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LOW HEAD POWER GENERATION WITH BULB TURBINES

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Abstract

Because of uncertainties, delays, and high costs associated with alternative electric energy sources, many agencies responsible for generation of electrical power are investigating means of replacing or supplementing their existing hydroelectric facilities. In the head range between 10 and 60 feet, the bulb-type generating unit, in which the generator is enclosed in a metal capsule within the water passage, has many advantages, including higher efficiency and lower cost, over other types of turbines. Two of the municipalities in the United States which have recently conducted feasibility studies for installing bulb turbines in their systems are the City of Idaho Falls, Idaho, and the City of Vanceburg, Kentucky. For the City of Idaho Falls, International Engineering Company, Inc. prepared feasibility studies which demonstrated that for 7 MW units installed in existing plants, (1) bulb turbines are more economical than comparable conventional (vertical shaft Kaplan) units, (2) installation of new bulb turbine units is preferable to rehabilitating and/or relocating the existing generating units, and (3) the cost of energy generated by the proposed bulb turbine installations would be less than that from alternative sources of energy. At locations at existing dams on the Ohio River, the Vanceburg Electric Light, Heat and Power System studied installations comprised of 3 - 23 MW bulb turbines per plant and also found that the cost of energy from these facilities would be less than from other sources.

1. INTRODUCTION

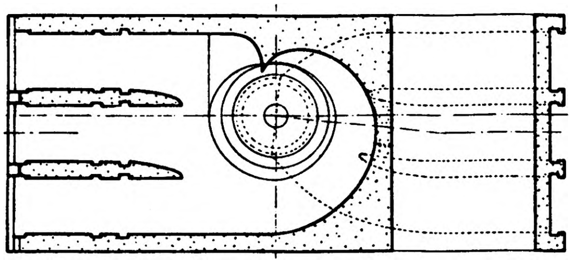
In recent years, many utilities and municipalities have been actively exploring the possibilities of increasing the output of their existing hydroelectric plants by replacing or supplementing existing generating units. Several factors have prompted them to take these actions. First, they can project significant growth in the demand for electrical energy. Utilities and municipalities have also noted that there will be few, if any, additional major high-head hydroelectric sites developed since practically all of the economically feasible and environmentally acceptable high-head dam sites have been developed. The future availability of low-cost energy from existing hydroelectric facilities is also in question. For example, Bonneville Power Administration is planning rate increases in the near future and has given customers a notice of insufficiency as of 1983. Alternate sources of energy (thermal) are also becoming less attractive. New nuclear projects have been plagued by spiralling costs and excessive delays. New coal-fired plants have met with opposition from the public. For these reasons, development of existing low-head hydro sites is being increasingly studied and often has been found to be an economical alternative to other energy sources. In addition to the economies that can be achieved, hydroelectric power has the additional advantages of being a clean, pollution-free resource that is perpetually renewable.

The most efficient and economical unit for supplying power at very low-head hydroelectric installations is the axial turbine, which is described in more detail later in this article. Planned installations of bulb turbines, a type of axial turbine, at two locations; on the Snake River in Idaho for the City of Idaho Falls, and on the Ohio River in Kentucky for the City of Vanceburg, are described. The economic analyses which demonstrated the feasibility of these two projects are included.

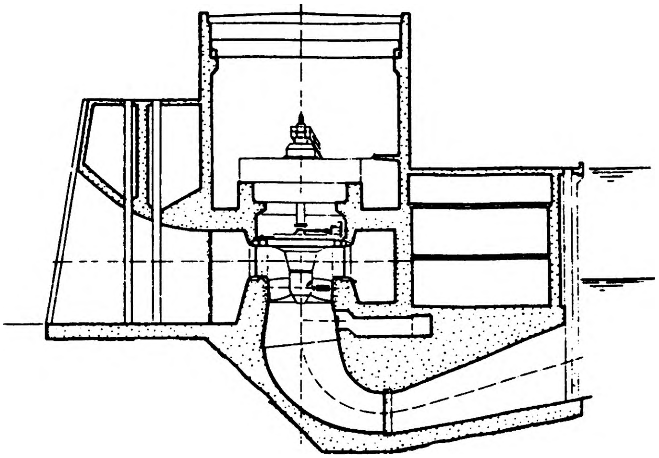
2. LOW HEAD TURBINES

In the low-head range, between 10 and 150 feet (3 to 45 meters), turbines with propeller-type runners are almost universally used in new installations. Commonly, these turbines are arranged with a vertical shaft, a spiral case to guide the water to the runner, and an elbow-type draft tube to return the water to the river. They may have either fixed or adjustable runner blades. The fixed-blade machines are called "propeller turbines" and the machines with adjustable blades have been named "Kaplan turbines" after their inventor, Viktor Kaplan, an Austrian who patented the concept in 1915. A typical vertical-shaft Kaplan turbine installation is shown in Figure 1.

Turbines in which the water is conducted to the distributor coaxially with the shaft are called "axial" turbines and sometimes "tubular" turbines. Usually they have a horizontal or slightly inclined shaft and may have either fixed or adjustable runner blades. In this discussion we refer to this type of machine either by the term "axial turbine" or by the name of the three specific types of machines that are a part of this group: 1) the rim-generator type, in which the generator rotor is located on the periphery of the turbine runner; 2) the tube type, in which the generator is located outside the water passage; and 3) the bulb turbine, in which both the runner and the generator are enclosed within the water passage. This last type derives its name from the steel capsule (or bulb) that encloses the generator. Typical examples of the three types are shown in Figure 2.



PLAN



SECTION

Figure 1 - Kaplan Turbine Installation

The bulb turbine is a compact, self-contained, operationally flexible installation. The main advantage over the other types of axial turbines is its good operating record, since it lacks the seal problems that have occurred with the rim-generator type or alignment problems evident in tube type turbine installations. There are some disadvantages such as poor access to the generator, low flywheel inertia of the generator, and difficult generator cooling.

3. COMPARISON OF AXIAL AND KAPLAN TURBINES

For installations where the net operating head is less than about 60 feet, the axial turbine may have significant advantages over the vertical shaft Kaplan turbine.*

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* In the following discussion, we follow the customary practice in this country and refer to a vertical shaft Kaplan turbine simply as a Kaplan turbine.

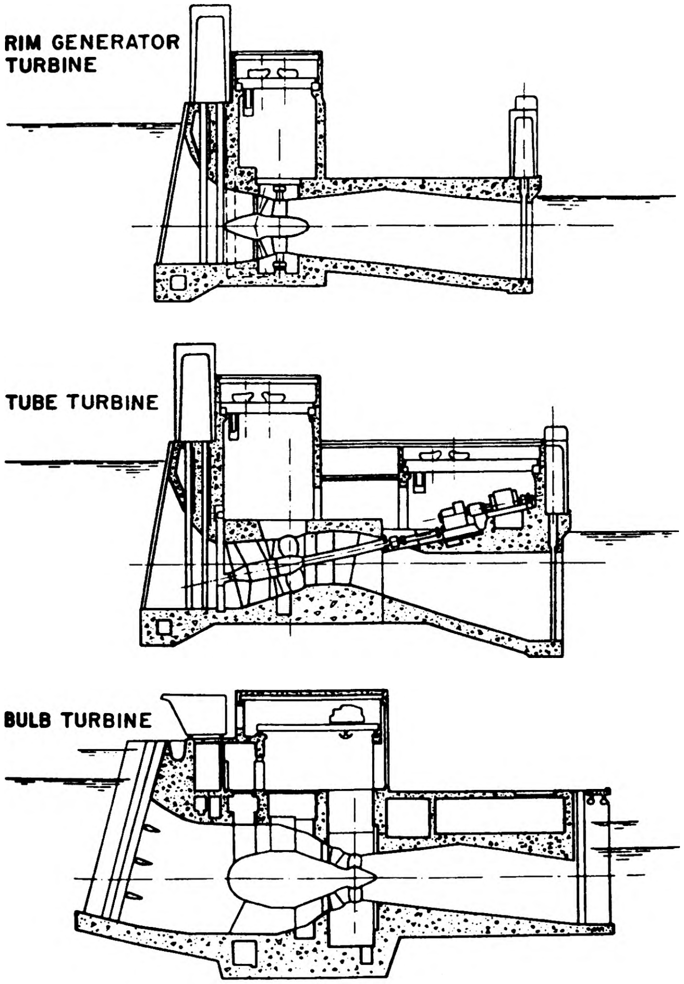

Figure 2 - Axial Turbines

Figure 3 is a comparison of the efficiency vs. discharge of Kaplan and axial turbines of the same diameter and speed, both designed for a head of 19 feet (5.8 meters). It is noted that for the same efficiency, the discharge of an axial turbine is some 40 percent higher than that of a Kaplan unit. It therefore follows that for the same output, a bulb turbine would be smaller than a Kaplan. A comparison of units having the same rated output and efficiency at that point is shown in Figure 4. In this case, the rated discharge is 5000 cfs and the head is 19 feet. As can be seen, the efficiency of the bulb turbine is higher than that of a Kaplan over most of the operating range. In this case, the axial turbine has a runner diameter approximately 15 percent smaller and a speed 25 percent higher than the equivalent Kaplan turbine.

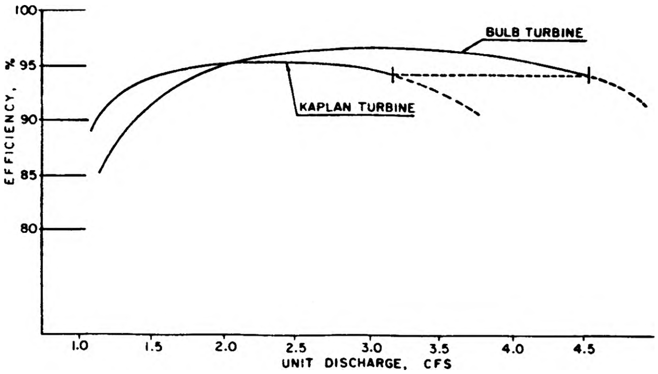

Figure 3 - Bulb and Kaplan Turbine Efficiencies
(Units of Same Size)

There are two principal reasons for this increase in performance, both relating to the configuration of the flow passages: first, there is less head loss in the generally straight passages of the axial turbine, which is a significant percentage at low heads. Second, the axial turbine can economically be set lower than the Kaplan turbine in respect to the tailwater, which allows higher rotational speeds.

From an economic standpoint, it is desirable to select the highest speed possible for a given installation, since this results in a smaller, lighter generating unit. However, it is characteristic of hydraulic turbines that, as the speed increases at a given head and output, the runner must be set lower with respect to the minimum tailwater elevation to prevent cavitation damage. This, in effect, limits the allowable operating speed. The

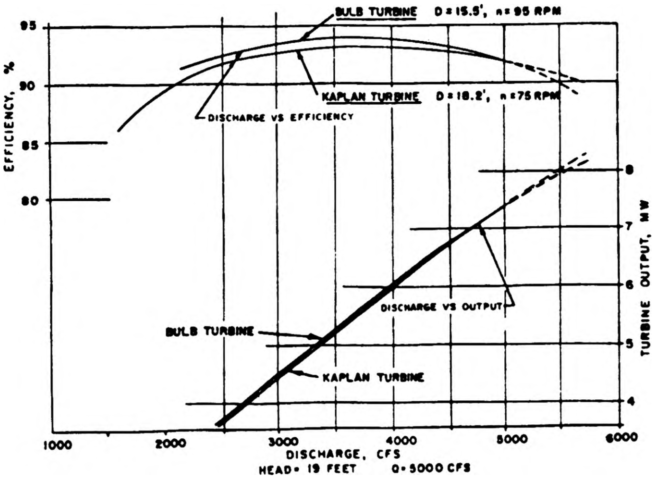

Figure 4 - Bulb vs. Kaplan Turbines
(Units with Comparable Output)

normal solution is to adopt a higher speed for the bulb turbine with a correspondingly smaller runner diameter which requires that the top of the runner blades, which is the critical point for cavitation in a horizontal unit, be set lower than the runner centerline for a vertical Kaplan turbine. However, due to the absence of a draft tube elbow, the excavation is less than would be required for the Kaplan turbine.

In the final selection of a turbine, many factors must be considered, including site conditions, operating conditions, and economics. Most of the factors are related and interdependent and must be weighed and balanced to obtain the best solution.

To summarize, at low heads (between 10 and 60 feet), the advantages of a bulb turbine are, in general:

Lower Machinery Costs - Bulb turbines are smaller and lighter units with a higher speed, and therefore machinery costs are lower. The reduction in weight and cost of the bulb turbine as compared with the Kaplan varies with the installation. Experience in Europe and studies in the United States have indicated cost savings of 10 to 15 percent.

Operating and maintenance costs for bulb turbines are somewhat difficult to ascertain because of the limited operational experience with units of sizes comparable to Kaplans. However, based upon fifteen years of operating experience, Electricité de France concluded that bulb and Kaplan operating costs are comparable.

Construction Savings - Construction time for a bulb turbine installation can be substantially shorter than that for a vertical turbine because there are no complicated spiral casings, draft tubes, or other curved water passages to construct.

Runner Accessibility - The runner for a bulb turbine is more accessible than that for a vertical turbine and can be disassembled without disturbing the generator.

Lower Costs for Civil Engineering Features - Perhaps the most important advantage of bulb turbines is the reduction in costs of civil engineering features. For example, because a bulb turbine installation is more compact than a comparable vertical unit, both the substructure and superstructure are smaller. With the bulb turbine, concrete shapes are less complicated and thus less expensive to build. Because the excavation area is smaller and not as deep, use of the bulb turbine results in savings in foundation excavations. Savings in the cost of civil features vary, of course, with the design and size of the installation; estimates of the savings are from 25 to 50 percent.

Low Profile - The configuration of an axial turbine is such that it is naturally adaptable to an installation under a spillway or a weir. The configuration also allows the axial turbine to be installed at existing developments where the space for conventional units may be restricted by spillways or other obstructions.

Bulb turbines do have some limitations when compared to Kaplan and other types of turbines, including lower inertia of the generator because of the fact that it must have as small a diameter as possible, more difficult access, special problems in mounting the bulb in the water passage, and special cooling requirements.

As will be demonstrated in the following section, for low-head sites, the advantages of a bulb turbine over a Kaplan outweigh the disadvantages.

4. ECONOMICS OF BULB TURBINES

As noted earlier, many communities and agencies in the United States have been actively studying the feasibility of increasing their generating capacity by adding bulb turbine units. Two cities which have demonstrated the economic feasibility of such projects are described in the following paragraphs.

The first proposed installation, at Idaho Falls, Idaho, includes three powerplants, each housing a 7.2 megawatt bulb turbine. The second, for the City of Vanceburg, Kentucky, on the Ohio River, includes two power plants, each containing 3 - 23 megawatt bulb turbines.

4.1 IDAHO FALLS

4.1.1 General

There are three existing power plants on the Snake River owned and operated by the City of Idaho Falls, known as the Upper, City, and Lower plants. International Engineering Company, Inc. (IECO) has completed preliminary studies for upgrading these plants and is presently preparing Federal Power Commission (FPC) license applications for the projects.

As part of the studies, IECO investigated alternative development plans for the Upper and Lower sites. The studies included investigation of four alternative development plans for the two sites, including rebuilding or relocation of the existing units and/or installation of new turbine units.

4.1.2 Comparison of Bulb and Kaplan Installations

An early part of the study was directed toward a comparison of bulb turbines with comparable Kaplan units. Conceptual designs were prepared for installations of the same output (7.2 MW) and efficiency (93-94%) at the same head (19 ft.). The main economic advantage of using bulb turbines at Idaho Falls stems from the large savings possible in construction costs. Layouts of powerhouses at the Upper Power Plant Site for both types of machines showed that the bulb turbine installation has the advantages of reducing the width of the powerhouse from 58 to 38 feet, lowering the elevation of the top of the powerhouse 5 feet, and decreasing the foundation depth by 12½ feet. The bulb turbine installation also has a simpler concrete shape, which reduces the cost further.

The above advantages will result in a saving of about 50% in the cost of the civil works, as shown by the comparison in Table 1.

4.1.3 Alternative Redevelopment Plans

The alternative redevelopment plans are shown in Table 2.

An economic analysis was made which involved the computation of capital costs for the installations, calculation of annual costs (capital recovery plus operation and maintenance costs) and calculations of the unit cost of energy on an annual basis. These costs were compared with the benefits (costs of providing equivalent energy by the most economical alternative available to the City). In addition, the value of the benefits minus the costs was calculated. Table 3 summarizes the economic analyses.

In weighing the alternatives, other criteria than purely economic ones were used, such as the service life of new vs. existing structures and machinery, total annual

TABLE I

QUANTITY AND COST ESTIMATES
KAPLAN TURBINE VERSUS BULB TURBINE INSTALLATION
AT IDAHO FALLS

Item	Unit	Unit Cost ($)	Kaplan Turbine		Bulb Turbine	
			Quantity	Total Cost ($)	Quantity	Total Cost ($)
Rock excavation	CY	12	16,500	198,000	8800	105,600
Concrete	CY	120	10,200	1,224,000	5000	600,000
Reinforcement	Ton	1000	510	510,000	250	250,000
Subtotal				1,932,000		955,600
Contingencies (20%)				386,400		191,100
Total Construction Cost				2,318,400		1,146,700
Savings (equals difference)						1,171,700

TABLE 2

REDEVELOPMENT ALTERNATIVES - IDAHO FALLS

Alternative	Upper Site	Lower Site
1	Demolish existing facilities, salvaging any equipment that has salvage value. Provide new dams and powerhouse. Install one new bulb turbine.	Upgrade existing facilities, except the turbine-generator units. Add new powerhouse adjacent to existing powerhouse. Install one new bulb turbine in new powerhouse.
2	Upgrade and rehabilitate existing facilities, except the turbine-generator units.	Upgrade existing facilities, except the turbine-generator units.
3	Same as in Alternative 1, except that the existing turbine-generator units must be removed with great care (for reconditioning) before the other facilities are demolished.	Upgrade existing facilities, except the turbine-generator units. Add new powerhouse adjacent to existing powerhouse. Recondition units removed from Upper Plant and install them in new powerhouse at Lower Site.
4	Upgrade and rehabilitate existing facilities, except the turbine-generator units. Add new powerhouse adjacent to existing powerhouse. Install one new bulb turbine in new powerhouse.	Same as in Alternative 1.

energy, etc. The advantages and disadvantages of the four alternatives are summarized below:

Alternative 1 - Advantages include maximum power production from new bulb turbines, new powerhouses at both sites, a new dam at the Upper Site, development of 95% of the river potential at both sites, and use of the existing units at the Lower Plant as standby machines, with consequent longer machine life.

The disadvangates are that the initial investment of capital will be about 5 times that required for Alternative 2 and that the equivalent annual costs will be about 3 times greater over the entire repayment period.

Alternative 2 - Advantages are that it will require the least initial investment of capital, it will have the lowest total annual cost, and will provide new or rehabilitated structures at the Upper Site.

Disadvantages are that it will develop only 39% of the power potential of the sites, that the remaining service life of the existing machines will not be improved (they are estimated to have 4 to 20 years of service life remaining), and the operating and maintenance costs will be increasingly high because of the age of the machines.

Alternative 3 - Advantages are that the existing facilities at the Upper Site will be replaced with all new structures and a new modern power plant with a new bulb turbine will be provided. It will develop 79% of the power potential of the two sites, or about twice the energy of Alternative 2.

Disadvantages are that the initial investment of capital will be about 3½ times that for Alternative 2, the annual cost will be about 2½ times that of Alternative 2, and the machines at the Lower Plant will not permit utilization of full flows and will have increasingly high operation and maintenance costs because of the age of the existing machines.

Alternative 4 - This alternative has essentially the same advantages and disadvantages as Alternative 1; however, it has the added disadvantages that the structures of the Upper Site are deteriorated and will have to be replaced

TABLE 3

ECONOMIC COMPARISONS OF REDEVELOPMENT ALTERNATIVES - IDAHO FALLS

Item	Alternative 1	Alternative 2	Alternative 3	Alternative 4
AVERAGE ANNUAL ENERGY (kWh)	115,500,000	47,300,000	96,800,000	121,900,000
COSTS				
Capital Costs ($)				
Total Construction Cost (incl. contingencies)	16,879,000*	3,313,000	11,734,000	16,894,000
Engineering and Administration	2,534,000	497,000	1,760,000	2,534,000
Interest during Construction	1,360,000	266,000	944,000	1,360,000
Total Capital Cost	20,773,000	4,076,000	14,438,000	20,788,000
Equivalent Annual Cost ($/yr)				
Capital Recovery (assuming 50-yr repayment period at 7% interest)	1,505,211	295,346	1,046,177	1,506,298
Operation and Maintenance	137,000	237,000	299,000	147,000
Total Equivalent Annual Cost	1,642,211	532,346	1,345,177	1,653,298
Energy Cost ($/kWh)	0.01422	0.01125	0.01389	0.01356
BENEFITS				
Total Annual Benefits ($/yr)**	3,465,000	1,419,000	2,904,000	3,657,000
Benefit to Cost Ratio	2.110	2.665	2.158	2.212
Benefits Minus Costs ($/yr)	1,822,789	886,654	1,558,823	2,003,702

* Includes salvage allowance for existing units.

** Power benefits are based on the cost of providing equivalent energy by the most economical alternative means. A value of $0.030/kWh was used.

Costs are as of 1976.

eventually; also, the structural integrity of the concrete in the existing powerhouse is questionable.

Table 3 shows that all four projects have a benefit-cost (B/C) ratio of greater than 1.0, and thus should be justifiable economically. Alternative 2 has the highest B/C ratio (2.665). However, upon further analysis it was seen that alternatives 1 and 4 are more attractive than the others because of (1) higher benefits minus costs, (2) higher benefit-to-cost ratios for the additional benefits (in excess of those for Alternative 2,) (3) higher average annual energy, and (4) higher installed capacities. Comparing Alternatives 1 and 4, significant practical factors threw the balance toward Alternative 1, i.e., the longer service life of the units and structures.

Therefore, Alternative I was recommended for implementation and is the plan for which the FPC application is being prepared.

4.1.4 Financing of Idaho Falls Facilities

In addition to applying for an FPC License, the City of Idaho Falls has also applied to the Energy Research and Development Administration for a grant to fund the bulb turbine plants as demonstration projects to be used as models for future development of this type in the United States.

4.2 OHIO RIVER PROJECTS

The City of Vanceburg (Kentucky) Electric Light, Heat and Power System has obtained FPC licenses to construct power plants at two existing Corps of Engineers dams on the Ohio River - Greenup Dam near Portsmouth, Ohio, and the Cannelton Dam near Tell City, Indiana. These are planned to be considerably larger than the Idaho Falls installations, with 3 - 23 MW units planned for each dam. The dams are used primarily for navigation of the Ohio River and there are no existing power installations. Therefore, there was no comparison of the use of existing machinery vs. installing new units. Based upon experience with similar sized installations in Europe, it was found that a bulb turbine installation would be more economical than a Kaplan installation of comparable size. However, in order to show that the project was feasible, it was necessary to make an economic analysis.

The following data, developed by IECO and associated companies, apply to the W. T. Love Station at the Greenup Dam; the Cannelton analysis would be similar.

A breakdown of the construction cost of the Greenup power plant is as follows:

Item	Total Cash
Cofferdam	$ 1,524,000
Dewatering	70,000
Excavation - Common	165,000
Excavation - Rock	315,000
Removal of dam section	495,000
Reinforcing steel	1,495,000
Concrete	8,506,000
Mechanical	870,000
Electrical	1,020,000
Painting	100,000
Landscaping	75,000
TOTAL DIRECT COST	$14,599,000
Overhead	3,141,230
Labor escalation	1,197,390
Material escalation	1,245,324
Markup	3,475,034
TOTAL CONSTRUCTION COST	$23,657,978

The equipment cost was estimated to be the following:

Turbines, governors and generators	$12,364,549
Gates, stoplogs and trashracks	1,826,668
Cranes	1,202,447
Transformers and switchyard	1,515,987
Miscellaneous equipment	351,720
Spare parts	152,205
Model tests	108,820
Erection supervision	57,000
Powerhouse design and construction inspection*	3,543,538
Startup, commissioning, and training	131,000
Performance bond	276,805
TOTAL EQUIPMENT AND ENGINEERING COST	$21,530,739

* The specifications require that the design of the powerhouse be the responsibility of the equipment supplier.

The project will be financed by the sale of tax free municipal bonds to be retired over a 40-year period with equal yearly payments. Based on an average interest rate of 5.5%, the project cost is:

Construction cost	$23,657,978
Equipment and engineering	21,530,739
Transmission line	5,000,000
Contingency	1,000,000
Initial Costs	600,000
Bond costs @ 3.7%	2,312,024
Debt service reserve @ 7%	4,374,099
Interest during construction	4,012,289
TOTAL BOND ISSUE	$62,487,129

The estimated yearly operating expenses are:

Bond retirement	$ 3,995,341
Operation and maintenance	562,900
Use of Government facilities	227,000
Administration	146,000
	$ 4,931,241

For an annual energy production of 360,000,000 kWh per year, the unit cost of energy is estimated to be $\frac{\$4,931,241}{360,000,000}$ = $0.0137 per kWh. Since the agency estimates that future energy from alternative sources will be well over 20 mills per kWh by the time the Ohio River plants are on the line, the projects were considered feasible.

5. CONCLUSIONS

The practical application of installation of bulb turbines at existing dams, as demonstrated by the Idaho Falls and Vanceburg projects, indicates that bulb turbines are destined to play a major role in the future development of low head hydroelectric power in the United States.

BIOGRAPHIES

James L. Carson, Principal Mechanical Engineer with International Engineering Company, has a Mechanical Engineering degree from the University of California at Berkeley and is a registered Mechanical Engineer in California. He has more than 18 years experience in the field of hydraulic machinery, including turbines, pumps, and large valves. He was involved with engineering of large turbines and pumps for the Baldwin-Lima-Hamilton Corporation, and was involved in design of major mechanical features of the California Water Project for the California Department of Water Resources. With IECO since 1969, he has been involved in a variety of hydroelectric projects, including major installations in Brazil and elsewhere. He has prepared conceptual designs for bulb turbine installations at Idaho Falls, Idaho and other locations.

Ray S. Samuelson, Principal Civil Engineer with IECO, has BS and MS degrees in Civil Engineering from Stanford University and is a registered Civil Engineer in California. He has a broad background in planning, design, and construction of major civil engineering projects. He has been with IECO since 1972, where he has been project manager on studies and designs for water resources projects in the United States and overseas, including dams and power plants for hydroelectric projects. Earlier experience includes design and construction assignments with the California Department of Water Resources, California Division of Highways, and the U.S. Navy.