IT'S NOT EASY BEING GREEN: Environmental Technologies Enhance Conventional Hydropower's Role in Sustainable Development

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Annual Review of Energy and the Environment, December 1999, Volume 24

ABSTRACT

Conventional hydroelectric generation uses a renewable energy source and currently supplies about ten percent of the United States' annual output of electricity and about twenty percent of electricity generated worldwide. To provide a significant contribution to sustainable development, the hydropower industry must address a variety of environmental concerns, including water quality and fish passage issues. The paper discusses new technologies for turbine design and control systems to improve dissolved oxygen levels in turbine discharges and survival of fish during turbine passage. The paper describes development, testing, and test results for these technologies, with an emphasis on collaboration of stakeholders and balance between environmental stewardship and economical power production.

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by

Patrick A. March and Richard K. Fisher

Introduction

In “The Muppet Movie,” Kermit the Frog sits in the swamp and sings pensively,

> It’s not easy being green.
> It seems you blend in with so many other ordinary things.
> And people tend to pass you over ’cause you’re not standing out
> Like flashy sparkles in the water or stars in the sky.

As the hydropower industry struggles for public recognition as a renewable and sustainable energy source, it can identify with Kermit’s lament.

Hydropower plays an important role in a variety of long-term scenarios for sustainable development [Moore, 1998; Mintzer, 1991]. However, the hydropower industry faces increasing environmental pressures, including demands for the breaching or complete removal of some existing dams. In the United States, the Federal Energy Regulatory Commission (FERC) has ordered the removal of Edwards Dam (with a generating capacity of 3.5 MW and an annual production of 19 GWh) on the Kennebec River in Maine to improve aquatic habitat. The U. S. Secretary of the Interior was recently quoted as saying that he would like to “tear down a really large dam [HCI, 1998, p. 4].” The Department of Energy’s Bonneville Power Administration, which markets the electricity generated by the U. S. Army Corps of Engineers’ and the Department of the Interior’s hydro projects on the Columbia and Snake River basins, is evaluating proposals to breach four dams (with a generating capacity of over 3,000 MW and an annual production of 10,500 GWh) on the Lower Snake River in Washington in an attempt to improve the declining salmon population. These “threatened and endangered” hydroelectric projects provide not only hydroelectric generation, but also multi-purpose benefits from inland navigation, recreation, reservoir fisheries, and incidental irrigation (see Figure 1).

This paper reviews socioeconomic benefits and environmental costs associated with conventional hydroelectric generation. The paper focuses on new technologies which address major hydro-related environmental concerns, including water quality and fish passage issues. During the development of these technologies, care was taken to minimize the impact on power generation and, in several cases, to improve power generation. The collaborative approach used in the development of these technologies is discussed, and recommendations for improvements in environmental accounting are provided.

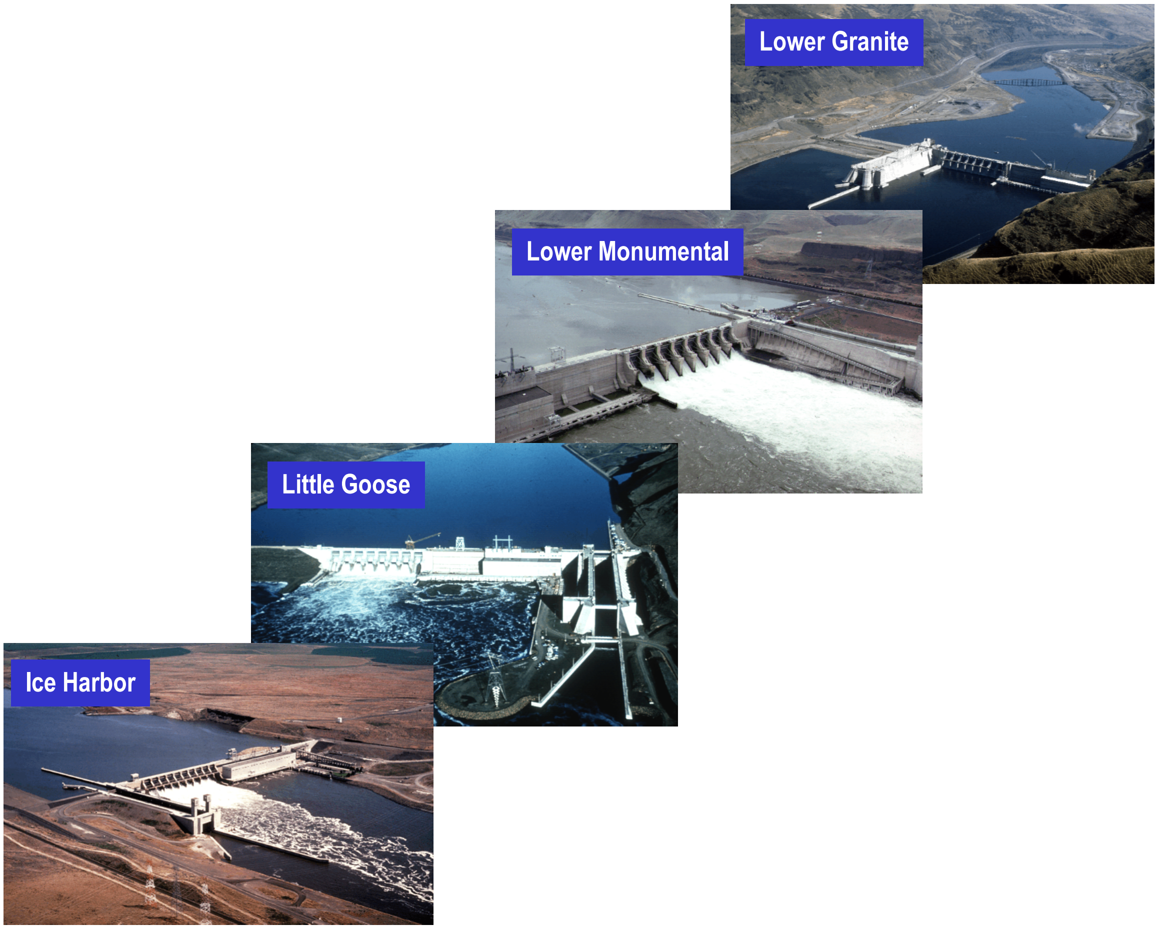


Figure 1: Federal Multi-Purpose Power Projects on the Lower Snake River

Hydropower Benefits

Hydropower is “renewable, clean, efficient, economical, and domestically produced [HCI, 1992].” Hydroelectric plants provide, by far, the most widely used source of renewable energy for the generation of electricity. The U. S. Department of Energy’s 1995 statistics for electric utilities credit hydroelectric plants with 97.9 percent of the total generation by renewables, geothermal with 1.6 percent, biomass with 0.5 percent, wind with 0.004 percent, and photovoltaic with 0.001 percent. Hydropower currently supplies about ten percent of the United States’ annual output of electricity. Throughout the world, hydropower provides over two million GWh per year, which is about twenty percent of all electricity generated [SERI, 1990]. In both the short term and the long term, further development of conventional hydroelectric energy generation, through rehabilitation of existing plants and installation of new facilities, can increase clean, sustainable energy production and make an important contribution to the reduction of greenhouse gas emissions [Moore, 1998; Sale and Brown, 1998; Sale and Newman, 1998; IWG, 1997; NLD, 1997; Francfort, 1997; Mintzer, 1991].

Water resource developments typically provide multiple socioeconomic benefits to the public:

1. "Green," renewable hydroelectric power, produced at a much lower cost than other forms of generation and produced without significant air or water pollution;
2. Flood control, which protects lives and property, reduces risk, and encourages investment and economic development;
3. Navigation on inland waterways, which improves public safety by reducing truck traffic on roadways, dramatically reduces energy-related transportation costs for bulk materials, and encourages investment and economic development;
4. Industrial, municipal, and agricultural water supply, which are crucial for economic development;
5. Recreational opportunities, such as boating, water-skiing, kayaking, picnicking, hiking, camping, lake fishing, and stream fishing;
6. Fishery, wildlife, land, and forest management, including reforestation and reclamation.

Environmental Concerns

Serious concerns about the environmental consequences of hydro development must also be addressed. Mattice [1991] provides an excellent overview of the environmental effects from conventional hydropower facilities. Significant issues for new projects, particularly in developing countries, include forced resettlement of people from inundated lands, the potential for outbreaks of water-borne diseases, and intensification of regional water rights conflicts [Sale and Brown, 1998; DOI-AID, 1997]. Some of the negative effects on ecosystems observed in established water resource developments include modification or destruction of aquatic and terrestrial habitat, interruption of daily and seasonal stream flows, alteration of seasonal temperature patterns, reduction in sediments, disruptions to the natural flow of organic materials and nutrients through the aquatic ecosystem, and a consequent decrease in biodiversity [Yeager, 1993].

Impoundments and flow releases from hydropower facilities can adversely impact the aquatic life upstream, downstream, and passing through the sites. In the United States, regional environmental concerns include the improvement of dissolved oxygen (DO) levels and minimum flows to protect aquatic habitat in tailwaters below dams, the release of higher spills from impoundments to increase fish passage survival, and, in some cases, demands for the removal of dams [Ruane and Hauser, 1993; DOE, 1991]. All of these environmental needs can have the effect of reducing hydroelectric generation, which may adversely impact the multi-purpose benefits or force the substitution of less benign generation alternatives.

New technologies are emerging which reduce environmental effects of conventional hydroelectric power generation and enhance the acceptance of hydro power as a source of renewable energy with an important role in sustainable development. Some of these new technologies reduce hydro's impact on water quality and aquatic habitat and some enhance the survival of fish passing through hydroturbines. Progressive water resource agencies and utilities are upgrading turbines to "environmentally friendly" designs as a part of their programs for generation improvements, maintenance improvements, and relicensing. Agencies and utilities are also developing strategies for system optimization and implementing control systems that improve turbine operations to improve water quality and fish survival. The direct fish mortality associated with turbine bypass systems, including spillways (which may also add harmful levels of dissolved nitrogen) and fish collecting structures, are under investigation to provide an overall understanding of a hydro project's environmental compatibility. In many cases, passing fish through environmentally enhanced turbine designs can result in higher overall survival than bypassing fish through the dam's spillways [Ledgerwood et al., 1990; Normandeau and Skalski, 1997; Franke et al., 1997].

This paper discusses work currently underway in the United States related to these issues, focusing primarily on designs and technologies for environmentally advanced turbines and control systems that are being developed to improve levels of dissolved oxygen in turbine discharges and to increase fish passage survival in conventional hydro plants. Important research for unconventional turbine designs, such as micro-head turbines and helical turbines [Cook et al., 1997; ENR, 1997], is not included.

Increasing Dissolved Oxygen in Turbine Discharges

In the Southeast, the Tennessee Valley Authority (TVA) has had responsibilities for integrated management and operation of the Tennessee River basin, including navigation, flood control, reforestation and reclamation, agricultural and industrial development, electric power production, water supply, and recreation. The agency has pioneered the development of management methods, system models, and optimization techniques for integrated resource management [Wunderlich, 1991]. TVA, in alignment with its history of environmental stewardship and its corporate goals for supplying low-cost and reliable power, supporting a thriving river system, and stimulating economic growth, has invested significantly in research to develop new technologies and in capital equipment to implement the new technologies and improve operations of its power and water resources system [TVA, 1990]. Under the self-imposed targets and deadlines of a five-year, power-funded, $50,000,000 Lake Improvement Program (LIP), TVA developed a variety of new technologies for re-oxygenation of turbine discharges and successfully resolved minimum flow and dissolved oxygen problems throughout its reservoir system. The minimum flow and water quality enhancements have been responsible for the recovery of 290 km of aquatic habitat lost due to intermittent drying of the riverbed and for DO improvements in more than 480 km of rivers below TVA dams [Brock and Adams, 1997]. An increase in diversity of aquatic insects and small fish such as rollers, darters, and shiners has been documented in the improved tailwaters [Scott and Yeager, 1997]. The technologies developed under the LIP range from reliable line diffusers for low-cost aeration of reservoirs upstream from hydro plants [Mobley and Brock, 1996] to effective labyrinth weirs and infuser weirs (see Figure 2) which provide minimum flows and aerated flows downstream from hydro plants [Hauser and Brock, 1994; Hauser and Morris, 1995].

Figure 2: Aerating Weirs downstream from TVA Hydro Plants

In the 1950s, Voith conducted research in Europe to develop turbine designs that would boost dissolved oxygen (DO) levels in water passing through low head turbines [Wagner, 1958]. In the 1980s, Voith Hydro, Inc., and TVA invested in a joint research partnership to develop improved hydro turbine designs to enhance DO concentrations in releases from Francis-type turbines. "Auto-venting," or "self-aerating," technologies, using the low pressures created by flows through turbines to induce additional air flows, are typically the most cost-effective technologies for Francis turbines.

The ongoing joint development effort by TVA and Voith Hydro, Inc., has made substantial improvements in the design of technologies for "auto-venting" turbines (AVT) [March et al., 1992; March and Fisher, 1996; Hopping et al., 1996; Hopping et al., 1997a; Hopping et al., 1997b]. Scale models, numerical models, and full-scale field tests are used in an extensive effort to validate aeration concepts and quantify key parameters affecting aeration performance. Specially-shaped geometries for turbine components have been developed and refined to enhance low pressures at appropriate locations, allowing the air to be drawn into an efficiently absorbed bubble cloud as a natural consequence of the design and minimizing power losses due to the aeration. New methods have also been developed to manufacture turbine components for effective aeration. TVA's Norris Dam was selected as the first site to demonstrate the AVT technologies. The two Norris AVT units contain options to aerate the flow through central, distributed, and peripheral air outlets at the exit of the turbines, as shown in Figure 3.

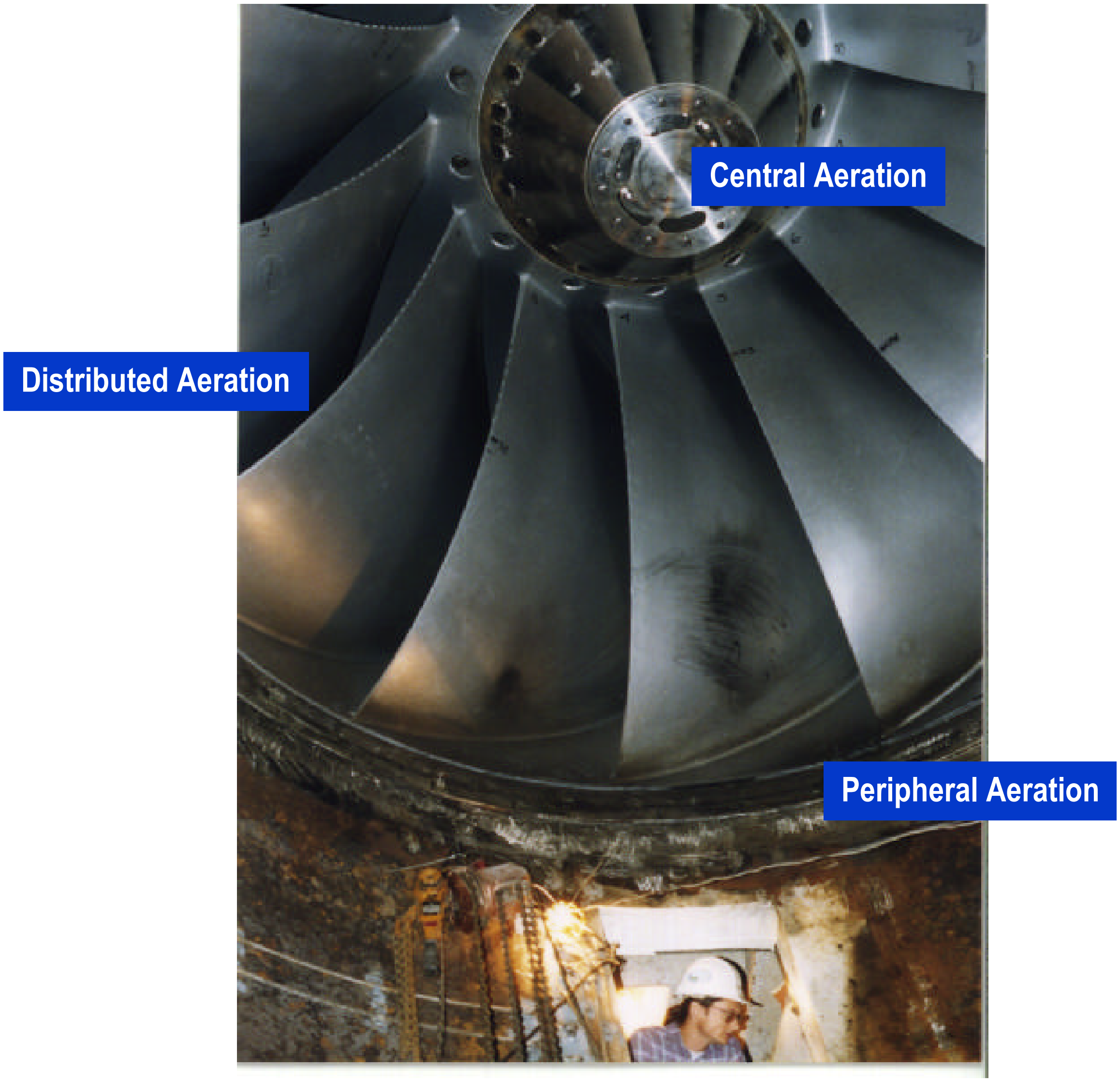
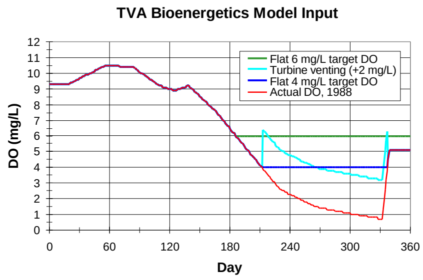
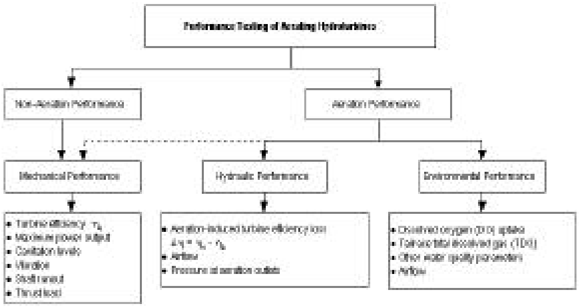


Figure 3: Auto-Venting Turbine During Initial Installation at the Tennessee Valley Authority's Norris Dam

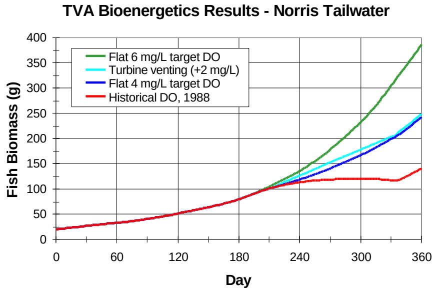
In testing the new auto-venting turbines, measurements are required to evaluate both the environmental and hydraulic performance of the aeration options (see Figure 4). The environmental performance is evaluated primarily by the amount of the DO uptake, while the hydraulic performance is based on the amount of aeration-induced efficiency loss. At Norris, each aeration option has been tested in single and combined operation over a wide range of turbine flow conditions [Hopping et al., 1996; Hopping et al., 1997a; Hopping et al., 1997b]. For environmental performance, results show that up to 5.5 mg/L of additional DO uptake can be obtained for single-unit operation, with all aeration options operating and a zero level of incoming DO. In this case, the amount of air induced into the turbine is more than twice that obtained in the original turbines, which had a retrofitted aeration system utilizing hub baffles.



Input Data for Bioenergetics Model



Methodology for Evaluating AVT Performance



Bioenergetics Model Results

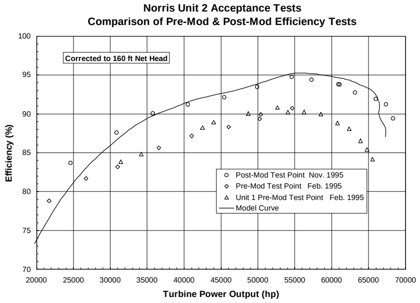


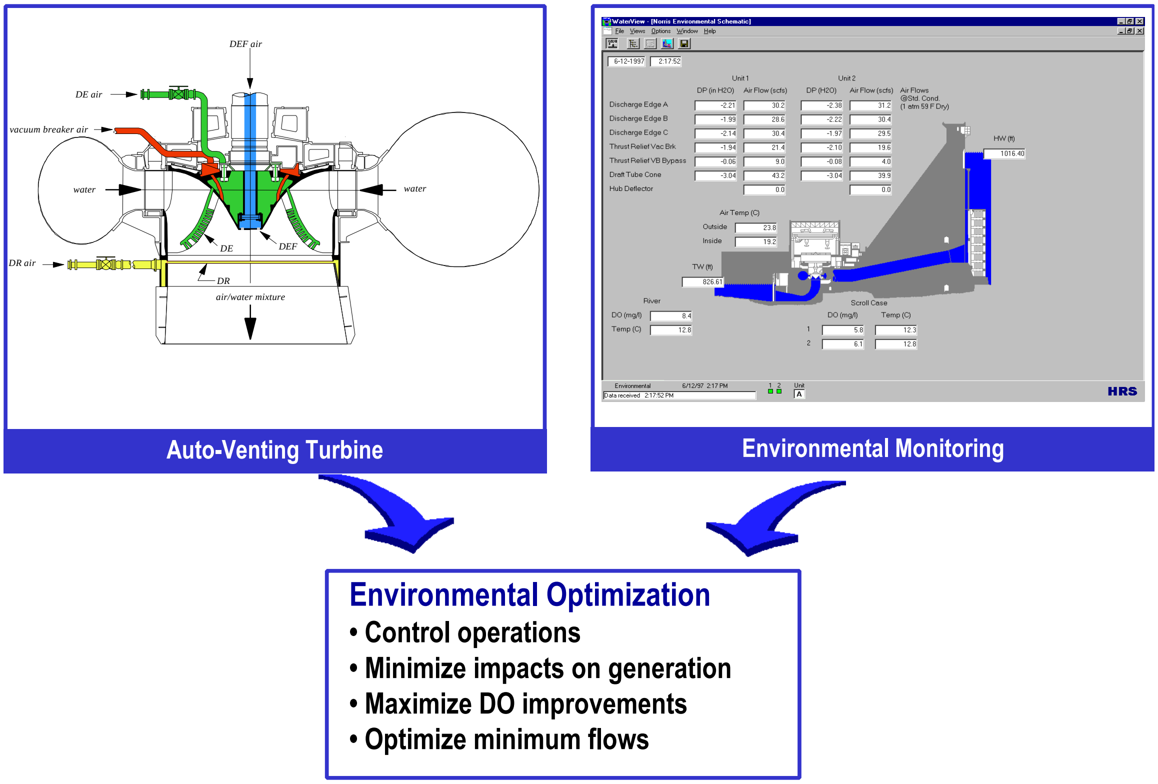
Figure 8.5

Hydraulic Performance of Norris AVT

Figure 4: Environmental and Hydraulic Performance of Norris Auto-Venting Turbines

At the Norris Project, turbine aeration is typically initiated in July, when the DO level monitored upstream from the turbines begins to drop. Throughout the low DO season, various combinations of AVT options are used, based on the head, power, and required DO uptake. Aeration typically ends in November, when cold, dense surface water promotes enough vertical mixing to reduce the thermal stratification. An additional 0.5 mg/L of DO improvement is obtained from air entrainment in the flow over a re-regulating weir that provides minimum flows downstream from the powerhouse. The downstream DO target level established for the Norris Project is 6.0 mg/L. Results from bioenergetics modeling of trout growth, calibrated and confirmed by fishery studies, indicate a 270 percent increase in the annual growth for a downstream DO of 6 mg/L compared to the base case without environmental improvements and a 160 percent increase in the annual growth compared to the previous Norris aeration system that maintained a downstream DO of approximately 4 mg/L (see Figure 4).

Compared to the original Norris turbines, these innovative AVT replacement units provide overall efficiency and capacity improvements, weighted over the operating range, of 3.7 percent and 10 percent, respectively, as shown in Figure 4 [March and Fisher, 1996]. This corresponds to an additional annual generation, for the same amount of rainfall, of about 17 GWh for the Norris Project. Efficiency losses during aeration range from 0 to 4 percent, depending on the operating conditions and the aeration options. The average aeration-related turbine efficiency loss during the July - November aeration period has been held to less than 2 percent. The new turbines have also shown significant reductions in both cavitation and vibration. As part of TVA's Hydro Modernization Program, twenty-six auto-venting turbines will be installed in the TVA system at thirteen tributary hydro projects that experience tailwater deficiencies in dissolved oxygen. The estimated total savings from the use of the AVT technologies is $7,600,000, compared with costs for other aeration options [Hopping et al., 1997].



6-12-1997 2:17:52

	Unit 1 DP (in H2O)	Unit 1 Air Flow (scfs)	Unit 2 DP (H2O)	Unit 2 Air Flow (scfs)
Discharge Edge A	-2.21	30.2	-2.38	31.2
Discharge Edge B	-1.99	28.6	-2.22	30.4
Discharge Edge C	-2.14	30.4	-1.97	29.5
Thrust Relief Vac Brk	-1.94	21.4	-2.10	19.6
Thrust Relief VB Bypass	-0.06	9.0	-0.08	4.0
Draft Tube Cone	-3.04	43.2	-3.04	39.9
Hub Deflector		0.0		0.0

Air Flows @Std. Cond. (1 atm 59 F Dry)

HW (ft) 1016.40

Air Temp (C)
Outside 23.8
Inside 19.2

TW (ft) 826.61

River
DO (mg/l) 8.4
Temp (C) 12.8

Scroll Case

	DO (mg/l)	Temp (C)
1	5.8	12.3
2	6.1	12.8

Environmental 6/12/97 2:17 PM
Data received 2:17:52 PM
1 2 Unit A

Environmental Optimization

- Control operations
- Minimize impacts on generation
- Maximize DO improvements
- Optimize minimum flows

Figure 5: Environmental Optimization of Auto-Venting Turbine

The environmental and hydraulic performance of a specific AVT technology or option typically varies with a site's head and power output. Under varying reservoir conditions and unit operating conditions, the options used to meet a target DO are strategically chosen to minimize the aeration-induced efficiency losses. With careful monitoring of operating conditions and environmental conditions, individual operator judgment and appropriate optimization software are utilized to balance the energy needs and the environmental needs, as illustrated above in Figure 5. Improved and updated performance characteristics, multiunit optimization software, changes in operational policy, and on-line performance monitoring systems, initially developed under the Lake

Improvement Program for environmental monitoring, are important components in improving average efficiencies for the TVA system. The monitoring and optimization systems are installed in seventeen hydro plants, which include thirty-three vertical Francis units, twenty-eight Kaplan units, eighteen fixed-propeller or diagonal flow units, and five reversible pump-turbine units. The additional annual generation for the TVA system is more than 250 GWh.

Research is underway to improve aeration performance and reduce efficiency losses in aerating turbines. In one project, CFD simulations using advanced numerical methods have been developed to model the processes involved in increasing the effectiveness of aeration. “Virtual bubbles” are injected into computed turbine flows and used to calculate bubble properties and oxygen transfer efficiencies (see Figure 6) [Ventikos et al., 1998; Ventikos et al., 1999]. Through the use of the advanced numerical simulation, oxygen uptake efficiency as a function of changing design and operating parameters can be further refined. Improved software to calculate the influence of aspirated air on turbine performance and on the pressure at the air admission point is under development, and the design of improved mechanical systems for transporting air to critical locations is underway. Detailed field tests to verify design assumptions continue to play an important role in improving the methodology [Hopping et al., 1999].

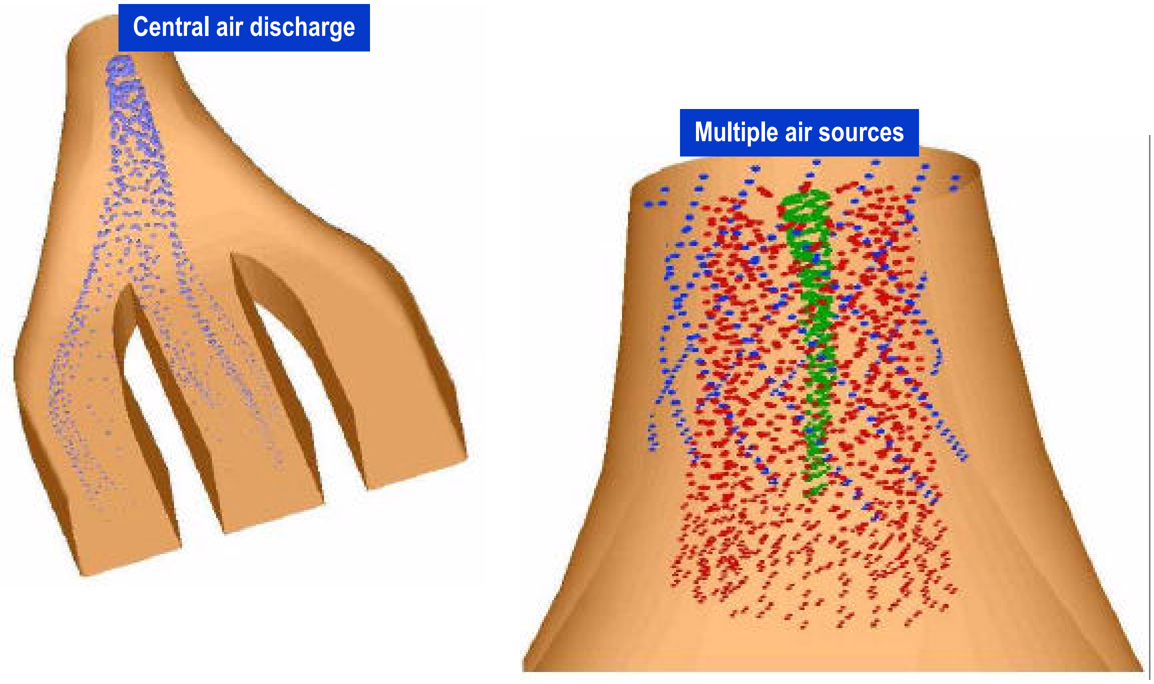


Figure 6: Numerical Models Include “Virtual Bubbles” Passing through the Draft Tube

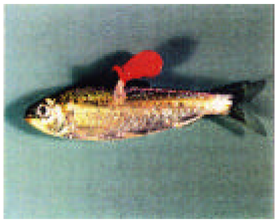
Increasing Fish Passage Survival

In the 1980s, Voith, with others in the industry, began research and development directed toward the reduction of fish mortality during turbine passage [Breymaier, 1994; Eicher Associates, 1987]. Before 1990, fish passage studies were conducted by catching fish downstream from the turbines. These studies provided few insights into the actual mechanisms affecting fish survival and fish mortality. The turbine was treated as a "black box" by many researchers, and only vague rules-of-thumb were developed to characterize the turbines' environmental effects. Statements such as "Turbines are like blenders — they chop and kill a significant portion of passing fish," "Kaplan turbines are more fish friendly than Francis turbines," and "Operation at best efficiency is best for survival" were used regularly to characterize hydroturbines and to determine environmental policies [Fisher and Roth, 1995].

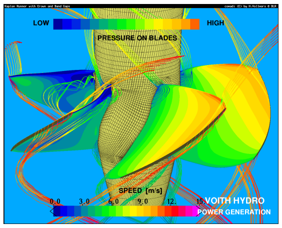
Beginning in 1990, a more precise method for measuring fish passage survival was introduced. This technique uses carefully designed and controlled testing with fish which can be recovered with "balloon tags" [Heisey et al., 1992]. Based on the results from these studies, statistical characterizations demonstrating much higher fish survival began to emerge [Mathur and Heisey, 1992]. Survival rates measured for fish passing directly through large turbines ranged from 88 to 94 percent. By comparison, survival rates measured for fish passing through fish bypass systems typically range from 95 to 98 percent, and survival rates measured for fish passing through spillway systems typically range from 95 to 99 percent.

The U. S. Department of Energy's (DOE) Advanced Hydro Turbine System (AHTS) program has stimulated an in-depth investigation into mechanisms for fish passage mortality. In the past 5 years, important research aimed at further understanding the mechanisms leading to fish mortality has been completed [ada et al., 1999; ada et al., 1997; ada, 1997]. Numerous workshops, bringing aquatic biologists, operators, regulators, and designers together to exchange views, have improved insight into factors which may influence survival. The DOE's AHTS program has stimulated the use of 3-D viscous computational fluid dynamics (CFD) methods for detailed numerical simulations of fluid flows in turbines [Franke et al., 1997], and CFD results have been supplemented with careful field tests using the balloon tag technique (see Figure 7).

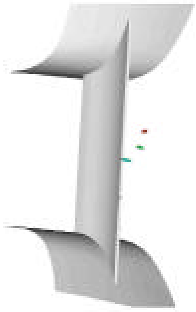
An advanced computational method for estimating trajectories of fish-like bodies passing through hydropower installations is currently under development [Ventikos et al., 1999]. The method is based on the assumption that a fish progressing through the complex, three-dimensional flow field of a hydro turbine (obtained using a separate 3-D viscous calculation) can be approximated as a body of simplified, yet "fish-like," geometry moving through the precomputed flow field. The motion of the "virtual fish" is governed by a set of differential equations that account for the fish mass and various flow-induced forces. This model can not only be used to estimate the trajectory of a virtual fish from the forebay to the tailrace, but can also provide specific information about a variety of flow-induced loads on fish passing through various zones of turbine flow, as shown in Figure 7 [Venttikos et al., 1999; Sotiropoulos et al., 1997].



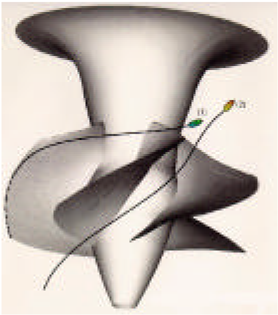
Live Fish Testing with Balloon Tags



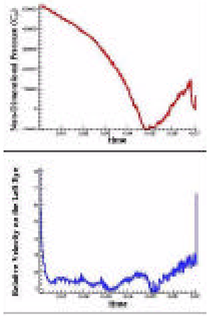
Computed Flow through Kaplan Turbine



Virtual Fish Approach a Stay Vane



Virtual Fish Pass a Kaplan Turbine



Loading History on Virtual Fish

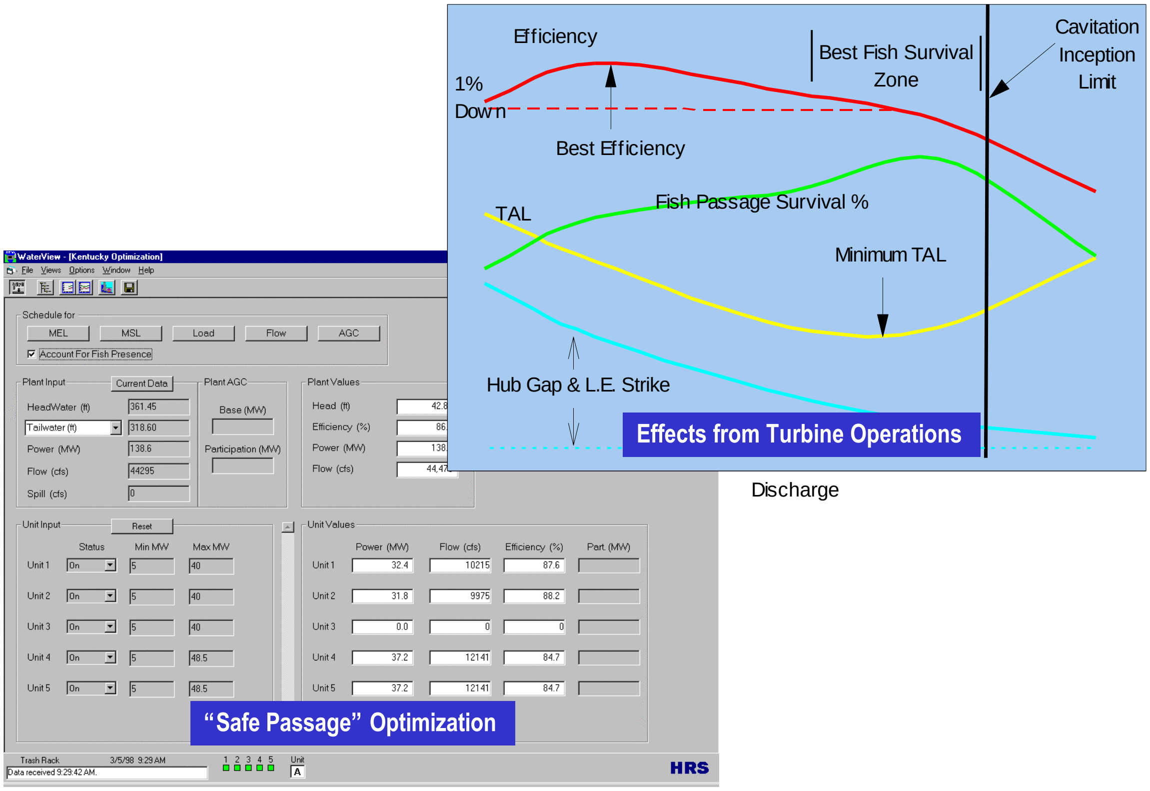
Figure 7: Field Testing and "Virtual Laboratory" Testing to Improve Fish Passage

Turbine design improvements, which can be implemented in new machines or through rehabilitation of existing machines, have been developed [Franke et al., 1997]. Limited field testing to date has verified the design improvements [Normandeau and Skalski, 1996; Normandeau and Skalski, 1998]. An enlightening test of the existing turbines at Grant County Public Utility District's Wanapum Dam used balloon-tagged fish to verify many of the fish mortality mechanism included in evaluative models [Normandeau et al., 1996; Fisher et al., 1997]. These tests clearly demonstrated that best efficiency operation of Kaplan turbines is not necessarily the most favorable operating condition for fish survival, as was previously believed. Instead, operation at higher flows was found to be safer for passing fish (see Figure 8).

The research stimulated insights into mortality mechanisms and improved survival models for Kaplan turbines, with mortality being related to:

1. Turbulent flows resulting from low efficiency designs or plant operating strategies;
2. Turbulent flows and the trapping and cutting of fish in the zone of flow passing near the turbine hub when large gaps between blade and hub exist (characterizing the lower output operation of Kaplan turbines);
3. Strike of fish by turbine blades or impact of fish on other turbine structures;
4. Cavitation in turbine water passages;
5. Abrasion of fish driven into rough turbine surfaces by flow turbulence; and

6. Turbulence-induced or impact-induced dizziness, increasing the chance for predation losses as disoriented migrating fish are eaten by birds or other fish when they emerge from the draft tube.



☑ Account For Fish Presence

Plant Input

HeadWater (ft) 361.45
Tailwater (ft) 318.60
Power (MW) 138.6
Flow (cfs) 44295
Spill (cfs) 0

Plant AGC

Base (MW)
Participation (MW)

Plant Values

Head (ft) 42.8
Efficiency (%) 86
Power (MW) 138
Flow (cfs) 44,47

Unit Input

	Status	Min MW	Max MW
Unit 1	On	5	40
Unit 2	On	5	40
Unit 3	On	5	40
Unit 4	On	5	48.5
Unit 5	On	5	48.5

Unit Values

	Power (MW)	Flow (cfs)	Efficiency (%)	Part. (MW)
Unit 1	32.4	10215	87.6	
Unit 2	31.8	9975	88.2	
Unit 3	0.0	0	0	
Unit 4	37.2	12141	84.7	
Unit 5	37.2	12141	84.7	

Trash Rack 3/5/98 9:29 AM
Data received 9:29:42 AM.
1 2 3 4 5
Unit A

Figure 8: Optimizing Turbine Operations for Fish Survival

The number of turbine blades and stay vanes, the length of the fish compared to the size of the turbine, and the quality of the flow at the point of operation are key elements that characterize survival [Franke et al., 1997; Fisher et al., 1997]. Also, the location of the fish in the water column and the zones of flow through which the fish pass are observed to be important.

As a result of these insights, a comprehensive design concept was developed for an environmentally-enhanced Kaplan turbine. The required features depend on site-specific goals and include designs having:

1. High efficiency over a wide operating range with reduced cavitation potential;
2. Gapless design for the hub, discharge ring, and blades that enhances fish passage survival;
3. Non-overhanging design for wicket gates;
4. Environmentally compatible hydraulic fluid and lubricants;
5. Greaseless wicket gate bushings;
6. Smooth surface finishes in conjunction with upgrades for the stay vanes, wicket gates, and draft tube cone.

To address the changes in mortality associated with turbine operations, new technologies in measurement transducers and control systems have been used to develop designs that:

1. Sense the presence of fish at each turbine and limit turbine operation to "fish-friendly" modes when fish are present;
2. Automatically update a Kaplan turbine's "digital cams" to provide the most efficient operation at each head and flow, ensure proper optimization of operations, and minimize fish-damaging flow turbulence;
3. Sense active cavitation and limit turbine operation to non-cavitating conditions; and
4. Optimize plant output when fish are present to achieve targeted fish passage survival, based on fish presence, location, turbine passage mortality, spillway mortality, fish bypass characteristics, and total dissolved gas generated during spilling. An implementation of these concepts, the "Safe Passage" optimization module, is shown in Figure 8.

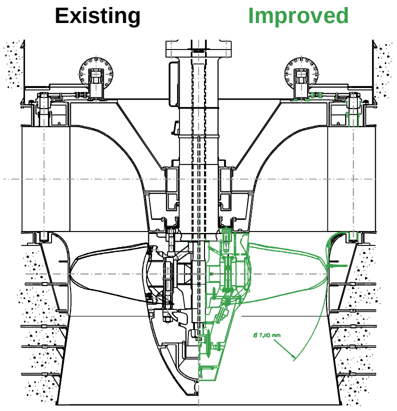
Elements of these advanced Kaplan design concepts have been implemented in the rehabilitated units installed at the Chelan County Public Utility District's Rocky Reach power plant [McKee and Rossi, 1995], at the U. S. Army Corps of Engineers' Bonneville Dam [Moentenich, 1997], and at the Tennessee Valley Authority's Kentucky Dam. A design utilizing most of the advanced Kaplan concepts has been developed and model tested for the Grant County Public Utility District's Wanapum Dam [Hron et al., 1997]. Design features for the advanced Kaplan turbine and the technologies implemented or planned at each site are summarized in Figure 9.

	Advanced Kaplan Design Feature	**Kentucky**	**Rocky Reach**	**Bonneville**	**Wanapum**
		(TVA)	(CCPUD)	(USACE)	(GCPUD)
1	Gapless upstream at hub with pocket		X	X	
2	Gapless upstream at hub on spherical hub				X
3	Gapless downstream at hub	X		X	X
4	Partially gapless at outer periphery segment above CL			X	
5	Fully gapless at outer periphery segment above CL				X
6	Hydraulically optimized stay vanes				X
7	Hydraulically optimized wicket gates with overhang		X		
8	Hydraulically optimized wicket gates, no overhang				
9	Hydraulically optimized vanes and gates aligned, no overhang				X
10	Hydraulically optimized blading	X	X	X	X
11	Hydraulically optimized blading with thick leading edges				X
12	Hydraulically improved draft tube			X	
13	Reduced cavitation	X	X	X	X
14	Higher design capacity	X			X
15	Improved efficiency design	X	X	X	X
16	Oil-free hub				
17	Greaseless bushings	X	X	X	X
18	Upgraded and hydraulically smooth surfaces				
19	Improved draft tube to minimize backroll				
20	Advanced control system	X			X

Figure 9: Summary of "Fish-Friendly" Features for Advanced Kaplan Design

For each of these sites, the turbines feature partially or fully gapless designs as well as a mix of the other advanced features. Fish survival testing using balloon tags at Rocky Reach showed that elimination of the gaps downstream from the turbine blade's center of rotation resulted in a four percent improvement in fish passage survival at the lower operating powers where gap size was large [Franke et al., 1997, p. 110]. Testing of fish passage survival for the minimum gap design at Bonneville Dam is planned for the spring of 1999.

Advanced zonal matrix models to estimate fish passage survival as a consequence of turbine geometry and operational characteristics have been developed and are currently being evaluated [Ellis et al., 1999; Fisher et al., 1998]. Using the model results, lines of constant fish passage survival can be superimposed on the turbine performance characteristics [Fisher et al., 1998]. Field tests of eel survival for a propeller turbine design correlated well with predicted survival [Normandeau and Skalski, 1998] using the zonal matrix model. Figure 10 shows some of the design details and presents the results from application of the zonal matrix model to the existing Bonneville turbine design, the minimum gap design which is being installed at Bonneville, and a hypothetical "Wanapum-style 95% AHT" design. For these designs, the model predicts maximum fish survivals of 88 percent for the existing Bonneville design, 95 percent for the minimum gap Bonneville design, and 97 percent for the "Wanapum-style 95% AHT" design.



- **Minimum gap**
- **High efficiency**
- **Special blade shapes**
- **No oil or grease**
- **Smooth surfaces**
- **Advanced controls**

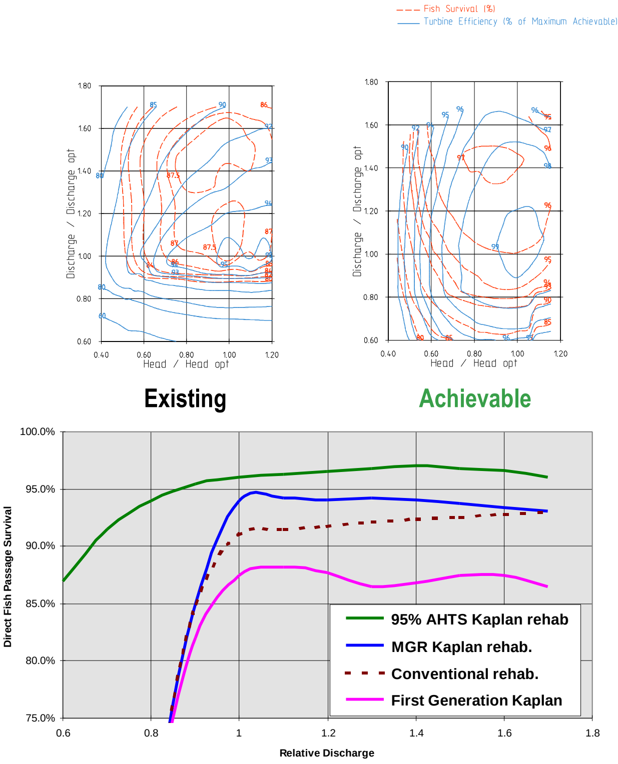
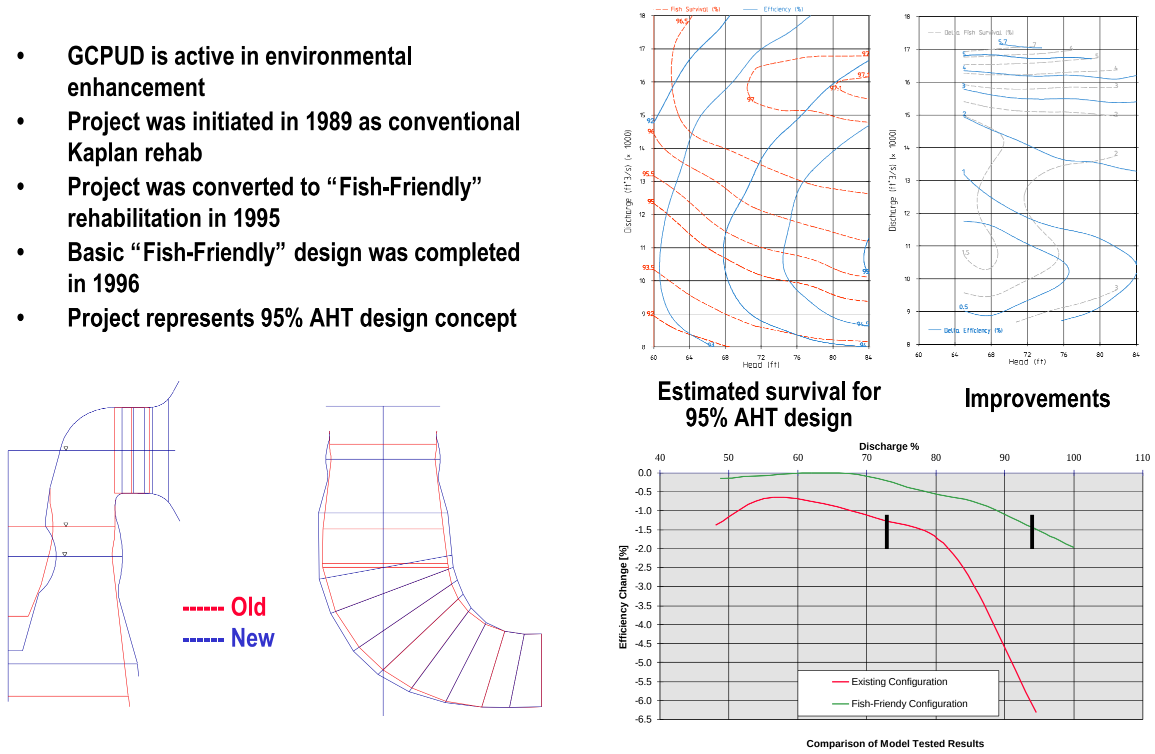


Figure 10: Partial Implementation of Advanced Kaplan Turbine - Bonneville

Figure 11 shows some of the design details and presents additional results from application of the zonal matrix model to the "Wanapum-style 95% AHT" design. The maximum fish survival of 97 percent predicted by the model is up to 7 percent higher than the predicted survival with the existing Wanapum design. Results from scale-model tests, also presented in Figure 11, indicate a capacity improvement and efficiency improvements with the new design ranging from about one percent at best efficiency to five percent at maximum capacity.



- **GCPUD is active in environmental enhancement**
- **Project was initiated in 1989 as conventional Kaplan rehab**
- **Project was converted to "Fish-Friendly" rehabilitation in 1995**
- **Basic "Fish-Friendly" design was completed in 1996**
- **Project represents 95% AHT design concept**

Figure 11: Proposed Implementation of "95%" Advanced Kaplan Turbine - Wanapum

Collaborative Approaches to Environmental Improvements

The President's Council on Sustainable Development has concluded, "…in order to meet the needs of the present while ensuring that future generations have the same opportunities, the United States must change by moving from conflict to collaboration and adopting stewardship and individual responsibility as tenets by which to live." [PCSD, 1996]. The development and implementation of the environmental technologies described in this paper have been achieved through cooperation and collaboration.

For the auto-venting turbine technologies, important developmental work was completed in collaboration with the Electric Power Research Institute, the U. S. Army Corps of Engineers, the U. S. Bureau of Reclamation, the U. S. Department of Energy, the University of Iowa, Colorado State University, the University of Minnesota, and the Georgia Institute of Technology. Significant AVT and control system technologies were developed under a long-term cooperative research agreement between TVA and Voith Hydro, leading to a partnering agreement for hydro modernization and a jointly owned technology development company, Hydro Resource Solutions LLC. The AVT development was accomplished as part of TVA's Lake Improvement Program, which involved a wide variety of agencies, local stakeholder groups, and environmental advocacy groups such as Trout Unlimited.

The advanced Kaplan concepts and the "Safe Passage" optimization were stimulated by DOE's Advanced Hydro Turbine Program, which has received financial, political, and technical support from a variety of sources, including the Grant County Public Utility District, HCI Publications, the Electric Power Research Institute, the U. S. Army Corps of Engineers, the U. S. Bureau of Reclamation, the U. S. Department of Energy, the Bonneville Power Administration, the National Marine Fisheries Service, Oak Ridge National Laboratory, Idaho National Engineering and Environmental Laboratory, Pacific Northwest National Laboratory, Southern Company, the Tennessee Valley Authority, Alden Research Laboratory, the National Hydropower Association, and others.

There is a trend toward cooperative environmental problem-solving throughout the hydro industry [Culligan and Sabattis, 1998]. The hydropower industry's primary trade association, the National Hydropower Association, has established principles for hydropower relicensing reform that focus on a collaborative rather than a confrontational approach and seek "to address problems in the underlying statutes that unduly hinder hydropower's ability to compete on its merit and serve the energy needs of consumers" and "to eliminate duplicative permit authority, reduce costly and time-consuming litigation, and support a responsible balance between economic and environmental concerns [NHA, 1998]."

Balancing Energy and Environment

The difficulty in understanding and achieving what the NHA calls "a responsible balance between economic and environmental concerns" is the hydropower industry's primary reason that "It's not easy being green." Deregulation and restructuring of the electric power industry promise reduced costs for electricity. But, as observed by Herman Daly, a former World Bank economist and co-founder of the International Society for Ecological Economics, reductions in costs can be achieved in two very different ways. The appropriate way is through actual improvements in efficiency, such as the new environmental technologies described above. The more common way is through externalizing costs so they are borne by a segment of the society or the society as a whole rather than by the organization creating the costs [Daly, 1996]. The Group for Research in Applied Macro Ecology (GRAME) recently concluded:

> Hydroelectricity appears to be the energy source that makes the best showing in any analysis that places significant importance on sustainable development, including global pollution and long-term impacts. We are thus faced with a paradox: the burden of hydroelectric development (including external and

> internal costs) is borne by the current generation for the benefit of future generations. But unlike most other energy sources, which externalize their impacts over space and time, the environmental impacts of hydro power are local, visible, and immediate, which makes this energy option particularly vulnerable [Lefebvre et al., 1998].

The hydropower industry carries a regulatory burden that is equaled only by the nuclear power industry. Legislation, including the Electric Consumers Protection Act of 1986, and subsequent judicial interpretations have created a labyrinth of regulatory processes that increase costs without corresponding benefits [Sale and Brown, 1998]. Additionally, the structure of the hydropower market is complex, including multi-purpose state and federal power projects, private FERC-regulated utilities, and federal power marketing agencies, with generation, transmission, and distribution supported in various combinations by congressional appropriations (taxpayers) and power customers (ratepayers), as illustrated in Figure 12.

Category	Hydro Capacity (MW)	National Proportion (%)	Generation	Transmission	Marketing, Distribution
USACE (DOD)	21,000	28	T	T, R	T, R
USBR (DOI)	13,000	17	T	T, R	T, R
TVA	5,000	6	R	R	R
PMAs (DOE)	-	-	T, R	T, R	T, R
Other Federal	250	0	T, R	T, R	T, R
FERC-Reg.	37,200	49	R	R	R
TOTAL	76,450	100	-	-	-

Figure 12: "Structural" Issues in the Hydro Industry

In Bachman et al. [1997], the authors articulate concerns that "…the current non-power related public interest burdens imposed on hydroelectric facilities could price hydroelectric power out of competitive wholesale and retail markets. In a restructured electric power industry driven by competition, the marketplace will compel power producers to reduce costs and will place at risk utility-funded public interest programs. In turn, this will produce 'stranded benefits' - public interest programs that are rendered uneconomic by a competitive marketplace." These "stranded benefits" may include environmental enhancements; navigation; flood control; irrigation; industrial and municipal water supply; fish, land, and wildlife management; recreational facilities (campgrounds, launching facilities for boats, special operations for whitewater sports, etc.); and public education. These factors must receive full consideration in deregulating and restructuring the electric utility industry.

The hydropower industry, in particular, has a critical need for improvements in “environmental accounting” to evaluate the socioeconomic benefits and environmental costs in a scientific, defensible, and consistent way and to ensure a balanced comparison with other “green” alternatives [Rhodes and Brown, 1999; Boschee, 1998]. One such approach, recently applied by Scientific Certification Systems to a hydropower plant in Sweden, utilizes the ISO 14000 “life-cycle impact assessment” standards and compares specific energy production systems against the power system average for all energy generation in the same region [Rhodes, 1998], as illustrated in Figure 13.

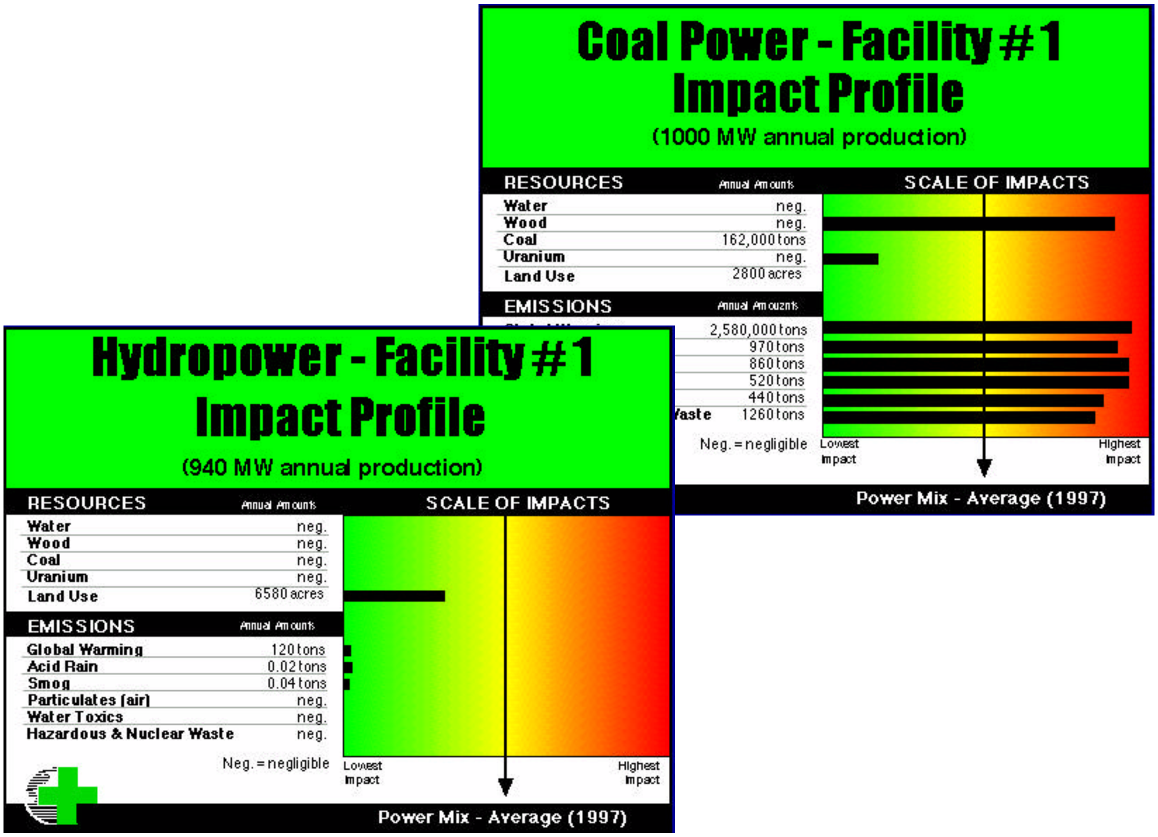


Figure 13: Environmental Comparisons Based on Life-Cycle Impact Assessment, Adapted from Rhodes [1998]

Another applicable approach using life-cycle impact assessment is described by the World Business Council for Sustainable Development as “eco-efficiency” [DeSimone and Popoff, 1997]. This methodology, which is systematized and quantified in Fussler and James [1996], includes six dimensions and incorporates both business and environmental objectives:

1. Health risks and other environmental risks;
2. Conservation of resources;
3. Energy intensity;
4. Raw materials intensity;
5. Revalorization (i.e., reuse, recycling, remanufacturing, etc.); and
6. Extension of service life.

On a national and international scale, Daly [1996] proposes the elimination of Gross National Product (GNP) as an economic indicator and the substitution of three national accounting indicators:

1. A benefits account that would measure the value for all the services and activities;
2. A cost account that would measure the costs associated with depletion and pollution; and
3. A capital account that would measure not only stocks and funds, but also natural capital such as ecosystem infrastructure, mines, wells, and water resources.

These approaches to environmental accounting can lead to increased public understanding of the complex balance between the multipurpose economic and social benefits of hydropower and its environmental costs; to increased individual responsibility in rationally assessing the impacts of various energy production alternatives and choosing among the alternatives under deregulation; to the creation of more enlightened and sustainable regulations and policies; to an improved understanding of the overall "business ecosystem [Moore, 1996];" and to the promotion of innovative systems-approaches, such as pollution trading arrangements for environmental enhancement [Ruane et al., 1998; Hauser et al., 1999].

Conclusion

C. Herman Pritchett, an early observer of the Tennessee Valley Authority's integrated approach to resource management, noted:

> "...the damming of a river creates an entirely new physical environment. Napoleon is reported to have said that man could have no more absolute authority than control over the waters that cover the earth. He who undertakes to wipe out by flood a valley where men have lived plays God, and incurs obligations proportionately heavy. There must be a weighing of consequences, and a new equilibrium must be fashioned to replace the one destroyed [Pritchett, 1942]."

Kermit’s song in “The Muppet Movie” expresses the same conclusion in a more personal way:

> When green is all there is to be
> It could make you wonder why, but why wonder why?
> Wonder, I am green and it’ll do fine, it’s beautiful!
> And I think it’s what I want to be.

By proactively addressing environmental responsibilities and fashioning this new equilibrium, the hydropower industry and the environmental community can provide a national and international model for sustainable development through cooperative and cost-effective resolution to the competing priorities of environmental stewardship and economical power production.

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