A COST EFFECTIVE AND ENVIRONMENTALLY SUSTAINABLE APPROACH TO RETROFITTING EXISTING DAMS FOR HYDROELECTRIC POWER GENERATION

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SYNOPSIS

Hydraulic potential stored in water reservoirs can be converted to useful power through the work of turbomachinery. However, nations around the world have large numbers of existing dams with hydropower potential left unused. These dams were mostly built during the latter half of the 20th century. At that time, thermal electric energy supply, generated with abundant cheap fossil fuels made small scale hydropower generation less attractive. Another reason for such low utilization of these clean renewable energy resources is the significant capital cost of equipment and hydropower plant construction. This made small hydropower development economically noncompetitive. With the rapid depletion of fossil fuel and the increased environmental and global warming concerns, it becomes highly desirable to harness clean renewable energy sources.

To retrofit a conventional hydroturbine onto an existing dam brings out several major issues. They include structural integrity and safety of the dam, and the cost of construction and complex engineering tasks involved in properly integrating a powerhouse into the existing structure. These issues have seriously impeded the progress in developing these hydroelectric potentials. In addition, available data indicates that existing hydroturbine technology has some undesirable ecological impacts by causing injury and mortality to passing fish and deterioration of downstream environmental condition resulting from undesirable levels of dissolved gas.

In this paper the authors will first briefly summarize current hydropower development needs and challenges, and then describe a new approach to effectively meeting these challenges by using an innovative hydroturbine system. The new hydroturbine system consists of four key design innovations: 1) an updraft flow arrangement, 2) a vertical pressure-balanced turbine flow control valve in place of the conventional wicket gates, 3) a divergent runner flow chamber serving the function of the draft tube, and 4) exit flow at the free surface in the tailwater terrace.

Comparing with the conventional hydropower technology, the new system costs less to build; is easier to operate and maintain, is more efficient; has open flow-passage reducing fish injury; eliminates flow cavitation to minimize fish mortality; and aerates exit flow to help improve downstream water quality. Furthermore, depending on the condition of the existing dam, the new hydroturbine system can be connected directly onto the existing dam’s normal or natural outflow; or onto a new siphon penstock, modified spillway or flow diversion pipe. The new approach makes the retrofitting simple to achieve without affecting the dam itself and provides a cost effective and environmentally sustainable approach to new hydroelectric power generation from available hydropower resources stored behind existing dams.

Introduction

Water has long been realized as the foundation for existence of life and is increasingly recognized as the most important commodity that sustains healthy human development. The former is evident knowing water constitutes 60 to more than 90% of various living things. Its importance becomes obvious in the way water fulfills our drinking, irrigation, industrial application, energy production, recreational and transportation needs. It is said that water, superseding all others, will become the most precious resource affecting a nation's security, societal well being and the very existence of human kind in the years to come.

Use of water resources can be categorized into three types: 1) Consumptive Type – drinking water supply and irrigation water. Usage belonging to this type depletes or transforms water and makes it unavailable for other use; 2) Polluting Type – cleansing and most industrial applications are examples of this type. It changes the quality of water and makes it unusable without further treatment; and 3) Non-consumptive and Non-polluting Type – hydropower generation belongs to this category. It leaves the water with exactly the same properties as before it went through the hydroturbine and thus is usable for other purposes. Although reusable, there are arguments on both sides of the issue on whether the amount of CO_2 discharged from a hydropower facility amounts to a harmful amount of greenhouse gas. However in the case of an existing reservoir the effect is likely minimal because the equilibrium of CO_2 captured within the reservoir and transferred to the atmosphere is stable with no net increase.

With conventional hydropower generation the potential energy stored in the elevated water is extracted and converted to mechanical and eventually electrical energy. The potential energy is stored in natural lakes at higher elevation or man-made reservoirs by damming up a section of river. Reservoir building along river channels can have certain negative ecological and environmental impact on the river. However, such impact is relatively small in comparison with most of the other forms of energy production practices, especially thermal electric power generation (Spadaro, 2000, Kao, 2008). And it can be mitigated to minimize its long term effect with well planned design and operational practices (Chen, 2006; Mahar, 2008).

Hydropower generation is not the only purpose for construction of dams. In fact, only a small fraction of the enormous number of dams built around the world are used for hydroelectric power generation. According to the US Army Corp of Engineers national inventory of dams, only 2% of the US dams, large and small, are used to generate electricity. The rest are constructed for flood control (15%), water supply (12%), irrigation (11%), recreation (35%), stock/farm pond (18%), and multi-purposes (7%), such as projects on the main stem of the Columbia River, navigation and irrigation are authorized purposes of equal significance to their hydropower capability.

The similar situation exists elsewhere around the world. Table-1 below (data was made available from the International Hydropower Association) illustrates that only 6 to 11% of the constructed dams in Africa, Asia and North/Central America are built with some hydropower generation capability.

TABLE–1: Usage of existing dams in various Continents

Region	Hydropower	Flood Control	Drinking	Irrigation	Multi Purpose	Other
Africa	6%	1%	20%	50%	21%	2%
Asia	7%	2%	2%	63%	26%	0%
N&C Am.	11%	13%	10%	11%	40%	15%

This leaves a large number of dam-reservoir systems worldwide with untapped hydropower potential. They could be retrofitted to generate electricity without requiring construction of new dams and with substantial savings on capital cost. However, to retrofit a hydropower facility into an existing dam can raise some different issues. It is crucial therefore to develop a new design approach and advanced turbine system to effectively address these concerns.

Untapped Hydropower Resources

Worldwide there is a significant amount of hydropower potential with an estimated total at 1,760,000 MW. 79% of these resources, (an equivalent of 2,400 nuclear power plants of 600 MW each) are untapped (Taylor, 2006). Of this underutilized hydro-potential, more than 95% falls within power generation applications at sites with ultra low (<2 meters) to medium (<50 meters) water heads.

The United States currently has 2,378 hydropower plants generating at an annual average rate of 35,432 MW (Hall, et al., 2006). This represents only about 50% of the hydropower resources feasible for development in the US. China and Asia have the world's largest hydroelectric energy reserve of a single nation (541,000 MW) and a continent (875,445 MW) respectively. China has developed only about 20% and Asia 22% of their full hydropower potential. Asian nations, including China, have established their long-term energy policy, making the development of their untapped hydropower a major source of renewable energy supply.

Recent US Water Resources Assessment Efforts

US Department of Energy (DOE), Idaho National Engineering and Environmental Laboratory (INEEL) reported its comprehensive study results in 2004 on "Water Resources of the United States with emphases on Low Head/Low Power Resources" (Hall, et al., 2004). The total available annual mean hydropower generation of all potential sites in the US is shown in Table 2 below.

The terms used in the report to categorize different classes of hydropower are defined as follows:

Low Head: H < 30 feet (<10 M);
Low Power: 100kW < P < 1 MW (P < 100 kW as Micro Power);
High Head: H ≥ 30 feet (≥10 M); and
High Power: P ≥ 1 MW

TABLE 2 – water energy resource assessment of the United States (Reprinted from Hall, et al., 2004)

Annual Mean Power (MW)	Total	Developed	Excluded	Available[a]
TOTAL POWER	**289,741**	35,429	88,761	165,551
TOTAL HIGH POWER	**229,794**	34,596	76,864	118,334
High Head/High Power	157,772	33,423	55,464	68,885
Low Head/High Power	72,022	1,173	21,400	49,449
TOTAL LOW POWER	**59,947**	833	11,897	47,217
High Head/Low Power	35,403	373	9,163	25,868
Low Head/Low Power	24,544	461	2,734	21,350
Conventional Turbine	8,470	319	899	7,253
Unconventional Systems	3,932	43	527	3,362
Microhydro	12,142	99	1,308	10,735

a. No feasibility or availability assessments have been performed. "Available" only indicates net potential after subtracting developed and excluded potentials from total potential.

Under the consideration of various other factors, some of the "Available" annual mean power listed in Table 2 may not be feasible for development. To assess the development feasibility, INEEL conducted further study on more than 500,000 validated stream reaches in the United States having a gross hydropower potential greater than 10 kW (Hall, et al., 2006). The work was done using Hydropower Evaluation Software (HES) modeling technique developed at INEEL (Conner, 1997). Among the sites assessed, only 874 sites (~0.2%) fall into large hydro (P > 30 MW) category The rest are small hydro (1 MW ≤ P ≤ 30 MW) with 43,533 sites (9%) and low power hydro (P < 1 MW) with 455,750 (91%) sites.

In the modeling process, HES takes into consideration the effect of development on various environmental attributes and development suitability including meeting the Federal Land Codes (Francfort, 2002). The resulting power generation potential of individual sites, in most cases, is significantly smaller than the "Available" gross amount. The results are reported for each of the assessed sites by state.

Hydroelectricity from Retrofitting Existing Dams in the United States

The tables below show results from the studies on feasible water power potentials in summary form of project sites in the authors' home states of Virginia and Oregon. In the "Category of the Site" column: the term "With Power" indicates the site has an existing dam with some hydropower generation capacity; and "W/O Power" indicates existing dam with no hydropower generation facility. The term "Name Plate Capacity" represents the additional gross hydro potential at these sites and "HES Adjusted Capacity" is the potential feasible for development at the project sites.

TABLE 2 – Feasible water power potential – Virginia

Category of The Site	Number of Projects	Name Plate Capacity (MW)	HES Adjusted Capacity (MW)
With Power	9	16	12
W/O Power	52	690	376
Undeveloped	27	544	299
State Total	88	1,250	617

TABLE 3 – Feasible water power potential – Oregon

Category of The Site	Number of Projects	Name Plate Capacity (MW)	HES Adjusted Capacity (MW)
With Power	3	45	11
W/O Power	101	2,549	1,916
Undeveloped	118	950	318
State Total	222	3,544	2,245

A close look at the numbers in the tables reveals that In Virginia, over two-thirds (61/88) of the project sites already have existing dams. In the state of Oregon, although only about one half of the sites have existing dams, over 85% of the feasible capacity (1,927/2245 MW) are residing at these sites that could be developed by retrofitting hydroelectric power generation facility. A recent report by the Electric Power Research Institute on "Assessment of Water Power Potential in the United States" summarizes the national total feasible potential to be at approximately 62,300 MW (EPRI, 2007).

Retrofitting Dams without Power Generation Facility Has a Global Appeal

In the US the current focus is not on building new dams but rather tapping existing ones for their hydroelectric potential. Nationwide the US has only 3% of its 82,000 existing dams, which are large enough to be regulated, equipped with hydropower generation facility. Similar situation occurs in China and nations of other continents. For instance, among the 85,000 type I (with storage capacity of 1,000,000 to 10,000,000M^3) and type II (100,000 to 1,000,000M^3) irrigation reservoirs in China, only 10% are utilized for electric power generation.

Using variety of engineering strategies, including adding small hydropower facilities on existing dams, installing turbine on water conveyances, expanding pump-storage stations, etc., there are more than 70 projects planned or in progress in the US[1]. China has demonstrated the viability of using irrigation flow to generate hydroelectric power and the turbine to dissipate kinetic energy carried in the flow at the outlet work (Zhong, 2007).

[1] International Water Power and Dam Construction ©2008: http://www.waterpowermagazine.com/

Retrofitting Reduces Certain Social and Environmental Impact

The advantages of retrofitting existing dams are many. They include providing a quick increase in power generation capacity at low cost without the social and environmental impacts of building new hydropower dams. These considerations make the current focus in the U.S. and China on harnessing, otherwise wasted, energy from water passing at the existing dams for additional electric power a very attractive and viable approach. One other advantage is the transmission infrastructure may already be nearby because where there exists reservoirs there are likely other hydropower facilities Thus, assuming bandwidth is not a problem, new construction for the supporting transmission system could be minimal.

Generating new electric energy can help solving other social and environmental problems. For instance, as a part of its environmental preservation strategy, China is developing small hydro “to supply electric power to take place of fuel wood” in rural and agricultural villages. The agricultural villages in China have abundant water resources with usable capacity of an estimated 155,000 MW with most of them located in China’s western underserved mountainous regions. Use of fuel wood as the primary energy source is common in these regions but produces undesirable consequences including loss of forests, soil erosion and the spread of noxious weeds causing more complex environmental consequences such as flooding. Localized small hydro generation can effectively address these problems (Li, 2007).

Other Social and Economic Benefits and Issues to Address

Retrofitting existing dams for additional hydropower generation, under the premise that original objectives of the facility are preserved, offers many other social and economic benefits. For example, the additional income from the electricity generated can be used to cover the management and maintenance of the facility and related infrastructure. However, to best realize the overall goals of retrofitting one needs to pay close attention to the following issues:

1. To avoid over spent water resources for the purpose of maximizing power generation at the expense of impacting on the original water use objectives;
2. To avoid an undesirable effect on the structure and safety of the dam;
3. To minimize the injury and mortality of fish passing through the turbine; and
4. To protect the water quality in the downstream river section from negative impact.

Items 3 and 4, which relates to turbine design and operational characteristics, are requirements the current turbine technology fails to fulfill.

Needs of Advance Hydropower Turbine Design

The Idaho National Laboratory, US DOE, describes the needs of advanced hydropower turbine design as follows:

> *“Current hydropower technology, while essentially emission-free, can have undesirable environmental effects, such as fish injury and mortality from passage through turbines, as well as detrimental changes in the quality (dissolved gases) of downstream water. Advanced hydropower turbine*

technology could minimize the adverse effects yet preserve the ability to generate electricity from an important renewable resource." [2]

Design Innovations of an Advanced Updraft Hydroturbine

The new *updraft flow turbine* is designed to address the issues raised above. The initial design of the updraft hydroturbine was conceived in 1982. The "updraft flow" design concept was adopted based on sound fluid mechanics principles which can be stated as follows:

> *"The same amount of energy carried in a flowing fluid of a given discharge, Q, and effective pressure head, H, can be converted into mechanical power regardless of which direction the turbine is set to allow the flow through. "*

The new design essentially turns the conventional turbine (Fig. 1) on its head – 180 degrees from the current downdraft flow arrangement – to vertically upward (Fig. 2). By doing so, it greatly simplifies the mechanical construction and flow patterns through the turbine. Figure 2 shows the CAD illustration obtained from the computational fluid dynamics (CFD) simulation result for a 3 MW unit.

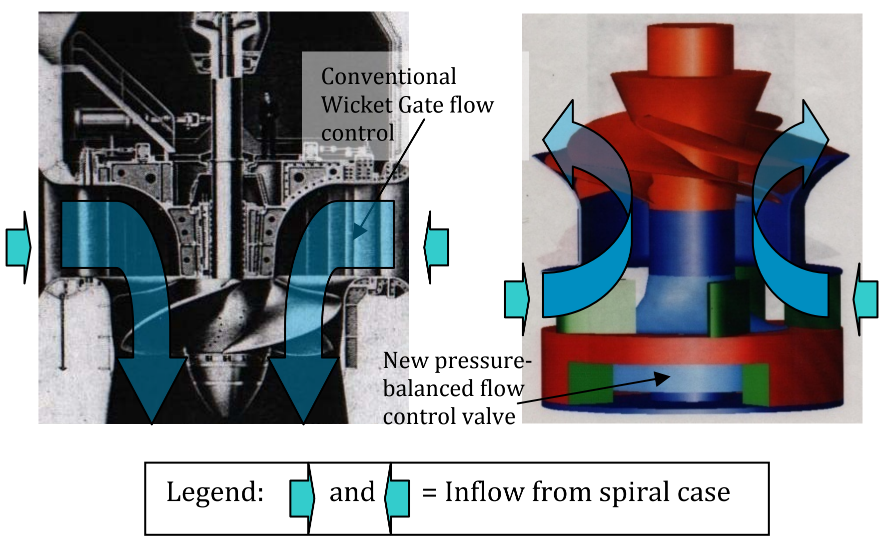

Figure 1 – Conventional down-draft turbine: Complex, heavy and costly

Figure 2 –Updraft divergent flow Turbine: Simple, light and cost less

Additional Key Design Features

The new updraft flow design approach leads to three additional innovations:

1. *<u>Turbine flow to exit at the free surface level in the tailwater terrace</u>: This creates an outflow aeration to improve dissolved gas levels and eliminates flow cavitation completely. The latter helps to minimize pressure spike*

[2] Idaho National Laboratory: http://hydropower.id.doe.gov/turbines/index.shtml

2. *<u>Use of a vertical pressure-balanced needle valve</u>: The new flow control device is substantially lighter and causes less energy loss than using the conventional wicket gates, It also creates a wide open flow passage further reducing fish injury.*
3. *<u>A divergent runner flow chamber design</u>: This allows kinetic energy (KE) recovery from exit flow without needing a draft tube resulting in a significant reduction in power station construction cost.*

Status of Research, Development, Demonstration and Deployment (RDD&D)

We have devoted, over the past 26 years, research and development efforts on the new updraft hydroturbine including design, laboratory testing and CFD analysis. The earlier model turbines were tested at University of Kentucky. The 3rd generation laboratory pilot turbine (200 mm nominal diameter) was tested first at Iowa State University, USA and later at Tsinghua University, Beijing, China.

The new hydroturbine is designed for use over head range from 1 to 80 meters and output from a few kilo-Watts to 25 MW. We have recently built a small prototype unit and will use it for further testing and field demonstration. INNOVIDE plans to collaborate with interested parties to construction additional units for field demonstration and additional data collection, leading to further improvement and broad deployment of the new hydroturbine.

The New Updraft Hydroturbine Is Easy to Install

Figure 3 below is a schematic drawing of a conventional hydroturbine installed inside the dam to accommodate the draft tube. A similar example could be used for facilities with penstocks. The new updraft flow turbine is installed outside the dam (Fig. 4) with flow exiting directly into the tailwater pool. This makes retrofitting the power station easier and construction and maintenance less costly.

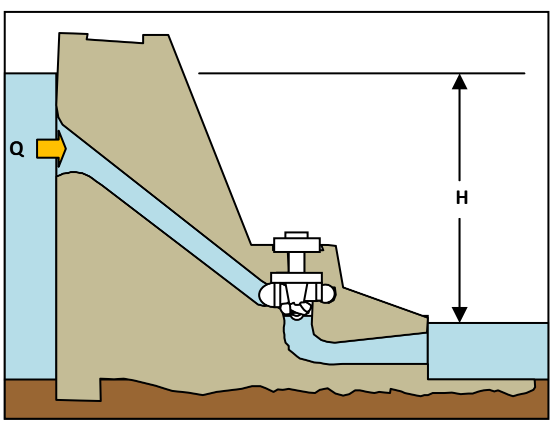

Fig. 3 – Conventional downdraft turbine

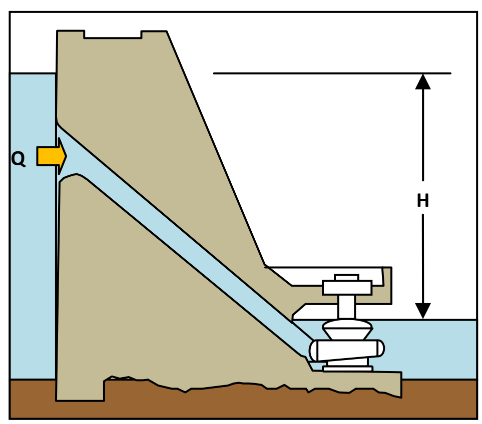

Fig. 4 New updraft flow turbine

As depicted in Fig. 4, depending on the local conditions of the existing dam, the new hydroturbine system can be connected onto the existing dam's normal flow outlet work, a new siphon penstock, modified spillway or a flow diversion pipe. The new approaches make the retrofitting simpler to achieve without affecting the structural integrity of the dam and its safety.

Additional Design Freedom and Mechanical Advantages

Assuming both systems illustrated in Figs 3 and 4 have the same hydraulic head difference, H, and flow rate, Q, as shown, the maximum amount of power, $P_{(max)}$, that can be extracted by these two turbine units is identical. However, the updraft flow turbine design offers many more additional design freedom and mechanical advantages to the power station construction including:

- partial balance of hydraulic pressure with the weight on the runner resulting in lighter support structure requirements;
- elimination of the high pressure seal around the power transmission shaft and its related maintenance;
- adoption of a new runner blade formation for optimal efficiency and extracting more power with the same or less amount of water; and
- Unaffected by tail-water pool elevation fluctuation (the new hydroturbine can self-prime and maintain always a full flow).

Full utilization of these advantages in the new turbine design also leads to efficiency improvement and substantial cost savings (Kao, 2006). The new updraft hydroturbine system is estimated to cost 35 to 66 % less than comparable conventional units (Kao, 2006). The improved efficiency and cost reduction could make even marginal sites – ranging from ultra low head sites with significant flow to medium-high head with limited flow – feasible for hydropower generation using single or multiple unit pico- to medium-scale[3] updraft hydroturbines.

Although not fully substantiated, studies indicate that there is an optimal 1% operating range for fish passing through a conventional hydroturbine safely. However this range is not always optimal for producing the maximum power with the minimum amount of water. Operating a generating unit for optimal fish survivability also adds undue wear and tear on a unit thus reducing the value of a facility's long-term investment. The updraft flow turbine may find common ground for optimal fish passage and power production because the operating curve has a greater range.

Improving Downstream Water Quality at no Extra Cost

Flow withdraw from hypolimnion regions (depth > 10 M) of lakes or reservoirs has very low levels of dissolved oxygen (DO). This can negatively impact water quality

[3] The term "hydroturbine scale" used in the updraft turbine design is categorized as: pico- (P <10 kW), micro- (10 kW ≤ P < 100 kW), mini- (100 kW ≤ P < 1 MW), Small- (1 MW ≤ P < 10 MW), medium- (10 MW ≤ P < 25 MW).

downstream of the facility. A method of air injection within the sub-atmospheric pressure region under the turbine runner is currently used to aerate the flow minimizing artificial levels of dissolved gas. This class of aeration is referred to as auto-venting turbines (AVT). In order to sufficiently improve the DO content in the flow, it is found that a longer deeper draft tube to increase the dwell time for the bubbles is needed (.McGinnis, 2007; Rohland, 2008). The extra cost for air injection and required system modifications makes such an approach less attractive.

On the other hand, highly aerated water flowing over the spillways and plunging into the deep stilling basing of dams is known to cause supersaturation of nitrogen (Kubo, 1984; Hibbs, 1997; Urban, 2008). This is also harmful to migrating fish. It is possible that, because of its inexpensive and easy to retrofit nature, the updraft hydroturbine could be used on a modified spillway to harness the water power while serving as an energy dissipater. This will eliminate plunging the high speed jet flow into deep water, and causing dissolved nitrogen from entrained bubbles under high water pressure to a supersaturated level.

The new updraft hydroturbine system utilizes the residual KE of the outflow to cause strong air-water mixing and air entrainment near the tailwater surface (Figs. 5 & 6). It is observed during various laboratory experimental runs that the fine entrained air bubbles stay in the water flow for a long distance (over 50 feet or 17 M) before disappearing. The aeration is accomplished without any additional cost.

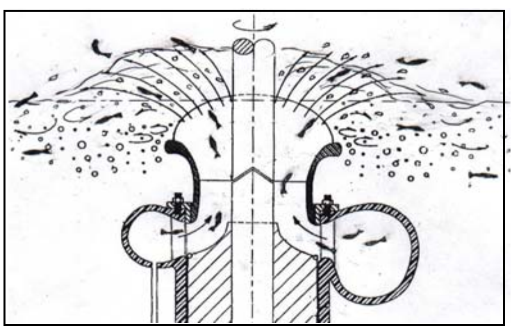

Fig. 5 – Schematic drawing of updraft hydroturbine operation

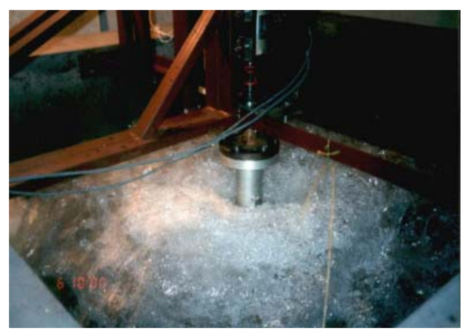

Fig. 6 – Air-water mixing and air entrainment in action

Minimizing Injury and Mortality to Passing Fish

Although the passage of anadromous fish does not typically take place within the dam and reservoir system there are cases of using fish ladders, elevators or trap and haul techniques to reintroduce the fish into a river system. Resident fish within a reservoir may also be impacted by the introduction of turbomachinery by inadvertently finding themselves caught in the flow. Therefore the integration of a power plant, if not designed with fish passage in mind, could negatively impact both anadromous and resident fish populations. Many hydropower facilities with fish passage systems included in the origin design have undergone extensive and expensive improvements as researches gained experience. Runner redesign, collections systems, optimal flow when operating a generating unit, spill patterns and intake screen protection are a few examples.

Mechanical abrasion, grinding, and strike on flow control gates and the runner blades; turbulent shear stress; and sudden pressure changes – pressure spikes from positive hydraulic pressure to negative cavitation pressure across the turbine runner – are identified as the major causes for fish injury and mortality (Li, 2002A; Deng, 2005; Ahmann, 2008).

The current mitigation practice in protecting juvenile migrating fish involves guiding the fish to by-pass the turbine. Bonneville Lock and Dam, for example, places submerged traveling fish screens in front of the intakes to direct fish toward the downstream migration transport channel. These screens, however, introduce additional power production and maintenance complexities. When a screen malfunctions, the generating unit must be shutdown (Mahar, 2008). The costs of implementing such mitigation approaches can be high.

The areas containing potentially lethal shear stresses were identified between the stay ring and the draft tube (Čada, 2006). In the new updraft hydroturbine areas subject to large shear causing fish injuries are reduced – no draft tube; protruding elements causing direct fish strike is minimized – no wicket gates; and major mortality causing cavitation pressure is eliminated – flow exits directly at the free water surface (Kao, 2007). These drastic design improvements make safe fish passage through the turbine highly achievable.

Electric Power Income from Irrigation outflow for Infrastructure Maintenance

Large percentages of the dams in agricultural oriented regions (Africa 50%, Asia 61%) are constructed for irrigation use. Hydropower potential carried in the irrigation flow is usually dissipated mechanically, for instance, using a hydraulic jump as shown in Fig. 7-(A). The power can be harnessed by passing the flow through two 650 kW updraft flow hydroturbines as illustrated in Fig. 7 – (B). The income from the electricity provides additional resource for operation and maintenance of the irrigation system and related infrastructure (Pittock, 2007).

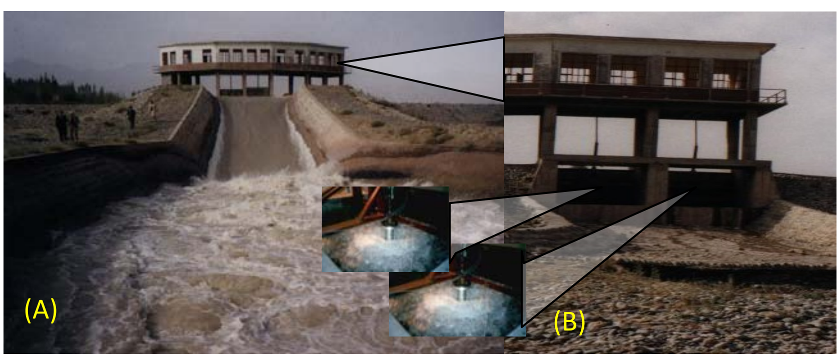

Fig. 7 – (A) Hydraulic jump energy dissipater (B) Side gates for hydropower generation

Electric Power Income from Environmental Flow for Ecosystem Protection

The international "Low Impact Hydropower Institute (LIHI)," offers a voluntary Hydropower Certification Program to help promote designs that minimize environmental impacts. LIHI uses eight environmental attributes in the process.[4] The first three – *river flow* (also refers to as "environmental flow"), *water quality* and *fish passage and protection* – are related specifically to the turbine design and its operational characteristics.

Environmental Flow Releases (EFRs) are regarded as an important tool for managing the ecosystem and associated impacts of dams. EFRs are not the same as 'minimum flow releases.' They aim for reaching a balance in water volume, quality and timing of needs of ecosystems and downstream communities.

It is estimated that the total global value of ecosystem products such as wildlife, fisheries and forest resources is estimated at US$ 33 trillion per year of which roughly 25% relate directly to freshwater ecosystems (Bergkamp, 2000). The importance of protecting the ecosystem is broadly recognized. It is now increasingly common to integrate the expenses of environmental mitigation measures into the new project costs. Extensive data generated on the subject are presented in the study by Hall, et al (Hall, 2003). For developed river reaches, these costs can be offset by income from additional power generated from the environmental flow via retrofitting existing dams.

Concluding Remarks

The light weight and easy to install updraft hydroturbine can readily be used to serve the purpose of retrofitting. The safe passage of fish through the new updraft turbine system is achieved by minimizing fish striking injury using a much simplified turbine flow regulating mechanism, and by completely eliminating turbine flow cavitation. Water quality enhancement is accomplished by utilizing the remnant kinetic energy to mix and aerate the exit flow near the free surface in the tail water terrace. The new turbine system offers a cost effective and environmentally friendly choice for use in retrofitting hydropower generation on existing dams.

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