Wanapum Dam in 1996 to evaluate surface spill. Tests will also be conducted in 1996 at The Dalles, and Lower Granite dams to determine whether an overflow weir improves passage at the spillway and to determine at what location and under what conditions an overflow weir will operate most efficiently at those projects.

Implementation of Spill as a Means of Smolt Bypass

The following discussion is an overview of spill as a measure implemented for passage of juvenile salmon at projects in the mainstem Columbia and Snake rivers. More detail is provided in Appendix A about requirements by FERC, the NPPC and NMFS/NOAA for spill and other bypass measures. Appendix B then provides an analysis of the effectiveness of the bypass measures, including spill, in achieving the goals for fish passage and other goals established by those agencies, using the 1995 experience as an example.

As a result of increased storage from river development, high flows previously experienced in the spring during the peak of outmigration of juvenile salmon were reduced in the late 1970's. This decreased spill, which forced a higher percentage of the fish to pass through the turbines. One early consequence was a complaint filed before the FERC in 1976 by the State of Washington Department of Fisheries, later joined by the Oregon Department of Fish and Wildlife, certain Columbia River Treaty Tribes, and the United States National Marine Fisheries Service against the three mid-Columbia Public Utility Districts. A contributing factor to the complaint was a low flow of 36 kcfs between April 9-11, 1996. The Washington Public Power Supply System requested this flow to test water intake structures at Hanford (Carlson and Dell, 1989). This low flow caused a kill of chinook in the Hanford Reach. The complaint requested provision of minimum flows for fish at the five projects operated by the public utility district’s in the mid-Columbia reach, (FERC mid-Columbia Proceeding, Docket # E-9569).

The primary objective of the petition was to stabilize flows for spawning fall chinook in the Hanford Reach below Priest Rapids Dam, and especially to establish minimum flows to prevent exposure of redds. The result was a more far-reaching settlement agreement that the parties reached in October 1979. This agreement consisted of two parts. One, the Vernita Settlement Agreement called for a four-year study of chinook spawning at Vernita Bar. Two, the mid-Columbia Settlement Agreement provided for studies over a five-year period to find ways to measure the effects of the projects on the downstream migration of juvenile salmonids in the mid-Columbia reach and to find ways to improve production of salmonids (Settlement Agreement of 1979, FERC Docket No. E-9569). As an interim measure, the agreement provided for spill of 10 percent of the river flow at each of the projects during the period in the spring when the middle 80 percent of the migrating juvenile salmon were determined to be present. This spill program, which began in the spring of 1980, was the first formal application of spill as a bypass measure for juvenile salmon in the Columbia Basin. Spill continues to be the primary method for bypass of juvenile salmon at four of the mid-Columbia projects. Wells Dam, the fifth dam and the one exception, is equipped with a mechanical bypass system, which will be described below.

In 1994, the FERC ordered Grant County Public Utility District to provide sufficient spill at Wanapum and Priest Rapids dams to pass 70 percent of outmigrating juvenile salmon during 80 percent of the migration in the spring and 50 percent during 80 percent of the migration in the summer (FERC Docket No. E-9569-003, Grant County Phase. Order of May 24, 1994). Those spill levels are to be interim measures pending installation of mechanical bypass systems or a contrary order of the Commission. Production of gas supersaturation by these spill amounts has prevented full implementation of the order. Consequently, spill of 17 percent was provided in spring and 14 percent in summer in 1994. These amounts provided passage for an estimated 50 percent of the fish in spring and 25 percent in summer at Wanapum Dam in 1994, while at Priest Rapids Dam 50 percent were passed in the spring and 62 percent in the summer (Hammond, 1994). More details are provided in Appendix B.

In 1989, pursuant to a measure in the NPPC's Fish and Wildlife Program of 1984, the fishery agencies, tribes, and BPA reached a memorandum of agreement on spill at federal projects. This agreement established the amount of spill to be used in spring and summer as an interim measure at Lower Monumental, Ice Harbor, The Dalles, and John Day dams, pending the development of solutions to fish passage problems (FPC, 1990). However, this agreement has been superseded by requirements of the NMFS/NOAA Biological Opinion for endangered Snake River salmon, which requires a standard of 80 percent fish passage during time periods set for spring and summer migrants (NMFS/NOAA, 1995B). At the Corps projects, implementation of this standard is complicated, because the bypass facilities' effectiveness in providing fish passage varies. This variation depends on a number of factors, but is less than the 80 percent standard for some species at all projects and for all species at some projects. Spill amounts are to be provided to make up the difference up to the 80 percent passage standard. More information on this subject appears below and in Appendix B, which is an analysis of attempts to achieve the goals in practice during 1995.

MECHANICAL BYPASS SYSTEMS

Introduction

Early studies of mortality in turbines stimulated studies of juvenile salmon behavior. Biologists sought to find a clue that might lead to directing juveniles away from the intakes (Summarized to 1960 by Andrew and Geen, 1960: Examples are Brett and MacKinnon, 1953; Brett, 1957; Brett and Alderdice, 1958; also Collins and Elling, 1964). They investigated batteries of lights, bubble curtains, electric fields, and sound, among other things. None of these methods was found to be sufficiently effective in directing fish movements to justify full-scale or prototype field testing for application at large hydroelectric projects (Ebel, 1981; Mighetto and Ebel, 1995; Office of Technology Assessment, 1995). More information on these is provided below.

Improved Turbine Efficiency

The studies summarized above show higher fish passage survival when turbine efficiency is higher. In addition, damage to machinery is minimized at high efficiencies. These two factors provide incentives to operate the machines in the region of their highest efficiency. Furthermore, improvements have been made in the design of turbines to increase their efficiency, and these have been fitted at a number of projects as replacement is required. One example is Wells Dam where installation began in 1987 and was completed in 1990 (personal communication Ken Pflueger, Douglas County Public Utility District). At Rocky Reach Dam, planning for installation of such improved turbines began in 1993, and is under way in 1995 with a schedule for completion in the year 2001 (personal communication Bill Christman, Chelan County Public Utility District). At Rocky Reach Dam the schedule for installation of new runners was expedited and improvements were included that incorporated designs based on studies of juvenile salmon mortality in the turbines. The studies indicated such changes might improve fish survival by 1.7 percent)(RMC Environmental Services and Skalski, 1993). Ledgerwood, et al. (1994) measured mortality of juvenile salmon that passed through turbines at Bonneville’s second powerhouse. Their mortality estimates of 2.3 percent were lower than most elsewhere (Ledgerwood, et al., 1993). They suggested that the lower estimates were due to higher efficiency of the turbines at that project and a deeper submergence of the blades. However, their conclusion needs to be considered in the context of our previous discussion indicating that many of the estimates of mortality in turbines include mortality that occurs in the tailrace or below. The Corps is working to develop an advanced turbine design aimed at improving efficiency and reducing smolt mortality (Office of Technology Assessment, 1995).

Turbine Intake as a Passage Route

Free wheeling, or locking of the runners of turbines was investigated at Rocky Reach Dam as a possible means of passing juvenile fish without harm (Stone and Webster, 1982). It was concluded that this would not prevent pressure changes in the scroll case, which would lead to cavitation and injuries caused by fish strikes in transit.

Division Barriers Upstream of the Powerhouse

Prior to the construction of Hells Canyon Dam in 1967 and following construction of Brownlee Dam in 1958, it was found that juvenile salmon experienced great difficulty in passing through the reservoir above Brownlee Dam (Graban, 1964; Haas, 1965). As a consequence of the high storage volume relative to inflow and outflow, water velocities were judged to be too low to stimulate movement of the juvenile salmon. An additional difficulty was that the turbine intakes were located at depths of over 200 feet, too deep for surface oriented juvenile salmon to readily use for passage. This difficulty was well documented elsewhere, as noted by Eicher (1988). A barrier net was placed in the reservoir above Brownlee Dam. The net extended completely across the river at a point 4800 feet upstream of the dam and reached to a depth of 120 feet. The barrier was equipped with a walkway to provide access to three inclined-plane fish traps located at the surface along its length. Each of the traps was equipped with a pump to provide appropriate flow to attract juvenile salmon. (See "gulpers" described below.) The equipment was difficult to keep in place because of adverse weather and accumulation of debris. Furthermore, efficiency of the net in guiding fish was poor as fish passed through or under it. The idea was abandoned (Mighetto and Ebel, 1995). The problem became moot when Hells Canyon Dam was built in 1967 and provisions for adult passage there failed (Petersen, 1995).

At Wanapum Dam, a barrier net 12,000 feet long and 40 feet deep was tested. The net extended laterally from a point on the left bank upstream of the powerhouse across the powerhouse to a point 800 feet west of the powerhouse, leading toward the spillway. In this case, the intention was to lead fish away from the turbine intakes toward the spillway (Tyler and Pock, 1989). However, many problems had to be overcome. Strong currents required heavy anchoring systems. Accumulation of debris required deployment of the net with its cork line below the surface. Regular cleaning was needed because of accumulation of periphyton. In addition, the net only briefly affected migration of juvenile salmon that encountered it. After three years, further testing was abandoned when it was concluded that the net was not effective at diverting juvenile salmon away from the powerhouse.

In 1989, a "forebay wedge screen" was tested at Priest Rapids Dam (Ransom and Malone, 1989). It consisted of a wedge wire barrier mounted on a framework in the forebay in front of turbine unit 9. Although it diverted some juvenile salmon, counts of fish in the gatewells were about 10 percent of those in adjacent gatewells, the frame was difficult to handle, and periphyton accumulation led to unacceptable head loss. Further tests were abandoned.

Fish “Gulpers”

While the barrier net concept has used nets stretched across the migration path, a related concept has been employed, based on the idea that migrating fish could be attracted or directed to a collection device without completely blocking their path. In some of these, pumps were used to create attraction flows for outmigrants that brought the fish into an enclosure of some kind (e.g. “Merwin” Trap). Such devices were tested at Pelton Dam on the Deschutes River, Mud Mountain Dam, and Merwin Dam on the Lewis River (Stockley, 1959; see DeHart, 1987). A device with much higher attraction flows was used with some success at Green Peter Dam on the Middle Fork Santiam River, Oregon, where the device is built into the upstream face of the dam (Wagner and Ingram, 1973). At Baker Lake, Washington, a surface collection device of this type was found to be effective at collecting sockeye juvenile salmon for transportation below the powerhouse (Wayne, 1961; Quistorff, 1966). It became a viable solution to the problem of collecting juvenile salmon in the reservoir when a lead net was added to the “gulper” (Cary Feldmann, Puget Sound Power and Light, personal communication).

Gatewell Salvage

It was early observed that juvenile salmon accumulate in turbine intake gatewell slots, a result of their tendency to pass through the intakes near the ceiling (First observed by C.W. Long, and G. Schneider, according to Mighetto and Ebel, 1995). Bentley and Raymond (1969) describe the use of a dip basket for salvage of juvenile salmonids from gatewells at dams in the Columbia River.

A fish salvage operation was undertaken at John Day Dam in 1977, in anticipation of low flows that were expected to lead to accumulation of fish in the gatewells (Johnsen, 1978). The numbers removed from the gatewells were disappointingly low, about 21,000 juvenile salmonids, mostly chinook yearlings.

On the other hand, marked juveniles that were released in the Wanapum reservoir were recovered downstream in the gatewells at Priest Rapids Dam at the rate of 5 percent for coho, 2.1 percent for chinook yearlings and 3.6 percent for steelhead (CH$_2$M Hill and Wash. Dept. Fish., 1980). During the initial five years of the mid-Columbia Settlement Agreement, the gatewells at Wanapum and Priest Rapids dams were emptied regularly and enumerated to obtain an index of fish passage. Following the Stipulation of 1985, Grant County Public Utility District has salvaged fish from the gatewells at Wanapum and Priest Rapids dams on a daily basis during the outmigration, weather permitting. Specially designed nets deployed by mobile cranes from the deck of the powerhouse are used to remove fish that have accumulated. Captured fish are placed into tank trucks and transported to below the dam where they are released into the tailrace. In the neighborhood of 150,000 to 200,000 fish are salvaged at each of the two projects each year in the spring and an additional 30,000 to 50,000 in the summer (personal communication Stuart Hammond, Grant County Public Utility District No.2).

Airlift

A gatewell airlift system was tested at McNary Dam in 1981. This test was part of a study of a proposed intake screen configuration at John Day Dam. While the airlift did not affect the guidance of fish, the turbulence it created in the gatewell made it difficult for the fish to exit through the orifices which led to unacceptably low orifice passage efficiency (Swan, et al., 1982; Krcma, et al. 1983). An airlift installed at John Day Dam is now used to sample fish diverted into the gatewell by intake screens (Brege, et al., 1990; Wood, 1993).

At Rocky Reach Dam, in 1980, an airlift was investigated as a means of drawing fish out of the gatewells. It was concluded that the airlift was not effective in drawing a significant number of fish up the gatewell, although it could be used to remove some fish from the gatewell (CH$_2$M Hill, 1982).

Gatewell Conduit

When the second powerhouse at Rock Island Dam went into service in 1979 it included, as a provision for juvenile fish passage, orifices between the gatewells and a conduit leading from there to the tailrace. It also included a feature allowing for diversion of a portion of the fish thus collected, into a sampling facility (Olson, 1981, 1982). The effectiveness of the system in diverting fish from the turbine intakes was found to vary among species and from year to year. Effectiveness depended upon levels of spill relative to river flow, and ranged around 5 to 15 percent. Effectiveness was higher in years with low spill, as might be expected.

Other

The Office of Technology Assessment (1995) refers to these as “Alternative Behavioral Guidance Devices.” They concluded that for the most part, these devices have not been accepted by the resource agencies because they have not been shown to divert a high enough percentage of the fish (Office of Technology Assessment, 1995 p. 87). Stone and Webster (1987) concluded that, up to the time of their review for EPRI, such devices had not offered much promise of meeting agency goals.

Nevertheless, from time to time, there is a revival of interest in these methods. Investigators either have a new perspective on the method (e.g. Carlson, 1995) or are unaware that it has been tried. Some of these methods have met with varying degrees of success for other species in different applications, such as at pump intake diversions or irrigation diversions (Office of Technology Assessment, 1995).

As mentioned previously, in the 1950s and 1960s the Fish Passage Program of the then Bureau of Commercial Fisheries (now NMFS/NOAA), under the direction of Gerald B. Collins, investigated a number of potential methods for their efficacy in directing movements of fish. These methods included banks of lights, bubble curtains, sound, and electric fields, none of which proved to be practical for application in the field (Mighetto and Ebel, 1995). Andrew and Geen (1960) reviewed the studies beyond those of the Bureau of Commercial Fisheries and came to the same conclusion. Some other pertinent studies are summarized below.

Electric Fields

Effectiveness of electrical barriers at power plant intakes has been generally poor (Stone and Webster, 1987). Collins and his colleagues found that successful application of this technology would be limited to situations where velocity of flow was less than 1 fps (summarized by Mighetto and Ebel, 1995). This would represent a serious limitation at the turbine intakes in the Columbia Basin. For example, Odgaard, et al. (1990) determined that the approach velocity measured immediately upstream from the intake screen at Wanapum and Priest Rapids dams was on the order of 1.1-1.2 m/s. (3.6-3.9 fps). There are other serious drawbacks with the application of electricity. Electric fields are potentially dangerous to other fish that may be present. Susceptibility to dangerous shock is a function of fish size. Adult fish are more vulnerable than juveniles (Office of Technology Assessment, 1995).

Sound

Recently, Carlson (1994) reviewed the extensive literature base regarding studies that have been conducted to direct fish by means of sound. He concluded that sound deterrence for salmonids is possible only at short ranges using very low frequencies. Significant challenges remain in the possible application of sound to address problems of systems intended to modify fish behavior. Dolat, et al. (1995) reported success in using sound to divert a portion of the juvenile salmon that approached the intake of an irrigation diversion at Dryden Dam on the Wenatchee River. Although a clear effect of sound was established, it was not as effective as the screen that is in place (Mueller, et al., 1995).

Light

Mighetto and Ebel (1995) report that Paul Fields was able, using lights, to divert juvenile salmon away from the turbine intakes and toward the spillway, but was unable to sustain that response over a 24 hour period. Fields (e.g. 1966) developed a large body of information on the effects of light on migration of salmonids, most of which fits the summary in the previous sentence.

In 1986, strobe lights mounted on the trash racks in the turbine intakes were investigated at Rocky Reach Dam as a possible means of guiding fish away from the intakes, (Hays and Truscott, 1986). Although the lights affected the vertical distribution of juvenile salmon entering the gatewell, it was concluded that there was no way to use them effectively to assist fish in avoiding the intake. Mercury vapor lights attached to the frame of a guidance device at Bonneville Dam in tests over several years did not significantly increase guidance or decrease descaling of subyearling chinook (Gessel,, et al., 1990).

Louvers

Angled louvers have been used effectively at pump intakes and irrigation diversions to divert juvenile salmon and other small fish into alternate channels (Stone and Webster, 1986; Office of Technology Assessment, 1995). Louvers have been widely applied in the Sacramento River system as fish protection devices (Stone and Webster, 1986). They are considered to be standard technologies for turbine intakes in the Northeast but not in the Northwest (Office of Technology Assessment, 1995). The difference is apparently due to the high water volumes and velocities present in Northwest river applications. In the Columbia Basin, the primary application has been at irrigation diversions in conjunction with screens. Collins' group found that louvers would only be effective in diverting a high enough percentage of juvenile salmon in situations where flows were carefully regulated at low levels and floating debris was sparse (summarized in Mighetto and Ebel, 1995). At Sullivan Dam on the Willamette River, louvers, made of modified trash racks, guide fish from intakes at units 1 through 12 into the intake for unit 13 where an inclined screen diverts them away from the turbines (Stone and Webster, 1986). Best estimates of effectiveness ranged from about 40 percent for subyearling chinook to 80 percent for yearling chinook approaching the project (Clark and Cramer, 1977, as cited in Stone and Webster, 1986).

Vertical louvers were located behind each screen panel at the Dryden Reclamation District Canal on the Wenatchee River. This was done to facilitate the workings of the screens and to balance the flow across the set of screen panels. This effort was not completely successful in balancing the flow (Mueller, et al., 1995).

Turbine Intake Screens

Submerged Traveling Screens (STS)

In the early 1960’s, studies by Bureau of Commercial Fisheries investigators showed that juvenile salmon tended to be concentrated near the ceiling of the turbine intakes, and a portion of them were drawn above into the gatewells (Long, 1968). This led to the idea that fish might be screened or deflected from the upper portion of the intake, with minimal effect on the generating capacity of the unit. The concept was first tested at model facilities at Washington State University. These initial studies, conducted under the aegis of the Bureau of Commercial Fisheries, also identified optimum screen porosities and deflection angles to minimize impingement of fish on the screen. The model studies led to predictions of a unit head loss of less than 10 percent resulting from placement of the screen at the intake, which was deemed acceptable. A cleaning mechanism was recommended in order to avoid violation of the operating criteria (Mueller and Osborn, 1969). The first test of a prototype device in the field took place in 1969 and 1970 at Ice Harbor Dam on the lower Snake River (Long, et al., 1970). The first design incorporated a traveling screen as a self-cleaning feature. Consequently, the device was named the submerged traveling screen (STS). Mighetto and Ebel (1995) summarized the decades of work by the Bureau (later NMFS/NOAA) and the Corps to develop a satisfactory intake screen, Figure 4.

Figure 4. Cross sectional diagram showing the locations of the turbine intake screen, a bank of fyke nets behind the screen and across the entrance to the turbine intake to capture fish not guided, and the gatewell area above the screen. Guided fish are restrained from other exits to the gatewell by the vertical barrier screen. Fish may exit the gatewell by way of a submerged orifice into the juvenile bypass flume. Diagram of configuration used at Little Goose Dam to measure FGE of prototype intake screens. Fyke nets are not present in completed installations. (Source: Gessel et al, 1995.)

The first screen tested in prototype was approximately 24 feet in length, which corresponded with dimensions in the model, and could be deployed at angles of 45 to 60 degrees (Marquett, et al., 1970). It was tested at Ice Harbor Dam in 1969 and 1970. These tests showed that by using the screen the relative number of juvenile salmon in the gatewell could be increased by a factor of three. Later, to refine an estimate of the fish guidance efficiency of the screen, i.e. the percentage of fish entering the turbine intake that are guided by the screen, an array of fyke nets was placed below the screen in the intake to capture fish not guided by the screens. Guided fish were removed from the gatewell and counted, which made it possible to estimate fish guidance efficiency. Over the next several years, devices were also tested at Little Goose and Lower Granite dams, and improvements were made in the design. Details are to be found in Ebel, et al. (1974) and Park, et al. (1977). Addition of a porosity plate behind the screen reduced impingement of fish to acceptable levels. Perforated steel panels, referred to as a vertical barrier screen (VBS), split the gatewell. These panels distributed the flow upward and discouraged fish from sounding out of the gatewell and back into the intake.

Fixed Bar Screens

In the mid-1970s planning for addition of a second powerhouse at Bonneville Dam led to testing of an intake screen at that project (Ruehle, et al., 1978). Experience with the traveling screens showed that they were costly to build and maintain. These Bonneville intake screen tests used a fixed screen concept that would be less complex and less costly. It was five feet wide and extended across the full width of one intake slot. Results were promising and led to testing of a full-scale device at McNary Dam in 1978 that had somewhat different features (Krcma, et al., 1978). Rather than flat steel bars used in the test at Bonneville, the McNary test used smooth steel bars, triangular in cross section (wedge wire). Cleaning could be accomplished by periodically raising the angle of the screen to create a backflush through the mesh. Results were favorable (Ruehle, et al., 1978; Krcma, et al., 1980). Tests of a bar screen design in prototype at Priest Rapids and Wanapum dams later confirmed the favorable results of the NMFS/NOAA test of the bar screen design at Bonneville and McNary dams (mid-Columbia Coordinating Committee, 1988). On the other hand, problems with accumulation of trash in tests of bar screens at the Bonneville second powerhouse led to a recommendation initially to proceed with traveling screens there and at other Corps projects (Gessel, et al., 1991).

Extended-length Screens

Initial tests in 1983 of a submerged traveling screen at Bonneville Dam’s second powerhouse showed surprisingly poor effectiveness in guiding fish, with fish guidance efficiency less than 25 percent for chinook and coho. It was also observed that effectiveness of the intake screens at the first powerhouse had declined substantially since tests in 1981, from about 75 percent for yearling and subyearling chinook to about 20 percent in 1983 (Krcma, et al., 1982; Krcma, et al., 1994). The probable cause was modification of the navigation lock during construction of the second powerhouse, which involved removal of part of Bradford Island (Gessel, et al., 1991). Efforts were thus directed at improving fish guidance (Gessel, et al., 1992). In 1994, a frame with bar screen was attached to the trash rack in a position where it would simulate an extension of the submerged traveling screen - an extended screen. Fish guidance efficiency was improved.

Similarly, at Lower Granite Dam, initial tests in 1982 of the submerged traveling screen indicated poor effectiveness (about 50 percent) in guiding yearling chinook. From 1984 to 1989, NMFS investigators sought ways to increase fish guidance efficiency (Swan, et al., 1992). A fixed bar screen was tested in conjunction with a standard submerged traveling screen in a configuration that simulated an extended screen, 40 feet in length compared to the standard screen of 24 feet. With extended screens, significant increases in fish guidance efficiency were measured, 66 percent for yearling chinook compared to 57 percent with the standard submerged traveling screen, and 83 percent for steelhead compared to 77 percent with a standard submerged traveling screen (Swan, et al., 1990). See Table 6.

Encouraging results at Lower Granite Dam led to the design of two types of prototype extended-length screens, a bar screen and a submerged traveling screen that were tested at McNary Dam from 1991 to 1994. The results of the simulated extended screen tests were not directly transferable to the design of the new units due to differences in hydraulic characteristics as shown by model studies. Appropriate modifications were made (Swan, et al., 1990). Tests of full extended screens were also initiated at The Dalles and Little Goose Dams in 1993 (Gessel, et al., 1994). At McNary Dam extended length screens, either bar screens or submerged traveling screens have produced estimates of fish guidance efficiency of over 80 percent for yearling chinook (81 percent for the extended bar screen and 88 percent for the extended submerged traveling screen), Table 6 (McComas, et al., 1993). For sub yearling chinook, fish guidance efficiency of 67 percent was measured with the extended submerged traveling screen and 52 percent with the extended bar screen.

At Little Goose Dam, tests of the full prototype in 1993 and 1994 brought fish guidance efficiencies of greater than 80 and 77 percent for yearling chinook, Table 6 (Gessel, et al., 1994, 1995). For steelhead, fish guidance efficiency averaged 90 percent in the best configuration. No significant increases in descaling were observed for the extended screen at Little Goose Dam in comparisons with a standard submerged traveling screen (Gessel, et al., 1994, 1995).

Recently, a question was raised as to whether these measurements of fish guidance efficiency for the extended screens may not be directly comparable to the measurements for the standard screens (personal communication with James Ceballos, NMFS/NOAA, Portland, Oregon). Because the measurements for the extended screens were made with the array of fyke nets in the bulkhead slot rather than in the gatewell slot upstream, it is thought that the estimates of fish guidance efficiency for the extended screens may be on the high side. This question is currently being evaluated.

Effectiveness of Fish Bypass Systems: Fish Guidance Efficiency, Mortality, Descaling, and Stress

Introduction

As noted previously, the primary criterion in evaluating the effectiveness of mechanical bypass systems is their fish guidance efficiency (FGE), i.e. the percentage of fish approaching the powerhouse that are diverted from the turbine intakes into the system. In the case of turbine intake screens, impingement and injury of diverted fish are problems that have had to be addressed by manipulations of screen openings, angle of deployment of the screen, velocity at the screen and other factors.

Fish Guidance Efficiency (FGE)

Estimates of fish guidance efficiency are variable from one test to another. Estimates differ with respect to the project, design and configuration of the apparatus, fish species, degree of smoltification, time of day (particularly day versus night), and progress of the season (Swan, et al. 1983; Swan, et al., 1985; Swan, et al., 1986; Swan, et al., 1987; Swan and Norman, 1987; Giorgi, et al., 1988; Hays and Truscott, 1986; Peven, 1995; Peven and Keesee, 1992). Information on fish guidance efficiency included in Table 6 must be interpreted in that context. Because fish guidance efficiency estimates have improved due to modifications of the screens, we have attempted to provide in Table 6 the most recent applicable estimates of fish guidance efficiency for a given project. Older information is provided in some cases for comparison.

An example of the variability of fish guidance efficiency measurements was mentioned above, with respect to studies at Bonneville Dam, where installation of an approach channel for a new navigation lock brought about a reduction in fish guidance efficiency measured at the first powerhouse (Krcma, et al., 1984; Gessel, et al., 1991). Modifications to the screen and its deployment brought fish guidance efficiency up to 26 to 44 percent for yearlings and 20 to 32 percent for subyearlings (Krcma, et al., 1984). At the second powerhouse, fish guidance efficiency was poor at the outset, less than 25 percent for yearling and subyearling chinook (Gessel, et al., 1993). Modifications of the apparatus and extensions of the turbine intakes into the forebay brought improvements by 1986 to around 60 percent for chinook yearlings, 55 percent for subyearlings, and 46 percent for steelhead (Gessel, et al., 1991). Further tests were conducted each year through 1989. Best observed fish guidance efficiency was 78 percent for chinook yearlings and coho, 69 percent for steelhead, and 25 percent for subyearling chinook (Gessel, et al., 1991). On the basis of these studies, a new configuration was recommended for full installation across the second powerhouse. (Gessel, et al., 1993).

In most cases, the fish guidance efficiency measured applies to a prototype tested at the project in a series of tests over one or more seasons. The estimates given in Table 6 are projections for the particular project based on a series of samples. Ordinarily, the sample is taken from one of three intake slots at a sample turbine, where fish that are not guided are captured for counting in fyke nets in the intake behind the screen. Guided fish rise in the gatewell where they are removed and counted. In many instances, the samples came from one slot where the adjacent slots were not equipped with screens. Studies at Wanapum Dam verified that although flow patterns were affected by screens in the adjacent slots, the resulting fish guidance efficiency measurements showed little or no effect (mid-Columbia Coordinating Committee, 1995). Since 1995, with the ESA listing of Snake River stocks, hydroacoustic methods have been employed for measurement of fish guidance efficiency at the Snake River and lower Columbia River dams, rather than fyke nets.

In summary, estimated fish guidance efficiency in presently installed systems or prototype extended-length screens tested and scheduled for installation range from 26 percent (Bonneville I) to 88 percent for yearling chinook, with most (6 of 11) in the range of 65 to 80 percent. For steelhead, fish guidance efficiency ranges from 76 to 93 percent, with most (6 of 8) above 80 percent. For the two studies that were able to include coho, fish guidance efficiency estimates were 93 and 98 percent. For sockeye fish guidance efficiency ranged from 14 to 73 percent in 6 studies, with only 1 estimate above 53 percent.[4] Wells Dam in the mid-Columbia reach is the only project in the basin with a bypass system for juvenile salmon that can achieve the fish passage goals established by FERC, the NPPC and NMFS/NOAA. (Although the NMFS/NOAA goals do not apply in the mid-Columbia reach.)

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[4] These ranges include measurements for extended length screens which, as mentioned earlier in the text have come under question. (James Ceballos, NMFS, Portland, Oregon, personal communication)

TABLE 6. FISH GUIDANCE EFFICIENCY MEASURED AT COLUMBIA BASIN PROJECTS. MOST RECENT DATA.* Because over the years improvements have been made in configurations of screens at the projects, early measurements are mostly of historic interest and do not apply to the existing bypass systems. Some historic information from Bonneville Dam is provided as an example, showing improvement in fish guidance efficiency as turbine intake extensions were provided and flows around the screen were modified in other ways. (Sources: Cited in the table. Data for Wanapum and Priest Rapids dams from personal communication Stuart Hammond, Grant County Public Utility District No 2, Ephrata, Washington. Data for Rocky Reach and Rock Island, from personal communication Charles Peven, Chelan County Public Utility District No. 1, Wenatchee, Washington)

PROJECT	**FGE**	**NOTES**
MID-COLUMBIA PROJECTS		
Wells (Fully equipped)	89%	Skalski, (1993). Spring and Summer. Surface attraction device. Hydroacoustic estimate provides no species separation.
Rocky Reach	30.8%	Combined species. Highest achieved for yearling chinook 38.9%; for subyearling chinook 21.9%; for steelhead 40.2%; and sockeye 24.1%. None of the prototype screens tested 1985-1992 and 1994 met criteria. Surface collector device being evaluated, 1995.
Rock Island		
Second Powerhouse	n/a	Prototype screens tested at powerhouse no.2 determined to be unfeasible.
First Powerhouse (1994)	85.7%	Yearling chinook
	29.6%	Subyearling chinook during the spring outmigration
	63.7%	Subyearling Chinook during the summer
	60.9%	Steelhead
	64.4%	Sockeye
Wanapum	75%	Yearling chinook in 1992
	50%	Subyearling chinook in 1992
	26%	Sockeye, Hammond (1991)

Table 6. (Continued). Fish Guidance Efficiency Measured at Columbia Basin Projects. Most recent data.*

Priest Rapids	84%	Average for chinook yearlings
	52%	Average for sockeye,
	76-90%	Range for steelhead, Hammond (1991).
SNAKE RIVER PROJECTS		
Lower Granite		
(Standard STS)	57.3%	Yearling chinook (Swan, et al. 1990)
	77.3%	Steelhead (Swan, et al., 1990)
(Extended Screen - Simulated)		
	66%	Yearling chinook (Swan, et al., 1990)
	82.4%	Steelhead (Swan, et al., 1990)
Little Goose		
(Standard STS)	73%	Yearling chinook - with raised gate (Swan, et al., 1986)
(Extended Screen)	77.3%	Yearling chinook (Gessel, et al., 1995)
	89.6%	Steelhead (Gessel, et al., 1995)
Lower Monumental	69%	Yearling chinook (Gessel, et al., 1993)
	85.3%	Steelhead (Gessel, et al., 1993)
	35.2%	Subyearling chinook (Ledgerwood, et al., 1987)
Ice Harbor	78%	Yearling chinook (Brege, et al., 1988)
	92%	Steelhead (Brege, et al., 1988)
LOWER COLUMBIA RIVER PROJECTS		
McNary		
(Standard STS)	83%	Yearling chinook (Krcma, et al., 1982)
	76%	Steelhead (Krcma, et al., 1982)
	34-46%	Sub yearling chinook (Swan, et al., 1984)

Table 6. (Continued). Fish Guidance Efficiency Measured at Columbia Basin Projects. Most recent data.*

McNary (continued)		
(Extended STS)		
	88%	Yearling chinook (McComas, et al., 1994)
	67%	Sub yearling chinook (McComas, et al., 1994)
	93%	Steelhead (McComas, et al., 1994)
	73%	Sockeye (McComas, et al., 1994)
	98%	Coho (McComas, et al., 1994)
John Day	75%	Yearling chinook (Swan, et al., 1982) [Tests of John Day configuration conducted at McNary Dam]
	79%	Steelhead (Swan, et al., 1982. [Tests at McNary Dam]
	88%	Yearling chinook (Krcma, et al., 1983). [Tests at McNary Dam]
	87%	Steelhead (Krcma, et al., 1983) [Tests at McNary Dam]
	72%	Yearling chinook (Krcma, 1985; Brege, et al., 1992) [Test at John Day Dam]
	20%	Subyearling chinook (Krcma, 1985; Krcma, et al., 1986) [Test at John Day Dam]
	35%	Subyearling chinook (Brege, et al., 1987; Brege, et al. 1988)
	41%	Sockeye (Krcma, et al., 1986; Brege, et al., 1992)
	86%	Steelhead (Krcma, et al., 1986)
The Dalles		
Standard STS	44-56%	Yearling chinook (Krcma, 1985)
	71-80%	Steelhead (Krcma, 1985)
	40-60%	Sockeye (Monk, et al., 1987)

Table 6. (Continued). Fish Guidance Efficiency Measured at Columbia Basin Projects. Most recent data.*

The Dalles (continued)			
(Extended-length screens)			Scheduled for installation in 1998
		69%	Yearling chinook (Absolon, et al., 1995)
		54%	Subyearling chinook (Absolon, et al., 1995)
		83%	Steelhead (Brege, et al., 1994)
		53%	Sockeye (Brege, et al., 1994)
		93%	Coho (Brege, et al., 1994)
Bonneville			
Powerhouse number 1			
	(1981)	76%	Yearling chinook (Krcma, et al. 1982)
		72%	Subyearling chinook (Krcma, et al., 1982
	(1983) Measurements following modification of navigation channel		
		21%	Yearling chinook (Krcma, et al., 1984)
		24%	Subyearling chinook (Krcma, et al., 1984)
		14%	Sockeye (Krcma, et al., 1984)
		34%	Steelhead (Krcma, et al., 1984)
	(1984)	26-44%	Yearling chinook (Krcma, et al., 1984B)
		20-32%	Subyearling chinook (Krcma, et al., 1984B)
Powerhouse number 2			
		32-46%	Yearling chinook (Monk, et al., 1992)
		11%	Subyearling chinook (Gessel, et al., 1989)
		4%	Subyearling chinook (Gessel, et al., 1990).
	Measurements following full installation of turbine intake extensions		
		36-57	Yearling chinook (Monk, et al., 1995)
		23-42	Subyearling chinook (Monk, et al., 1994)

Bonneville Dam is below criteria. The NPPC calls for shutdown of second powerhouse and provision of spill during smolt migration.

Conduit to the Tailrace

As the tests of intake screens proceeded with promising results, appropriate means were sought for encouraging movement of the fish upward in the gatewells, removing the guided fish from the gatewells on a mass scale, and providing an exit to the tailrace below the dam (Mighetto and Ebel, 1995). At Bonneville Dam's first powerhouse, orifices were cut from the gatewells to the ice and trash sluiceway to provide an exit for fish. A vertical barrier screen (VBS) was installed in the gatewell to create an upward flow that would encourage movement of the fish toward the orifices near the surface. A dewatering system was provided at the end of the sluiceway, where water was pumped back into the forebay in order to reduce the volume of water that entered a 20 inch conduit leading to the tailrace. At McNary Dam and other Corps projects, a separate bypass flume was constructed within the ice and trash sluiceway. Evaluations of effectiveness of the systems led to improvements in designs, (Krcma, et al., 1982; Krcma, et al., 1983; Krcma, et al., 1984; Krcma, et al., 1985; Krcma, et al., 1986; Swan, et al., 1982; Swan, et al., 1983; Swan and Krcma, 1986).

Once diverted into the gatewells, guided fish exit from there by way of orifices that lead into a conduit to the tailrace. Orifice passage efficiency (OPE) is a measure of the percentage of fish that leave the gatewell during a specified time period, normally 24 hours. Orifice passage efficiency of 70 percent is considered satisfactory (NRC, 1995, p. 191). Various opening sizes and locations have been investigated for their effects on orifice passage efficiency (Mighetto and Ebel, 1995; Liscom, 1971). At Wanapum Dam, two baffle systems in the gatewell were tested for their effects on orifice passage efficiency. The best system produced an orifice passage efficiency of near 90 percent (mid-Columbia Coordinating Committee, 1993).

Mortality and Descaling of Juvenile Salmon in Bypass Systems

Mortality and Descaling at the Screen

Another factor in evaluating the effectiveness of intake screens is mortality of fish caused by striking the screen or other objects in the bypass system. A percentage of the approaching fish may strike the screen in passing and lose some scales. Other fish, particularly small sub-yearling chinook, may become impinged on the screen. Impinged fish are observed when the screens are raised for inspection during prototype tests. The number of impinged and descaled fish are collected at the time of the tests and are useful in evaluating the performance of the prototypes. For our purposes, the pertinent numbers are the percentage of dead and descaled fish in the bypass system as a whole. This percentage reflects the effects of the screen after the final design is adopted. We did not attempt to provide a thorough review of available information on direct effects of the screens, because it is difficult to relate the results to the final design and installation. The direct effects would have been measured during prototype tests. However, we provide some examples in the following paragraphs.

Impingement rates of yearling chinook are negligible in properly tuned systems, but impingement of subyearling chinook may be "high" in prototypes (e.g. Peven, 1993).

At Lower Granite Dam, impingement that had ranged from 0.04 to 3 percent was reduced to less than 1 percent by design changes to the extended length screen that was tested in 1990 (Wik and Barila, 1990).

Descaling, caused by contact with the screen, may be observed with fish diverted into the gatewells during prototype tests. Descaling standards have been developed that set a threshold level of a percentage of missing scales (Koski, et al., 1986). Implications of descaling are not clear, because no direct relationship with survival has been established. As an example, descaling of guided fish at Lower Granite Dam during prototype testing was estimated to be 1.7 percent (Wik and Barila, 1990). No significant increase in descaling of guided fish at McNary Dam was observed with the extended screen (McComas, et al., 1993) compared to a standard submerged traveling screen that was used as a control.

Mortality of Juvenile Salmon in the Bypass System as a Whole

Performance of the bypass system as a whole (as far as the sampler) is monitored daily at those projects equipped with sampling systems in the bypasses. Dead fish are observed in the samples. These deaths may have occurred at any location within the bypass facility, from the screen to the sampler. At Little Goose Dam in the years from 1981 to 1993, average annual mortality of juvenile salmon observed in the facility ranged from 0.9 to 6.2 percent, for chinook, 0.1 to 0.8 percent for steelhead and 0.6 to 6.3 percent for sockeye; and at Lower Granite Dam from 0.3 to 1.2 percent for chinook, and 0.1 to 0.4 percent for steelhead (Koski, et al., 1989; FTOT, 1994). At Lower Granite Dam, studies of delayed mortality due to effects of passage through the entire bypass produced estimated losses of 7.6, 4.4 and 5.1 percent in 1984, 1985 and 1986 (Mathews, et al., 1987, as summarized by Chapman, et al., 1991). However, in the years 1989 to 1993, total facility mortality at McNary Dam ranged from 0.4 to 1.9 percent for chinook yearlings, from 1.2 to 5.0 percent for chinook sub-yearlings, from 0.2 to 1.5 percent for steelhead, and from 0.5 to 4.1 percent for sockeye (FTOT, 1994).

In addition to this monitoring of fish at the sampler, there have been estimates of mortality using marked fish. At McNary Dam in 1983, mortality of marked yearling chinook during passage from the gatewells to the bypass sampler ranged from 2 to 4 percent, depending upon the location of the gatewell (Park, et al., 1984).

Gilbreath, et al. (1992) state that in the first years of evaluation in the 1980s, the bypass facilities at both power houses at Bonneville Dam had a number of internal mechanical problems. The Corps subsequently corrected these problems. Thus, the present internal systems have a minimum impact on fish. For example, in 1983, excessive delay and exhaustion of fish was documented at the Bonneville second powerhouse bypass system (Krcma, et al., 1984). Now, juvenile mortality within the Bonneville Dam bypass system, as measured at the bypass sampler, generally ranges from less than 1 to 4 percent (Ceballos, et al., 1993). The Corps reports that survival rate in bypass systems is approximately 97 to 98 percent (Corps Salmon Passage Notes, 1992).

Descaling of Juvenile Salmon in the Bypass System as a Whole

Descaling is monitored daily in the samplers located in the Corps bypass system (e.g. Koski, et al., 1989). As observed at that point, descaling may have occurred at any point in the system from the screen downstream. The following are examples of numbers observed. As a result of improvements in the system and its operation, descaling rates at Lower Granite Dam declined in 1988 to 1.7 percent of the total sample. Of these, 2.4 percent of the chinook were defined as descaled, and 1.4 percent of the steelhead. This was an improvement over 1987, when the total rate was 3.3 percent (Koski, et al., 1989). It was also an improvement over 1981 and 1982 descaling rates that had been recorded as 15.5 percent for chinook and 16.8 percent for steelhead in 1981, and 8.8 and 10.1 percent in 1982 (Koski, et al., 1985).

At Little Goose Dam the combined rate in 1988 was 3.4 percent. At McNary Dam the rate was 10.4 percent. Muir, et al. (1995A) estimated there was addition of 2.8 percent to the rate of descaling of river-run steelhead as a result of passage through the bypass conduit at Lower Granite Dam. They thought that the 7 percent descaling rate of hatchery steelhead observed after the fish passed through the bypass was not excessive.

Sampler to Outfall and Below

An additional source of mortality to guided fish is the portion of the conduit leading from the dewatering screens at the sampler to the tailrace. Marked fish released out of the north shore outfall at McNary Dam were recovered at half the rate of other release groups. This finding suggested that predation in the vicinity of the outfall was responsible for added mortality (Sims and Johnson, 1977).

Results of studies at Bonneville Dam were initially surprising. The results indicated that survival in the bypass system as a whole, from gatewells to a point downstream of the outfall, was no better than survival in passing through the turbines (Ferguson, 1993; Ledgerwood, et al., 1990; 1991; Dawley, et al., 1992; Gilbreath, et al., 1993). During 1987 and 1988, the first two years of the study at Bonneville’s second powerhouse, Ledgerwood, et al. (1991) reported that rates of recovery in the estuary of marked subyearling chinook that had transited the bypass were significantly lower than fish that had passed through the turbines. This finding indicated higher mortality of juvenile salmon in the bypass than in the turbines. In the following two years there was no significant difference in recovery rates, suggesting that the bypass was not accomplishing any reduction in mortality compared to the turbines (Ferguson, 1993). However, it was then found that the conduit itself contributed only an estimated 3 percent mortality to juvenile salmon diverted by the intake screens (Dawley, et al., 1992). Therefore, Dawley, et al. (1992) and Gilbreath, et al. (1993) concluded that the primary source of mortality was outside of the bypass itself. The location of the outfall, in a place where predators could congregate, was identified as the most likely source of the high mortality measured by Ledgerwood, et al. (1991).

Ledgerwood, et al. (1994) have begun a similar study of survival in the bypass and turbines at Bonneville’s Powerhouse I. First year study results indicated, as with the bypass at the second powerhouse, that survival of juvenile salmon was lower for juveniles that passed through the bypass than for juveniles that passed through the turbines. Again, predation at the outfall was thought to be the principal source of mortality. Tom Poe of the U.S. Fish and Wildlife Service (now U.S. Geological Survey) reported to Ledgerwood, et al. that a higher proportion of marked fish released into the bypass were consumed by northern squawfish in the tailrace than were other groups of fish released at the same time.

Ferguson (1993) observed that bypass evaluations at other mainstem hydroelectric projects have been limited to assessing survival at a collection point within the system, but not below the tailrace. Chapman, et al. (1991) recommended further research to evaluate mortality associated with bypass.

Stress as it Affects Juvenile Salmon in Bypasses

Concerns have been expressed about levels of stress induced on the juveniles as they encounter the screens and associated bypass systems (Congleton, et al., 1984; Schreck, et al., 1984). Bjornn (1992) found no difference in survival rates of marked chinook that were subjected to high stress prior to release as juveniles compared to those that were not stressed.

Summary of Fish Guidance Efficiency, Mortality and Descaling in Bypass Systems

Following studies by NMFS/NOAA and others, a set of criteria for successful bypass systems has been developed and approved by NMFS/NOAA, and fisheries agencies form Wahington, Oregon and Idaho. These criteria are available from NMFS Environmental and Technical Services Division in Portland, Oregon. They are reproduced as Appendix A in Neitzel, et al., 1997. These criteria establish maximum velocities, advise avoidance of pressurization, set appropriate angles for curves and changes in elevation, set standards for dewatering and other factors in design (Rainey, 1995; Bates, 1992; NMFS/NOAA, 1990). These criteria are being used in the design of bypass systems at Rocky Reach, Wanapum and Priest Rapids dams, and in the improvement of systems at Corps projects. In addition to providing criteria for performance of juvenile fish screens, NMFS has adopted a policy statement that provides for development and evaluation of new technology under controlled conditions (Office of Technology Assessment, 1995, recorded in their Appendix B.)

Implementation of Findings on Turbine Intake Screens

Success with tests of prototype screens has led either to their installation or to schedules for installation at most of the projects in the mid-Columbia, Snake and lower Columbia rivers. Details on FERC, NPPC, and NMFS/NOAA requirements and resulting installations are provided in Appendix A. The Corps has installed standard submerged traveling screens at all of their projects except The Dalles. Now, in response to NMFS/NOAA and NPPC requirements, installation of extended length screens was scheduled by the Corps for 1996 at Lower Granite, and Little Goose dams, for 1997 at McNary Dam, and for 1998 at John Day Dam (Corps, 1992; 1995). The bar screen design is being used in these installations, rather than the submerged traveling screen. Projects not yet equipped with turbine intake screens are The Dalles, Priest Rapids, Wanapum, Rock Island, and Rocky Reach dams (Corps, 1992; mid-Columbia

Coordinating Committee Findings 1993). Wells Dam also is not equipped with turbine intake screens but has a different type of bypass, which is explained later in the report. Intake screen prototypes have been tested with success and schedules set for installation at The Dalles (1998), Priest Rapids and Wanapum dams. At Rocky Reach Dam, prototype tests of intake screens annually from 1985 to 1994 did not produce satisfactory results (Peven, et al., 1996). At Rock Island Dam, the idea of screening powerhouse number 2 was abandoned, based on poor performance of prototypes tested, while at powerhouse number 1, tests have shown some promise and are continuing (Peven, 1995).

Although it is not associated with a dam, the hydroelectric facility at Hanford (Hanford Generating Plant) should be mentioned here. It has a cooling water intake with six bays, each equipped with a traveling screen designed to protect juvenile fish (Stone and Webster, 1987). Average survival of chinook yearlings encountering the screen was found to be 97.9 percent (Page, et al., 1975).

Summary of Effectiveness of Bypass Systems

In the final analysis, effectiveness of bypass systems must be evaluated in terms of their ability to achieve performance goals established by FERC, the NPPC and NMFS/NOAA. We provide a detailed evaluation in Appendix B, where we describe the goals, and the efforts to achieve them at each project, using the experience in 1995 as an example. In summary, the goals of NPPC and NMFS/NOAA are stated as 80 percent fish passage at each project. The NMFS/NOAA goals apply to the Snake River and lower Columbia River, while the NPPC goals apply to the basin as a whole and the FERC goals apply only to the Public Utility District projects in the mid-Columbia reach. The NPPC goals apply to time periods that are different from the NMFS/NOA time periods. FERC requirements for the mid-Columbia projects differ from project to project and do not correspond with the NPPC goals. None of the intake screens in place at the Snake River or lower Columbia River projects achieve fish guidance efficiency high enough to reach the 80 percent fish passage goal. Thus, it is necessary to add spill in sufficient quantities to make up the difference between a "standard" fish guidance efficiency and the fish passage goal. Spill amounts are therefore different from project to project because of differences in fish guidance efficiency, differences in spill effectiveness among projects, and changes in mixes of species between spring and summer. The result is a complex situation that we explain in detail in Appendix B.

Analysis by the Fish Passage Center (1995) showed that the NMFS/NOAA or NPPC goals for 80 percent fish passage were not met at any of the Snake River or lower Columbia River projects in 1995, except at Ice Harbor Dam. At Ice Harbor Dam, 80 percent fish passage occurred only because turbines were out of operation, which necessitated spill in amounts that led to production of gas saturation levels that went beyond permitted levels. At none of the other Snake River or lower Columbia river projects were the fish passage goals achieved, because spill amounts required to supplement the fish guidance efficiencies to reach the goals could not be provided. The spill amounts were reduced in practice because of limitations on gas saturation levels that were permitted. See Appendix B. The experience in 1995 is not unique. It represents a good example of a year with flows that are average or below. In years of high flow, hydraulic capacities of the projects will be exceeded, leading to spill in amounts that will lead to gas saturation levels above the permitted levels of 120 percent.

Surface Collection Devices

Ice and Trash Sluiceways

Ice and trash sluiceways are in good position to attract fish approaching the powerhouse, because they are located at the surface directly above the turbine intakes and are included at the time of construction at some projects. Juvenile salmon were observed in the sluiceways at Bonneville (first powerhouse) and The Dalles dams. This observation led to initial testing of juvenile salmon passage through sluiceways (Michimoto and Korn, 1969). Efficiency of the sluiceways in diverting juvenile salmon from the turbine intakes generally ranged from 20 to 40 percent (Nichols, et al., 1978; Willis and Uremovich, 1982; and Willis, 1982, 1983). However, Giorgi and Stevenson (1995) point out that because major modifications were made to the bypass system at the Bonneville Dam Powerhouse I in the early 1980's, it is doubtful that those estimates would apply under current conditions. In 1987, at the Bonneville Dam second powerhouse, the ice and trash sluiceway was shown to pass an estimated 81 percent of juvenile salmon passing the powerhouse in the daytime and 30 percent at night (Magne, 1987).

At The Dalles Dam, as previously discussed under the subject of spill effectiveness, the sluiceway passed an estimated 40 percent of the fish approaching the project when there was no spill (Willis, 1982). Confirming Willis' results at The Dalles Dam, hydroacoustic studies showed fish were more concentrated in the volume of water entering the ice and trash sluiceway than in water entering the turbines (Nichols and Ransom, 1980; 1981; Steig and Johnson, 1986). At Ice Harbor Dam, the sluiceway was estimated to pass 48 percent of the migrants in the daytime in 4 percent of the water, and pass 21 percent of the migrants at night in 6 percent of the water (Ransom and Ouellette, 1991)

There is much current interest in surface collection devices, including ice and trash sluiceways for passing juvenile salmon. Investigations that are under way are described below.

Wells Dam Hydrocombine

The hydrocombine at Wells Dam is uniquely designed. Its spillway is located directly above the turbine intakes. This design provided a situation in which it was thought that juvenile salmonids that were observed to enter the turbines near the ceiling might be diverted into the spillbays above.

Two-dimensional model studies were undertaken that were designed to determine the feasibility of altering the approach flow to direct the juvenile salmonids away from the turbine intakes (under the leadership of Mike Erho and the late John Gregg; see Johnson, Sullivan and Erho, 1992; Sverdrup and Parcel Assoc. Inc., 1982; Johnson, Giorgi and Erho, 1997). The design included placement of solid covers on the turbine intake emergency gate slots, opening the flap gate in the top leaf of the spillway gate (surface spill), and installing solid baffles in front of the spillway to a point 30 to 40 feet below the surface, Figure 5. Testing of a prototype began in 1983 (Biosonics, 1983B). Alternative dimensions and configurations of openings in the intake baffles were tested in prototype in the next several years. These tests showed that a vertical slot configuration in the center baffle of three spillbay baffles was most effective at diverting fish (Sullivan and Johnson, 1986). The volume of water required for operation of the bypass varies somewhat depending on river flow and the powerhouse load. In 1995 it ranged between 1.2 and 7.5 percent of the daily average river flow.

One difficulty arising from the surface collection concept is that it requires a different method of evaluation than the method used to measure fish guidance efficiency with the turbine intake screens. With a surface collection device in prototype, investigators are faced with the practical problem of not being able to directly associate a fyke net catch in an intake with an assignable number of guided fish that may be drawn from a wide area across the powerhouse. The hydroacoustic method was used at Wells Dam in evaluating the performance of the surface collector. Currently, the hydroacoustic method is being employed in general for evaluation of intake screens. This is being done because of concerns about the impact of sampling with fyke nets where Snake River stocks are present. Also, it is questioned whether the presence of the fyke net array may itself affect measurement of fish guidance efficiency through influence on water movement (e.g. Thorne and Kuehl, 1989, 1990; Magne, et al., 1989; Stansell, et al., 1990; 1991). A major disadvantage of the hydroacoustic method is that it is not possible to estimate fish guidance efficiency separately for each species of salmon, as it is with fyke nets. This is particularly important for fall chinook and sockeye, which have shown low fish guidance efficiencies, Table 6.

At Wells Dam, initial evaluations were based on hydroacoustic counts in a set of spillbays and the associated turbine intakes directly below them. The final measurements of fish passage effectiveness were based on timed samples across the entire hydrocombine after the project was fully equipped with the bypass (Biosonics, 1983B; Kudera, et al., 1990; Skalski, 1993)

Figure 5. Wells Dam hydrocombine, as a three dimensional schematic cross section. Direction of flow is from lower right hand corner of the diagram to upper left hand corner. The dark areas on the upstream face of the dam and sidewall are panels placed across the entrances to the spillbays. Note the vertical opening in the middle panel, labeled the C slot, which is not present in the A or B slots. Note also that the second B and C slots are shown with panels removed in order to provide a picture of their appearance without the panels. In the full installation, panels are present across the full face of the hydrocombine. (Source: Johnson, Giorgi and Erho, 1997)

Implementation of Surface Collection at Wells Dam

By 1987, a sufficient array of baffles was in place across the powerhouse at Wells Dam that it was operated as though it was complete. Spill beyond the amount necessary to operate the bypass has not been required for fish passage since then (Kudera and Sullivan, 1993). The system was fully installed in 1989.

In January 1991, FERC approved a long-term settlement agreement that was developed by parties to the mid-Columbia agreement and applies to issues at Wells Dam. The agreement calls for operation of the juvenile fish bypass during the spring and summer outmigrations, at times to be determined by representatives of the parties to the mid-Columbia Proceeding. Among other things, the agreement called for a three-year study to measure the effectiveness of the bypass. It established a bypass criterion of at least 80 percent of the juvenile salmon for the spring period and at least 70 percent for the summer. From the resulting studies, the three year average bypass effectiveness during both the spring and summer outmigrations was estimated to be 89 percent (Skalski, 1993). It is currently the most effective bypass system in the basin, and the only one that can meet the standards for fish passage set by FERC, the NPPC, or NMFS/NOAA, without adding spill. (The NMFS/NOAA standard does not apply in the mid-Columbia because endangered Snake River chinook and sockeye are not found there.)

Rocky Reach Dam

The success at Wells Dam has stimulated studies of the possibility of applications elsewhere, as recommended by Bevan, et al. (1994). The technology used at Wells Dam is not directly transferable to any other mainstem or Snake River project in the basin because Wells Dam is a hydrocombine. Unlike any of the other dams, the Wells Dam spillway is located directly above the turbine intakes.[5] The failure of conventional intake screens that had been tested in prototype from 1985 to 1992 at Rocky Reach Dam was a factor in the decision to study a surface collection device, which was prepared for testing in 1995 (Peven, et al., 1995).

It was estimated that in 1995 over 725,000 juvenile salmon and steelhead passed through the prototype device during the spring outmigration, April 26 to June 15 (Peven, et al., 1995). Development of the concept is proceeding (Peven, 1996). Surface collection is also being investigated for juvenile fish bypass at Rock Island Dam.

Wanapum Dam

A parallel effort to develop a surface oriented juvenile bypass system began at Wanapum Dam in 1995 (Ransom, et al., 1995). The physical conditions at Wanapum Dam are much different from conditions at either Rocky Reach or Wells dams. At Wanapum Dam, the spillway portion of the dam is downstream of the powerhouse, and

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[5] The Cowlitz Falls Project on the Cowlitz River is a hydrocombine design where the Wells concept is being tested (Solonsky, et al., 1995).

the reservoir is much wider. Hydroacoustic evaluation brought estimates of fish passage efficiency in relation to unit 8 of 12.2 to 68.8 percent and averaged 35 percent for the spring migration season. Grant County Public Utility District plans to enlarge the prototype for testing in 1996. (Personal communication Stuart Hammond, Grant County Public Utility District)

Ice Harbor and Other Corps of Engineers Projects

Bevan, et al. (1994) and the NMFS/NOAA Proposed Recovery Plan refer to the success at Wells Dam and call upon the Corps to investigate potential applications at Corps projects. Accordingly, in 1995 the Corps conducted several studies of prototype surface collection configurations at Ice Harbor Dam. Three types of surface collectors were installed: vertical slots in front of two turbine intake slots (in conjunction with the ice and trash sluiceway), a sluiceway surface skimming gate, and stop logs that allowed surface spill at two spillbays (Swan, et al., 1995). The effectiveness was evaluated by radiotelemetry of juveniles and by hydroacoustics. The hydroacoustic study showed that the density of juvenile salmon was greatest in the sluiceway, although more total fish passed in spill because of the high volume of spill (Biosonics, 1995). Further tests are scheduled for 1996 at Lower Granite and The Dalles dams.

CONCLUSIONS

1. Juvenile salmon mortality in turbine passage is between 2.3 and 19 percent. Concern about this mortality has led to the development, construction and operation of bypass systems at all of the projects on the mainstem Columbia River and in the Snake River except The Dalles, Rocky Reach, Rock Island, Wanapum and Priest Rapids dams. The Dalles Dam has used the ice and trash sluiceway to pass at least 40 percent of the juvenile salmon approaching the dam.
2. Only turbine intake screens, surface collectors and spill have been found to be sufficiently successful in bypassing adequate percentages of juvenile salmon at the dams to justify full installation. Many other approaches have been tried.
3. Turbine intake screens have been the primary choice by the Corps at their projects. The Corps has a schedule for replacement of standard screens and installation of extended-length screens at all eight of their projects, including The Dalles.
4. Whether it be through spill, intake screens or surface collection, the most successful bypass systems have taken advantage of a surface orientation of juvenile salmon as they move downstream.
5. Effectiveness of turbine intake screens seems to have reached an upper limit that is less than the surface collector at Wells Dam, which passes 89 percent of the fish that approach the dam. Intake screens are unlikely to prove 100 percent effective in diverting juvenile salmon (Office of Technology Assessment, 1995, p.127). Although some measurements of effectiveness of extended screens showed values as high as 93 percent for steelhead and coho, and 88 percent for chinook yearlings, none of the screens tested to date approach that value for subyearling chinook or sockeye, most of which are less than 50 percent, Table 6.

6. Although extended length screens have demonstrated improvements over standard length screens, their fish guidance efficiency for subyearlings chinook are still below criteria set for fish passage by the NPPC and NMFS. The NPPC criterion is for 80 percent fish passage at each Snake River project from April 15 to July 31, and at each Columbia River project from May 1 to August 31. The NMFS Snake River Salmon Recovery Plan criterion is for 80 percent fish passage at each Snake River project from April 10 through June 20, and at each Columbia River project from April 20 through June 30. The inability to meet the criteria with extended length screens presents a particularly difficult problem in the Snake River, where subyearling chinook are listed as threatened or endangered, and in the lower Columbia River through which these fish must pass.

7. Spill is effective as an interim measure, or a supplement to mechanical bypasses, that has been shown to offer high survival of fish up to the point where supersaturation of atmospheric gas becomes a problem.

8. Fish guidance efficiency of turbine intake screens varies widely from project to project because of many factors, particularly the species of fish. Spill effectiveness also varies, particularly among projects and has not been measured at many Corps projects. Thus, the determination of spill levels, that are set each year to attain the NPPC or NMFS/NOAA passage goals, is complex and requires assumptions that go considerably beyond available information.

9. Because of limits on gas saturation and the high levels of gas produced by the spill amounts required to supplement fish guidance by intake bypass screens, the NPPC and NMFS goals of 80 percent fish passage cannot be achieved at any project except Wells Dam. Measures are needed to reduce gas saturation levels when spill is to be used as a bypass measure to achieve the 80 percent fish passage goals. Further studies in the open river are needed in order to establish the appropriate upper limit for gas saturation that can be tolerated by salmon in the natural situation.

10. The most effective spill is surface spill. Spill spread over 24 hours a day was more than twice as effective per unit volume of water used than night-time spill for 12 hours at Priest Rapids Dam.

11. Effectiveness of spill differs among the projects. More information is needed at most of the Corps projects. In addition, effectiveness of surface spill needs to be defined at each project, along with determination of the effects of spilling for different time intervals, such as spilling for 24 hours per day versus 12 hours.

12. The NPPC criterion of 98 percent smolt survival within bypass and collection systems from the screen to the end of the outfall that is specified in the 1994 Fish and Wildlife Program appears to be attainable. However, losses due to predation at the outfalls and in the tailraces can be substantial in some situations.

13. Surface collectors are the most promising devices for attaining the fish passage goals established by the Council in the fish and wildlife program or NMFS/NOAA in the Snake River Salmon Recovery Plan.

14. Current developments are shifting toward provision of surface spill and surface collection, as opposed to turbine intake screens for bypass of juvenile salmon. The attractiveness of surface spill and surface collection over standard spill comes from the possibility of passing a high percentage of the juveniles of all species and sizes in a small volume of water by taking advantage of the natural behavior of the fish.

15. Modification of ice and trash sluiceways offers a potentially effective means of providing a surface exit for juvenile salmon.

APPENDICES

INTRODUCTION

The Appendices draw upon the review of studies contained in the text. In the interest of continuity and brevity, we have omitted citations to sources here wherever statements are supported in the text. They may be found under the appropriate headings there. Appendix A lists the specific requirements by the Federal Energy Regulatory Commission (FERC), the Northwest Power Planning Council (NPPC), and the National Marine Fisheries Service (NMFS/NOAA) for installation and operation of bypass facilities at each project. It also lists the bypass systems that are in place or scheduled for installation at each of the 13 projects on the mainstem Columbia and Snake rivers. Appendix B is in two parts. Part 1 describes the fish passage goals of FERC, the NPPC and NMFS/NOAA. Part 2 evaluates the effectiveness of the bypass systems in achieving the goals in 1995 as an example. The NPPC and NMFS/NOAA specify a goal for fish passage efficiency (FPE), which is the percentage of fish approaching a project that is diverted away from the turbine intakes either through a bypass system or spill. The bypass system at Wells Dam is the only one that can achieve the fish passage efficiency goals without the addition of spill. Fish passage efficiency at the other projects depends upon the sum of the fish guidance efficiency (FGE) of the bypass system and the effectiveness of spill in passing fish. Requirements for spill by the NPPC and NMFS/NOAA are discussed in Appendix B because they have to be considered in the context of the fish passage goals and the effectiveness of the bypass systems that are in place.

APPENDIX A: REQUIREMENTS BY FERC, THE NPPC AND NMFS/NOAA FOR INSTALLATION OF MECHANICAL BYPASS SYSTEMS

FERC and NPPC Requirements in mid-Columbia

Background

The FERC regulates the operations of the five non-federal dams in the mid-Columbia Reach. The FERC has established requirements for operation of these projects to provide for increased survival of migrating juvenile salmon in the spring and summer. Because only Wells Dam has a bypass facility in place, spill is required at the other projects as an interim measure for passage of juvenile salmonids. FERC requirements, applying to the public utility district projects in the mid-Columbia have, as a rule, been repeated by the NPPC as requirements in the Council's fish and wildlife programs. In the mid-Columbia Settlement Agreement of 1979 and subsequent stipulations, the parties to the mid-Columbia FERC proceeding agreed to work together to improve production of salmonids. Methods agreed upon included provision of spill, investigation of diversion of smolts from intakes, and collection and transportation of smolts (Offer of Settlement.

Public Utility District Number 2 of Grant County, Washington. 10 FERC ¶ 61,257 (1980) Adopted by FERC March 23, 1980).

FERC Requirements for Juvenile Fish Passage including Spill

Wells Dam

Surface Collector. The settlement agreement for Wells Dam, adopted by FERC, set a fish passage goal for the bypass of 80 percent for spring migrants and 70 percent for the summer. As described in the body of the text, there is a bypass system in place, a surface collector that achieves 89 percent fish passage efficiency in both spring and summer. It is operated during spring and summer at times that are agreed upon by the Wells Project Coordinating Committee. The committee consists of parties to the mid-Columbia Proceeding, which includes representatives of Douglas County Public Utility District, the fishery agencies, and tribes.

Spill. No spill is required for fish passage at Wells Dam because the bypass system has higher fish passage efficiency than the 80 percent in spring and 70 percent in summer required by FERC.

Rocky Reach Dam

Intake Screens. As agreed in the mid-Columbia Settlement Agreement, prototype submerged traveling screens of various configurations were tested from 1985 to 1988 (Peven and Keesee, 1992). Bar screens of various configurations were then tested from 1989 to 1992. None performed satisfactorily. Highest measured fish guidance efficiency for chinook yearlings was about 50 percent. It was concluded that it would not be possible to meet criteria with intake screens at that project (Peven and Keesee, 1992). The project has a peculiar configuration. A powerhouse is nearly parallel to the river flow and a cul-de-sac is between the powerhouse and the right bank. This configuration led to development of unusual flow patterns that affect fish behavior. The unusual configuration and flow pattern are thought to be factors in the inability to apply the screen technology to this project.

Surface Collector. In 1995, testing began of a surface collection device. The prototype being tested shows promise. Further tests of a modified device were scheduled for 1996 and 1997.

Spill. (FERC). In a stipulation with FERC for 1994 and 1995, spill levels at Rocky Reach Dam were specified as 15 percent for 30 days during the spring outmigration. An option was included to increase the number of days by up to 6 additional days if necessary to encompass 90 percent of the Okanogan River sockeye outmigration. Levels were specified as 10 percent for 34 days between June 15 and August 15.

Spill. (NPPC). The 1987 Fish and Wildlife Program called for 20 percent spill at each of the mid-Columbia public utility district projects. However, the 1994 Fish and Wildlife Program merely calls upon the parties to the mid-Columbia Proceeding to annually develop plans for spill at Rocky Reach and Rock Island dams.

Rock Island Dam

Intake Screens. Rock Island Dam was removed from the mid-Columbia proceeding in 1984 when issues with respect to the need for intake screens were undergoing hearing with the FERC. A long-term settlement agreement was reached in 1987 and adopted by FERC. The agreement included a provision for evaluation of prototype intake screens at both powerhouses. Following tests of prototypes, Chelan County Public Utility District concluded that installation at the second powerhouse was not feasible due to the limited space available in front of the horizontally oriented bulb turbines. Tests at the first powerhouse have shown some promise, with fish guidance efficiency measured in the range of 70 to 75 percent for chinook yearlings, about 60 percent for chinook subyearlings, and 45 to 55 percent for sockeye in 1994 (Peven, 1994).

Surface Collector. Chelan Public Utility District is investigating the feasibility of using a surface collection device at Rock Island Dam that might serve both powerhouses.

Spill. The settlement agreement allowed for substitution of spill valued at $1 million (in 1986 dollars) if no screens are installed at the second powerhouse, at the option of the parties to the proceeding. As of 1996, this option has not been invoked. On issues relating to Rock Island Dam, the Long-term Settlement Agreement of 1987 did not include provision for interim spill. A clause in the agreement did provide for substitution of spill for bypass development. However, in 1985 FERC ordered spill as an interim measure at a level of 10 percent spill of the volume of water passing through the second powerhouse and 50 percent of the volume that would have gone through the first powerhouse in the absence of spill.

Wanapum and Priest Rapids Dams

Intake Screens. The FERC agreement of 1979 called for tests of intake screens at Wanapum and Priest Rapids dams. Based on the success of the fixed bar screen design demonstrated by the earlier NMFS/NOAA tests, the Grant County Public Utility District used the fixed bar design with other desirable features for prototype tests at Priest Rapids Dam. Prototypes were tested at Priest Rapids Dam from 1986 to1988. The tests produced fish guidance efficiencies satisfactory to representatives of the mid-Columbia Coordinating Committee.

The intake geometry at Wanapum Dam is similar to Priest Rapids Dam, such that the screen configuration tested at Wanapum Dam was also similar. Attainment of fish guidance efficiency near 75 percent for yearling chinook during the spring and 50 percent for sub-yearlings during the summer led to design and testing of an orifice passage system beginning in 1993.

In 1992, Grant County Public Utility District proposed to install a full bypass and collection system at Wanapum Dam and to provide transportation of the collected fish for release below Priest Rapids Dam. This would have avoided the need for intake screens and an associated bypass system at Priest Rapids Dam. The parties to the mid-Columbia proceeding were unable to agree on this proposal. Grant County Public Utility District requested a hearing before a FERC administrative law judge, who ruled against the Grant County Public Utility District proposal and ordered installation of turbine intake screens

[State of Washington Department of Fisheries v Public Utility District No. 2 of Grant County. FERC Proceeding. Docket No. E-9569-003 (Grant County Phase), re Project No. 2134-024. Ruling of March 23, 1992, Hon. Stephen L. Grossman presiding.] This ruling does not become final until it is formally adopted by FERC.

Grant County Public Utility District is proceeding with design and installation of a full bypass system with completion scheduled for 1999 at Wanapum Dam and 2000 at Priest Rapids Dam.

Surface Collector. Grant County Public Utility District is evaluating surface collection as an alternative to intake screens at Wanapum Dam.

Spill. (FERC). In 1994, in response to a petition from the fishery parties, FERC required Grant County Public Utility District to provide spill for juvenile salmonids at Wanapum and Priest Rapids dams. The spill requirement was an interim fish protection measure. The spill amount was to be sufficient to ensure passage of 70 percent of the juvenile salmonids during 80 percent of the spring outmigration and 50 percent passage during 80 percent of the summer outmigration. (FERC Docket No. E-9569-003, Grant County Phase. Order of May 24, 1994). The effectiveness of these measures is reviewed in Appendix B.

Spill. (NMFS/NOAA). The NMFS/NOAA Proposed Recovery Plan calls upon Grant County Public Utility District to install flip-lip spillways and/or a stilling basin at Wanapum Dam. Grant County Public Utility District planned to begin design for installation of flip-lips in the spillway at Wanapum Dam in 1996.

NPPC Requirements in the Fish and Wildlife Program and NMFS/NOAA Requirements in the Proposed Recovery Plan

NPPC Requirements for Mechanical Spill

Requirements of the NPPC and NMFS/NOAA with respect to installation and improvement of bypass devices are somewhat similar. However, most of the Corps projects were equipped with intake screens either before the NPPC was formed or during the time when the NPPC's authority over this subject was not shared with NMFS/NOAA.

Although the experiments with the bar screen showed promising results, there were difficulties with debris and the Corps elected initially to proceed with installation of submerged traveling screens (STS) at all eight of its projects on the Snake River and lower Columbia (Corps Salmon Passage Notes 1992). In the 1991 Amendments to the Fish and Wildlife Program and the 1994 Fish and Wildlife Program, the Council called for completion by 1998 of turbine intake screens and juvenile fish bypass systems at all of the Corps dams on the lower Columbia River and Snake River. All but The Dalles Dam are now fully equipped with intake screens.

In addition, the 1994 Fish and Wildlife Program called for installation of extended length screens at McNary (1995), Lower Granite (1996), Little Goose (1996), John Day (1998), and The Dalles (1998), if they prove to be effective.

Based on the studies that demonstrated improved fish guidance efficiency with extended-length screens, the Corps is proceeding with testing and installation of extended-length screens at the eight projects to replace the standard screens (U.S. Army Corps of Engineers, 1996). Four of the projects, Lower Granite, Little Goose, Lower

Monumental, and McNary dams were expected to be equipped in time for the 1996 outmigration (Filardo, January 18, 1996 Memorandum to FPAC). As mentioned in the text, the extended length screens that are being installed are bar screens rather than traveling screens.

NMFS/NOAA Requirements for Mechanical Bypass Systems

The NMFS/NOAA Proposed Recovery Plan specifies a general strategy whose first two measures focus on: 1) improvements in downstream survival through increased flows and controlled spill in the Columbia and Snake Rivers; and 2) modifications to dams and their operations to bring about improvements in juvenile downstream passage survival and upstream adult survival (NMFS/NOAA, 1995, p. 1-8).

To improve survival of juvenile salmonids in passage through turbines, the plan calls for operating turbines at the eight federal projects within 1 percent of peak efficiency during March 15 through October 31 in the Columbia River and March 15 through November 30 in the Snake River.

The plan provides strategies for installation, improvement, or testing of bypass facilities at each of the eight Corps projects. The plan also calls for installation of flip-lip spillways or a stilling basin at the base of the spillway at Wanapum Dam, as previously discussed.

The plan calls for studies to improve efficiency in the bypass systems at Columbia Basin hydroelectric projects. It lists five kinds of studies, including studies that re-evaluate the existing bypass systems, evaluate all new systems, develop new means of collection and bypass, develop better methods for counting fish that are bypassed and held, and assess the impacts of supersaturated gas on juvenile and adult salmonids. In addition, specific measures are called for at certain projects, as described below.

Intake Screens. The Proposed Recovery Plan calls upon the Corps to reduce loss of juvenile fish through structural and operational improvements of bypass facilities. See the note above under NPPC, regarding the Corps schedule for installation of extended length intake screens at the eight Corps projects.

Surface Collector. The Proposed Recovery Plan produced by the Snake River Salmon Recovery Team, referred to the success at Wells Dam and called for investigation of the application of surface collection technology at the Snake River and Columbia River projects, (Bevan, et al., 1994; NMFS/NOAA, 1995). Surface collector studies are proposed for 1996 in the Portland District of the Corps to cover: (a) hydroacoustic evaluations of fish passage, (b) fish condition studies, and (c) radio telemetry for fine scale behavior information of juvenile salmonids in the forebay, through surface passage routes, and through the tailrace at Lower Granite, The Dalles, and Bonneville dams, and for 1997 at Ice Harbor Dam (Draft Corps Mitigation Project 11/2/95). Criteria are to be developed to design, model and evaluate surface bypass devices. (Corps Workshop, 1995)

Flip-Lip Spillways. Five of the eight Corps projects were equipped with flip-lip spillways in 1995, Table A.1 (Detailed Fishery Operating Plan, (DFOP) 1993, and personal communication Larry Basham, Fish Passage Center). John Day, Ice Harbor and The Dalles dams were not equipped. At The Dalles Dam, the shallow spill basin is not believed to cause high gas saturation (personal communication, Larry Basham, Fish

Passage Center, 1996). However, of the equipped dams, only Lower Granite Dam is fully equipped across the spillway. Equipped spill bays are used as the first alternative for spill. When spill exceeds the capacity of equipped bays the remaining spill bays are employed.

Table A.1. Installation date and numbers of "flip-lip" spill bays at Corps projects. (From Detailed Fishery Operating Plan, 1993)

Project	Date	Number of Flip-lips
Lower Granite	2/75	8 of 8 bays
Little Goose	2/76	6 of 8 bays
Lower Monumental	8/74	6 of 8 bays
Ice Harbor		Recommended by NMFS/NOAA Proposed Recovery Plan
McNary	1/76	18 of 22 bays (2 outer bays on each end not equipped)
John Day		none
The Dalles		none (Spill through the shallow basin is thought not to cause high gas saturation)
Bonneville	3/75	13 of 18 bays (3 outer bays on north shore and 2 outer bays on south shore)

NPPC AND NMFS/NOAA Requirements for Mechanical Bypass at Snake River Projects

(Spill Requirements are complex and will be discussed in Appendix B.)

Lower Granite Dam

Intake Screens (NPPC). The 1987 Fish and Wildlife Program called upon the Corps to continue to evaluate and improve the effectiveness of the juvenile bypass system, to improve fish guidance efficiency, and continue studies to determine whether it was necessary to modify the existing juvenile fish bypass system to reduce mortalities and injuries. The 1991 Amendments to the Fish and Wildlife Program called for improvement of the existing fish collection and bypass system at Lower Granite Dam by March, 1996. Accordingly, the Corps modified gates in the bypass system in 1992.

Intake Screens. (NMFS/NOAA). The Proposed Recovery Plan specifies that by 1997, or as soon as possible, the Corps should develop a plan and proceed with improvement of the juvenile passage facility at lower Granite Dam. Some specific requirements for improvement are listed in the Plan

Extended Length Screens (NPPC). The 1994 Fish and Wildlife Program showed a schedule for installation of extended length screens at Lower Granite Dam by March, 1996.

Extended Length Screens (NMFS/NOAA). The Proposed Recovery Plan calls upon the Corps to continue its planned installation of extended length screens in time for the1996 smolt migration season. The Corps indicates they will be ready in March 1996 (Corps Salmon Passage Notes 1992).

Surface Collector. (NMFS/NOAA). The Proposed Recovery Plan calls upon the Corps to investigate the application of surface collection technology by June 1996. The Walla Walla District proposed a test of a prototype surface bypass and collection device at Lower Granite Dam in 1996, with full installation to follow in 1997 and 1998, depending on the results of tests. The prototype to be tested in 1996 will include configurations similar to those found to be the most successful at Ice Harbor Dam in 1995 (Corps Workshop, 1995)

Little Goose Dam

Intake Screens. (NPPC). Little Goose Dam was equipped with turbine intake screens when it began operation in 1970. However, after1979 to 1980 when the conduit was reconstructed to enlarge the system, juvenile mortality had increased. The 1987 Fish and Wildlife Program called upon the Corps to study whether it was necessary to modify the bypass system to reduce mortalities to juvenile fish. The fish and wildlife program called for installation of improvements by April 1989. The Corps modified gates in the bypass in 1991.

Extended Screens (NPPC). The 1994 Fish and Wildlife Program showed a schedule for installation at Little Goose Dam by March 1996. Accordingly, the Corps has scheduled installation of extended screens at Little Goose by March 1996 (Corps Salmon Passage Notes 1992).

Extended Screens (NMFS/NOAA). Extended Screens. The Proposed Recovery Plan called for the Corps to install extended length screens at Little Goose in time for the 1996 smolt migration season.

Lower Monumental Dam

Intake Screens (NPPC). The Fish and Wildlife Program of 1987 called upon the Corps to develop a plan for installation of a juvenile fish bypass system and install a screening and bypass system at Lower Monumental Dam by April 1990.

There is no sluiceway at Lower Monumental Dam, which greatly complicated the provision of a conduit for juveniles to the tailrace. The Corps therefore developed an alternate plan to use Lower Monumental as a collection facility for transportation. However, the Council felt the results were uncertain, and called for prototype testing of turbine intake screens there. The 1991 Amendments to the Fish and Wildlife Program called for Lower Monumental Dam to be equipped with screens and a bypass system by 1992. The Corps complied with installation.

Extended Screens. (NPPC). The 1994 Fish and Wildlife Program calls upon the Corps to plan for installation of extended length screens and structural modifications to improve gatewell hydraulics, contingent upon the results of prototype testing at Little Goose and Lower Granite dams.

Ice Harbor Dam

Intake Screens. (NPPC). The 1994 Fish and Wildlife Program called upon the Corps to provide a completed and operational screening and low-velocity flume bypass system by March 1996. The 1987 Fish and Wildlife Program had called for testing of screens in prototype and installation by April 1990. The 1991 Amendments to the Fish and Wildlife Program called for installation of screens and a bypass system at Ice Harbor by 1994. The Corps complied by 1994. Screens were in place in 1993 and the full bypass by 1994.

Extended Screens. (NMFS/NOAA). The Proposed Recovery Plan calls for planning for extended length screens and structural improvements to improve gatewell hydraulics at Ice Harbor Dam, contingent upon the results of prototype screen testing at Little Goose and Lower Granite dams.

Surface Collector. (NMFS/NOAA). The Proposed Recovery Plan adopted by NMFS/NOAA in 1995 states that testing of the surface collector concept will begin in 1995 at Ice Harbor and The Dalles dams. Tests were to be implemented at Lower Granite Dam in 1996. The plan states that if successful, they should be installed in 1996 at the projects where they have been tested. In 1995, the Corps conducted several studies of prototype surface attraction configurations at Ice Harbor Dam.

Surface Spill. (No requirement). The Corps is investigating the possibility of employing surface spill at Ice Harbor Dam, (Biosonics, 1995 Abstract presented at Corps Workshop, September 1995).

Flip-lip Spillway. (NMFS/NOAA). The Plan calls for the Corps to install stilling basins and spillway modifications (such as a flip-lip) to reduce dissolved gas levels at Ice Harbor Dam as soon as possible. The Corps plans to design a flip-lip spillway for Ice Harbor Dam in 1996 and construct it in 1997. (Corps Columbia River Fish Mitigation Project Draft Plan, November 2, 1995.)

NPPC AND NMFS/NOAA Requirements for Mechanical Bypass at Lower River Projects

McNary Dam

Intake Screens. (NPPC). The Council's Fish and Wildlife Program of 1987 called for the Corps to continue to evaluate and improve the effectiveness of the juvenile fish bypass system at McNary Dam, because of changes that had been made since 1968 when installation of the system was begun.

Extended Screens. (NPPC). The 1994 Fish and Wildlife Program calls for extended length screens to be installed by March 1995. The Corps scheduled prototype tests for 1995, (Corps, 1992).

Extended Screens. (NMFS/NOAA). The Proposed Recovery Plan calls upon the Corps to continue the scheduled installation of extended-length screens in 1997. The Corps completed installation in time for the 1996 outmigration. (Filardo memo, January 18, 1996)

Operate Bypass. (NMFS/NOAA). The Proposed Recovery Plan states that the bypass system should be operated according to criteria that will mitigate adverse warm water conditions in the summer. It calls for shading over the raceways by the end of 1995.

John Day Dam

Intake Screens. (NPPC). The 1987 Fish and Wildlife Program called upon the Corps to proceed with its plan to install a complete bypass system with turbine intake screens at John Day Dam. Screens and the bypass system were in place by 1993 (Corps Salmon Passage Notes, 1992). The 1994 Fish and Wildlife Program called upon the Corps to install extended length screens by March 1998.

Extended Length Screens. (NMFS/NOAA). The Proposed Recovery Plan says that extended length screens should be installed at John Day Dam by spring, 1998.

Surface Collector. (NMFS/NOAA). The Proposed Recovery Plan states that if testing of surface collection is successful at Ice Harbor and The Dalles, the Corps should proceed with testing at John Day Dam in 1997. The Corps has scheduled studies of surface collection at John Day Dam in 1997 and 1998.

Flip-lip Spillway. (NMFS/NOAA). The Proposed Recovery Plan calls for the Corps to install stilling basins and spillway modifications (such as a flip-lip) as soon as possible at John Day Dam to reduce dissolved gas levels. The Corps intends to design a flip-lip spillway in 1996 and begin construction in 1997 for completion in 1998. (Corps Columbia River Fish Mitigation Project Draft Plan, November 2, 1995).

The Dalles Dam

Intake Screens. (NPPC). The 1987 Fish and Wildlife Program states that the Corps should proceed with installation of turbine intake screens at the Dalles Dam, where the Corps had depended upon an ice and trash sluiceway for juvenile fish bypass.

Intake Screens. (NMFS/NOAA). The Proposed Recovery Plan says the Corps should continue designing a conventional intake screen system for installation at The Dalles. Following prototype testing, a decision should be made whether to continue developing a surface collection system or to proceed with installation of the screens by 1999.

Extended Screens. (NPPC). In the 1987 Fish and Wildlife Program, the Corps was called upon to complete prototype testing of extended screens by April, 1991, and to complete design and installation of a juvenile fish screen and bypass system by April, 1993. The 1991 Amendments to the Fish and Wildlife Program called for the installation of screens and a bypass system at The Dalles by 1998. In 1992, the Corps scheduled installation of extended length screens by March 1998 (Salmon Passage Notes. Special Edition, 1992)

Surface Collector. (NMFS/NOAA). The Proposed Recovery Plan notes that the Corps plans to test a surface collector at The Dalles Dam in 1995. The Corps will test the surface collector in 1996.

Bonneville Dam

Intake Screens. (NPPC). The 1987 Fish and Wildlife Program called upon the Corps to continue feasibility studies of means to improve juvenile fish guidance at the second powerhouse. Because of low fish guidance efficiency measured for the screens at the second powerhouse, the second powerhouse was to be closed when necessary to achieve an 85 percent juvenile fish passage through combinations of spill and bypass operation at Bonneville Dam. The Corps was called upon to provide annual progress reports until an 85 percent juvenile fish passage is achieved.

As of 1995, this goal had not been attained. The 1991 Amendments to the Fish and Wildlife Program called for installation of improved screens and bypass at Bonneville Dam's second powerhouse by March 1993, and evaluation of fish guidance efficiency at the first powerhouse.

Intake Screens. (NMFS/NOAA). The Proposed Recovery Plan calls for improved fish guidance efficiency at the Bonneville first powerhouse, with no date specified.

Improve Bypass. (NMFS/NOAA). The Proposed Recovery Plan calls upon the Corps to relocate the downstream migrant outfalls at Bonneville Dam by spring 1999. Bypass survival tests at Bonneville Dam suggest that predation in the tailrace may be substantial (Ledgerwood, et al., 1990. See text.). The Corps should improve hydraulic conditions at the dewatering systems in both bypass systems at Bonneville Dam by the year 2000.

APPENDIX B: IN TWO PARTS

PART 1. GOALS FOR JUVENILE FISH PASSAGE BY FERC, NPPC AND NMFS/NOAA

PART 2. EVALUATION OF FISH PASSAGE ACHIEVED IN 1995

Part 1. Goals for Juvenile Fish Passage by FERC, NPPC, and NMFS/NOAA

FERC Requirements for Bypass and Spill

There is a mix of requirements by FERC for provision of bypass of juvenile salmonids at the mid-Columbia projects. At Wells Dam, the requirement is for bypass of a specified percentage of the juvenile migrants, 80 percent during spring and 70 percent during summer. At Wanapum and Priest Rapids Dams, the requirement is for bypass of 70 percent during spring and 50 percent during summer. At Rocky Reach and Rock Island dams, the requirement is for a specified amount of spill during spring and summer.

NPPC Requirements for Mechanical Bypass Systems and Spill

In contrast to the mixed FERC requirements, both the NPPC and NMFS/NOAA have established fish passage goals that apply to all projects under their jurisdiction. Those goals are to be achieved using bypass facilities that are present along with spill as needed to achieve the fish passage goals. The NPPC in its fish and wildlife program has established goals for passage which apply to each of the projects in the Snake River and mainstem Columbia River, as well as the FERC projects in the mid-Columbia Reach.

The 1994 Fish and Wildlife Program requires 80 percent fish passage efficiency (FPE) over specified spring and summer periods that are intended to encompass juvenile migrations in the mainstem Columbia and Snake rivers (NPPC 1994). Note the distinction between fish guidance efficiency (FGE) and fish passage efficiency (FPE). As previously explained, fish guidance efficiency is a measure of the percentage of fish diverted by screens in turbine intakes. Fish passage efficiency is a measure of the percentage of total fish passing a project through routes other than the turbines. These other routes include the intake bypass systems, spill, or the ice and trash sluiceways. The NMFS/NOAA goal is for 80 percent fish passage efficiency, but over different time periods than the NPPC. The NPPC schedule is from April 15 to July 31 at the Snake River projects and May 1 to August 31 at the lower Columbia River projects. The NMFS/NOAA schedule is from April 10 to June 20 at the Snake Rover projects and April 20 to June 30 at the lower Columbia River projects. Since the NMFS/NOAA Proposed Recovery Plan supersedes the fish and wildlife program, the NMFS/NOAA time periods are discussed below.

The 1987 Fish and Wildlife Program set a standard of 90 percent fish guidance efficiency as a design criterion for intake screens. This standard was modified in the 1994 Fish and Wildlife Program to specify "if it can be achieved." It is unlikely that this standard can be achieved with turbine intake screens for the mix of species present at any given project, as discussed in the text. The 1994 Fish and Wildlife Program set a standard of 98 percent survival to be achieved in bypass and collector facilities throughout the basin. This goal is probably achievable in properly operated and maintained systems

NPPC Requirements for Spill

The 1994 Fish and Wildlife Program established spill as an interim measure to produce 90 percent survival during the middle 80 percent of the spring and summer outmigrations at specified projects "…. until mechanical bypass systems are installed" (NPPC, 1994, p 5-25). Mechanical bypass systems are now in place at Wells Dam in the mid-Columbia Reach, and at all the Snake River and lower Columbia River projects except The Dalles Dam.

In addition, the 1994 Fish and Wildlife Program calls for 80 percent fish passage efficiency at each Snake River project from April 15 to July 31 each year and at each Columbia River project (presumably lower Columbia) from May 1 to August 31. Because none of the bypass systems except Wells Dam can achieve 80 percent fish passage efficiency, spill is required to make up the difference between the fish guidance efficiency of the bypass systems in place and the 80 percent goal.

The 1994 Fish and Wildlife Program refers to a 10-year “Spill Agreement”, reached in 1988 by the Mainstem Executive Committee. The committee consisted of representatives from BPA, the fishery agencies, tribes, and utility representatives. The agreement was developed in response to the Council’s call for coordinated interim fish passage plans in the 1984 Fish and Wildlife Program. The Corps agreed to adhere to the provisions of the agreement as these were described in the NPPC Amendments to the Fish and Wildlife Program for 1989, with some conditions. Levels of spill were specified for Lower Monumental, Ice Harbor, and The Dalles dams during spring and summer outmigration periods, and John Day dam during the summer, Table B.1. These are now superseded by the more stringent requirements of the Proposed Recovery Plan for Endangered Snake River Salmon to be described later (NMFS/NOAA, 1995).

Table B.1. Spill amounts specified in the Spill Agreement of 1989 for Corps Projects The agreement was somewhat complex. Among other things, it attempted to take load factoring into account in determining an appropriate percentage of flow to be spilled. (Source: Fish Passage Managers, 1990)

Project	**Summer Spill**		**Spring Spill**	
	Instantaneous	Daily Average	Instantaneous	Daily Average
Lower Monumental	70%	35%	70%	35%
Ice Harbor	25%	12.4%	25%	12.5%
The Dalles	--	10%	--	5%
John Day	--	20%	--	8.3%

NMFS/NOAA Recovery Plan Requirements for Mechanical Bypass and Spill

Background

Now and for the foreseeable future, the 1995 NMFS/NOAA Proposed Recovery Plan for Snake River Salmon is the governing factor in implementation of measures for survival of migrating juvenile salmon in the Snake River and lower Columbia River. It was developed because certain Snake River stocks of salmon were listed as threatened or endangered under the Endangered Species Act (NMFS/NOAA, 1995)._ Implementation of the provisions of the plan is accomplished primarily through the Technical Management Team composed of federal managers from NMFS, the U.S. Fish and Wildlife Service, the Bureau of Reclamation, BPA, and the Corps. [6]

The NMFS/NOAA Proposed Recovery Plan, "... is based on the premise that there is sufficient uncertainty about the benefits of transportation to warrant an evaluation of whether improved inriver migration might result in as many (or more) returning adults than does the transportation program." (NMFS/NOAA, 1995, p. V-2-50.) Accordingly, specific standards are established for inriver passage and a study is recommended to compare adult return rates from transported fish with return rates from inriver migrants that have had the benefit of improved inriver conditions.

NMFS/NOAA, in their draft recovery plan for endangered Snake River salmon has established goals for passage applying to the projects in the Snake River and lower Columbia River. Because the bypass facilities that are in place on the Snake River and lower Columbia River do not guide enough fish to meet the 80 percent fish passage goal, spill must be provided in sufficient amounts to make up the difference. Calculation of the spill amount required at each project to achieve the NMFS/NOAA goal of 80 percent fish passage is not a simple matter, as will be explained below.

The NMFS/NOAA goal provides a refinement over the NPPC goal in the manner in which it distinguishes between the spring and summer migrations. The salmonid components of the migrations differ in spring and summer and the fish guidance efficiency for the components differ. This makes it is necessary to define fish guidance efficiency levels separately for spring and summer for each project.[7] The NMFS/NOAA goal, in practice, is more stringent than the NPPC goal, because NMFS/NOAA is

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[6] NMFS/NOAA has made a commitment to the Council to coordinate planning and implementation efforts, (Stelle, 1994). [Statement on actions necessary for the recovery of Snake River salmon presented to the NPPC by William Stelle, Jr., Northwest Regional Director, NMFS/NOAA on November, 1994. - Cited in Recovery Plan p.I-12.]

[7] The spill levels specified in the Proposed Recovery Plan (p. V-2-31 and 32) are not the levels actually used, as we explain later in the text.

concerned with threatened or endangered species, which include sockeye and fall chinook that universally have shown low fish guidance efficiency. Spring/summer chinook, also threatened, show a higher fish guidance efficiency. Because fish guidance efficiency varies among the projects, the relative spill amounts required to achieve the standard also vary.

With respect to spill requirements, the NMFS/NOAA Proposed Recovery Plan set limits on gas saturation at 115 percent in the forebay, on a 12 hour average, or 120 percent in the tailrace for 12 hours. The Proposed Recovery Plan recognizes there are differences among projects in levels of gas saturation produced by given spill volumes, as well as an interaction between gas saturation levels at successive projects, and recommends studies to optimize spill levels within the limits set by gas saturation criteria.

Part 2. Evaluation of Fish Passage Achieved in 1995

Background

At Wells Dam the decision to operate the bypass is made by a committee of representatives of the parties to the long-term settlement agreement, based upon information from hydroacoustic monitoring at the dam. At the other mid-Columbia projects the mid-Columbia Coordinating Committee and the Rock Island Coordinating Committee are given the responsibility of implementing the requirements. In particular, because the timing of outmigration differs from year to year, the committees have the responsibility of determining when the first 10 percent of the outmigration has appeared in order to commence the spill programs, for interrupting it if the data suggest it, and for terminating bypass operation and spill when appropriate.

Achievement of FERC Requirements for Fish Passage and Spill in 1995

Wells Dam

In 1995, the bypass system at Wells Dam was operated on the agreed upon schedule. It is therefore reasonable to conclude that 89 percent of the juvenile salmonids were passed during the spring and summer migrations.

Rocky Reach Dam

Spill was provided at Rocky Reach Dam in the amounts specified for the spring and summer periods. Using the spill effectiveness curve developed for Rocky Reach Dam, an estimate of 10 percent fish passage can be obtained with 15 percent spill in spring and 6.6 percent fish passage with 10 percent spill in summer.

Rock Island Dam

The spill amount required can vary from day to day, because the formula in the FERC order depends upon the distribution of the load between the first and second powerhouses. The order requires spill of 10 percent of the flow volume through the second powerhouse and spill of 50 percent of the flow through the first powerhouse. In 1995, spill amounted to 17 percent of the daily average flow in spring and 3.3 percent in summer. According to the spill effectiveness curve, an estimated 27 percent of the migrants were passed in spill in the spring and a small percentage in summer. These estimates do not take into account an estimated additional 5 to 10 percent of the migrants at the second powerhouse that enter the gatewells and are passed to the tailrace through the gatewell conduit.

Wanapum and Priest Rapids Dams

In 1995, based on past experience at Wanapum and Priest Rapids dams, the mid-Columbia Coordinating Committee agreed upon a schedule for a fixed number of days (35) of spill. The schedule included an option to apply for additional days if it appeared that 80 percent of migrating juvenile salmon had not yet passed the projects, as required by FERC.

In 1994 and 1995, the committee found itself in a conflict at Wanapum and Priest Rapids dams between the FERC order to spill for fish passage and limits on spill because of water quality standards set by the Washington State Department of Ecology. The FERC order called for sufficient spill to achieve 70 percent fish passage during 80 percent of the spring outmigration and 50 percent for the summer at Wanapum and Priest Rapids dams. This could not be achieved because of limits on gas supersaturation set in the special permit issued by the Washington Department of Ecology. The permit allowed Grant County Public Utility District to exceed the normal limit of 110 percent gas saturation in the river below the projects, but maintain it below 120 percent. In 1994, some exploratory manipulations of spill levels were required to comply with the limit on gas saturation. Spill of 17 percent of the daily average river flow for 24 hours a day for 47 days was provided at Wanapum Dam in the spring and spill of 14 percent for 14 hours a day for 63 days was provided in the summer in 1995. At Priest Rapids Dam spill of 17 percent for 24 hours a day for 47 days was provided in spring and spill of 14 percent for 14 hours a day for 63 days was provided in the summer in 1995.

The FERC requirement for 50 percent fish passage in the summer at Priest Rapids was achieved by spill at that project in 1995, when 62 percent of the fish were passed.

Failure to Achieve FERC Goals for Fish Passage in 1995 at Wanapum and Priest Rapids Dams

Wanapum Dam did not achieve the FERC requirements of 70 percent fish passage in the spring and 50 percent in the summer. Fish passage was 52 percent in the spring and 25 percent in the summer. At Priest Rapids Dam, fish passage in the spring was 54 percent, which did not meet the FERC requirement of 70 percent. The fish passage requirements were not reached, except at Priest Rapids in the summer, because spill was limited to avoid gas supersaturation.

Failure to Achieve NPPC Goals or NMFS/NOAA Goals for Fish Passage in 1995

Background

Our discussion focuses on the question whether the NMFS/NOAA goals were achieved in 1995, as an example, or whether they are likely to be achieved in the future. We focus on the NMFS/NOAA goals because those goals are more stringent in one way than the NPPC goals. The NMFS/NOAA goals take into account differences in fish guidance efficiency between spring and summer.

To attempt to achieve the NMFS goal of 80 percent fish passage, spill was required at the four lower Snake River dams from April 10 through June 20, and at the lower Columbia River dams from April 20 through June 30. The spill was to be in sufficient amounts to make up the difference between what could be accomplished with the fish guidance efficiency of the intake screens or sluiceways at the given project and the 80 percent goal, taking into account spill effectiveness at the project as well. (NMFS/NOAA, 1995 p. V-2-31.) The required spill amounts are larger than those in the 10 year spill agreement that was reached according to NPPC requirements that were previously discussed and shown in Table B.1. The Proposed Recovery Plan set an upper limit on spill to be determined by dissolved gas concentrations. Spill was to be reduced at a project whenever a 12 hour average of total dissolved gas concentration exceeded 115 percent in the forebay of any project or 120 percent at the tailrace.

The Proposed Recovery Plan provided an exception during periods of low flow, during which there was to be no spill at certain projects in order to divert more fish into bypass systems where they could be transported by barge to below Bonneville Dam for release. The three lower Snake River projects, Lower Granite, Little Goose and Lower Monumental, were designated as “collector dams” where the focus was to be on transportation of smolts by barge as long as river flows remained below specified limits. Low flow was defined at Lower Granite Dam when the projected unregulated weekly average flow there is less than 100 kcfs or less than 85 kcfs. At flows from 85 kcfs to100 kcfs no spill should occur at Lower Granite Dam. At flows less than 85 kcfs no spill should occur at Lower Granite, Little Goose or Lower Monumental dams. The Proposed Recovery Plan provides for exceptions if the Technical Management Team (TMT) so recommends. The team is made up of representatives of NMFS, Corps, BPA, Bureau of Reclamation, and the U.S. Fish and Wildlife Service. The plan also specifies that the team’s recommendations should consider the need for a credible evaluation.

In 1995, flow at Lower Granite Dam was beneath the specified 85 kcfs in the period from April 10 to May 2 (FPC, 1995). Spill began at Lower Granite Dam on May 3, 1995, when flow exceeded 100 kcfs, as provided for in the Proposed Recovery Plan. However, at Little Goose Dam spill began on April 14 and continued through May 2 at a level averaging 24.1 percent of the river flow during the period specified for no spill. At Lower Monumental Dam spill began on April 14 and continued through May 2, averaging 16 percent of the river flow during the time period specified for no spill (spill data courtesy of Fish Passage Center). Thus, in 1995, Little Goose and Lower Monumental dams were not operated as collector dams for transportation of juvenile salmonids, contrary to what is called for in the Proposed Recovery Plan. Probably, this was brought about by evaluations by the Technical Management Team of the flow forecast for Lower Granite Dam, rather than the actual flow.

Specific Requirements for Spill

Spill requirements, as applied by NMFS/NOAA, vary with the mix of yearling and subyearling chinook, steelhead, and sockeye, because the fish guidance efficiency varies among the species. Values for yearling chinook and steelhead are much higher than sockeye and subyearling chinook. A further complication is that yearling chinook and steelhead are early emigrants, with sockeye somewhat later, while subyearling chinook, though present through the season, predominate among the later emigrants (Fish Passage Center Annual Reports). For setting spill levels required to achieve the 80 percent passage goal, the Proposed Recovery Plan uses two standard sets of fish guidance efficiency levels, one for spring and one for summer. These standards were adopted by NMFS/NOAA using what was judged to be the best available information (Detailed Fishery Operating Plan, 1993, according to FPAC, 1995), Table B.2. The fact that these "standard" values of fish guidance efficiency are higher in the spring period than in the summer might suggest that more spill would be required in the summer in order to achieve the 80 percent fish passage goal in summer. This refinement would lead to a situation that calls for more relative spill later in the season when water is in shortest supply. To circumvent this problem the Proposed Recovery Plan specifies that there should be no spill for summer migrants at Lower Granite, Little Goose, Lower Monumental, or McNary dams. The first three are named as the “collector dams”, as described above, where the emphasis is to be on collection of fish for transportation in the barges. The Proposed Recovery Plan also identifies a "spill cap" of 75 kcfs at Bonneville Dam to reduce adult fallback.

Table B.2. Standard Fish Guidance Efficiency Used in 1995 by NMFS/NOAA to Calculate Spill Needed to Achieve 80 Percent Fish Passage. (Personal communication, Tom Berggren, Fish Passage Center). The values to be used for 1996 (shown in parentheses) will be somewhat higher in response to installation of extended screens at Lower Granite, Little Goose, Lower Monumental and McNary dams. (Source: Memo of Margaret Filardo, Fish Passage Center, to FPAC, January 18, 1996)

Project:	**L. Granite**	**L. Goose**	**L. Monumental**	**Ice Harbor**
4/10-6/20	.50 (.57)	.56 (.63)	.55 (.62)	.73
Summer	.25 (..50)	.25 (..50)	.31(..54)	.33

	McNary	**J. Day**	**The Dalles**	**Bonn. (1 & 2)**	
4/20-6/30	.70	.72	.43	.37	.44
summer	.47 (.58)	.26	.43	.10	.40

As stated in the text, estimates of fish guidance efficiency have been found to differ from project to project, and differ with other factors. These factors include the design and configuration of the apparatus, species, degree of smoltification, time of day (especially day vs. night), and the season. Therefore, we emphasize that the numbers for fish guidance efficiency shown in Table B.2. represent the judgment of those involved, and are not susceptible to duplication by purely technical analysis.

Calculated Spill Amounts required in 1995 to Achieve 80 Percent Fish Passage

As mentioned previously, the amount of spill required to bring fish passage efficiency up to the 80 percent level at individual projects depends upon several factors. These factors include whether or not the project is equipped with turbine intake screens, the fish guidance efficiency of the screens, the effectiveness of ice and trash sluiceways, and the effectiveness of spill in passing fish. In the absence of better information, calculation of the amount of spill required assumes a 1:1 relationship between the percentage of total river flow that is spilled and the percentage of fish that are passed in spill at each project. (See text for a critique of this assumption.) Spill levels calculated in this way, i.e. with the fish guidance efficiencies from Table B.2 judged to be the applicable ones, and with an assumption of a 1:1 spill effectiveness relationship, are those required to achieve the NMFS/NOAA bypass goals, Table B.3.

The complexity of attempting to manage spill levels to attain a passage goal is illustrated in examples A and B in Table B.3. Method A is the simplest. It uses the fish guidance efficiency judged to be applicable over all species and conditions, as given in Table B.2. The estimation procedure is explained in the footnote in Table B.3. Method B depends upon the fish guidance efficiency judged to be applicable for each project and for each stock of chinook. Spill levels are determined for a 12 hour night period during which a higher percentage of fish are expected to pass and during which there is expected to be less demand for power. Method B then calculates what that total spill volume over 12 hours would amount to relative to a 24 hour period of flow. Method B was used in The Detailed Fishery Operating Plan of the Agencies and Tribes (Detailed Operating Fishery Plan, 1993).

To determine how much spill should be required to achieve the goals by Method A, we needed to assume a 1:1 relationship of percentage of river flow spilled to the percentage of fish passage, except at John Day and The Dalles, where specific information is available. (See text, and Magne, et al. 1987, and Willis, 1982.) Sluiceway passage, where present, is included within the 80 percent passage. Sluiceway passage at Bonneville Dam is not included. More information is needed there. Method B assumes a 1:1 relationship at all projects.

Table B.3. Spill Amounts (As a Percentage of Total River Flow) Calculated to be Required for 80% Fish Passage

Method A. Method B. Numbers from DFOP (1993)

Project	Spring Spill (%)	Summer Spill (%)	Spring Chinook Spill (%)	Fall Chinook (Summer Migrants) Spill (%)
Lower Granite	60	73	39	49.5
Little Goose	54	73	24	49.5
Lower Monumental	56	71	27	50
Ice Harbor	26	70	47	47
McNary	33	62	24	45
John Day	36*	73*	17.5	42
The Dalles	31*	31*	40	40
Bonneville I	68	77	68	77
Bonneville II	64	67	(powerhouse should not operate)	

* For John Day and The Dalles dams, spill effectiveness curves were used in method A. They differ from the 1:1 relationship assumed for the other projects and for method B.
**Spill percentages required for Method A were calculated from the equation $0.8N = NX + (FGE)(N-NX)$, where N is the number of downstream migrants, and X is the spill percentage required to provide 80 percent fish passage. Percentages for John Day and The Dalles were adjusted according to their spill effectiveness curves.
***If mortality rates of 2 percent in spill and 2 percent in bypass systems are assumed, along with an assumed 11 percent mortality in turbines, the total survival at each project, with 80 percent fish passage would be a little over 95 percent.
****The spill amounts that will be required in 1996 to achieve the 80 percent passage goal, with new extended screens in place, have been calculated by Margaret Filardo, Fish Passage Center. Generally, they are less than in 1995 by about 10 percent. (Memo of January 18, 1996 to FPAC).

Discussion

The primary point that emerges from Table B.2 is that there can be considerable difference in the calculations of the amount of spill required to supplement the bypass system to achieve 80 percent fish passage at particular projects. Method A estimated spill amounts required to achieve the 80 percent fish passage that were higher than method B at most of the projects, but lower at Ice Harbor and The Dalles dams. The lower estimate of spill amount required at Ice Harbor Dam in the spring using method A results from the high fish guidance efficiency value in the table. The lower estimate for spill with method A at The Dalles is due to use of the spill effectiveness curve, rather than the 1:1 assumption. Spill required at John Day is higher in method A because spill effectiveness there is less than 1:1. The spill estimates for Bonneville Dam are the same by both methods. Whether or not they would fall within the 75 kcfs cap on spill set at Bonneville by NMFS/NOAA would depend upon river flow.

The differences between methods A and B arise because of 1) differences in the assumption regarding spill effectiveness and effectiveness of the ice and trash sluiceways, 2) differences in adjustments of fish guidance efficiency made on the basis of a judgment as to the mix of stocks expected at each project, and 3) differences brought about by adjusting 12 hour night-time spill over a 24 hour period. Calculation of spill amounts is sensitive to information on spill effectiveness, and this information is not sufficient at most of the Corps projects to warrant the assumption of a 1:1 relationship. The judgment as to an appropriate adjustment of fish guidance efficiency requires predictions of all of those factors we pointed out in the text that can affect measurement of fish guidance efficiency. These factors include the performance of the bypass at the particular project, stock of fish, size of fish, degree of smoltification, time of day, and progress of the season. While it appears to be unlikely that estimates independently arrived at would coincide, the process used is a group analysis where collective judgment enters in and appears to be satisfactory to the participants.

Our analysis of diel passage in the text suggests both methods probably overestimate the amount of spill required as a percentage of river flow, for two reasons. First, spill over a 24 hour period may be nearly twice as effective as spill of the same water volume for 12 hours (based on data at Wanapum and Priest Rapids dams). Second, if surface spill is provided, it is likely that fish passage efficiency can be further increased. Further studies are needed.

Failure to Achieve Goals in the NMFS/NOAA Proposed Recovery Plan

Background

Achievement of fish passage goals can now be evaluated by comparing the spill levels actually provided with the spill levels specified in Table B.3. Method B is used here so as to be able to use the estimates of fish passage calculated by the Fish Passage Center (1995). At most of the projects in 1995, spill levels could not be increased enough to meet the 80 percent passage goal, in spite of the provision allowing gas saturation levels to 120 percent. This was true even though by 1995, five of the eight federal mainstem and Snake River projects were at least partially equipped with flip-lip spillway deflectors. See Appendix A, Table A.1.

Ice Harbor Dam was the one Corps' project where the 80 percent fish passage goal was achieved in 1995, when outages of units led to forced spill and gas saturation that exceeded the permitted limits. Fish passage goals were not attained elsewhere in the Snake River or lower Columbia River (Fish Passage Center, 1995).

Evaluation of Fish Passage Goals at Each Project

Introduction

From late May into June 1995 Snake River runoff could not be regulated within lower levels. Flows at Lower Granite, Little Goose and Lower Monumental dams exceeded powerhouse capacities. Consequently, there was "inadvertent spill" that contributed toward the goal of attaining 80 percent passage efficiency but led to exceeding the gas saturation limits (Fish Passage Center, 1995). The 115 percent criterion in the Proposed Recovery Plan was exceeded during half or more of the spill period specified in the plan. From April 10 to June 20, the criterion was exceeded at three of the four Snake River projects, Little Goose, Lower Monumental and Ice Harbor dams. For most of the April 20 to June 30 spill period, the criterion was exceeded at three of the four lower river projects, McNary, John Day, and Bonneville dams. The 120 percent criterion was also exceeded for several days at Little Goose Dam, about 10 days at Lower Monumental, about 3 weeks at Ice Harbor Dam, for several days at McNary Dam, and intermittently over the spill period at John Day Dam.

The Fish Passage Center provided spill data for the following description of operations at each project. Estimates of fish passage appear in Fish Passage Center (1995).

Snake River Projects

Lower Granite Dam

Spill at Lower Granite Dam began on May 3, when flow exceeded 100 kcfs as provided in the Plan, and extended through June 20, 1995. Spill amounted to 14.6 percent of the daily average flow. An estimated 50 to 56 percent of the fish were successfully passed through a combination of bypass facilities and spill.

Little Goose Dam

Spill began at Little Goose Dam on April 14 and extended to June 30, 1995 at 21.7 percent of the daily average flow. An estimated 60 percent of the fish were passed in the combination of bypass facilities and spill.

Lower Monumental Dam

Spill began at Lower Monumental Dam on April 14 and continued through June 28. Spill amounted to 16.6 percent of the daily average flow. The combination of bypass operation and spill passed an estimated 58 to 60 percent of the fish.

Ice Harbor Dam.

At Ice Harbor Dam, the volume of spill observed during the interval specified in the NMFS Proposed Recovery Plan amounted to 35.9 percent of the daily average flow, which exceeded the 26 percent calculated to meet the 80 percent passage goal. (Data from Fish Passage Center, 1995.) Gas saturation levels of 130 to 138 percent were recorded from May 25 to June 8 in the tailrace. The 115 percent criterion was exceeded during most of the days between April 20 and June 30. An estimated 79 to 84 percent of the fish were passed in the combination of turbine intake bypass and spill.

Lower Columbia River Projects

McNary Dam

Spill intended for fish passage began at McNary Dam on April 20 and extended through June 30, 1995. There was inadvertent spill prior to April 20, 1995 when river flows exceeded plant capacity. Spill amounted to 39.8 percent of the daily average flow in the interval from April 20 to June 30, 1995. Through a combination of bypass operation and spill an estimated 73 to 77 percent of the fish were successfully passed.

John Day Dam

Spill began on April 25 and extended through June 30, 1995 at a level of 3.8 percent of the daily average flow. Through combinations of the intake bypass system and spill an estimated 72 to 72 percent of the fish were passed.

The Dalles Dam

Spill for fish began on April 20 and extended through June 30, 1995. Spill averaged 57.2 percent of the daily average flow in that interval. An estimated 78 percent of the fish were successfully pass through combinations of the ice and trash sluiceway and spill.

Bonneville Dam

Inadvertent spill occurred from April 14 to 19, 1995. Spill for fish began on April 20 and continued through June 30, 1995. Spill amounted to 34.5 percent of the daily average flow during that period. Through combinations of bypass and spill an estimated 55 to 62 percent of the fish were passed.

SUMMARY

1. With respect to the NMFS/NOAA requirements, that apply in the Snake River and lower Columbia River, fish passage efficiencies achieved at projects other than Ice Harbor Dam were below the 80 percent called for in the Proposed Recovery Plan (Fish Passage Center, 1995).

2. Under the NMFS/NOAA requirements, highest fish passage, 78 percent, was achieved at The Dalles Dam. All of the lower river projects achieved fish passages in the 70 percent range, with the exception of Bonneville Dam at 55 to 62 percent. Snake River projects achieved fish passages in the 50 to 60 percent range, with the exception of Ice Harbor Dam, where there was excessive spill due to outages of turbines.

3. As long as limits on gas saturation restrict the volume of spill permitted at Snake River or Columbia River projects, spill cannot be used either alone or as a supplement to intake screens at levels required to achieve fish passage goals established either by FERC, the NPPC, or NMFS/NOAA at any of the 13 projects on the Snake River or Columbia River Mainstem. Exceptions include Wells Dam (no spill required) in both spring and summer, Priest Rapids Dam (spill alone) in the summer, and perhaps The Dalles (ice and trash sluiceway and spill) in spring. The flip-lip spillways that are in place at some of the Corps projects are not effective enough to circumvent the problem of gas supersaturation

4. The upper limit of 115 percent gas saturation, specified in the NMFS/NOAA Proposed Recovery Plan, can not be adhered to during normal spring runoff.

5. The calculated spill amounts in the Detailed Fishery Operating Plan depend upon an assumption (or conclusion) that there is an advantage to spilling 12 hours at night versus 24 hours a day as a benefit to power production. Our review suggests that it would be worthwhile to conduct a more detailed examination of fish passage data related to duration of spill and of surface spill versus standard spill. This examination would include analysis of costs and benefits to the power system in various scenarios of spill duration. The goal of the examination would be to find an optimum strategy for fish and power. Spill of a given volume of water (in acre feet) at Grant County Public Utility District projects was found to be twice as effective in providing fish passage when spread over a 24 hour period as when the same number of acre feet was used over a 12 hour period.

6. Spill effectiveness curves are needed for the Corps' projects, in order to calculate the spill amounts needed to achieve the 80 percent fish passage goal. Current practice of assuming a 1:1 relationship between percentage of the river spilled and percentage of fish passed could lead to significant error. At John Day Dam, the effect would amount to a difference in fish passage of about 10 percent less fish passage at spill levels around 50 percent of river flow. At The Dalles Dam, where spill is more effective, 20 percent spill gives about 50 percent fish passage (Willis, 1982).

DISCUSSION

At the so-called collector dams, Lower Granite, Little Goose and Lower Monumental dams, the 80 percent fish passage goal in 1995 presumably applied after May 3 when flows exceeded 100 kcfs. At Lower Granite Dam, if we consider that 49 days remained out of the total 68 day period, then the estimated 50 to 60 percent fish passage over the season might be considered to represent perhaps 76 percent fish passage during the time when flows exceeded 100 kcfs and the dam was operated for in-river passage. On the other hand, the early starts of spill at Little Goose and Lower Monumental Dams, where only four days were without spill, would lead to negligible adjustments in the estimates of fish passage (58 to 60 percent) at those projects.

In years when river flow exceeds generating capacities at the Snake River projects (780,000 kilowatts at Ice Harbor and 930,000 kilowatts at the others), or plant capacity is reduced due to outages of turbines, there will be inadvertent spill which at some point will reach levels sufficient to achieve the fish passage goals. However, this will be at the expense of juvenile salmonid mortality caused by gas supersaturation. There is a need for more information on this subject.

Although laboratory studies and studies of captive fish held in the river would have predicted juvenile salmon loss caused by high gas saturation levels measured in the Snake River, recoveries of PIT-tagged smolts led to estimates of survival from the tailrace at Lower Monumental Dam to the McNary Dam tailrace. These survival estimates were 84 percent from April 27 to May 10, 98 percent in the interval from May 11 to May 24, and 100 percent in the interval from May 25 to June 11 (Fish Passage Center, 1995). At Ice Harbor Dam, during those three periods, average daily spill was 35.1, 38.2 and 43.5 percent of the flow. At McNary Dam spill was 39.6, 44.3 and 43.0 percent of river flow. Gas saturation levels were above 120 percent for three of those weeks at Ice Harbor Dam, for several days at Little Goose Dam, 10 days at Lower Monumental Dam, and for several days at McNary Dam, as described above. (Fish Passage Center, 1995). Contrary to expectations the survival of smolts in this river reach was high and did not decrease as the percentage of spill increased.

The NMFS/NOAA Proposed Recovery Plan states that the spill program it specifies is experimental. The Proposed Recovery Plan also calls for study of gas saturation. In view of the Fish Passage Center analysis showing high survival of smolts from Lower Granite to McNary Dam during high spill episodes in the Snake River in 1995, we believe further consideration of the limits are in order. Specifically, a study should be designed that measures survival of smolts from upper river to lower river projects under varying volumes of spill relative to river flow. The study could be like the Fish Passage Center study that used data available from the NMFS Snake River survival study.

NMFS/NOAA requirements for spill are founded upon a conclusion that the rate of survival of juvenile salmonids in spill is 98 percent. (Personal communication, Tom Berggren, FPC.) If the 80 percent fish passage goal is achieved, survival at each of the projects would probably be about 95 percent. If 90 percent survival were taken as the primary criterion, rather than 80 percent fish passage efficiency, then less spill would be required. As an example, we can calculate the mortality at McNary Dam for an 80 percent fish passage goal using 33 percent spill as was previously used. Additional assumptions include 11 percent mortality of smolts in turbines, 2 percent mortality in the bypass, 2 percent mortality in spill and 70 percent fish guidance efficiency for the spring.

Then mortality at the project would be estimated as 2.2 percent in the turbines, (0.70 X 0.67 = 0.469; 0.67 - 0.469 = 0.201; 0.201 X 0.11 = 0.022): perhaps 0.6 percent in spill, (0.33 X 0.02 = 0.006), and 0.9 percent in the bypass (0.469 X 0.02 = 0.009), for a total of 3.7 percent mortality at the project. The 90 percent survival criterion of NMFS/NOAA would thus be exceeded by means of the 80 percent fish passage criterion. However, this estimate does not include mortality in the reservoir.

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Determining the Effect of Shear Stress on Fish Mortality during Turbine Passage

Researchers quantified the effects of shear stress on fish passing through Kaplan turbines by combining data from laboratory tests, computational fluid dynamics modeling, and field studies. The results of this research are helping to reduce mortality of fish passing through turbines.

By Glenn F. Cada, Laura A. Garrison, and Richard K. Fisher, Jr.

A continuing environmental concern for hydroelectric power production is injury and mortality to fish passing through the turbines. Depending on the turbine design, fish mortality during passage can range from 5 percent to more than 30 percent.[1] Improving the survival of turbine-passed fish can preserve or restore fish stocks while maintaining an important source of renewable electricity.

For more than a decade, the U.S. Department of Energy's (DOE) Hydropower Program supported the development of "environmentally friendly" turbines — i.e., turbines that emphasize environmental attributes such as fish passage survival. Research in this field included laboratory bioassays (to measure fish responses to expected conditions inside turbines), computational fluid dynamics (CFD) modeling (to extend the results of bioassays to unstudied conditions), and field testing (to evaluate new turbine prototypes).

Integrating the results of these studies provides an opportunity to address concerns about the potential for shear stress to injure turbine-passed fish. Details are available on this approach,[2] and the underlying test reports are on the DOE Hydropower Program website (http://hydropower.inel.gov).

Glenn Cada, PhD, research staff member in the Environmental Sciences Division of Oak Ridge National Laboratory, helped design and interpret the laboratory fish tests. Laura Garrison, PhD, is assistant professor of mathematics with York College of Pennsylvania. Richard Fisher, Jr., P.E., is senior vice president with Voith Siemens Hydro Power Generation. Garrison and Fisher carried out the computational modeling.

Mechanisms for fish injury during turbine passage

Fish passing through hydroelectric turbines can be injured or killed as a result of rapid and extreme pressure changes, cavitation, strike, grinding, turbulence, and shear stress.[3,4] Until recently, little was known about the distribution and magnitude of these injury mechanisms within turbines.[5] Of these, the effects of the related phenomena of shear stress and turbulence have been the most difficult to gauge.

Briefly, fluid stresses result from forces acting on an area, such as a fish body. The components of the force that are parallel to the surface area create shear stress. These fluid forces are normally a result of changing velocity within a flow field and/or turbulence. Shear stress is most obvious where two masses of water moving in different directions intersect, or where moving water slows near a solid structure.

In most natural environments, shear stresses are small and non-damaging. However, potentially lethal levels of shear stress can occur where rapidly flowing water passes near structures such as dam spillways, internal structures of hydroelectric turbines, pipelines, and canals.[4] Relative scale is important. High levels of shear stress are less damaging if they occur at a scale much smaller than the size of the fish.

The effects of shear stresses on turbine-passed fish are poorly known because of the difficulties in determining their magnitudes and distributions within hydroelectric turbine systems, then recreating these scenarios in a controlled laboratory environment. Limited laboratory and field observations suggest these fluid forces can cause descaling, tearing or bruising of tissues, and even decapitation of fish.

Methods to quantify shear stress

By coupling the findings of shear stress bioassays with CFD modeling of a turbine environment, we were able to make predictions regarding the locations and extent of potentially damaging shear stresses within a common type of turbine. Comparing the resulting model predictions to estimates of injury and mortality for field tests at an operating turbine illustrates an approach for systematically evaluating and mitigating the effects of turbine-passage stresses.

Laboratory bioassays

Bioassay data for this study came from a series of experiments where juvenile fish were exposed to a high-velocity, submerged jet in a large laboratory test flume.[6] Water entered the flume through a circular nozzle at velocities ranging from 0 to 23 meters per second. Contact with the boundary of the jet exposed the fish to average rates of strain (shear) up to 1,185 per second. The values of shear that caused minor injuries, major in-

Table 1: **Comparison of Mortality of Juvenile Coho Salmon Passing Two Regions of a Kaplan Turbine at Wanapum Dam**[1]

	Hub Passage Region		*Mid-Blade Passage Region*	
Turbine Flow (in cubic meters per second)	*Percent of Flow above Shear Stress Threshold*	*Mortality (%)*	*Percent of Flow above Shear Stress Threshold*	*Mortality (%)*
255	0.001	10.3	0.068	5.1
311	0.007	7.6	0.022	3.2
425	0.025	5.2	0.125	0.0
481	0.048	11.5	0.069	3.2

Note:

[1] The mortality percentages listed in the table come from *Fish Survival Investigation Relative to Turbine Rehabilitation at Wanapum Dam, Columbia River, Washington*, Report prepared by Normandeau Associates Inc., J.R. Skalski, and Mid Columbia Consulting Inc. for Grant County Public Utility District No. 2, Ephrata, Wash., 1996.

juries, or mortalities were estimated using logistic regressions. Injuries and mortalities caused by shear stress were related to the species of the fish and also to its orientation when contacting the jet. Fish that were struck head first by the jet suffered fewer descaling and tearing injuries that fish struck from behind.

Strain rates estimated in the laboratory experiments were converted to shear stress values.[7] The conditions under which minor injuries (such as descaling) to fall chinook salmon were first observed (jet velocity of 9.1 meters per second and strain rate of 517 per second) were used as a threshold value for CFD estimates of damaging fluid stresses within a turbine. The resultant shear stress value of 1,600 Pa (Pascals), the maximum shear stress corresponding to a strain rate of 517 per second, was taken as a threshold for fish injury resulting from shear stress inside the turbine. That is, areas within the turbine that had estimated shear stress values greater than 1,600 Pa were assumed to cause injury or mortality to fish.

CFD modeling

Voith Siemens Hydro Power Generation used time-averaged CFD models to estimate shear stresses within a Kaplan turbine at the 1,038-MW Wanapum project on the Columbia River in Washington. The flow passage was divided into three sections for this analysis: intake region (including semi-spiral case, stay vanes, and wicket gates); runner (hub and blades); and draft tube region. Details of the modeling effort are available.[2,7]

Shear stress values within the turbine were calculated for four flow rates: 255, 311, 425, and 481 cubic meters per second (cms), all at a net hydraulic head of 23 meters. These flow conditions were chosen to correspond to those used during field tests of fish passage survival at Wanapum in 1996.[8]

Field studies

For the field studies, a total of 1,278 fish were passed through a Kaplan turbine at the same four flow rates used for CFD modeling. In addition, fish were introduced into the intake at two depths from the turbine ceiling, 3 meters and 9.1 meters, to ascertain whether different paths through the turbine resulted in different survivals. Fish introduced closer to the ceiling were believed to pass through the runner near the hub, whereas those introduced at 9.1 meters were expected to pass in the mid-blade area.

A total of 21 coho salmon were recovered dead and 33 were not recovered and were assumed dead or preyed upon before recovery. Estimated mortalities ranged from 0 percent to 11.5 percent, depending on turbine flow rate and travel route. (See Table 1.) For a given turbine flow, mortality was significantly lower ($P < 0.05$) at the 9.1-meter release depth (mid-blade passage) than at the 3-meter release depth (hub passage). Surprisingly, a larger predicted volume of high shear stress seemed to be associated with lower mortality. In most cases, however, the differences in percent mortality between test conditions were not statistically significant.

Because a fish passes through all three sections of the turbine (intake, runner, and draft tube), it is impossible to assign mortalities from these field tests to shear stresses experienced in, for example, the boundary layer are expected because water velocities drop from more than 10 meters per second in the main flow to zero at the blade surface over a small lineal distance. And in the boundary layer, mechanical contact (strike) and abrasion are likely to contribute to injury as well. The high shear stresses near the blade tips and hub are caused by some of the turbine flow being "squeezed" through the small gaps and creating high-energy vortices in the wake.

Finally, the spinning runner imparts a rotational motion on the bulk of the flow. CFD analyses predict that this rotation results in a vortex with high angular velocities (and thus high values of shear stress) directly downstream from the hub. Damaging shear stress also occurs where the rotating flow below the runner strikes the draft tube support piers at a sharp angle.

The sizes of the turbine regions with shear stress values greater than 1,600 Pa were quantified and normalized by the amount of water passing that point. Adjustment for localized flow rates is necessary because velocities are not uniform across a cross section of the turbine passage. Presumably, regions with higher flow rates will expose more fish than those with lower flow rates. The sizes of areas with potentially damaging shear stress were predicted to vary not only with location but also with total turbine flow rate. (See Figure 2 on page 58.) Shear stresses in excess of the threshold value comprised relatively small percentages of the flow in the regions upstream from the runner (intake and stay vane-wicket gate region). The largest predicted volumes of water exposed to damaging shear stresses in the stay vane-wicket gate region were less than 0.2 percent of the overall flow volume.

Shear stress volumes were moderate in the runner area and were predicted to decline with increasing turbine flows. This is likely due to changes in the angle at which water approaches the adjustable blades in a Kaplan turbine. At low flow rates into a turbine, the blades are flatter, i.e., tilted at a low angle so they are more perpendicular to the flow lines. At low flows, the ratio of volume of the blade wakes (with potentially damaging shear stresses) to the overall volume of the turbine is higher. At the highest flow tested, the blades are tilted at a 43-degree angle and are better aligned with the overall water-flow streamlines.

Downstream from the runner, the predicted volumes of flow containing potentially damaging shear stresses increased greatly with increasing turbine flow rates. (See Figure 1 and Figure 2 on page 58.) Even so, the volume of damaging shear stresses accounted for no more than 1.6 percent of the total turbine flow. Turbulent shear stresses in this area occur especially in the vortex immediately below the hub and near the draft tube piers. Here, the water spreads out and slows down as it is discharged to the tailwater, in some cases impacting the draft tube support piers.

It has been suggested that severe fluid forces (e.g., shear stress) are a source of injury and mortality to hydroelectric turbine-passed fish. Laboratory studies indicated that rates of strain of as low as 517 per second can injure juvenile fall chinook salmon, and even smaller values will injure sensitive fish like American shad.[6] Converting that threshold to a shear stress value, our steady-state CFD

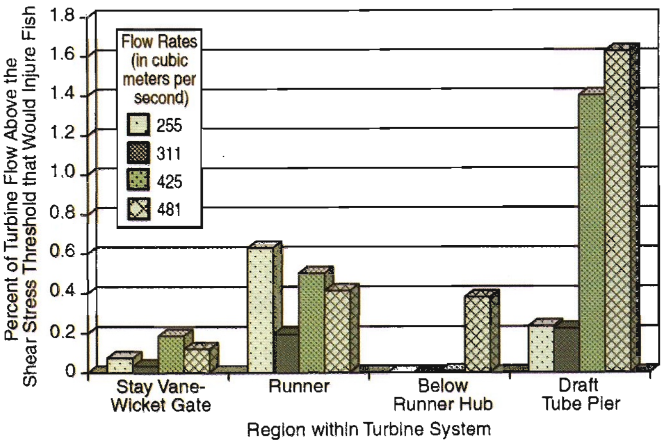

Figure 1: Researchers estimated the percent of flow through a Kaplan turbine at Wanapum Dam that exhibited shear stress values capable of injuring fish. The greatest percent of flows with damaging shear stress occurs at the draft tube pier at the two highest flows.

intake region. However, if it is assumed that fish followed the streamlines as they traveled through the turbine, the mortalities of fish that traveled through these areas can be compared to the predicted volumes of damaging shear stresses in these runner locations.

Significant differences in mortality between hub-passed and mid-blade-passed fish were detected only at the two highest turbine flows. (See Table 1 on page 54.) The highest mortality observed in this study, 11.5 percent at 481 cms, occurred among fish that are assumed to have passed through areas that are predicted to have relatively small volumes of high shear stresses along the hub but large volumes in the draft tube region below the hub. (See Figure 1.) The runner mid-blade was predicted to have larger flow-weighted volumes of damaging shear than the hub region under all flows. Contrary to expectations, mid-blade-passed coho salmon had lower mortalities than hub-passed fish under all flows, although these differences were statistically significant only for the two highest flows.

Results of combining the three methods

The CFD analyses predicted no large areas of damaging shear stress in the intake region upstream of the stay vanes at any of the four flows.[7] Small areas of shear stress above the 1,600-Pa threshold value were found in the wakes of the wicket gates under all conditions and at the entrance edge of stay vanes at higher flows.

The Kaplan runner at Wanapum was predicted to have damaging shear stress in four areas:

— Near the surface (boundary layer) of the runner blades;

— At or near the gap between the blade tips and the discharge ring that encases the runner;

— At or near the gaps where the moveable blades are attached to the hub; and

— In the wakes downstream from the blades.

Shear stresses in the first three (runner) areas vary with flow. In the draft tube downstream from the runner, shear stresses are largest at the highest turbine flow rate. High shear stresses in the

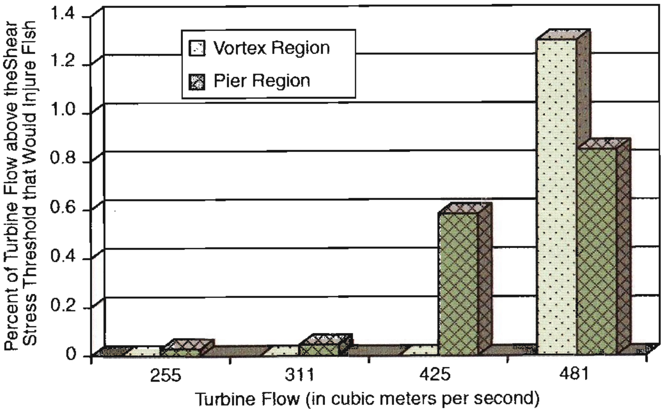

Figure 2: Researchers estimated the percent of total flow in the draft tube below a Kaplan turbine at the 1,038-MW Wanapum project that exhibited shear stress values capable of injuring fish. The greatest percent of injury occurs at the highest flow rate.

model predicted that volumes of damaging shear stress were present in small percentages of the overall flow passage. Highest values were estimated to occur in the runner and draft tube areas, and even these areas did not exceed about 1.6 percent of the volume of passage, weighted by localized flow rate.

This suggests that very large portions of the water passage through large Kaplan turbines do not exhibit shear stresses that are damaging to fish. If it is assumed that mortality resulting from this injury mechanism is proportional to the flow-weighted volumes estimated by this model, then less than 0.6 percent of the fish passing through the Wanapum turbine would be killed by shear stresses under most of the flows tested.

Our findings suggest that other injury mechanisms (e.g., strike) have a greater influence on fish injury and mortality in this turbine. However, it should be remembered that fish may follow a different path through the turbine than predicted by the streamlines, and thus could have a greater or lesser exposure to threshold values of shear stress than we estimated.

Further direction for research

By integrating laboratory bioassays, CFD models, and field studies, we were able to identify areas of potentially lethal shear stresses in the regions of the stay vanes and wicket gates, runner, and draft tube. Under typical turbine operating conditions, time-averaged CFD models estimated that these dangerous areas comprise less than 2 percent of the flow path through the turbine. However, the estimated volumes of damaging shear stress in the turbine did not correlate well with observed fish mortality at Wanapum, which ranged from less than 1 percent to nearly 12 percent. Possible reasons for the poor correlation include:

— Influence of other, potentially more important injury mechanisms;

— Uncertainty about the path that fish follow through the turbine;

— Narrow range of hydraulic conditions (shear stress exposures) in the field tests;

— Uncertainty about the appropriate threshold for effects on fish; and

— Use of a steady-state, time-averaged CFD model, which may underestimate the damaging effects of instantaneous, turbulent flows.

Each of these possibilities suggests a direction for further research.

CFD models are not yet reliable for precisely predicting mortality for particular turbine systems. However, the models are useful for comparing alternative turbine designs. ■

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Effects of Turbine Operating Efficiency on Smolt Passage Survival

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Abstract.—A retrospective analysis of data on the relationship between turbine operating efficiency of Kaplan turbines and passage survival of salmonid smolts was performed. A review of a key report instrumental in establishing ±1% turbine efficiency rule for operating Snake-Columbia River hydroelectric stations found a weak association $\left(r^2 = 0.112\right)$ but also misspecification of the turbine efficiency data. At four Snake-Columbia River dams, manipulative studies were performed to investigate the relationship between turbine performance and smolt passage survival using balloon-tag release-recovery method. At all four sites, peak observed survival did not coincide with peak turbine efficiency. The difference between peak survival and survival at peak turbine efficiency was as much as 3.4%. However, at three of the four sites, peak survival was within the ±1% peak efficiency operating rule. A meta-analysis using balloon-tag survival results from 11 different hydroprojects also found no association

between relative turbine efficiency at a site and smolt passage survival $\left(r^2 = 0.0311, P = 0.2640\right)$. Recommendation is to manage turbine operations to achieve peak survival rather than focusing solely on peak operating efficiency.

Introduction

The current operating requirements for the major hydroelectric projects on the Snake and Columbia rivers is to operate turbine units within ±1% of peak operating efficiency. Both the Biological Opinion issued by the National Marine Fisheries Service (NMFS) in 1995 and the 1994 Columbia River Fish and Wildlife Program (Section 5.6D.1) have similar specifications. This operating requirement is based on the belief that "turbine survival is directly related to turbine efficiency" (Biological Opinion 1995) with highest survival rates at peak turbine efficiency. However, NMFS acknowledges that, "the precise benefits of increased turbine efficiency . . . are unknown" (Biological Opinion 1995). This empirical survival relationship is based on early investigations such as Long and Marquette (1967) and Bell (1981).

The purpose of this paper is to reexamine the evidence presented in Bell (1981) and compare it to more recent data generated by balloon-tag release-recovery studies conducted by Normandeau Associates (1994 - 2000) (Appendix A). The balloon-tag release-recovery studies include site-specific investigations where turbine passage survival was estimated at alternative operating levels at four different hydroprojects in the Pacific Northwest. Our review concludes with an extensive analysis of 49 different smolt survival studies at 14 turbine units from 11 different hydroprojects across the county. Throughout these retrospective analyses, only Kaplan turbines will be considered to enhance the comparability of the comparisons.

Historical Data

Bell (1981) compiled results on turbine passage survival of salmonid smolts and turbine operating conditions at numerous hydroelectric projects. Among these turbine operating considerations were head, turbine efficiency, discharge, and blade style. Despite the many comparisons performed in the Bell (1981) compendium, only at Big Cliff Dam in 1964 and 1966 was smolt survival regressed against turbine efficiency for Kaplan-type turbines. In the first year of study, a significant relationship was found $\left(P = 0.017, r^2 = 0.254, n = 39\right)$. During the second year of trials, no significant relationship was found between turbine efficiency and smolt survival $\left(P = 0.258, r^2 = 0.020, n = 36\right)$. Nevertheless, the combined two-year study found a significant relationship $\left(P = 0.003, r^2 = 0.112, n = 75\right)$. The combined r^2 for the study suggests only about 11% of the variation in smolt survival could be explained by the turbine efficiency. Smolt survival was investigated at turbine efficiencies thought to range from 32.7% -96% for chinook salmon smolts averaging 101 mm in length. Bell (1981) concluded, “There does not seem to be a smooth ascending and descending curve following the efficiency line of the turbines as might have been expected.” The likely reason why a curvilinear survivorship curve against efficiency was not observed was because Bell (1981) wrongly equated turbine efficiency with percent wicket-gate opening. In his analyses, he used percent wicket-gate opening as a surrogate for turbine efficiency. While percent wicket-gate opening has an effect on turbine efficiency, they are not synonymous. Nevertheless, he concluded that, “The data offer some support, however, to the hypotheses that the best points of machine efficiency should give the best points of fish passage survival.” In actuality, Bell (1981) presents no information on the relationship between turbine efficiency of Kaplan turbines and smolt passage survival.

Site-Specific Balloon-Tag Investigations

At four Snake-Columbia river projects (i.e., Lower Granite, Wanapum, Rocky Reach, and Bonneville dams), turbine operating levels were purposefully manipulated to investigate the relationship between smolt survival and turbine efficiency. All reported survival estimates were for 1-hr observed survival following the balloon-tag release-recovery trials. Details of the balloon-tag release-recovery method can be found in Mathur et al. (1996).

At Lower Granite Dam (Normandeau and Skalski 1995), a Kaplan turbine was operated at three different discharge levels of 13.5, 18, and 19 kcfs corresponding to the low end of 1%, nominally within 1%, and at a cavitation mode, respectively. Spring chinook salmon smolt (mean length 150 mm) survival was estimated to be 0.972 $\left(\hat{S}E = 0.012\right)$, 0.953 $\left(\hat{S}E = 0.013\right)$, and 0.946 $\left(\hat{S}E = 0.013\right)$, respectively (Figure 1). This six-blade Kaplan turbine was operated at 90 rpm, with a head of 98 ft. None of the survival estimates were significantly different at P = 0.05. In this study, maximum survival did not occur at peak efficiency nor was survival significantly lower under cavitation mode than $\pm$1% peak operating levels.

At Wanapum Dam (Normandeau et al. 1996), a five-blade Kaplan turbine with a speed of 87.5 rpm was operated at four different discharge levels (i.e., 9, 11, 15, and 17 kcfs) during balloon-tag trials. Coho smolts (mean length 154 mm) were released during these trials at two different locations, 10 ft and 30 ft below the turbine intake ceilings. Figure 2 illustrates the estimated turbine survival rates along with discharge and turbine efficiency levels. The study found a significant release location effect on smolt survival, and a curvilinear trend in survival rates versus discharge levels. However, peak survival at neither release location corresponded to peak turbine efficiency. Moreover, peak survival occurred outside the zone of $\pm$1% of peak efficiency (Figure 2).

At Rocky Reach Dam (Normandeau et al. 1997), balloon-tag trials were performed at two different release locations within the turbine intake (i.e., 10 ft and 30 ft below the intake ceiling) and at three different turbine operating levels of a six-blade Kaplan turbine. The turbine operated at 90 rpm with an approximate head of 92 ft. The discharge levels for the three different turbine operating levels were 8, 12, and 16 kcfs. Once again, release location had an appreciable effect on chinook salmon smolt (mean length 184 mm) survival with a curvilinear trend as a function of discharge. In this test, peak survival for both release locations did not coincide with peak efficiency (Figure 3). The efficiency curve in this test had a very gentle slope, wherein all test conditions were within ±1% of peak turbine efficiency. Consequently, while peak survival did not coincide with peak efficiency, peak survival was within the zone of ±1% of peak efficiency.

During the winter of 1999-2000, an intensive balloon-tag study (Normandeau et al. 2000) was performed at Bonneville Dam where a minimum gap runner turbine (MGR) and standard Kaplan turbine were tested with smolt survival estimated at four different operating levels (6.2, 7, 10.5, and 12 kcfs) and releases at three different locations (i.e., hub, tip, and mid-blade). Only the standard five-blade Kaplan turbine run at a speed of 75 rpm with an average head of 57 ft will be discussed here.

The survivorship profiles for the tip and mid-blade releases show strong parallelism with both profiles showing maximum survival at 10.5 kcfs. The highest efficiency tested (0.865) occurred at 7 kcfs. Again, maximum survival did not occur at peak efficiency, although maximum survival was within the zone of ±1% of peak efficiency (Figure 4a). For the hub release, maximum survival coincided with the peak efficiency level tested in the study (Figure 4b).

Additional analyses, regressing daily survival estimates against turbine operating conditions during the course of the three-month Bonneville study, were performed. No significant relationship was found between chinook salmon smolt survival (mean length 166 mm) and turbine efficiency for the hub ($P = 0.5892$, $r^2 = 0.0213$), tip ($P = 1.0$, $r^2 = 0$) , or mid-blade ($P = 0.9276$, $r^2 = 0.0005$) releases (Figure 5). Similarly, no relationships were found between smolt survival and average head, blade angle, generation level, or discharge ($P > 0.05$) during the Bonneville Dam trials.

Cross-Study Analysis

Using survival estimates generated from balloon-tag release-recovery studies from 49 different trials, from 14 different turbine units at 11 different hydroprojects, relationships between smolt survival and species, size, and turbine operating conditions were investigated. Although these studies are observational in design, they provide an additional context for making inferences between smolt survival and turbine efficiency. This exploratory investigation between turbine efficiency and smolt survival also provides little evidence to support the 1% peak efficiency rule. While smolt size had a significant relationship with turbine passage survival ($P = 0.0016$, $r^2 = 0.1930$), turbine efficiency did not ($P = 0.2640$, $r^2 = 0.0311$) (Figure 6). Other turbine conditions such as blade number ($P = 0.0260$, $r^2 = 0.1011$), speed ($P = 0.0180$, $r^2 = 0.1135$), and head ($P = 0.1145$, $r^2 = 0.0522$) appear more likely related to smolt survival than turbine efficiency.

Conclusion

The results of the Kaplan turbine studies reported by Bell (1981) show a linear trend of increased turbine passage survival with increasing turbine efficiency. This linear trend, significant in one year but not the next, was contrary to the expectations of Bell (1981), who expected a curvilinear trend for survival as efficiency peaked and then waned. The two years of survival studies at Big Cliff had a combined $r^2 = 0.112$, i.e., 11.2% of the observed variation in survival estimates related to turbine efficiency. However, in reality, Bell (1981) did not measure turbine efficiency but used percent wicket-gate opening as a surrogate which potentially explains his incongruous findings.

In more recent studies using the balloon-tag release-recapture method, smolt passage survival demonstrated the expected curvilinear trend in survival with discharge volume. However, peak observed survival did not coincide with peak turbine efficiency at Lower Granite, Wanapum, or Rock Island dams. At Bonneville Dam, peak observed survival coincided with turbine efficiency for the hub release (Figure 4b) but not for the blade-tip or mid-blade releases (Figure 4a).

The meta-analysis using the results from 11 different hydroprojects also found no relationship between turbine passage survival and turbine efficiency. Although the data are quite variable, the regression analysis was sensitive enough to detect a relationship between smolt size and turbine passage survival as well as relationships between passage survival and blade number and speed. Hence, none of the investigations reported in this retrospective analysis provide compelling evidence for a strong relationship between turbine operating efficiency and turbine passage survival. If a survival relationship does exist, the more recent balloon-tag release-recovery studies suggest a curvilinear relationship, where peak survival is not necessarily coincident with peak turbine efficiency.

At three of the four hydroelectric projects detailed in this paper, peak survival did occur within the zone of ±1% of peak turbine efficiency. Generally, the turbine efficiency curves have shallow slopes such that the 1% rule encompasses a wide range of discharge levels. In so doing, the zone of operating conditions within the ±1% of peak efficiency range will likely encompass the maximum turbine passage survival as well. As such, the 1% efficiency rule is a general truism useful in principle for managing turbine operating conditions for the benefit of smolt passage survival. However, there can be an appreciable difference between peak observed survival and the survival at peak efficiency. For example, at Bonneville Dam, the difference between peak survival and survival at peak efficiency was as much as 3.4% (mid-blade release location). This difference in survival is as great as the benefits of some mitigation efforts under consideration at hydroprojects in the Snake-Columbia River basin. The survival benefit in this case, however, can be readily achieved by simply fine-tuning the turbine operations and modifying the 1% efficiency rule. As a new generation of turbines is developed to replace existing equipment, the premise of the 1% efficiency rule needs to be carefully reexamined so that optimal operating conditions for the fisheries resource can be defined by rigorous science rather than rhetoric and repetition.

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Normandeau Associates, J. R. Skalski, and Mid-Columbia Consulting, Inc. 2000. Passage survival and condition of chinook salmon smolts through an existing and new minimum gap runner turbines at Bonneville Dam, First Powerhouse, Columbia River. Report by Normandeau Associates, Inc., for Department of the Army, Portland District, Corps of Engineers, Portland, Oregon.

Figure 1. Plots of survival estimates (and associated 95% confidence intervals) versus discharge level for a Kaplan turbine at Lower Granite Dam, WA, 1995. Shaded area indicates treatments within ±1% of peak turbine efficiency.

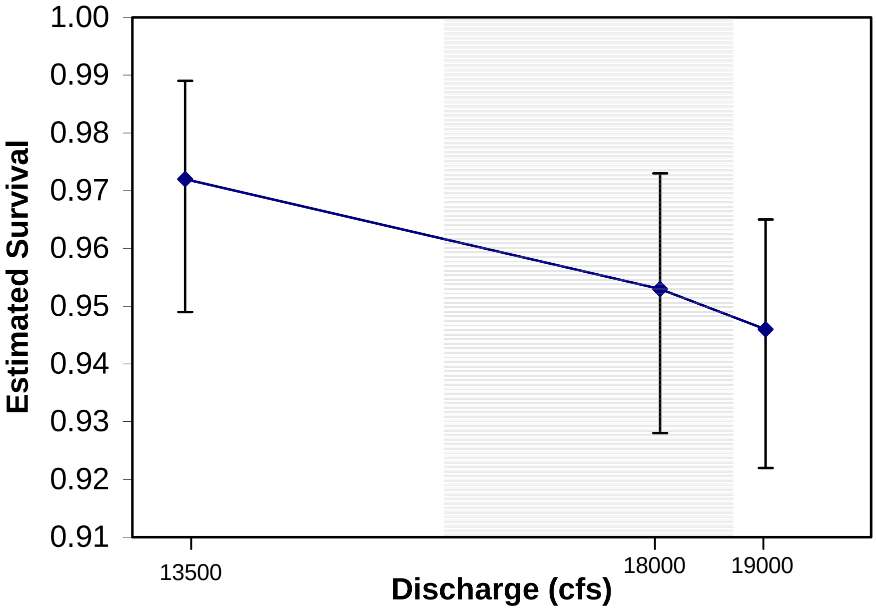


Figure 2. Plots of estimated smolt survival at Wanapum Dam, WA, as a function of release locations within the turbine intake and discharge levels (cfs). Also plotted are the turbine efficiencies as a function of different discharge levels. Shaded area is within the zone of ±1% about peak turbine efficiency.

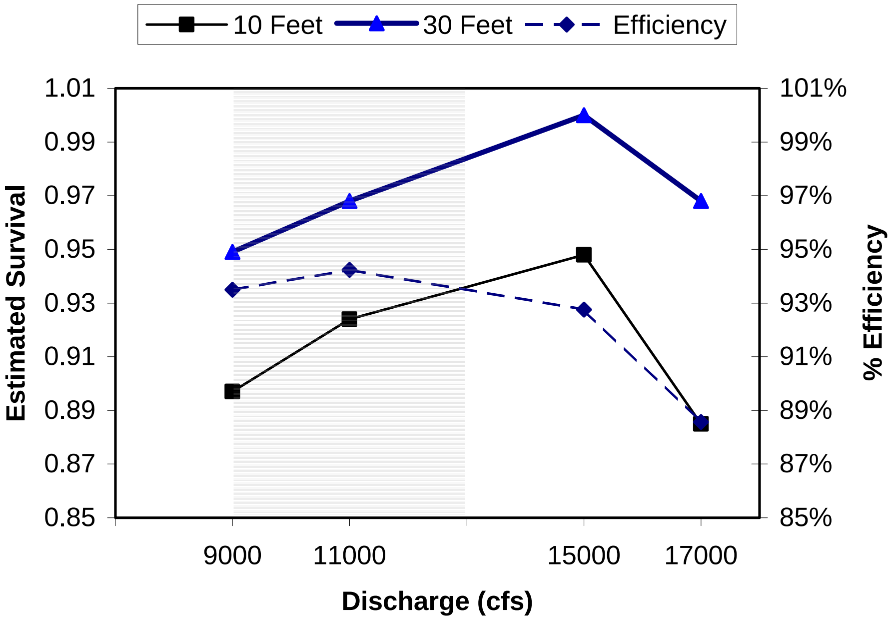


Figure 3. Plots of estimated smolt survival at Rocky Reach Dam, WA, 1996, as a function of release location within the turbine intake and discharge levels (cfs). Also plotted are turbine efficiencies as a function of different discharge levels. Shaded area is within the zone of ±1% of peak turbine efficiency.

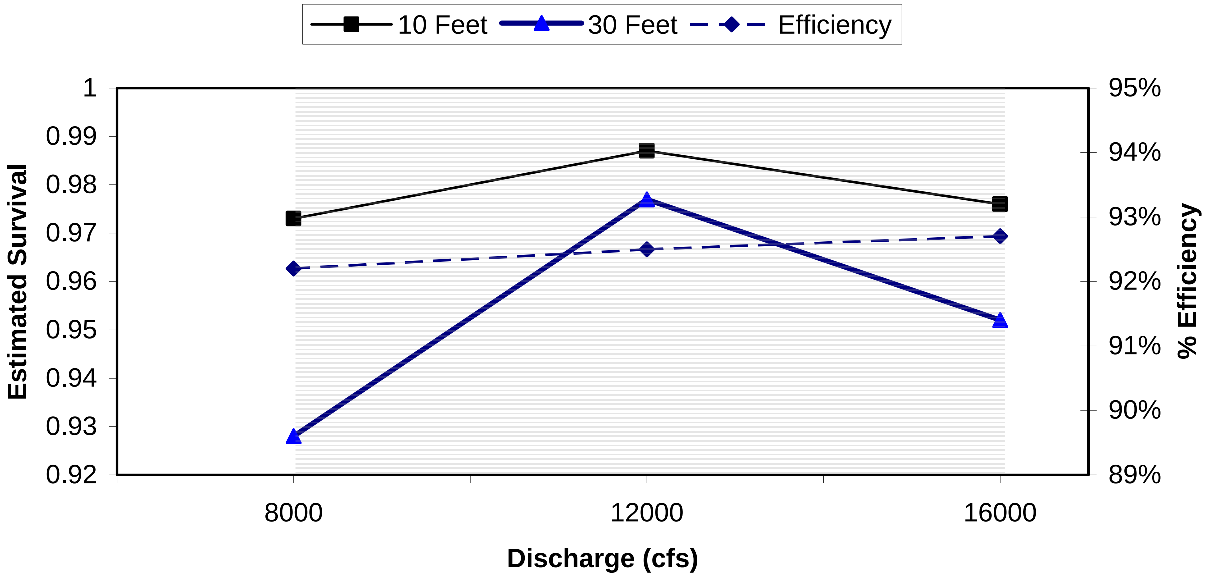
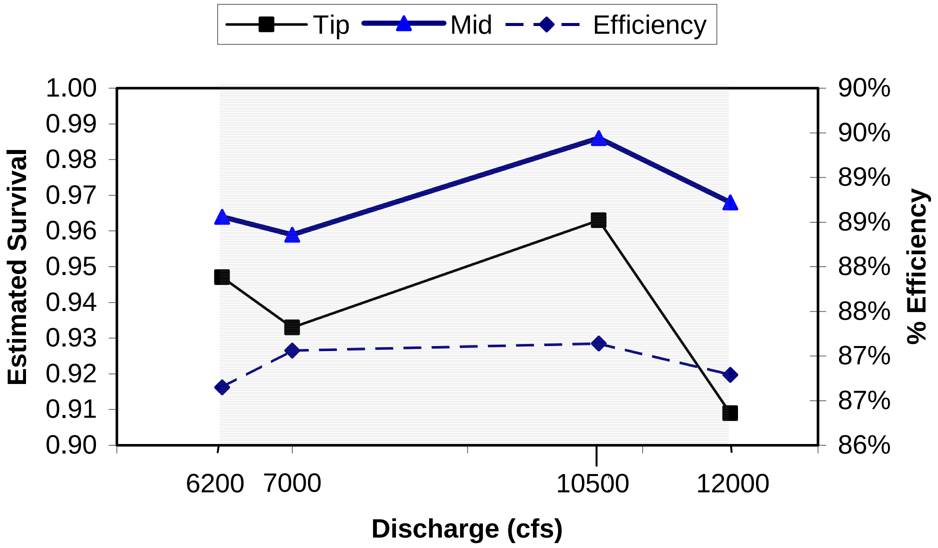


Figure 4. Plots of estimated smolt survival at Bonneville Dam, Powerhouse #1, WA, 1999-2000, as a function of release locations (a. tip and mid-blade, b. hub) within the turbine intake and discharge levels (cfs). Also plotted are turbine efficiencies as a function of discharge levels. Shaded area are within the zone of ±1% of peak turbine efficiency.

a.



b.

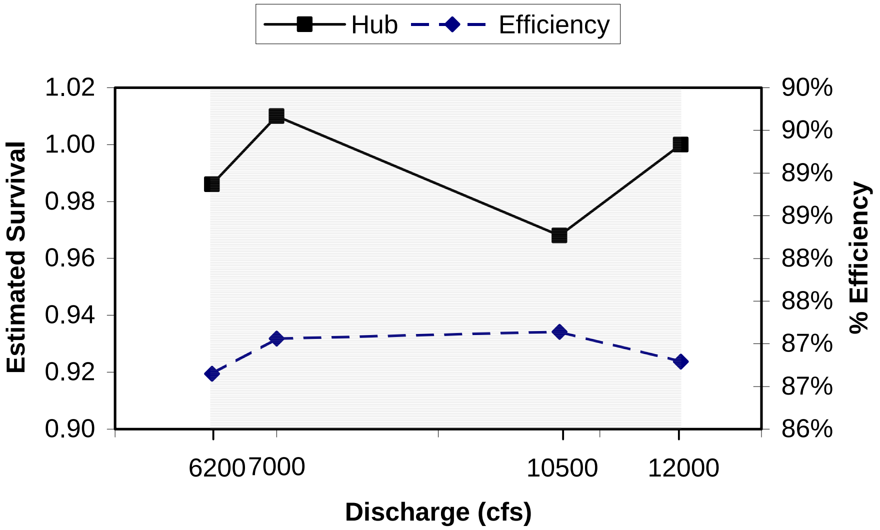
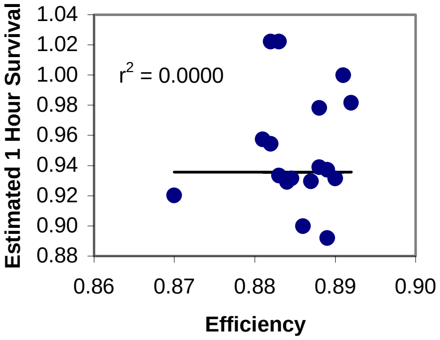
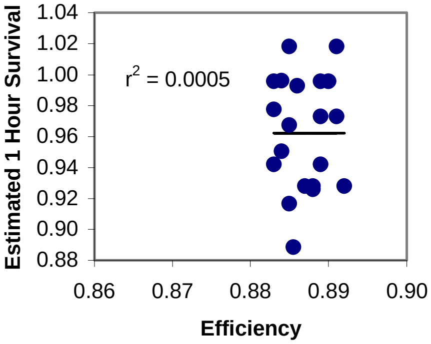


Figure 5. Scatterplots of estimated smolt survival versus turbine efficiency for the hub, tip, and mid-blade releases at turbine 5, Powerhouse #1, Bonneville Dam, WA. Horizontal lines are the mean survival estimates calculated from pooling the replicate release data.

a. Tip



b. Mid-blade



c. Hub

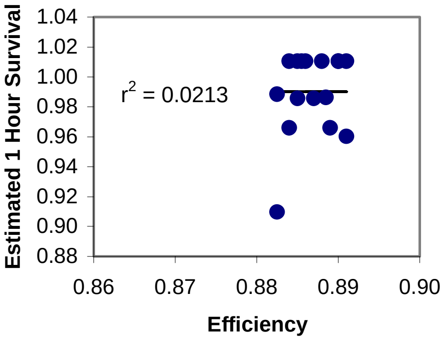
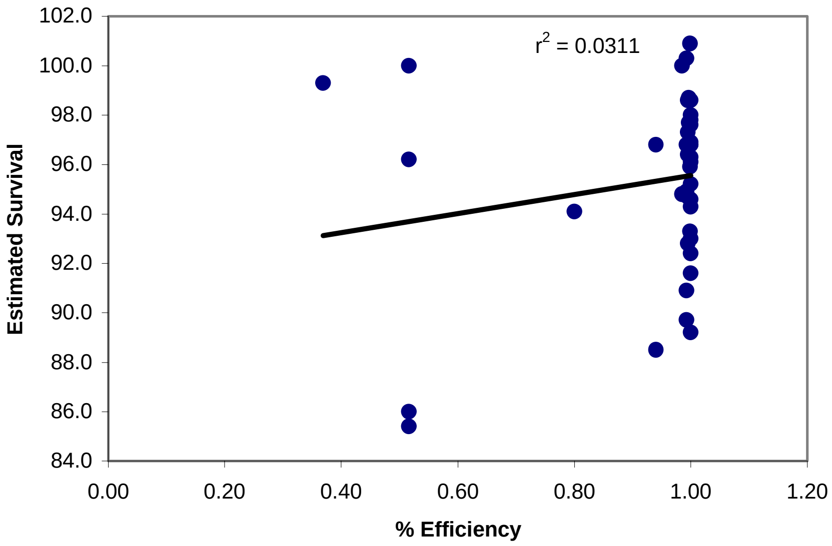


Figure 6. Scatterplot between smolt survival and turbine efficiency from studies at 11 different hydroprojects.



Appendix A

Compilation of balloon-tag release-recapture study results at Kaplan turbines distributed across the United States. Table includes turbine design factors concerning number of turbine blades, runner speed (rpm), and runner diameter as well as the turbine operating conditions at the time of trials including turbine discharge (cfs), head (ft), and relative efficiency. Species of fish, mean length, and 1-hr post turbine passage survival provided along with standard errors.

Table A. Summary of Kaplan turbine balloon-tag survival studies.

Location	Turbine Flow (cfs)	Number of Blades	Runner Speed (rpm)	Head (ft)	Runner Diameter (in)	Relative Efficiency (%)*	Species	Mean Size (mm)	% Survival 1-Hr (SE)
Chalk Hill, MI-WI	900	5	100	29	135	1.000	Rainbow Trout	220.0	89.2 (3.7)
Townsend Dam, PA	800	3	152	16	113	0.516	L.M. Bass	101.6	100.0 (NA)
“	“	“	“	“	“	0.516	L.M. Bass	215.9	86.0 (4.9)
“	“	“	“	“	“	0.516	Rainbow Trout	139.7	96.2 (2.6)
“	“	“	“	“	“	0.516	Rainbow Trout	342.9	85.4 (5.1)
Hadley Falls, MA (Unit 1)	1,550	5	128	52	170	0.369	Shad	82.0	99.3 (5.2)
Hadley Falls, MA (Unit 1)	4,200	“	“	“	“	1.000	“	“	93.0 (5.9)
Hadley Falls, MA (Unit 2)	“	“	150	“	“	1.000	“	“	91.6 (4.0)
Wilder, VT-NH	4,500	5	112.5	51	108	1.000	Salmon – Atlantic	191.0	96.1 (1.8)
Rocky Reach, WA (Unit 3)	16,000	6	90.0	92	280	1.000	Salmon – Chinook	145.0	94.3 (1.0)
Rocky Reach, WA (Unit 8)	20,000	5	85.7	86.5	311	1.000	Salmon – Chinook	130.0	96.9 (2.6)
Wanapum, WA (10 ft)	9,000	5	85.7	74.5	285	0.993	Salmon – Coho	154.0	89.7 (2.7)
“	11,000	“	“	“	“	1.000	“	“	92.4 (2.3)
“	15,000	“	“	“	“	0.985	“	“	94.8 (2.2)
“	17,000	“	“	“	“	0.940	“	“	88.5 (2.6)
Wanapum, WA (30 ft)	9,000	“	“	“	“	0.993	“	“	94.9 (2.0)
“	11,000	“	“	“	“	1.000	“	“	96.8 (1.7)
“	15,000	“	“	“	“	0.985	“	“	100.0 (1.3)
“	17,000		“	“	“	0.940	“	“	96.8 (1.4)
Lower Granite, WA	21,000	6	90.0	98	312	1.000	Salmon – Chinook	147.5	94.6 (1.0)
Safe Harbor, PA (Unit 7)	9,200	5	109	55	222	1.000	Shad	113.0	98.0 (1.4)
Safe Harbor, PA (Unit 9-unvented)	8,000	7	75.0	55	242	1.000	“	111.8	97.8 (1.5)
Safe Harbor, PA (Unit 9-vented)	“	“	“	“	“	1.000	“	117.1	96.8 (1.8)
Conowingo, MD	10,000	6	120	90	225	0.800	Shad	124.5	94.1 (4.4)
Rocky Reach, WA (Unit 5, 10 ft)	8,000	6	90	92	280	0.995	Salmon – Chinook	184.0	97.3 (1.9)
“	12,000	“	“	“	“	0.997	“	“	98.7 (1.3)
“	16,000	“	“	“	“	1.000	“	“	97.6 (2.3)

* Relative turbine efficiency standardized to percent of maximum peak efficiency within a turbine unit.

Table A. (Continued)

Location	Turbine Flow (cfs)	Number of Blades	Runner Speed (rpm)	Head (ft)	Runner Diameter (in)	Relative Efficiency (%)*	Species	Mean Size (mm)	% Survival 1-Hr (SE)
Rocky Reach, WA (Unit 5, 30 ft)	8,000	“	“	“	“	0.995	“	“	92.8 (4.3)
“	12,000	“	“	“	“	0.997	“	“	97.7 (3.0)
“	16,000	“	“	“	“	1.000	“	“	95.2 (2.3)
Bonneville, OR/WA (Unit 5, tip)	6,200	5	75	57	280	0.995	Salmon – Chinook	155.0	94.7 (1.6)
“	7,000	“	“	“	“	0.999	“	“	93.3 (1.7)
“	10,5000	“	“	“	“	1.000	“	“	96.3 (1.5)
“	12,000	“	“	“	“	0.993	“	“	90.9 (1.9)
Bonneville, OR/WA (Unit 5, mid)	6,200	“	“	“	“	0.995	“	“	96.4 (1.4)
“	7,000	“	“	“	“	0.999	“	“	95.9 (1.4)
“	10,500	“	“	“	“	1.000	“	“	98.6 (1.1)
“	12,000	“	“	“	“	0.993	“	“	96.8 (1.4)
Bonneville, OR/WA (Unit 5, hub)	6,200	“	“	“	“	0.995	“	“	98.6 (1.2)
“	7,000	“	“	“	“	0.999	“	“	100.9 (7.7)
“	10,500	“	“	“	“	1.000	“	“	96.8 (1.6)
“	12,000	“	“	“	“	0.993	“	“	100.3 (0.6)
Lower Granite, WA (Unit 4, mid, Intake A)	13,500	6	90	98	312	**	Salmon – Chinook	150	97.2 (1.2)
“	18,000	“	“	“	“	**	“	“	95.3 (1.3)
“	19,000	“	“	“	“	**	“	“	94.6 (1.3)
Lower Granite, WA (Unit 4, mid, Intake B)	18,000	“	“	“	“	**	“	“	97.5 (1.1)
Lower Granite, WA (Unit 4, mid, Intake C)	18,000	“	“	“	“	**	“	“	97.5 (1.1)
Rock Island, WA (Unit 5, PH#1)	8,000	6	100	45	226	**	Salmon - Chinook	179	97.9 (1.2)
“	8,000	“	“	“	“	**	“	“	95.7 (1.7)

* Relative turbine efficiency standardized to percent of maximum peak efficiency within a turbine unit.
** No turbine efficiencies available.

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Effects of Turbine Operating Efficiency on Smolt Passage Survival

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Abstract.—We conducted a retrospective analysis of data on the relationship between operating efficiency of Kaplan turbines and direct passage survival of salmonid smolts. A review of a key report instrumental in establishing ±1% turbine efficiency rule for operating Snake and Columbia river hydroelectric stations found a weak association ($r^2 = 0.112$) but also found misspecification of the turbine efficiency data. At four Snake and Columbia river dams, manipulative studies were performed to investigate the relationship between turbine performance and smolt passage survival, as estimated with balloon-tag releases and recoveries. At all sites, peak passage survival did not coincide with the observed turbine operating efficiency peak. The difference between maximum survival and survival at peak turbine efficiency was as much as 3.2%. However, at three sites, maximum survival was within the ±1% peak efficiency operating rule. A meta-analysis that used balloon-tag survival results from 11 different hydroprojects also found no association between relative turbine efficiency at a site and smolt passage survival ($r^2 = 0.0311$, $P = 0.2640$). For the benefit of smolt survival during passage, we recommend managing turbine operations to achieve maximum passage survival rather than focusing solely on peak operating efficiency of Kaplan turbines.

Safe downstream passage of salmonid smolts through hydroprojects is a key component of the recovery plan for Pacific Northwest stocks listed under the Endangered Species Act of 1973. Improving the prospects for safe passage have included increasing the likelihood that salmonid smolts bypass the turbine units entirely, as well as increasing the likelihood of survival of smolts that pass through the turbines. In the latter case, one approach has been to restrict turbine operation to conditions that are expected to optimize passage survival. Currently, the major hydroelectric projects on the Snake and Columbia rivers must operate turbine units within ±1% of peak operating efficiency. The Biological Opinion issued by the National Marine Fisheries Service (NMFS 1994, 2000) and the 1994 Columbia River Fish and Wildlife Program, Section 5.6D.1 (Northwest Power Planning Council 1994) have similar specifications. This operating requirement is based on the belief that ‘‘turbine survival is directly related to turbine efficiency’’ (NMFS 1994) with highest survival rates occurring at peak turbine operating efficiency. However, NMFS acknowledges that, ‘‘the precise benefits of increased turbine efficiency. . . are unknown’’ (NMFS 1994). The survival relationship used to establish this policy was based on the early investigations of Long and Marquette (1967) and M. C. Bell (U.S. Army Corps of Engineers, unpublished report). Gordon (2001) provides a review of the calculations for determining turbine efficiency.

The purpose of our investigation was to reexamine the evidence presented in Bell (unpublished report) and compare it with more recent data generated by balloon-tag releases and recoveries of salmonids conducted by Normandeau Associates (1994–2000; Appendix A). The balloon-tag studies include site-specific investigations where turbine passage survival was estimated at alternative operating levels at four different hydroprojects in the Pacific Northwest. Our review concludes with a meta-analysis of 49 different balloon-tag survival estimates from 14 turbine units at 11 different hydroprojects across the country. Throughout these retrospective analyses, only Kaplan turbines

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were considered to enhance the comparability of the comparisons. We examined Kaplan turbines because 13 of the 16 major hydroprojects on the Columbia and Snake river system use Kaplan turbines for some or all of their hydroelectric production.

Historical Data

For numerous hydroelectric projects, Bell (unpublished report) compiled results on turbine passage survival of salmonid smolts and turbine operating conditions, such as head, turbine efficiency, discharge, and blade style. Despite the many comparisons performed in the Bell compendium, only at Big Cliff Dam in 1964 and 1966 was smolt survival regressed against turbine efficiency for Kaplan-type turbines. In the first year of study, a significant relationship was found ($P = 0.017$, $r^2 = 0.254$, $N = 39$). During the second year of trials, no significant relationship was found between turbine efficiency and smolt survival ($P = 0.258$, $r^2 = 0.020$, $N = 36$). Nevertheless, the combined 2-year study found a significant relationship ($P = 0.003$, $r^2 = 0.112$, $N = 75$). For turbine efficiencies ranging from 33–96%, passage survival was investigated for chinook salmon *Onchorynchus tshawytscha* smolts averaging 101 mm long. Bell (unpublished report) concluded, ‘‘There does not seem to be a smooth ascending and descending curve following the efficiency line of the turbines as might have been expected.’’ The likely reason why a curvilinear survivorship curve with turbine efficiency was not observed was because Bell used percent wicket-gate opening as a surrogate for turbine efficiency. Although percent wicket-gate opening has an effect on turbine efficiency, they are not synonymous. Nevertheless, Bell (unpublished report) concluded that, ‘‘The data offer some support, however, to the hypothesis that the best points of machine efficiency should give the best points of fish passage survival.’’ However, we believe Bell presents no valid information on the relationship between turbine efficiency of Kaplan turbines and smolt passage survival.

Site-Specific Balloon-Tag Investigations

At four Snake and Columbia river projects (i.e., Lower Granite, Wanapum, Rocky Reach, and Bonneville dams), turbine operating levels were manipulated to investigate the relationship between smolt survival and turbine efficiency. All reported survival estimates were for 1-h observed survival following the balloon-tag release and recovery trials. The field trials consisted of paired releases of smolts that were uniquely coded and equipped with uninflated balloon tags and miniature radio tags. The test fish were released into the turbine unit though an induction tube with flowing river water; controls were concurrently released in a similar manner but into the turbine discharge. The balloon tag inflates shortly after release and, in conjunction with the radio tag, facilitates recovery. The tagged fish were released one at a time to permit downstream recovery crews to retrieve the individuals and assess their survival status. Alive fish upon recovery were held in flow-through tanks to determine their 1-h postrelease survival status. Number of tagged smolts recovered alive or dead or that escaped were counted for both turbine and control release groups. Maximum likelihood estimation was used to account for recovery efficiency and to estimate the probability of turbine passage survival. Details of the balloon-tagging and release methods and estimation procedure can be found in Mathur et al. (1996). The estimates of turbine passage survival from the analysis are functions of direct mortality and do not necessarily incorporate indirect or delayed effects associated with turbine passage.

At Lower Granite Dam (Normandeau Associates and Skalski 1995; Mathur et al. 2000), a Kaplan turbine was operated at three different discharge levels of 382.3, 509.7, and 538.0 m^3/s, which respectively correspond to discharge values at the low end of the ±1% peak efficiency, at or near peak efficiency, and at an excessive flow for the blade angle that resulted in cavitation of the turbine. Turbine cavitation occurs when the flow field is disrupted, resulting in partial vacuums that collapse, causing pitting and other damage to the metal surfaces in contact with the water. Releases through the turbine ranged from 250 to 320 fish/test condition; the corresponding control releases ranged from 250 to 320 fish/trial. Spring chinook salmon smolt (mean total length = 150 mm) survival was estimated to be 0.972 ($\widehat{SE} = 0.012$), 0.953 ($\widehat{SE} = 0.013$), and 0.946 ($\widehat{SE} = 0.013$), respectively (Figure 1). This six-blade Kaplan turbine was operated at 90 revolutions/m (rpm), with a head of 29.9 m. None of the survival estimates were significantly different ($P > 0.05$). In this study, maximum observed survival did not occur at peak observed efficiency nor was survival significantly lower under cavitation mode than within ±1% of peak operating levels.

At Wanapum Dam (Normandeau Associates et al. 1996), a five-blade Kaplan turbine with a speed of 87.5 rpm was operated at four different dis-

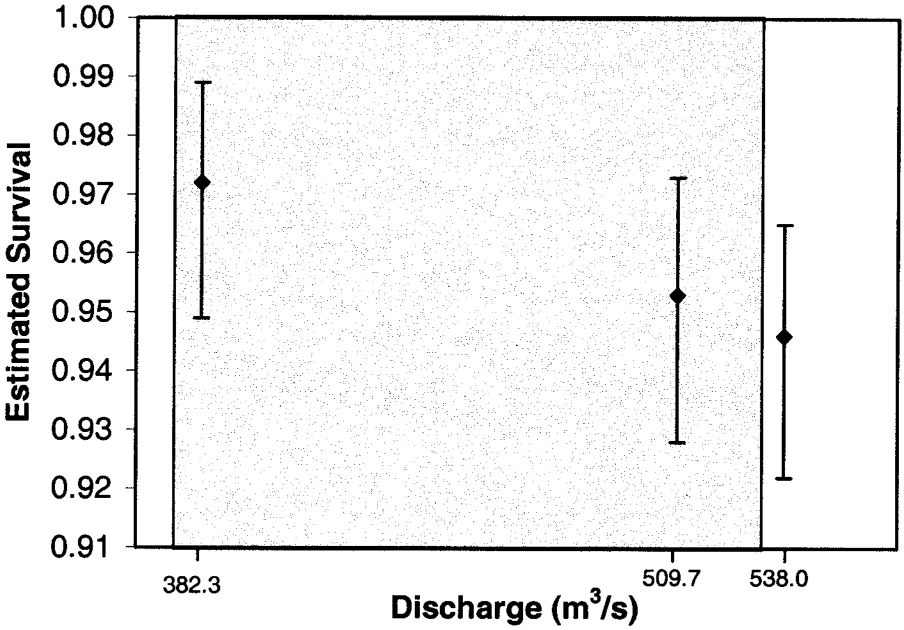

FIGURE 1.—Plots of salmonid smolt survival estimates and associated 95% confidence intervals versus discharge level for a Kaplan turbine at Lower Granite Dam, Washington, 1995. The shaded area indicates treatments that were within 1% of peak turbine efficiency.

charge levels (i.e., 254.9, 311.5, 424.8, and 481.4 m^3/s) during balloon-tag trials. Coho salmon *O. kisutch* smolts (mean total length = 154 mm) were released during these trials at two different locations, 3.0 m and 9.1 m below the turbine intake ceiling. The number of fish released through the turbine ranged from 158 to 160 per test condition; the paired control releases were 160 fish per trial. Fish released at the 9.1-m depth had consistently higher survival rates than fish released 3.0 m below the intake ceiling (Figure 2). The 3-m depth corresponds roughly to releases near the hub, whereas the 9.1-m depth corresponds to releases near the midblade, provided the fish remain in the flow lines. The release location effect ($P < 0.001$) on smolt survival was significant, as was a curvilinear trend ($P = 0.0273$) in survival rates versus discharge levels. The curvilinear survival trend with discharge is what Bell (unpublished report) anticipated but did not observe during his trials. However, the maximum observed survival did not correspond to the peak observed turbine efficiency at either release location. Moreover, the maximum observed survival occurred outside the zone of ±1% of peak efficiency (Figure 2).

At Rocky Reach Dam (Normandeau Associates et al. 1996), balloon-tag trials were performed at two different release locations within the turbine intake (3.0 and 9.1 m below the intake ceiling) and at three different turbine discharge levels of a six-blade Kaplan turbine. The turbine operated at 90 rpm with an approximate head of 28.0 m. The discharge levels for the three different turbine operating levels were 226.5, 339.8, and 453.1 m^3/s. The sample sizes for the in-turbine releases ranged from 71 to 165 fish/trial; the paired control releases ranged from 65 to 115 fish/trial. Once again, release location had an appreciable effect ($P = 0.1151$) on chinook salmon smolt (mean total length = 184 mm) survival with a nonsignificant curvilinear trend ($P = 0.1272$) as a function of discharge. Peak survival for both release locations occurred at a discharge of 339.8 m^3/s but did not coincide with peak observed turbine efficiency (Figure 3). The efficiency curve in this test had a very gentle slope, wherein all test conditions were within ±1% of peak turbine efficiency. Nevertheless, the parallelism and convex shape of the survivorship curves (Figure 3) suggest peak survival was within the range of discharge levels tested. Consequently, although peak survival did not coincide with peak observed efficiency, peak survival was within the zone of ±1% of peak efficiency.

During the winter of 1999–2000, an intensive balloon-tag study (Normandeau Assocaites et al.

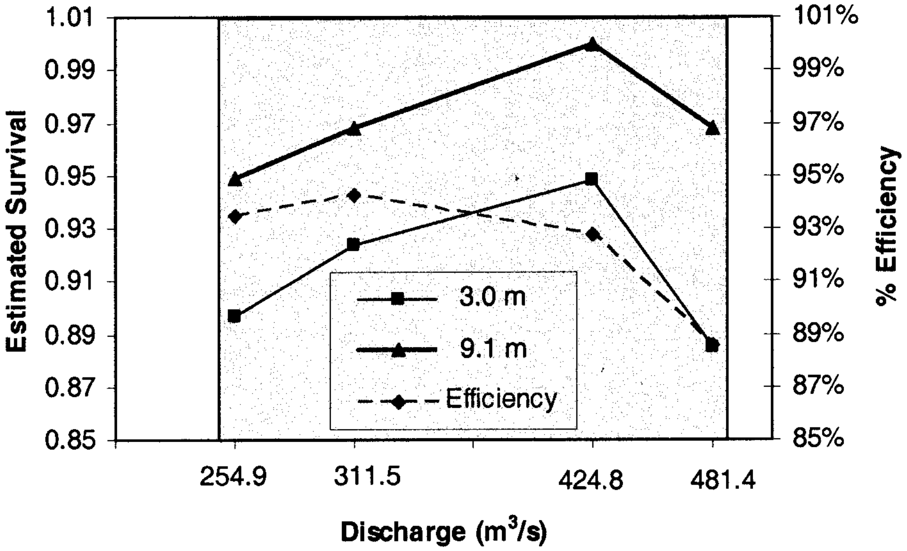

FIGURE 2.—Plots of estimated salmonid smolt survival at Wanapum Dam, Washington, in 1996 as a function of release location within the turbine intake and discharge level. Also plotted are the turbine efficiencies as a function of discharge level. The shaded area is within the zone of ±1% of peak turbine efficiency.

2000) was performed at Bonneville Dam, where at a standard Kaplan turbine, smolt survival was estimated at four different discharge levels (175.6, 198.2, 297.3, and 339.8 m^3/s) and at three different release locations (hub, tip, and mid-blade). The hub and midblade releases were 2 m and 0.9 m above the wicket gates, respectively. The tip release was 0.1 m below the wicket gate elevation. The standard five-blade Kaplan turbine ran at a speed of 75 rpm and an average head of 17.4 m. Releases through the turbine ranged from 170 to 264 fish/test condition; the paired control releases ranged from 140 to 200 fish/trial. The survivorship profiles for the tip and midblade releases show strong parallelism with both profiles showing maximum survival at 297.3 m^3/s. For the tip and midblade releases, maximum survival coincided with peak observed efficiency (Figure 4). For the hub releases, which had generally higher survival, maximum survival did not occur with peak observed turbine efficiency (Figure 4). Consequently, at Bonneville Dam, peak survival will depend on the distribution of the fish passage through the turbine unit.

Additional analyses, regressing daily survival estimates against turbine operating conditions dur-

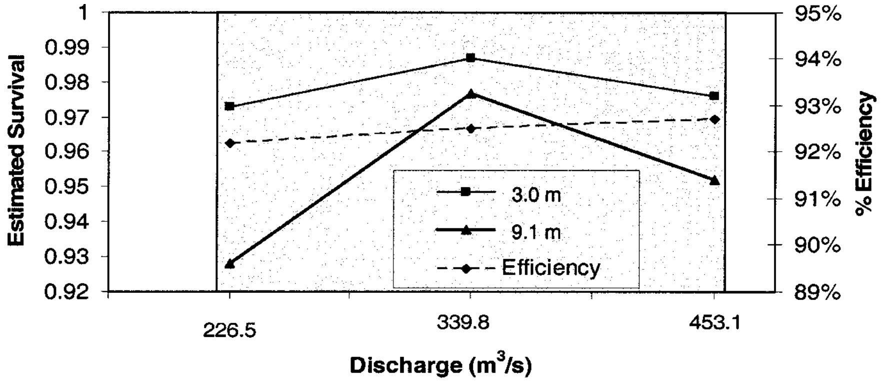

FIGURE 3.—Plots of estimated salmonid smolt survival at Rocky Reach Dam, Washington, 1996, as a function of release location within the turbine intake and discharge level. Also plotted are turbine efficiencies as a function of discharge level. The shaded area is within the zone of ±1% of peak turbine efficiency.

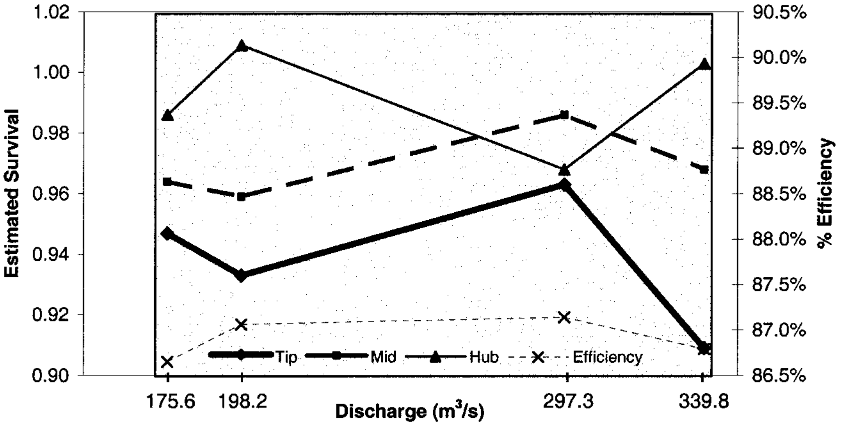

FIGURE 4.—Plots of estimated salmonid smolt survival at Powerhouse No. 1 of Bonneville Dam, Washington, 1999–2000, as a function of discharge level and release location (i.e., blade tip, midblade, or hub) within the turbine intake. Also plotted are turbine efficiencies as a function of discharge level. The shaded area is within the zone of ±1% of peak turbine efficiency.

ing the course of the 3-month Bonneville Dam study, were performed. No significant relationship was found between chinook salmon survival (mean total length = 166 mm) and turbine efficiency for smolts released at the hub ($P = 0.5892$, $r^2 = 0.0213$), tip ($P = 1.0$, $r^2 = 0$), or midblade ($P = 0.9276$, $r^2 = 0.0005$; Figure 5). Similarly, no relationships were found between smolt survival and average head, blade angle, power generation level, or discharge ($P > 0.05$) during the Bonneville Dam trials.

Cross-Study Analysis

Using survival estimates generated from balloon-tagging studies including 49 different trials, 14 different Kaplan turbine units, and 11 different hydroprojects (Appendix A), we investigated relationships between fish survival and species, size, and turbine operating conditions. Although these studies are observational, they provide an additional opportunity for examining the relationship between turbine passage survival and a wider range of conditions. This exploratory investigation between turbine efficiency and fish survival also provided little evidence to support the ±1% peak efficiency rule. Although fish size was significantly related to turbine passage survival ($P = 0.0016$, $r^2 = 0.1930$), turbine efficiency was not ($P = 0.2640$, $r^2 = 0.0311$; Figure 6). Over the range of fish sizes tested (mean total length = 82.0–342.9 mm), as fish size increased, so did turbine passage mortality. Other turbine conditions such as number of blades ($P = 0.0260$, $r^2 = 0.1011$), speed ($P = 0.0180$, $r^2 = 0.1135$), and head ($P = 0.1145$, $r^2 = 0.0522$) appear more likely to be related to fish survival than turbine efficiency. When only the data from salmonids are analyzed (Appendix A), conclusions concerning turbine efficiency remain unchanged ($P = 0.1320$, $r^2 = 0.0792$). Additional information on the relationship of blade number, rotational speed, and fish size on turbine passage survival is available in EPRI (1987).

Conclusion

The results of the Kaplan turbine studies reported by Bell (unpublished report) showed a linear trend of increased turbine passage survival with increasing turbine efficiency. This linear trend, significant in one year but not the next, was contrary to the expectations of Bell (unpublished report), who expected a curvilinear trend for survival as efficiency peaked and then waned. We contend that Bell (unpublished report) did not actually measure turbine efficiency during his experiments.

In more recent studies conducted in the Pacific Northwest using balloon-tagging and recapture, smolt passage survival demonstrated the expected curvilinear trend in survival as related to discharge volume and turbine operating efficiency. However, peak observed survival did not coincide with peak turbine efficiency at Lower Granite, Wanapum, or Rocky Reach dams. At Bonneville Dam, peak observed survival coincided with turbine efficiency for the blade-tip and midblade releases but not the hub release (Figure 4). However, the range of turbine efficiencies examined during these studies was somewhat limited. The existing turbine operating rules in the Snake and Columbia river basins do not readily permit data collection outside the ±1% narrow band of efficiency levels. Hence, inferences to turbine passage survival are limited by the very turbine operating rules we wished to test. For this reason, information outside the Pacific Northwest was also examined.

The meta-analysis using the results from 11 different hydroprojects also found no relationship between turbine passage survival and turbine operating efficiency. Although the data are quite variable and include salmonids and nonsalmonids, the regression analysis was sensitive enough to detect a relationship between fish size and turbine passage survival, as well as relationships between passage survival versus number of blaces and speed. These regression results are consistent with findings reported by EPRI (1987). Hence, none of the investigations reported in this retrospective analysis provide compelling evidence for a strong relationship between turbine operating efficiency and turbine passage survival. If a survival relationship does exist, the more recent balloon-tag studies suggest a curvilinear relationship, where peak survival is not necessarily coincident with peak turbine efficiency.

Generally, the turbine efficiency curves for Kaplan turbines have shallow slopes, such that the ±1% rule encompasses a wide range of discharge levels. In so doing, the zone of operating conditions within 1% of peak efficiency will probably also encompass the maximum turbine passage survival. As such, the ±1% efficiency rule, in the broadest sense, is a useful guide for managing turbine operating conditions for the benefit of smolt passage survival. However, there can be an appreciable difference between peak observed survival and the survival at peak turbine operating efficiency; for example, at Wanapum Dam, this difference was as much as 3.2% (9.1-m release location). This difference in survival is as great as the benefits of some other mitigation efforts under consideration at hydroprojects in the Snake and Columbia river basins (e.g., surface bypass col-

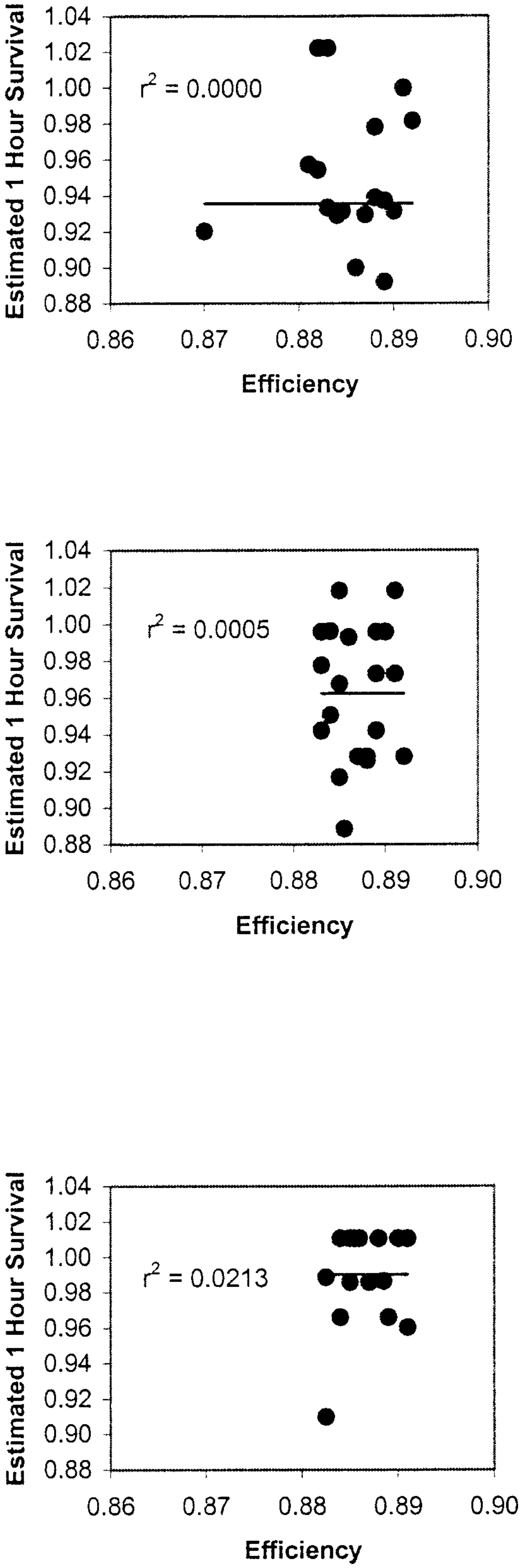

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FIGURE 5.—Scatter plots of estimated salmonid smolt survival versus turbine efficiency for the tip (top panel), mid-blade (middle panel), and hub (bottom panel) releases at turbine 5, Powerhouse No. 1, Bonneville Dam, Washington. The horizontal lines are the mean survival estimates calculated from pooling the replicate release data.

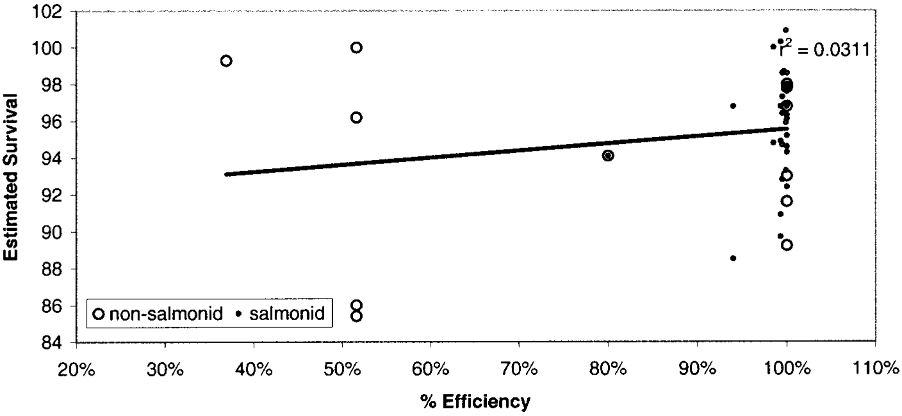

FIGURE 6.—Scatter plot of fish survival versus turbine efficiency from studies at 11 different hydroprojects. (See Appendix for details.)

lectors, diversion screens). The survival benefit in this case, however, can be more rapidly achieved, and without major new capital investment, by simply fine-tuning the turbine operations and modifying the ±1% efficiency rule. As a new generation of turbines is developed to replace existing equipment, the premise of the ±1% efficiency rule needs to be carefully reexamined so that optimal operating conditions for the fisheries resource can be better defined.

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Appendix: Summary of Kaplan turbine balloon-tag survival studies.

TABLE A.1.—Results from balloon-tagged salmonids released and recaptured in studies at Kaplan turbines across the United States.

Location	Turbine discharge (m^3/s)	Number of blades	Runner speed (rpm)	Head (m)	Runner diameter (cm)	Relative efficiency (%)[a]	Species	Mean total length (mm)	Mean (SE) % survival to 1 h
Chalk Hill, Michigan–Wisconsin	25.5	5	100	8.8	343	1.000	Rainbow trout	220.0	89.2 (3.7)
Townsend Dam, Pennsylvania	22.7	3	152	4.9	287	0.516	Largemouth bass	101.6	100.0
	22.7	3	152	4.9	287	0.516	Largemouth bass	215.9	86.0 (4.9)
	22.7	3	152	4.9	287	0.516	Rainbow trout	139.7	96.2 (2.6)
	22.7	3	152	4.9	287	0.516	Rainbow trout	342.9	85.4 (5.1)
Hadley Falls, Massachusetts (Unit 1)	43.9	5	128	15.8	432	0.369	Shad	82.0	99.3 (5.2)
Hadley Falls, Massachusetts (Unit 1)	118.9	5	128	15.8	432	1.000	Shad	82.0	93.0 (5.9)
Hadley Falls, Massachusetts (Unit 2)	118.9	5	150	15.8	432	1.000	Shad	82.0	91.6 (4.0)
Wilder, Vermont–New Hampshire	127.4	5	112.5	15.5	274	1.000	Atlantic salmon	191.0	96.1 (1.8)
Rocky Reach, Washington (Unit 3)	453.1	6	90.0	28.0	711	1.000	Chinook salmon	145.0	94.3 (1.0)
Rocky Reach, Washington (Unit 8)	566.3	5	85.7	26.4	790	1.000	Chinook salmon	130.0	96.9 (2.6)
Wanapum, Washington (3.0 m)	254.9	5	85.7	22.7	724	0.993	Coho salmon	154.0	89.7 (2.7)
	311.5	5	85.7	22.7	724	1.000	Coho salmon	154.0	92.4 (2.3)
	424.8	5	85.7	22.7	724	0.985	Coho salmon	154.0	94.8 (2.2)
	481.4	5	85.7	22.7	724	0.940	Coho salmon	154.0	88.5 (2.6)
Wanapum, Washington (9.1 m)	254.9	5	85.7	22.7	724	0.993	Coho salmon	154.0	94.9 (2.0)
	311.5	5	85.7	22.7	724	1.000	Coho salmon	154.0	96.8 (1.7)
	424.8	5	85.7	22.7	724	0.985	Coho salmon	154.0	100.0 (1.3)
	481.4		85.7	22.7	724	0.940	Coho salmon	154.0	96.8 (1.4)
Lower Granite, Washington	594.7	6	90.0	29.9	792	1.000	Chinook salmon	147.5	94.6 (1.0)
Safe Harbor, Pennsylvania (Unit 7)	260.5	5	109	16.8	564	1.000	Shad	113.0	98.0 (1.4)
Safe Harbor, Pennsylvania (Unit 9–unvented)	226.5	7	75.0	16.8	615	1.000	Shad	111.8	97.8 (1.5)
Safe Harbor, Pennsylvania (Unit 9–vented)	226.5	7	75.0	16.8	615	1.000	Shad	117.1	96.8 (1.8)
Conowingo, Maryland	283.2	6	120	27.4	572	0.800	Shad	124.5	94.1 (4.4)
Rocky Reach, Washington (Unit 5, 3 m)	226.5	6	90	28.0	711	0.995	Chinook salmon	184.0	97.3 (1.9)
	339.8	6	90	28.0	711	0.997	Chinook salmon	184.0	98.7 (1.3)
	453.1	6	90	28.0	711	1.000	Chinook salmon	184.0	97.6 (2.3)
Rocky Reach, Washington (Unit 5, 9.1 m)	226.5	6	90	28.0	711	0.995	Chinook salmon	184.0	92.8 (4.3)
	339.8	6	90	28.0	711	0.997	Chinook salmon	184.0	97.7 (3.0)
	453.1	6	90	28.0	711	1.000	Chinook salmon	184.0	95.2 (2.3)
Bonneville, Oregon–Washington (Unit 5, tip)	175.6	5	75	17.4	711	0.995	Chinook salmon	155.0	94.7 (1.6)
	198.2	5	75	17.4	711	0.999	Chinook salmon	155.0	93.3 (1.7)
	297.3	5	75	17.4	711	1.000	Chinook salmon	155.0	96.3 (1.5)
	339.8	5	75	17.4	711	0.993	Chinook salmon	155.0	90.9 (1.9)
Bonneville, Oregon–Washington (Unit 5, mid)	175.6	5	75	17.4	711	0.995	Chinook salmon	155.0	96.4 (1.4)
	198.2	5	75	17.4	711	0.999	Chinook salmon	155.0	95.9 (1.4)
	297.3	5	75	17.4	711	1.000	Chinook salmon	155.0	98.6 (1.1)
	339.8	5	75	17.4	711	0.993	Chinook salmon	155.0	96.8 (1.4)
Bonneville, Oregon–Washington (Unit 5, hub)	175.6	5	75	17.4	711	0.995	Chinook salmon	155.0	98.6 (1.2)
	198.2	5	75	17.4	711	0.999	Chinook salmon	155.0	100.9 (7.7)
	297.3	5	75	17.4	711	1.000	Chinook salmon	155.0	96.8 (1.6)
	339.8	5	75	17.4	711	0.993	Chinook salmon	155.0	100.3 (0.6)
Lower Granite, Washington (Unit 4, mid, Intake A)	382.3	6	90	29.9	792		Chinook salmon	150	97.2 (1.2)
	509.7	6	90	29.9	792		Chinook salmon	150	95.3 (1.3)
	538.0	6	90	29.9	792		Chinook salmon	150	94.6 (1.3)
Lower Granite, Washington (Unit 4, mid, Intake B)	509.7	6	90	29.9	792		Chinook salmon	150	97.5 (1.1)
Lower Granite, Washington (Unit 4, mid, Intake C)	509.7	6	90	29.9	792		Chinook salmon	150	97.5 (1.1)
Rock Island, Washington (Unit 5, PH#1)	226.5	6	100	13.7	574		Chinook salmon	179	97.9 (1.2)
	226.5	6	100	13.7	574		Chinook salmon	179	95.7 (1.7)

[a] Relative turbine efficiency standardized to percent of maximum peak efficiency within a turbine unit; where blank, turbine efficiency measurements were not available.