Draft Technical Memorandum

Literature Based Characterization of Resident Fish Entrainment and Turbine-Induced Mortality

Klamath Hydroelectric Project (FERC No. 2082)

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Introduction

J.C. Boyle, Copco, and Iron Gate Reservoirs support populations of resident fish including both native and non-native species. Popular sport fisheries occur in each reservoir targeting primarily bass, perch, and catfish. Rainbow trout, resident lamprey species, and Lost River and shortnose suckers also occur in the reservoirs.

Site-specific field studies to estimate fish entrainment and turbine survival rates are very costly and often subject to considerable uncertainty (Eicher and Associates 1992; FERC 1995). PacifiCorp is addressing this issue of entrainment and turbine mortality by reviewing existing fisheries information for the Project reservoirs and tailwaters, coupled with other entrainment and mortality studies at projects with similar fisheries and environments. The purpose of the evaluation is to characterize the potential for entrainment and to estimate turbine-induced mortality of the fish most likely to be entrained. This information can then be used in conjunction with other fisheries information for the Project area to determine if entrainment is adversely affecting fish populations. The evaluation is considered a first step by resource agencies and other relicensing participants. However, PacifiCorp at this time maintains it may be all the study that is necessary to develop appropriate mitigation measures. It is expected that the Aquatics Work Group and Fish Passage Work Group will revisit this issue once the evaluation is completed.

The Klamath River Hydroelectric Project (Project) consists of six developments on the Klamath River. This report characterizes the potential fish entrainment and mortality that occurs at four of the developments: J.C. Boyle, Copco Nos. 1 and 2, and Iron Gate. Of the other two developments, Keno Dam does not contain hydroelectric generating facilities, and entrainment estimates have previously been completed for the Link River hydroelectric developments (East Side and West Side) (New Earth/Cell Tech and PacifiCorp 1999). Although the intake to the J.C. Boyle powerhouse is already screened, it is included in the characterization. For the Copco No. 2 development, which has a small riverine-type reservoir, it is assumed that fish entrained through Copco No. 1 powerhouse will also pass through the Copco No. 2 powerhouse.

Objectives

The objectives of this review are to:

1. Characterize the potential magnitude, size composition, species composition, and seasonal distribution of the annual fish entrainment at J.C. Boyle, Copco, and Iron Gate dams
2. Develop estimates of potential turbine-induced mortality at each powerhouse by applying relevant study results from other projects with turbine types and operating characteristics similar to those at the Klamath Project
3. Evaluate whether the probable degree of entrainment mortality is adversely affecting fish populations of concern in the Project area (i.e., is screening project intakes or other mitigation measures appear biologically supportable), and

4. Use results of evaluation to determine need for additional study

Study Approach

Fish Entrainment

The general study approach for assessing fish entrainment was to apply existing study trends and data from similar projects and interpret this information in conjunction with known fisheries data for the Project reservoirs and dam tailwaters. In the past 20 years, there have been many entrainment studies conducted at dams in coolwater and warmwater environments similar to those conditions in the Klamath Project reservoirs. Although highly variable, common trends and correlations with a number of biological, environmental, and physical site conditions have been noted (FERC 1995). Potential physical factors affecting entrainment that will be addressed include reservoir size, dam height, forebay configuration, depth of intake, and water flow through the reservoir or powerhouse. Biological factors will include fish species present and those most likely to be entrained, fish size, seasonal and diurnal movements, and density dependent influences on fish movement.

Turbine-induced Mortality

A considerable amount of literature is available on the causes of injury and mortality to fish as they pass through hydroelectric turbines. Factors affecting mortality relate to the probability of physical contact with moving turbine blades, pressure changes and cavitation, and shear forces and turbulence. Information that will be used to estimate mortality rates of entrained fish at each powerhouse will include: turbine design, number of turbine runner blades, project head, peripheral runner velocity, intake depth, operating efficiency, and size of fish entrained.

Characterization of Fish Entrainment

A first step in characterizing potential fish entrainment is to identify the species of fish and their relative abundance in the reservoirs being evaluated. Extensive fish sampling was conducted in J.C. Boyle, Copco, and Iron Gate reservoirs in 1998 and 1999 by Oregon State University (Desjardins and Markle 1999). The sampling covered spring, summer, and fall seasons and included the use of six types of collection gear. Results of these studies are summarized below.

In J. C. Boyle reservoir, over 6,000 fish representing 19 species were collected (Table 1). Ten species were native (n); nine were non-native (nn). The five most abundant taxa collected were chub spp. (n), bullhead spp. (nn), fathead minnow (nn), pumpkinseed sunfish (nn), and tui chub (n).

In Copco reservoir, over 26,000 fish were collected (Table 2). Yellow perch (nn) made up 81.5 percent of those collected. Other most common taxa included sucker spp. (n), golden shiner (nn), bullhead spp.(nn), and tui chub (n). Ten of the 18 identified species were native.

TABLE 1
Species counts and percentage of total catch for fish sampled in J.C. Boyle Reservoir in 1998 and 1999 by seine, trawl, trammel and trap nets (Desjardins and Markle, 1999).

Common Name	Native/Non-Native	Number Caught	Percent of Total
Chub spp.	Native	1700	27.4%
Bullhead spp.	Non-native	771	12.4%
Fathead minnow	Non-native	722	11.6%
Pumpkinseed	Non-native	572	9.2%
Tui chub	Native	506	8.2%
Sunfish spp.	Non-native	383	6.2%
Sucker spp.	Native	269	4.3%
Sacramento perch	Non-native	221	3.6%
Crappie spp.	Non-native	198	3.2%
Blue chub	Non-native	196	3.2%
Smallscale sucker	Native	187	3.0%
Speckled dace	Native	170	2.7%
Largemouth bass	Non-native	95	1.5%
Redband trout	Native	61	1.0%
Shortnose sucker	Native	49	0.8%
Yellow perch	Non-native	47	0.8%
Cottid spp.	Native	40	0.6%
Lamprey spp.	Native	9	0.1%
Blue gill	Non-native	2	0.0%
Golden shiner	Non-native	2	0.0%
Lost River sucker	Native	2	0.0%
Largescale sucker	Native	1	0.0%
Total		**6,203**	**100.0%**

TABLE 2
Species counts and percentage of total catch for fish sampled in Copco Reservoir in 1998 and 1999 by seine, trawl, trammel and trap nets (Desjardins and Markle, 1999).

Common Name	Native/Non-Native	Number Caught	Percent of Total
Yellow perch	Non-native	26742	81.5%
Sucker spp.	Native	3077	9.4%
Golden shiner	Non-native	1123	3.4%
Bullhead spp.	Non-native	600	1.8%
Tui chub	Native	247	0.8%
Chub spp.	Native	197	0.6%
Crappie spp.	Non-native	187	0.6%
Largemouth bass	Non-native	175	0.5%
Shortnose sucker	Non-native	158	0.5%
Pumpkinseed	Non-native	85	0.3%
Unidentified spp.	Non-native / Native	84	0.3%
Blue chub	Non-native	70	0.2%
Centrachid spp.	Non-native	29	0.1%
Smallscale sucker	Native	17	0.1%
Speckled dace	Native	10	0.0%
Cottid spp.	Native	3	0.0%
Redband trout	Native	3	0.0%
Fathead minnow	Non-native	2	0.0%
Lamprey spp.	Native	2	0.0%
Largescale sucker	Native	2	0.0%
Lost River sucker	Native	2	0.0%
Sacramento perch	Non-native	1	0.0%
Total		**35,816**	**100.0%**

In Iron Gate reservoir, over 4,000 fish were collected representing 16 species, 8 of which were native (Table 3). The five most commonly collected taxa were chub spp. (n), yellow perch (nn), bullhead spp. (nn), largemouth bass (nn), and golden shiner (nn).

A second step in characterizing entrainment is to consider physical features of the reservoirs and dams that may affect entrainment rates. FERC (1995) conducted exploratory analysis of a number of physical characteristics of hydroelectric projects in an attempt to identify trends or associations between these characteristics and entrainment rates. Although the analysis indicated no strong statistically significant trends or correlations, due in part to the varying sampling methods and fish population vagaries among sites, some general trends were apparent for reservoir size, flow through the reservoir (or plant), and project head (or reservoir depth). These variables seem to relate to the potential fish abundance in the reservoir. Physical characteristics associated with the Klamath reservoirs are shown in Table 4.

The potential magnitude of annual entrainment at the Klamath Project developments was evaluated by first reviewing trends from entrainment field studies completed at hydropower projects from the late 1980s to the present (FERC 1995, 1996a, 1996b, 1997). Of about 50 projects, 26 projects were selected for review. Projects were included that had dam heights greater than 20 feet, reservoir surface areas greater than 100 acres, and reservoirs that did not contain major populations of pelagic fish, such as alewives and gizzard shad (which are known to dominate entrainment counts where they exist but are not present in the Klamath Project reservoirs). These physical characteristics were considered potentially important in covering a realistic range of conditions representing the Project reservoirs.

The 26 projects range in size from about 1.7 to 102 MW total generating capacity (Table 5); the Klamath Project developments range in size from 18 to 80 MW (see Table 1). All of the projects selected from the entrainment database were located on warmwater or coolwater river systems and most exhibit substantial overlap in the species composition of dominant resident fishes, which typically include largemouth bass, a variety of sunfishes, walleye, yellow perch, minnows, and catfishes/bullheads. Although entrainment sampling methods and analytical approaches varied considerably among the projects, all of the study plans were developed in consultation with, and in most cases approved by, state and federal resource agencies.

Potential fish entrainment at the Klamath Project reservoirs was characterized by reviewing trends from these other entrainment studies as follows:

Magnitude of Annual Entrainment - To provide a reasonable expectation of the magnitude of entrainment that could be occurring, the entrainment database presented in Table 5 was queried for median annual entrainment values for all projects combined and for several categories of projects with similar physical features. *Median* entrainment values were examined rather than *mean* values for each category to minimize the influence of outliers. To examine the relationship between annual entrainment and dam height, reservoir size, and total hydraulic capacity, each of these variables was broken into three categories for comparison.

TABLE 3
Species counts and percentage of total catch for fish sampled in Iron Gate Reservoir in 1998 and 1999 by seine, trawl, trammel and trap nets (Desjardins and Markle, 1999).

Common Name	Native/Non-Native	Number Caught	Percent of Total
Chub spp.	Native	1316	32.0%
Yellow perch	Non-native	562	13.7%
Bullhead spp.	Non-native	471	11.5%
Largemouth bass	Non-native	413	10.0%
Golden shiner	Non-native	399	9.7%
Crappie spp.	Non-native	222	5.4%
Tui chub	Native	201	4.9%
Pumpkinseed	Non-native	193	4.7%
Sucker spp.	Native	118	2.9%
Blue chub	Native	98	2.4%
Centrarchid spp.	Non-native	44	1.1%
Smallscale sucker	Native	22	0.5%
Redband trout	Native	17	0.4%
Shortnose sucker	Native	13	0.3%
Speckled dace	Native	9	0.2%
Green sunfish	Non-native	5	0.1%
Lamprey	Native	4	0.1%
Unidentified spp.	Non-native / Native	4	0.1%
Channel catfish	Non-native	1	0.0%
Fathead minnow	Non-native	1	0.0%
Total		**4,113**	**100.0%**

TABLE 4
Characteristics of J.C. Boyle, Copco No. 1, Copco No. 2, and Iron Gate reservoirs and hydroelectric intakes

Characteristics	J.C. Boyle	Copco No. 1	Copco No. 2	Iron Gate
River Mile	224.7	198.6	198.3	190.1
Dam Height	68	126	33	173
Reservoir Area (ac)	420	1,000	40	944
Reservoir Length (mi)	3.6	4.5	0.3	6.8
Total Storage (ac-ft)	3,495	46,867	73	58,794
Intake Ceiling Depth (ft)	10	22.5	0	23

TABLE 5
Estimates of fish entrainment at 26 hydropower projects (FERC, 1995a, 1996a, 1996b, 1997a, 1997b; RMC Environmental Services, Inc., 1995).

Project/River System	State	Reservoir Size (acres)	Dam Height (feet)	Total Hydraulic Capacity (cfs)	Total Generating Capacity (MW)	Operating Mode[a]	Total Annual Entrainment (fish)
Brule/Menominee	WI	545	63	1,377	5.3	PK	25,296
Grand Rapids/Menominee	WI	300	28	3,870	7.02	ROR	91,646
Park Mill/Menominee	WI	539	22	2,500	4.6	ROR	46,138
White Rapids/Menominee	WI	435	29	5,188	8	PK	144,554
Crowley/NF Flambeau	WI	422	28	1,480	1.74	ROR	66,920
Caldron Falls/Peshtigo	WI	1,180	80	1,430	6.4	PK	78,335
Sandstone Rapids/Peshtigo	WI	150	42	1,400	3.8	PK	81,303
Centralia/Wisconsin	WI	250	23	3,640	3.2	ROR	834,377
Rothschild/Wisconsin	WI	1,604	29	3,300	3.64	ROR	212,720
Wisconsin River Division	WI	240	29	5,120	1.8	ROR	705,804
Cooke/Au Sable	MI	1,320	48	3,600	9	PU	222,423
Five Channels/Au Sable	MI	250	40	3,000	6	PU	426,906
Foote/Au Sable	MI	1,800	52	4,050	9	PU	154,779
Loud/Au Sable	MI	790	31	2,600	4	PU	162,526
Mio/Au Sable	MI	860	36	2,700	5	ROR	120,323
Kleber/Black	MI	270	44	400	1.2	ROR	63,145
Tower/Black	MI	102	20	360	0.56	ROR	30,295
Cataract/Escanaba	MI	180	70[b]	450	2	PK	31,094
Escanaba Dam 3/Escanaba	MI	182	31	1,250	2.5	ROR	21,762
Moores Park/Grand	MI	240	21	1,200	1.08	ROR	85,848
Croton/Muskegon	MI	1,209	40	3,700	8.8	ROR	219,761
Hardy/Muskegon	MI	3,902	100	4,500	30	PU	25,947
Rogers/Muskegon	MI	610	39	2,400	6.8	ROR	55,875
Buchanan/St. Joseph	MI	423	20	3,798	4.1	ROR	70,006
Prickett/Sturgeon	MI	773	57	642	2.2	ROR	115,979
Hawks Nest/New	WV	243	56	10,000	102	ROR	48,269

[a] PK = peaking; PU = pulsed (intermittent operation to maximize turbine efficiency); ROR = run-of-river.

[b] Dam height represents vertical head between diversion dam and powerhouse.

- **Size Composition** - The likely size composition of entrained fish was inferred by reviewing data from entrainment studies where size information was available.
- **Species Composition** – Likely species composition was evaluated by characterizing trends in the top five species entrained at 10 projects for which there was available species composition data and comparing these trends against the relative species abundance data available for the Klamath reservoirs.
- **Seasonal Distribution** – Potential monthly variation and seasonal peaks in entrainment rates were evaluated by summarizing trends reported for dominant species at the projects reviewed for which there was seasonal data available.

Magnitude of Annual Entrainment

The median annual numbers of fish entrained at the 26 projects reviewed is 83,576 (Table 6). The 25 percent and 75 percent values are 48,269 and 162,526, respectively.

TABLE 6
Ranges and medians of total annual entrainment for various categories of hydroelectric projects (FERC, 1995a, 1996a, 1996b, 1997a, 1997b; RMC Environmental Services, Inc., 1995).

Project Category	Number of Projects	Range of Total Annual Entrainment (fish)	Median Annual Entrainment (fish)
All	26	21,762-834,377	**83,576**
Reservoir Size (acres)			
< 500	14	21,762-834,377	**75,655**
500 – 1500	9	25,296-222,423	**115,979**
>1500	3	25,947-212,720	154,779
Dam Height (ft.)			
<50	19	21,762-834,377	91,646
50-150	7	25,296-154,779	**48,269**
Hydraulic Capacity (cfs)			
<1000	4	30,295-115,979	47,120
1000 – 5000	19	21,762-834,377	**85,848**
> 5000	3	48,269-705,804	144,554

BOLD – indicates range applicable to the Klamath Project Reservoirs.

To further characterize potential entrainment occurring at the Klamath River facilities, we examined the relationship between annual entrainment and reservoir size, dam height, and hydraulic capacity.

Reservoir size (surface area) of the Project developments are 420 acres for J.C. Boyle, 1,000 acres for Copco, and 944 acres for Iron Gate. Reservoir size determines in large part the habitat characteristics and turnover rates of the reservoir, which in turn can influence the species composition, abundance, and population attributes of the resident fisheries subject to the risk of entrainment. The categorization of entrainment by reservoir size suggests that greater entrainment might be expected with larger reservoirs (see Table 6). For the middle size category (500 – 1,500 acres), which encompasses Copco and Iron Gate reservoirs, median entrainment for the reviewed database was 115,979 fish. The J.C. Boyle reservoir is 420 acres, which falls into the <500-acre category with a median entrainment of 75,655 fish.

Most of the projects available in the reviewed database were low head dams; all were less than 100 feet. Therefore, the database was separated into projects less than 50 feet (but over 20 feet) and those between 50 feet and 100 feet. This comparison suggests that entrainment potential is greater at the lower head projects. A possible explanation for the tendency of higher dams to have less entrainment potential is the fact that shallow water species, such as sunfish and minnows, which are the most commonly entrained species, are less likely to be occupying the deeper water habitat near higher dams. J.C. Boyle dam is 68 feet high and Copco No. 1 and Iron Gate dams are 126 and 173 feet high, respectively, suggesting that entrainment at these dams might be less than the entrainment at most dams in the database. For those dams higher than 50 feet, median entrainment was 48,269 fish.

Annual entrainment may also be related to hydraulic capacity of the projects. Therefore, annual entrainment estimates for the reviewed database were categorized by flows <1,000 cfs, 1,000 to 5,000 cfs, and >5,000 cfs (see Table 6). For the mid-flow-range projects, which encompass the Klamath powerhouses (1,735 to 3,200 cfs), median annual entrainment is 85,848 fish. This estimate is similar to the median for all projects combined (83,576).

Size Composition

Small young-of-year (YOY) fish would likely comprise the majority of fish entrained by the Project powerhouses. In most studies at other hydropower projects, fish smaller than 4 inches long represented the great majority of estimated annual entrainment (SWES 1992; FERC 1995, 1996a, 1997). Table 7 summarizes the proportion of entrainment as small or YOY fish at 12 projects for which size composition data were reported. The proportion of fish less than 4 inches long exceeded 75 percent at eight of the projects and 90 percent at three of the projects. Production of YOY fish in healthy reservoir systems is often high, and many of these small fish disperse from upstream habitats in response to changing habitat needs and density-dependent influences on resource availability. Compared to larger fish, YOY fish generally are more susceptible of being transported downstream during higher flow conditions and are less capable of escaping intake velocities.

Species Composition

Table 8 shows the relative abundance of the top five entrained species at 10 of the 26 projects reviewed. Species most commonly entrained include black crappie, bluegill, yellow perch, walleye, and shiners. Channel catfish (as fry) were common at two of the Wisconsin River projects (WI River Division and Centralia). White suckers were commonly entrained only at the Sandstone Rapids Project in Michigan. By families, the centrarchidae (bass and sunfish), percidae (yellow perch, walleye, logperch, and darters) and cyprinidae (minnows and shiners) were most commonly entrained (Table 9). Species of these families also are well represented in the Klamath impoundments: percids (yellow perches), centrarchids (sunfishes, bass), ictalurids (bullheads), and cyprinids (chubs and fathead minnows).

TABLE 7
Proportion of entrainment as small or young-of-year fish and game fish/pan fish (FERC, 1995a, 1995b, 1996a, 1996b, 1997b).

Project	River	Proportion as Small or Young-of-Year Fish
Rothschild	Wisconsin	88% YOY game fish and pan fish
Wisconsin River Division	Wisconsin	98% < 4 inches
Centralia	Wisconsin	97% < 4 inches
Brule	Menominee	86% ≤ 6 inches
White Rapids	Menominee	82% < 4 inches
Grand Rapids	Menominee	81% < 4 inches
Park Mill	Menominee	79% ≤ 4 inches
Caldron Falls	Peshtigo	63% < 4 inches 91% < 6 inches
Sandstone Rapids	Peshtigo	93% < 4 inches
Prickett	Sturgeon	84% ≤ 4 inches
Escanaba Dam 3	Escanaba	75% ≤ 6 inches
Crowley	N. Fork Flambeau	78% ≤ 4 inches

TABLE 8
Percent relative abundance of the Top 5 entrained species at 10 hydroelectric projects in the Upper Midwest (FERC, 1995a, 1997b; Normandeau Associates, Inc., 1994).

Species	Rothschild	WI River Division	Centralia	Crowley	Brule	White Rapids	Grand Rapids	Park Mill	Caldron Falls	Sandstone Rapids
CENTRARCHIDAE (SUNFISHES):										
Black crappie	48.4	--	1.9	5.7	--	11.3	--	--	30.8	25.4
Bluegill	17.6	25.4	4.2	--	--	13.7	--	18.6	4.8	--
Smallmouth bass	--	3.4	--	--	4.7	--	--	--	--	5.4
Largemouth bass	--	--	--	--	--	--	--	--	--	10.5
Rock bass	--	--	--	--	--	--	--	21.5	--	--
Pumpkinseed	--	--	--	--	--	--	--	--	--	--
ICTALURIDAE (BULLHEAD CATFISHES):										
Channel catfish	5.1	32.7	75.3	--	--	--	--	--	--	--
Yellow bullhead	--	19.2	3.0	--	--	--	--	--	--	--
Black bullhead	--	--	--	--	--	--	--	5.1	--	--
PERCIDAE (PERCHES AND DARTERS):										
Yellow perch	--	--	--	15.6	43.3	11.0	--	--	41.2	4.2
Walleye	--	--	--	34.8	15.5	10.8	--	6.2	5.7	--
Logperch	7.0	--	--	17.9	5.1	--	9.3	--	--	--
Blackside darter	--	--	--	4.8	--	--	11.9	--	--	--
Banded darter	--	--	--	--	--	--	7.7	--	--	--
CYPRINIDAE (MINNOWS):										
Common shiner	--	--	--	--	14.9	25.6	--	--	--	--
Emerald shiner	--	9.8	11.5	--	--	--	--	--	--	--
Fathead minnow	--	--	--	--	--	--	--	5.8	--	--
Golden shiner	--	--	--	--	--	--	--	--	3.4	--
Rosyface shiner	--	--	--	--	--	--	--	--	--	--
Unidentified cyprinids	5.7	--	--	--	--	--	10.3	--	--	--
CATOSTOMIDAE (SUCKERS):										
white sucker	--	--	--	--	--	--	--	--	--	32.7
GASTEROSTEIDAE (STICKELBACKS):										
Brook stickleback	--	--	--	--	--	--	7.6	--	--	--

TABLE 9
Species composition of J.C. Boyle, Copco, and Iron Gate reservoirs by family group as found by trammel net, trap net, trawl, and seine sampling in 1998 and 1999 by PacifiCorp and Oregon State University.

Family	J.C. Boyle	Copco	Iron Gate
Cyprinidae *(chubs, minnows, shiners)*	53.1%	5.0%	49.2%
Percidae *(yellow perch)*	0.8%	81.5%	13.7%
Centrarchidae *(bass, sunfish)*	23.7%	1.5%	21.3%
Ictaluridae *(bullheads, catfish)*	12.4%	1.8%	11.5%
Catostomidae *(suckers)*	8.1%	9.5%	3.4%
Salmonidae *(trout)*	1.0%	0.0%	0.4%
Cottidae *(sculpins)*	0.6%	0.0%	0.0%
Petromyzontidae *(lamprey)*	0.1%	0.0%	0.1%

The comparison suggests that sunfish and yellow perch probably dominate entrainment at the Klamath hydroelectric developments. These species as YOY tend to reside in shallow water and, thus, may be more prone to becoming entrained at the relatively shallow intakes at the four Project dams. Chubs may also be entrained at high rates because they are one of the most abundant species in the reservoirs. However, they are generally bottom dwellers and, thus, may not be as prone to entrainment as their relative abundance in the reservoirs might suggest. Similarly, bullheads and suckers are bottom dwellers and they too may be less prone to entrainment through the relatively shallow intakes especially at Copco and Iron Gate reservoirs. The intakes at both these reservoirs are shallow but are above water that is deeper than 100 feet near the dam. The projects in the database indicating high entrainment rates of catfish and bullheads (and total entrainment as well) were Wisconsin River projects with reservoir depths less than 30 feet (see Table 5) and consequently with intakes drawing water from the bottom.

Most of the entrainment at the Project developments likely consists of non-native fish species, including yellow perch (Copco and Iron Gate), pumpkinseed, bluegill, crappie, other sunfish, and bullheads. The most abundant native species found in the Klamath reservoirs are chubs (tui and blue) and they would undoubtedly make up a significant proportion of the entrainment. Suckers have not been found to be a highly susceptible species to entrainment at most projects, especially those with shallow intakes.

In 1997 and 1998 an entrainment study was conducted at the Link River developments; East Side and West Side powerhouses. The results provide useful information regarding species susceptibility to entrainment in the Klamath River system (New Earth/Cell Tech and PacifiCorp 1999). Although Upper Klamath Lake is much different than the downstream reservoirs in many ways, they share many of the same fish species. Minnow species (blue and tui chubs and fathead minnows) made up 78 percent of the entrainment at the powerhouse intake canals (Table 10). These were followed by yellow perch and sculpin (2 species). Suckers (4 species) made up 3.5 percent of the total entrainment.

TABLE 10
Relative abundance of fish entrained at Link River Dam into the East Side and West Side canals (New Earth/Cell Tech and PacifiCorp 1999).

Common Fish Name	No. of Fish	Relative Abundance
Blue chub	214204	48.99%
Fathead minnow	67577	15.46%
Tui chub	57675	13.19%
Yellow Perch	28534	6.53%
Klamath Lake sculpin	27068	6.19%
Marbled sculpin	11931	2.73%
Sucker unknown	8690	1.99%
Shortnose sucker	4687	1.07%
Sculpin unknown	4413	1.01%
Unknown species	4345	0.99%
Lamprey unknown	2340	0.54%
Lost River sucker	1664	0.38%
Unidentified partial remains	1003	0.23%
Slender sculpin	929	0.21%
Rainbow trout	624	0.14%
Minnow unknown	564	0.13%
Speckled dace	333	0.08%
Chubb unknown	298	0.07%
Klamath largescale sucker	257	0.06%
Brown Bullhead	65	0.01%
Sunfish	18	< 0.01%
Total	**437,219**	**100%**

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Another line of evidence regarding the potential entrainment rates and species for the Project reservoirs is the fish community data available for the Klamath River downstream of the J.C. Boyle dam and powerhouse. Some of the species commonly found in J.C. Boyle reservoir, especially bluegill and pumpkinseed sunfish, are also found in the area immediately below the dam where the water consists primarily of that from the fish ladder and fish screen/bypass system (Table 11). However, the lower segment of the bypass reach contains much fewer of these reservoir species. In the 16-mile reach between J.C. Boyle powerhouse and Copco reservoir, none of the sunfish, perch, or bullhead species commonly found in the reservoir were observed in the river (Table 12). This suggests that entrainment rates of these reservoir species may be low, turbine mortality may be very high, the riverine habitat does not support such species, and/or that those fish that are entrained move quickly downstream to Copco reservoir.

Additional evidence regarding species vulnerability to entrainment can be inferred from downstream fish trapping that was conducted by ODFW between 1988 and 1991 at the J.C. Boyle dam fish ladder. Although targeting trout, the trapping effort found that pumpkinseed made up nearly 90 percent of the non-trout species moving downstream through the ladder. (Table 13). Tui chub and smallscale sucker made up 5.4% and 2.0% of the non-trout species composition, respectively. The seemingly high susceptibility of pumpkinseed sunfish to entrainment comports with numerous other entrainment studies showing high entrainment rates for sunfishes.

Seasonal and Diurnal Distribution

Peak fish entrainment at the Project developments most likely occurs in spring and summer, following the spawning seasons of centrarchids, ictalurids, perch, and other species with high reproductive potential, when YOY fish are most abundant and tend to be dispersing into rearing habitats. Based on monthly variation in entrainment reported by FERC (1995), entrainment likely peaks between April and June, with entrainment of multiple-spawning species, such as bluegill and other sunfish, potentially showing secondary peaks in the fall. In the Link River study, most entrainment occurred in the late July through October period. Poor water quality conditions in Upper Klamath Lake during this period (high pH and temperature and low dissolved oxygen) may be contributing to the downstream movement of fish through the East Side and West Side powerhouses. The lowest entrainment for most species would be expected to occur from late fall through winter when fish movements generally are suppressed by colder water temperatures.

Most entrainment studies of resident fish indicate their there is little consistency in diurnal pattern among sites for the most commonly entrained species except for ichtalurids (catfish and bullheads), which show a much greater tendency for night movement. However, the East Side and West Side entrainment study found that the vast majority (>75 percent) of the total fish entrainment for all species combined as well as for sucker species occurred at night (New Earth/Cell Tech and PacifiCorp 1999). Therefore, it is reasonable to assume that most fish in the downstream Klamath River reservoirs also would have a tendency to become entrained at night. This strong nighttime tendency is an important factor to consider when characterizing entrainment potential at J.C. Boyle, Copco No. 1 and Copco No. 2 powerhouses, all of which do not operate at night during most of the year because of power

TABLE 11
Percent of total CPUE (fish per-hr) by near-shore backpack shocking - J.C. Boyle bypass reach, upper and lower segments.

Fish Species Common Name	Relative Abundance Upper Segment All Seasons Combined	Relative Abundance Lower Segment All Seasons Combined
Redband/Rainbow trout	11.1%	38.7%
Blue chub	4.5%	1.4%
Tui chub	5.0%	0.7%
Chubb spp.	-	-
Speckled dace	35.0%	2.6%
Sculpin (Marbled)	15.5%	53.3%
Lamprey	0.5%	-
Shortnosed sucker	-	-
Lost River sucker	-	-
Klamath sucker spp. [a]	-	-
Unknown sucker spp.	-	-
Largemouth bass	1.1%	0.7%
Smallmouth bass	0.5%	-
Bluegill	7.2%	-
Pumpkinseed	7.2%	1.4%
Black crappie	0.5%	-
White crappie	0.5%	-
Fathead minnow	-	1.4%
Yellow Perch	-	-
Bullhead spp.	11.1%	-
Unknown species[b]	-	-

[a] Largescale and/or smallscale suckers
[b] Most likely fathead minnows and/or chubs

TABLE 12
Percent of total CPUE (fish per-hr) near-shore backpack shocking – J.C. Boyle peaking reach.

Fish Species Common Name	Relative Abundance*
Redband/Rainbow trout	4.2%
Blue chub	1.0%
Tui chub	1.2%
Chubb spp.	-
Speckled dace	63.5%
Sculpin (Marbled)	23.5%
Lamprey	-
Shortnosed sucker	-
Lost River sucker	-
Klamath sucker spp. [a]	-
Unknown sucker spp.	6.7%
Largemouth bass	-
Smallmouth bass	-
Bluegill	-
Pumpkinseed	-
Black crappie	-
White crappie	-
Fathead minnow	-
Yellow Perch	-
Bullhead spp.	-
Unknown species[b]	-

*Based on electrofishing CPUE
[a] Largescale and/or smallscale suckers
[b] Most likely fathead minnows and/or chubs

TABLE 13
Number of identified non-trout species collected from downstream traps in the J.C. Boyle fish ladder (1988-1991, ODFW).

Species	Number caught	Percent of total
Pumpkinseed	263	89.5%
Tui chub	16	5.4%
Smallscale sucker	6	2.0%
Fathead minnow	4	1.4%
Blue chub	1	0.3%
Brown bullhead	1	0.3%
Largemouth bass	1	0.3%
Speckeld dace	1	0.3%
Yellow perch	1	0.3%
Total	**294**	**(99.8% - rounding)**

peaking operations. It may be too much to conclude that 80 percent of entrainment is avoided by not operating at night, but it is reasonable to assume that the nighttime shutdown would greatly minimize fish entrainment potential. In fact, the significant nighttime movement observed at Link River dam is the basis for the current summer shutdown of the West Side powerhouse and the requirement to minimize load (200 cfs) at the East Side powerhouse at night, per the USFWS 2002 Biological Opinion to reduce take of endangered shortnose and Lost River suckers.

Turbine Mortality

Causes of Mortality

Injury and mortality of entrained fish passing through hydroelectric turbines principally occur by the following mechanisms (based on reviews provided by Cada 1990, and Odeh 1999):

- **Mechanical injury** – Injury from direct strikes or collisions with turbine runner blades, abrading or rubbing against a turbine system component, and grinding when fish are drawn into small gaps with high-velocity zones.
- **Pressure changes** – Injuries caused by rapid pressure decreases that occur momentarily immediately behind the turbine blades. The main cause of pressure-related mortality is injury to the swim bladder from decompression.
- **Cavitation** – The rapid formation of vapor pockets or bubbles caused by subatmospheric pressures within a turbine. The bubbles collapse violently as they travel to areas with higher pressures, creating localized shock waves. Rapid exposure to hydrostatic pressures equal to the vapor pressure of water, followed by instantaneous return to

atmospheric pressure, appears to be the principal cause of cavitation-related fish mortality.

- **Turbulence and shear stresses** – Fluid-induced forces that occur when two masses of water moving at different velocities are incident with each other. Fish encounter shear forces through the turbine system as they move from one velocity zone to the next. Shear forces are most pronounced along the leading edges of the runner blades, vanes, and gates. Shear forces and turbulence can spin or deform entrained fish.

Physical characteristics of turbine systems affecting the mortality rates of entrained fish include: head, turbine design, peripheral runner velocity, wicket gate openings, number of runner blades, gap sizes, flow through the turbine, passage routes through the turbine, turbine blade angle, and the size and species of fish entrained (Cada 1990; Odeh 1999; Cada and Rinehart 2000). Many of these factors are sources of mechanical injury to fish and also produce turbulence, shear forces, and pressure changes that may injure fish (Cada and Rinehart 2000).

Actual pressures experienced by entrained fish depend on turbine design, flow rate, and head. High-head turbines tend to be smaller units and generally have a higher rate of pressure change per unit time than low-head turbines (Odeh 1999).

Design factors affecting cavitation include hydraulic head on the turbine runner, net head, surface irregularities on the turbine blades, and abrupt changes in flow direction (Cada 1990; Odeh 1999). Cavitation at hydroelectric facilities is difficult to predict, and turbine operators strive to minimize it through proper design to avoid costly damage to turbine surfaces (Cada 1990).

Factors Influencing Mortality

The probability that an entrained fish will survive passing through a turbine depends on the size of the fish, the characteristics of the turbine, and the operational parameters of the hydroelectric facility. A review of the literature shows that the following factors should be considered:

- Turbine type
- Net head
- Peripheral runner blade speed
- Operating efficiency
- Depth of intake
- Fish length

Turbine Type

Francis units were formerly believed to show higher mortality rates than propeller-type (Kaplan) turbines. However, the Francis units generally were operated at higher heads, turbine settings, and blade speeds than were the propeller-type turbines. More recent tests (Cramer and Oligher 1964) comparing the two types of turbines at the same head, turbine setting, and blade speed showed no significant difference in fish mortality between Francis and propeller-type turbines. This suggested that mortality was due to operating conditions, and not due to turbine design. Review of turbine-induced fish mortality tests by Bell et al. (1981), Turbak et al. (1981), and Eicher and Associates (1987), also indicated that at similar head, turbine setting, and blade speed no difference exists in fish mortality induced by Francis versus propeller-type units.

Net Head

A review by Eicher and Associates (1987) suggested that net head, by itself, was not a major factor affecting fish mortality induced by either Francis or Kaplan turbines. Heads varying from 40 feet to 410 feet were included in the review. Although greater mortality was shown to occur at higher head projects, the high runner speed and pressure were considered to be the actual cause of higher mortality at the higher head dams (Cramer and Oligher 1964).

Peripheral Runner Blade Speed

Eicher and Associates (1987) found a correlation (r=0.73) between fish mortality and peripheral runner blade speed for Francis runners. They rated blade speed as the principal variable related to fish mortality in Francis units. They obtained a regression of Y=.52X-18.52 for percent mortality vs. peripheral runner blade speed (feet per second) for 22 tests at 14 different Francis-turbine facilities. Most of the mortality estimates used in the Eicher regression were obtained from mark-recapture studies on anadromous salmonid smolts, and, thus, accounted for delayed mortality and any indirect mortality associated with predation in the tailrace. No correlation could be made between mortality and runner blade speed for Kaplan units.

Operating Efficiency

All studies reviewed indicated that mortality is lowest when turbines operate at peak efficiency. Peak turbine efficiency incorporates all operating parameters that produce low turbulence, low cavitation, and overall streamlined flow of water through the turbine. Parameters that are involved in peak efficiency are optimum wicket gate opening, optimum turbine setting, optimum runner blade speed, and optimum runner blade clearance. When units operate at high efficiency, cavitation is extremely low and a smooth flow is produced.

Intake Depth

Turbine intake depth can cause higher mortality if the intake is near the bottom of the water column in deep water. Mortality may occur from rapid decompression in the tailwater after fish are entrained from a deep water intake. The negative pressure behind the turbine blades can be substantially lower than the pressure to which bottom-dwelling fish are acclimated. Thus, bottom-dwelling fish may be more prone to pressure-related injuries. It also has been suggested that physostomous fish, such as trout and salmon, which have a pneumatic duct connecting the swim bladder to the esophagus, are more capable than physoclistous fish (lacking a pneumatic duct) of adjusting to rapid decompression by venting the swim bladder.

For fish that are entrained by shallow intakes, such as those at the Klamath Project, the pressure change experienced by the fish when passing through the powerhouse may be only slightly less than the pressure to which surface-dwelling fish are acclimated. Results of experiments with juvenile yellow perch showed mortality from rapid decompression occurred only when intake depths were greater than 33 feet (Cada 1990). Fish eggs and larvae are more tolerant to pressure change; their critical intake depth is about 160 feet.

Fish Length

Fish length has been found to be one of the most important variables affecting turbine mortality. Collins and Ruggles (1982), in testing trout of three size categories (65 mm - 99 mm, 100 mm - 119 mm, and 120 mm – 159 mm) passed through a Francis turbine, found that mortality increased approximately proportional to fish length. A similar relationship was identified via multiple regression analysis of survival data from 95 tests of axial flow turbines (Headrick 2001). Logically, the probability that an entrained fish will be struck by a turbine blade is a function of fish size as well as the characteristics of the turbine (runner velocity, number of blades, blade angle, and area of water passage). Formulas used to predict the probability of a blade strike incorporate fish length as a direct multiplier (Von Raben 1957; DOE 2003; Waporo 1987; Bell 1991).

The probability-of-strike equations have been used as surrogates to estimate mortality. While often the strike probability has closely matched empirically derived mortality estimates, technically, the strike formula alone does not account for all the variables known to affect mortality. On one hand, the formula underestimates mortality where other injury sources, such as hydraulic shear and pressure changes, are involved. On the other hand, the formula overestimates mortality because not all blade strikes result in mortality. Turnpenny et al, (1992) derived a regression equation that estimates the mortality-to-strike ratio (K) to the length of fish:

$$K=0.153(\mathit{ln}\ \mathrm{l})+0.012$$

where l is fish length in centimeters.

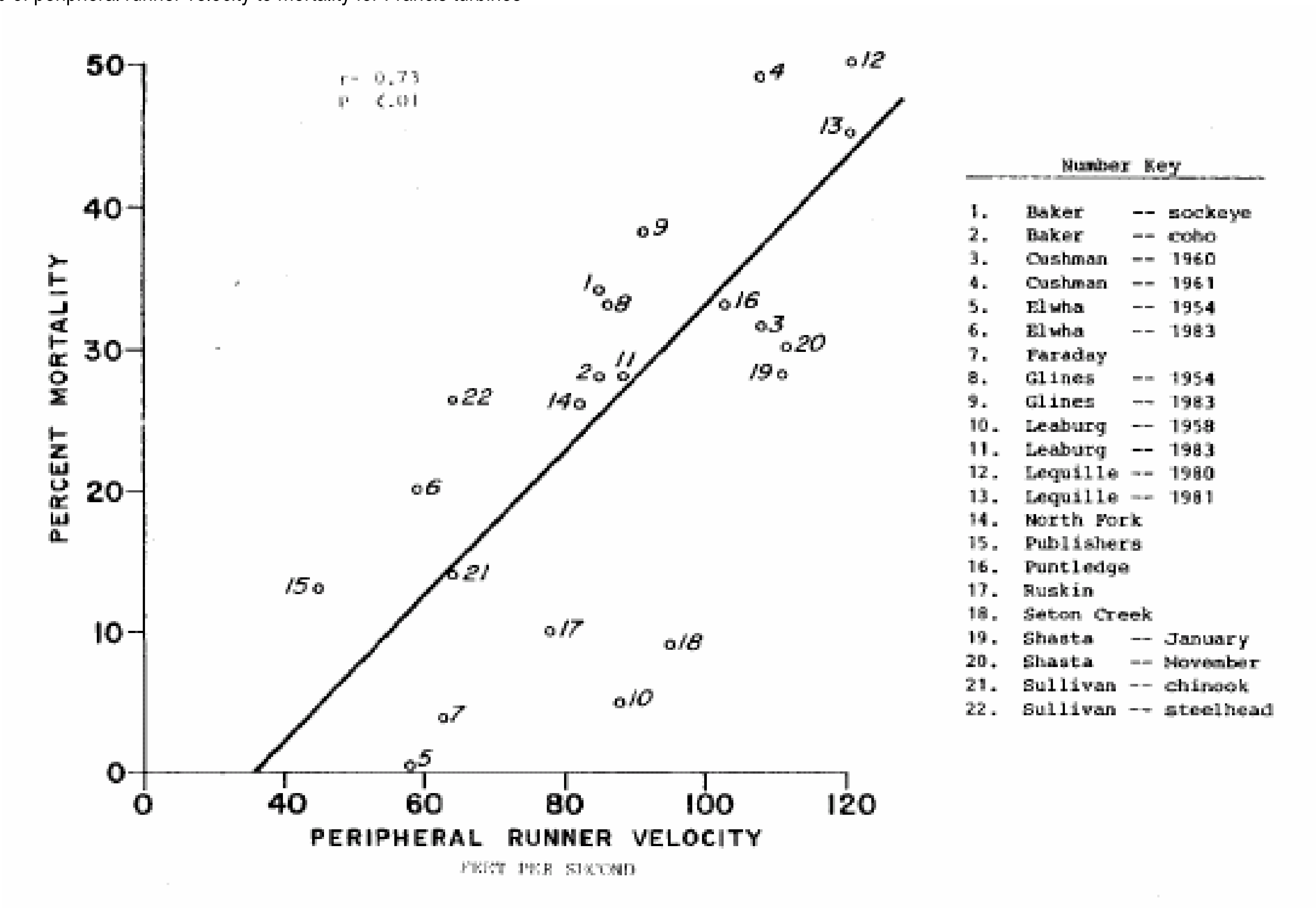
Applying this formula to a 10-cm fish, for example, would result is a predicted turbine blade strike-to-mortality ratio of 36 percent. Therefore, to obtain an estimate of total mortality due to a blade strike would require multiplying the strike probability by the mortality-to-strike ratio.

Mortality Estimates for Klamath Turbines

All of the turbines at the J.C. Boyle, Copco No. 1, Copco No. 2 and Iron Gate powerhouses have Francis runners. The mortality rates of fish entrained through these turbines is best estimated using the Eicher (1987) regression formula depicted in Figure 1, which relates mortality to peripheral runner velocity (Table 14).

In estimating turbine mortality using the Eicher formula it is critically important to account for the size of fish that are being entrained. Most studies used in the development of the Eicher regression equation were conducted on salmonid smolts between 100 and 200 mm in length. The average size of resident fish entrained at nearly all reviewed projects, and likely for the Project developments as well, is 50 to 75 mm in length. Thus, the mortality rate of the typical entrained resident would likely be about half or less than that of the fish used in the Eicher regression. Table 15 shows the estimated mortality rate for fish of various sizes for the J.C. Boyle, Copco No. 1, Copco No. 2 and Iron Gate turbines. It was assumed that the fish used in the Eicher regression averaged 150 mm in length and that mortality for other sizes are directly proportional to length.

FIGURE 1
Relationship of peripheral runner velocity to mortality for Francis turbines



Source: Eicher 1987

TABLE 14
Turbine characteristics of J.C. Boyle, Copco No. 1, Copco No. 2, and Iron Gate facilities.

Turbine Characteristics	J.C. Boyle		Copco 1		Copco 2		Iron Gate
	Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2	Unit 1
Turbine Type (e.g., Francis)	Francis	Francis	Francis	Francis	Francis	Francis	Francis
Orientation (vertical or horizontal)	Vertical	Vertical	Horizontal	Horizontal	Vertical	Vertical	Vertical
Hydraulic Capacity (cfs)	1,500	1,500	1,600	1,600	1,600	1,600	1,735
Generating Capacity (MW) (nameplate)	40	40	10	10	13.5	13.5	18
Head (ft)	463	463	123	123	152	152	158
Number of Runners	1	1	2	2	1	1	1
Number of Blades per Runner	15	15	17	19	17	19	15
Runner Diameter (inches)	88	88	82	79.75	99.57	97.82	98.25
Runner Speed (rpm)	277	277	200	200	171.5	171.5	180
Peripheral Runner Velocity (fps)	**106.2**	**106.2**	**71.6**	**69.6**	**74.5**	**73.2**	**77.2**

TABLE 15
Estimated percent turbine-induced fish mortality by fish size class at Klamath Project powerhouses.

Powerhouse	150mm	100mm	75mm	50mm
J.C. Boyle	36.6	24.4	18.3	12.2
Copco No. 1	17.9	11.9	8.9	6.0
Copco No. 2	20.0	13.3	10.0	6.7
Iron Gate	21.5	14.4	10.8	7.2

Turbine mortality at the two Copco powerhouses and at Iron Gate would be expected to be about 10 percent for the most likely size of fish (75 mm) to be entrained and about 20 percent for fish in the size range of 100 mm to 200 mm (see Table 14). Nearly all fish entrained at Copco No. 1 powerhouse would be expected to pass through the Copco No. 2 powerhouse, thus exposing those fish surviving the first powerhouse to the potential cumulative mortality at the second powerhouse. Potential mortality of fish passing through the high-head J.C. Boyle powerhouse would be 20 to 40 percent.

Potential Fisheries Impacts

A common understanding is that fish residing in hydroelectric reservoirs can become entrained through powerhouses and that a portion of them are killed as they pass through the turbines. The median number of fish entrained annually at the 26 FERC-reviewed projects summarized in this memorandum is approximately 83,000 fish. However, it is likely that the J.C. Boyle and Copco powerhouse intakes entrain fewer fish than observed at the other reviewed projects because of the frequent shut down of these powerhouses at night (for load following) when most native species appear to move downstream (based on Link River observations). Also, the shallow intakes at the deep-water dam faces at Copco and Iron Gate may further reduce the likelihood of bottom dwelling species such as suckers and bullheads from becoming entrained. However, even considering these possible minimizing factors, it is likely that annual entrainment still is several tens of thousands of fish at each of the Projects. Yellow perch, sunfishes, and chubs are likely to be the most commonly entrained species.

Even though entrainment may be less at the Klamath Project dams than observed at other sites, the rate of mortality associated with turbine passage is probably greater because of their relatively higher head (and thus greater turbine runner velocity).

The question as to whether entrainment mortality is causing a biologically significant impact to resident fish populations and whether this impact is great enough to require costly mitigation (typically in the form of fish exclusion/screen facilities) has been a significant challenge for resource agencies and hydropower licensees alike (FERC 1995). While the need for downstream protection facilities for anadromous fish is rarely disputed, the need to install facilities for resident fish is often debatable.

The response of resource agencies to the entrainment mortality issue has varied by state. In the most conservative cases, resource agencies have stated that “biological significant impacts” to fish populations is not relevant, but rather that individual fish are being killed and that protection measures are needed to mitigate the losses (FERC 1996a, 1996b). States that have taken this approach have nearly always recommended fish protection measures regardless of the results of site-specific entrainment mortality studies. FERC, in conducting their environmental analyses, generally has considered it important to review and interpret available information on potential impacts on fish populations because this could have a significant bearing on its balancing of developmental and nondevelopmental resources (FERC 1996a, 1996b).

In the assessments of environmental effects of turbine entrainment mortality, the following factors have been considered:

- **Native vs. non-native fish.** Entrainment at most of the midwest and eastern projects review by FERC (1995) consisted primarily of native fish species. However, reservoirs in the western United States, including those on the Klamath River, often are dominated by non-native species. Many of these non-native species, such as bass, catfish, perch, and sunfish, support popular sport fisheries. Resource agencies in the west are often confronted with management conflicts between protecting native species on one hand and supporting angler desires for game fish on the other hand.

  The Project reservoirs contain large populations of non-native species (see Tables 1, 2, and 3). Copco reservoir, in particular, contains over 80 percent yellow perch. This species, as well as the sunfishes and catfish/bullhead species, would likely make up a majority of the fish entrained. Chubs, both blue and tui, would be the most likely entrained native species.

- **Downstream habitat.** Entrainment mortality removes fish that would otherwise contribute to recruitment to waters downstream of the dam. Therefore, it is important to consider the type of downstream habitat available to these fish and whether recruitment from upstream is important to the downstream populations. At J. C. Boyle dam, fish that pass the dam enter a 20-mile high gradient stream reach. Nearly all of the species found in J.C. Boyle reservoir prefer slackwater lake habitat. The fact that few of these species are found in the river downstream of the powerhouse may attest to their strong lake preference and inability to remain in the riverine habitat. Those that do pass the dam (via screen/bypass system) probably reside in the river pools just downstream of the dam prior to cool spring water inputs, or move quickly downstream and enter Copco reservoir.

  Fish that become entrained at Copco No. 1 enter the short (0.3-mile) Copco No. 2 headwater pond, which is essentially riverine in nature. These fish most likely very quickly enter the Copco No. 2 powerhouse intake. Those that survive turbine passage at the Copco No. 2 powerhouse enter directly to Iron Gate reservoir, which provides similar habitat as Copco reservoir.

  Nearly all of the fish in Iron Gate reservoir are species that prefer lake habitat. Because there are no reservoirs downstream of Iron Gate, it is reasonable to assume that those fish that are entrained and survive through the turbines will eventually perish in the downstream riverine habitat.

- **Compensatory mortality.** Because the vast majority of fish entrained at hydroelectric projects consists of small YOY individuals, the principle of compensatory mortality has been applied to the interpretation of biological impacts associated with entrainment mortality on fish populations. Compensatory mortality refers to the fact that when the density of a fish population is reduced, the competition for population limiting resources, such as food or space, is also reduced thereby leading to higher survival rates of the remaining fish. Density-dependent compensation is important to fisheries management because it operates to offset the losses of individuals. It is the reality of this compensatory process upon which management of commercial and recreational fisheries is based (Ricker 1975). When assessing impacts of entrainment mortality, it has been argued that compensation tends to regulate the population toward a long-term average supported by habitat availability, and, therefore, higher mortality at the YOY stage has little or no impact on the population as a whole, especially when there appears to be an abundance of YOY fish as indicated by high entrainment rates.

- **Density dependent dispersal.** Most small fish that leave a reservoir may be "excess" fish from a habitat standpoint; i.e., as the rearing capacity of the upstream habitat becomes filled, the excess fish disperse downstream. High entrainment rates may just be indicative of a healthy up-stream population, which by definition would have surplus reproductive capacity.

References Cited

Bell, M.C. 1991. Revised Compendium on the Success of Passage of Small Fish Through Turbines. U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Bell, M.C., and K.J. Bruya. 1981. *Updated Compendium on the Success of Passage of Small Fish through Hydroelectric Turbines.* U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Cada, G. F. 1990. A review of studies relating to the effects of propeller-type turbine passage on fish early life stages. North American Journal of Fisheries Management 10:418-426.

Cada, G. F., and B. N. Rinehart. 2000. Hydropower R&D: recent advances in turbine passage technology. U.S. Department of Energy, Idaho Operations Office, DOE/ID-10753. April 2000.

Cramer, F.K., and R.C. Olighter. 1964. "Passing Fish through Hydraulic Turbines." *Transactions of the American Fisheries Society*, Volume 93, No. 3, 1964,pages 243-259.

Desjardins, M. and D.F. Markle. 1999. *Distribution and Biology of Suckers in Lower Klamath Reservoirs. 1999 Final Report.* Submitted to PacifiCorp by Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon.

Eicher and Associates, Inc. 1987. Turbine-related fish mortality: review and evaluation of studies. Research Project 2694-4. Electric Power Research Institute, Palo Alto, California.

Electric Power Research Institute. 1992. Fish Entrainment and Turbine Mortality Review and Guidelines. EPRI TR-101231. September 1992.

Federal Energy Regulatory Commission. 1995. Preliminary assessment of fish entrainment at hydropower projects, a report on studies and protective measures, volumes 1 and 2 (appendices). FERC Office of Hydropower Licensing, Washington, D.C. Paper No. DPR-10. June 1995 (volume 1) and December 1994 (volume 2).

Federal Energy Regulatory Commission. 1996a. Final environmental impact statement, Wisconsin River basin, Wisconsin. FERC/EIS-0089F. Prepared in cooperation with the U.S. Forest Service. FERC Office of Hydropower Licensing, Washington, D.C. June 1996.

Federal Energy Regulatory Commission. 1996b. Menominee River multiple project final environmental impact statement, Little Quinnesec Falls Hydroelectric Project (FERC No. 2536), Chalk Hill Hydroelectric Project (FERC No. 2394), White Rapids Hydroelectric Project (FERC No. 2357), Grand Rapids Hydroelectric Project (FERC No. 2433). FERC Office of Hydropower Licensing, Washington, D.C. October 1996.

Federal Energy Regulatory Commission. 1997. Final environmental impact statement for relicensing six existing hydroelectric projects in the Peshtigo River basin. FERC Project Nos. 2525 Caldron Falls, 2595 High Falls, 2522 Johnson Falls, 2546 Sandstone Rapids, 2560 Potato Rapids, 2581 Peshtigo. FERC Office of Hydropower Licensing, Washington, D.C. March 1997.

Headrick, Michael R. 2001. "Predicting Fish Survival in Axial Flow Turbines." *Hydro Review*, July 2001, pages 114-119.

Odeh, M. 1999. A summary of environmentally friendly turbine design concepts. U.S. Department of Energy, Idaho Operations Office, DOE/ID/13741. July 1999.

Stone & Webster Environmental Services. 1992. Fish entrainment and turbine mortality review and guidelines. Prepared for Electric Power Research Institute, Palo Alto, California. TR-101231, Research Project 2694-01. Final Report, September 1992.

Ricker, W.E. 1975. Computation and Interpretation of Biological Statistics of Fish Populations. *Bulletin of the Fisheries Research Board of Canada No. 191.* Ottawa, Ontario. 382 pp.

Turbak, S.C., D.R. Reichle, and C.R. Shriner. 1981. *Analysis of environmental issues related to smallscale hydroelectric development. IV: fish mortality resulting from turbine passage.* Oak Ridge National Laboratory, ORNL/TM-7521, Oak Ridge, Tennessee.

Von Raben, K. 1957. "Zur Frage der Beschadigung von Fischen durch Turbinen." *Die Wasserwirtschaft* 4: 97-100. (Fisheries Research Board of Canada Translation Series 448).

U.S. Department of Energy. 2003. Pilot Scale Tests Alden/Concepts NREC Turbine. U.S. Department of Energy Advanced Hydropower Turbine Systems Program, DOE/ID/13733. Draft Final Report, June 2003.

Waporo. 1987. Fish passage studies at the Racine and New Martinsville hydroelectric projects, volume II. Prepared for the City of New Martinsville and the Ohio Power Company, New Martinsville, West Virginia.