CIVIL ENGINEERING DEPARTMENT
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

Study of Factors Affecting Feasibility of Low Head Hydroelectric Generation

FINAL REPORT PREPARED FOR

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
Denver, Colorado

Contract No. 14-06-D-6586

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STUDY OF FACTORS AFFECTING FEASIBILITY OF LOW HEAD HYDROELECTRIC GENERATION

Submitted by

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PREFACE

Contract No. 14-06-D-6586 between Colorado State University and the United States Department of the Interior, Bureau of Reclamation, provided for a study of the factors affecting low head hydroelectric generation. This final report summarizes the results of this study which was conducted by Albert G. Mercer, Associate Professor of Civil Engineering, with the assistance of Quais Mufti and Y. P. Kapoor, graduate students in Civil Engineering, and R. Stringer, an undergraduate engineering student.

The writer wishes to express his thanks to all the consulting engineers and equipment manufacturers from many countries who supplied data and information used in this study.

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ABSTRACT

The feasibility of generating electricity from hydropower developments having low heads depends on the characteristics and the cost of the available equipment as well as the cost of producing electricity from alternative sources. The recent development of the tubular turbine has resulted in many advantages for the economical development of low head hydropower. Many units with heads as low as 10 feet have been built in Europe. Twenty five feet appears to be the practical lower limit in North America.

The flowing water of rivers provides a possible source of energy for generating electricity. This energy could be developed using turbines similar to some modern airfoil wind turbines but the economics are such that this source will probably never be exploited.

Head, itself, is the most important factor affecting the feasibility of low head hydropower. Given two well designed low head plants of equal discharge capacity, the lower head plant will be less feasible because the kw output will be lower but the costs will be higher. The lower head plant will have larger, slower turning turbines and larger inlet and outlet passages.

STUDY OF FACTORS AFFECTING FEASIBILITY
OF LOW HEAD HYDROELECTRIC GENERATION

by Albert G. Mercer*

I. INTRODUCTION

Of all the natural resources of the world, only a small part exists in a sufficiently concentrated form to warrant commercial exploitation. Water, and its by-product, hydropower, is not an exception.

Water everywhere, except possibly the ocean depths, contains some amount of kinetic or potential energy which, in turn, could produce electrical energy. However, it is only at sites where large amounts of energy per unit volume of water can be extracted that hydroelectric development is feasible.

At Hoover Dam, where the head exceeds 500 feet, it requires about 100 cubic feet of water passing through the turbines to produce one kwh of electrical energy. At St. Anthony Falls on the Mississippi River, there are turbines operating under approximately 20 feet of head causing approximately 2500 cubic feet of water to yield one kwh of electricity. All the water flowing in the Mississippi River contains a tremendous amount of kinetic energy. Some of this energy could be converted into electrical energy by turbines operating much like windmills. However, it would require approximately 500,000 cubic feet of water passing through these turbines to yield one kwh of energy.

In the more advanced countries of the world, most of the sites where water can be made to yield large amounts of energy have been developed. Therefore, the future of hydropower use in these countries depends, in part, on the feasibility of developing sites with low concentrations of energy. These would include:

1. River sites where small heads could be created with a minimum amount of expense for an impounding structure.
2. River sites where low impounding structures are to be built for purposes such as flood control, navigation or water diversion.
3. Drop structures on irrigation or water supply canals.
4. Tidal basins.
5. Fast flowing rivers suitable for wind turbine type plants.

The development of these low energy sites would benefit the country at least to the extent that hydropower represents the exploitation of a non-depletable resource.

The study reported here explored the factors affecting the feasibility of low head hydrogeneration in order to provide a background from which more complete studies could proceed. The scope of the study is limited to the following topics:

1. State of the art.
2. Governing physical laws.
3. Governing economics.
4. Cost characteristics.
5. Possible future technological improvements.
6. Secondary considerations.
7. Conclusions and comments.

The definition used in this study for low head plants includes only those with heads of less than 15 m (approximately 50 feet). Most emphasis, however, is placed on plants that fall within the lower range.

Tidal developments are considered only as far as they represent machinery for low head generation. Feasibility factors peculiar to tidal plants are not studied. The feasibility of generating electrical energy from freely flowing rivers is explored even though no plants of this type, other than the old mill wheels, are known to exist.

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II. STATE OF THE ART

A. Effect on Feasibility

The feasibility of low head hydroelectric generation, depends upon technical and economical factors. In general, technical knowledge must first advance to the stage where equipment works dependably and safely. After that, technical advances can be directed towards improving the economics.

The technology of low head hydroelectric generation is past the first stage and well into the second. Hydroelectric equipment manufacturers are prepared to design, build and guarantee efficient and dependable low head machinery for virtually any desired set of conditions. Most manufacturers have also made concentrated efforts towards the development of improved equipment. The result is a number of strikingly different arrangements which compete for the low head market.

In spite of these efforts, the economic position of low head hydropower has receded relative to other sources of energy available for the generation of electricity. Although the recent advances in low head design represent important technical achievements, large reductions in the cost of these installations have not been achieved. This is not stated to discredit the hydroelectric industry. It simply represents the difficulty of improving upon machinery that is already 90 percent efficient.

Low head hydrogeneration with a seemingly small margin for cost improvement, is in competition with thermal and nuclear plants, which are being developed fairly rapidly to produce cheap electricity. The further development of these plants will undoubtedly result in still lower costs.

While the price of electricity has dropped [2, p. 9]*, the cost of hydroelectric construction has risen [20]. The result is that low head generation has become less attractive with time rather than more so.

Nevertheless, low head hydrogeneration is economically feasible in many geographical areas at the present time, as witnessed by the many plants that have been built in the 1950's and 1960's (see Appendix A). These plants demonstrate the development of the state of the art.

B. Turbines with Spiral Cases

Low head hydroelectric generating units are divided into two main groups. The first group, representing earlier development, has a turbine arrangement that uses a spiral case with wicket gates to control the flow. This arrangement was specifically developed for, and is essential to, medium head Francis turbines. It was subsequently adopted in the development of low head propellor and Kaplan turbines.

The spiral case arrangement, except in some smaller units, utilizes a vertical turbine axis with an elbow draft tube as typified by the Säckingen plant on the Rhine River, as shown in Fig. 1a. This modern plant has 25,000 HP Kaplan turbines directly connected to synchronous generators installed in a very low profile structure. This type of design provides a compact and serviceable turbine-generator assembly but the complex flow passages require a civil structure with a relatively large plan area. It is undoubtedly the best arrangement available at the present time for high capacity units because the vertical shaft is more effective for supporting the heavy generator rotor which is required.

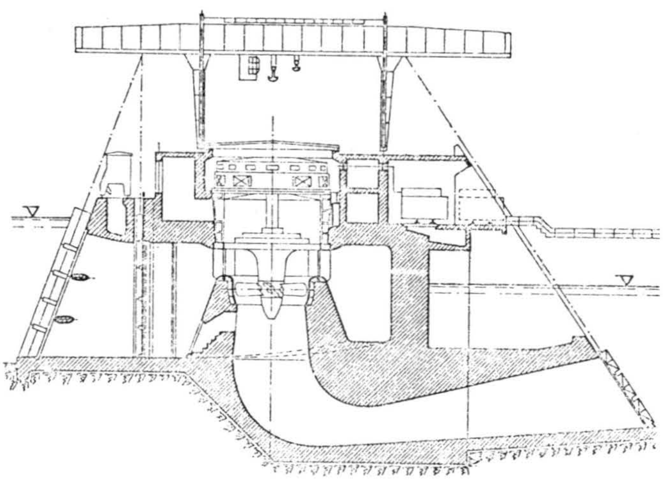

Fig. 1a Säckingen Powerhouse, Swiss-German Border, turbine dia 7.40 m

For lower heads and for capacities small enough that speed increasing gears can be utilized, arrangements with non-vertical shafts are more economical. At present, the practical upper limit that can be transmitted by gearing is around 30,000 HP.

The spiral case arrangement, however, is still used for some very low head, small capacity plants. The Petershagan installation shown in Fig. 1b is an example of this type of arrangement. This 1500 HP turbine has a rated head of eight feet and rotates at 68 rpm while the generator with a horizontal axis is gear driven at 500 rpm. An interesting feature of this Petershagan plant is the elevated syphon setting of the turbine. The entire runner can be de-watered for servicing simply by allowing air into the spiral case. The elevated setting of the turbine also reduces the depth of excavation required for the draft tube.

* Numbers in brackets refer to references in Section IX, List of References.

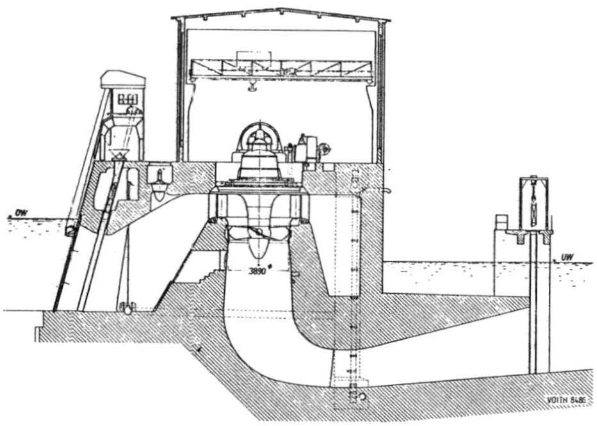

Fig. 1b Petershagen Plant, Weser River, Germany, turbine dia 2.70 m (J. M. Voith)

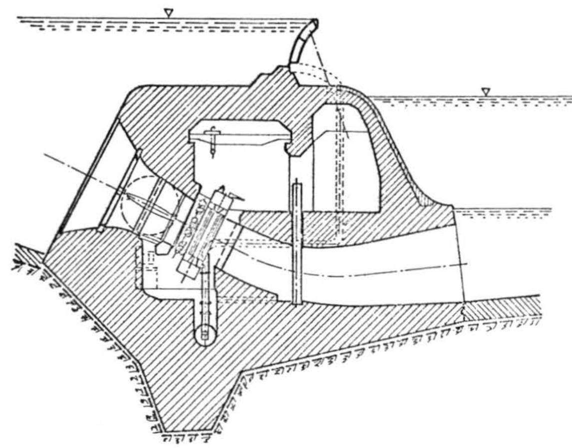

Fig. 2a Rott-Freilassing Plant, Austro-German Border, turbine dia 2.20 m

C. Turbines without Spiral Cases

Tubular turbines make up the second group of low head plants. They were developed to reduce the cost of low head plants by simplifying the flow passages and thereby reducing the size of the civil structure. There are several distinct arrangements for tubular turbines, but the feature they all have in common is the elimination of the spiral case.

Except for some small plants, all tubular turbines are oriented so that their axis is horizontal, or nearly so. The flow approaches the turbines axially but is first given a whirling motion by guide vanes located upstream of the runner. The whirling motion is converted to shaft torque by the turbine blades and the flow leaves the turbine with essentially axial flow. The draft tube geometry, which is simplified by the horizontal alignment, closely approaches the ideal shape for energy recovery.

The tubular turbine was first patented by an American, L. F. Harza [3, p. 4]. His arrangement was similar to that shown in Fig. 2a where the rotor of the generator is attached directly to the periphery of the fixed propeller blades and recessed into the conduit wall.

The practical development was evolved by Arno Fischer in Germany in conjunction with the Swiss firm, Escher Wyss. Over 60 units with capacities of 700 HP were built during the period from 1935 to 1951. Although these units are considered to operate with dependability, there has been limited interest in building new units because of newer and more competitive arrangements.

Interest in this type of unit has not lagged entirely, however. A Russian plant, Ortachalskara [4], was recently built with an 8600 HP annular generator unit. The English Electric Company also has been studying this type of unit [5] for tidal power developments in England.

The next development in tubular turbines was the bulb unit in which the generator is encased in a bulb in the middle of the flow conduit. Bulb units have been manufactured in many sizes since the first one was constructed in Poland in 1936. The best known are probably the 14,000 HP units designed for the Rance Tidal Power Plant in France [6,7]. These special units, shown in Fig. 2b, were designed for generating or pumping, with flows in either direction.

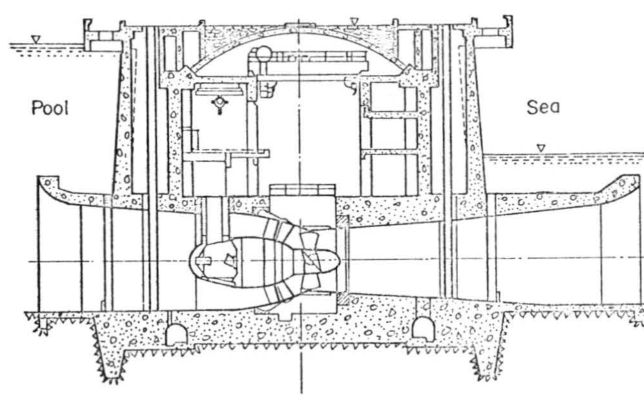

Fig. 2b Rance Tidal Power Plant, France, turbine dia 5.35 m

The successful development of the bulb unit is due largely to the efforts of the French National Electricity Authority (Electricite de France) whose research led to the best type of unit for the Rance project. The largest units of this type are those provided for the Beaucaire Plant in France. They have 6.5 m diameter runners developing 47,500 HP under a head of 37 feet. The lowest head unit of this type is one provided by Neyrpic for the experimental Kislogoubskaia tidal plant in Russia which will deliver 530 HP at a rated head of 4.2 feet.

Bulb units are very compact but generally require a sophisticated design in order to fit the generator into a bulb of acceptable size. This is particularly true of the higher capacity units with direct shaft connection between the turbine and generator. Smaller capacity units have intermediary speed increasing gears, usually of the planetary type, which permit the use of smaller, high speed generators. In some large units, a man-way is provided so that the generator enclosure is accessible, but in smaller units no access is provided and the plant must be unwatered to service the generator.

Several modifications of the bulb arrangement have been built. In Germany, a number of plants have a large stairway access passage to the generator so that the bulb has the appearance of a pier in the middle of the flow conduit. In smaller plants, an open generator pit is sometimes provided so that water flows around the sides to the runner. These arrangements are most suitable when used with the small generators that are connected to the runners by speed increasing gears.

Bulb type or annular generator type units have not been constructed in the Western Hemisphere because of the high costs associated with the engineering and manufacturing of these rather sophisticated designs. To avoid these problems, Allis Chalmers, an American firm, has developed the tube turbine arrangement [8]. Figure 2c shows the generating units for the Ozark Lock and Dam now being constructed on the Arkansas River, which is typical of this arrangement. These units, which will develop 27,000 HP with 8.0 m diameter runners, are probably the largest tubular turbines ever contracted. This tube turbine arrangement requires a slight bend in the flow passage which, in turn, permits the generator to be located outside of the passageway. The special advantage of the tube turbine arrangement is that the speed increasing gear and the generator are highly accessible. Another advantage is that the equipment is standard, requiring a minimum of special design or fabrication. Numerous variations of this arrangement are possible with the generator located either upstream or downstream of the runner according to the peculiarities of the site. The arrangement shown in Fig. 2c is, however, well suited to low head plants.

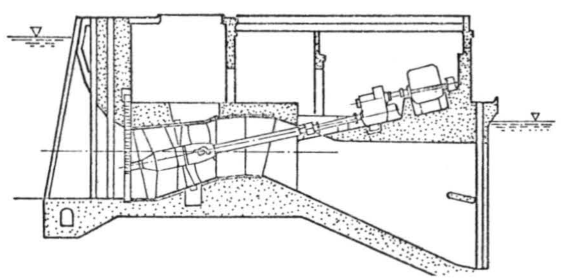

Fig. 2c. Ozark Lock and Dam, U.S.A., turbine dia 8.0 m (Allis Chalmers)

D. Head Increasers

A factor that is especially important for low head installations is the loss of head that occurs when river flows are high. When a river is carrying a large discharge, the depth of flow is relatively great and the water level downstream of the powerhouse is high. The water level upstream of the plant is not usually affected to as great an extent because this level is controlled by the spillway release gates. A number of plants have been designed to utilize the energy of the water released from the spillway to allow for the resulting decrease in head.

The arrangements for using excess spillway flows to lower draft tube pressures are called head increasers [1, p. 698]. One such arrangement is shown in Fig. 2a. In this instance, the spillway is built over the powerhouse and the flow is discharged into the river just above the draft tube, producing an aspirator effect that reduces the pressure and increases the head on the turbine. Other arrangements have been developed that introduce the excess flow right into the draft tube using a geometry similar to an ordinary jet pump. These internal devices are somewhat self-defeating in that the draft tube must be designed to handle both the turbine flow and the head increaser flow.

A combined spillway and powerhouse complex was utilized in the design of the recently completed Wells Project on the Columbia River partly to provide a compact arrangement and partly to make use of a head increasing effect.

E. Induction Generators

Induction generators [9] are used for low head plants wherever it is practical because they are cheaper than synchronous generators and because they require less control and less maintenance. At the present time, the trend is to use these generators for units up to 2500 kw [9, p. 4]. However, their efficiency is greatest at higher speeds so they should be operated above 600 rpm with speed increasing gears, if necessary. They cannot be used to establish frequency, however, and they will not operate at all unless connected in parallel with sizeable synchronous generators because they take their excitation from system current. They also cannot be used to match the power factor of the electrical load since their power factor output is not adjustable as with the synchronous machines. They will, however, serve the basic purpose of adding to the kilowatt output of a system with high efficiency.

The advantage of induction generators is their simplicity. They require no excitor and need only a squirrel cage rotor which uses no wire windings or brushes. Also, as they need not run at exact synchronous speed, complex synchronizing equipment is not needed to bring them onto line, and they usually do not require a complex governor.

F. Lower Limit for Head

A number of low head hydroelectric developments are shown plotted in Fig. 3 according to their rated head and discharge. The plot shows most of the tubular turbine installations of which the writer is aware and a number of the very low head propellor and Kaplan units.

The chart is not intended to be a complete record of installations, particularly in the region of higher head. As a result, the density of the plotted points is not too significant. There are, however, no known units which would plot below the broken line labeled "Approximate Lower Limit" except those shown. Furthermore, there are no known units with discharge capacities in excess of 10,000 cfs, other than those shown.

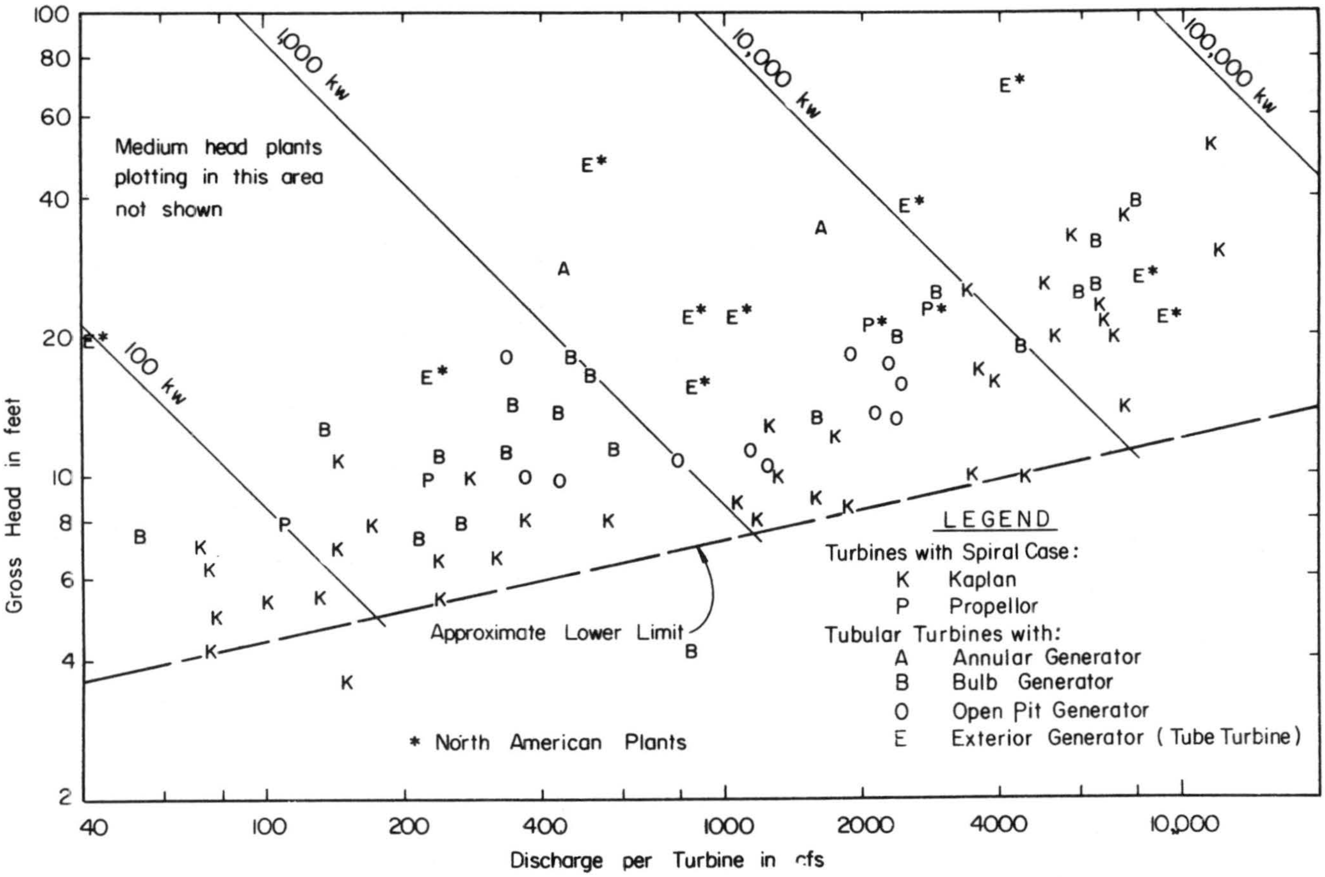

Fig. 3 Existing low head hydroelectric plants

Figure 3 defines a fairly sharp lower limit for the rated heads of existing plants and, significantly, this limit varies with capacity. The present actual lower limit for 10,000 kw units is about 12 feet while the limit for 100 kw units is only five feet. This chart emphasizes that there is a limit below which electric power organizations have never cared to invest in hydrogeneration. Although the tubular turbines seem best suited for very low heads, a surprising feature of the chart is that most of the borderline plants are vertical Kaplans with spiral case arrangements, and most of these have been constructed since 1950.

G. River Wheel Plants

As far as the writer is aware, there are no modern hydrogeneration facilities installed in free flowing rivers. There are a number of wind turbines [12] designed on modern air-foil principles. Experience gained with these machines could be applied to river wheels.

Several of the more important installations are shown in Table I.

TABLE I. WIND TURBINES

Project	Country	Year	Turbine Dia (ft)	Turbine Speed (rpm)	Rated Output (HP)	Rated Output (kw)	Rated Wind Speed (mph)	Tip* Speed Ratio
Smith Putnam	USA	1940	175	29	1680	1250	30	6
Balaclava	USSR	1931	98	30	135	100	24.6	4.75
John Brown	UK		50	130	135	100	35	6.5
SEAS	Denmark		43	56	61	45	28	5.4
Enfield-Andreau	UK		80	Variable	135	100	30	-

* Dimensionless ratio of turbine tip velocity to wind velocity

Probably the most notable experiment in aerogeneration was the Smith-Putnam turbine [11] built by S. Morgan Smith at Grandpa's Knob, Vermont. It had a propeller diameter of 175 feet and developed 1250 kw at a wind speed of 30 mph. It operated on an experimental basis for over a year before it was discontinued, having lost a blade through fatigue. The main problem with wind turbines is that their output is undependable because of the hour-by-hour variation of wind speed. This would not be so serious with river wheels, however, because river velocities are fairly constant with time.

The Enfield-Andreau wind turbine in Table I is unusual in that the two turbine blades are hollow. An air passage is provided from a small turbine at the base of the tower leading to the interior and then through the hollow blades to their tips. When the wind is driving the hollow blades, centrifugal action creates a suction at the hub which draws air through the turbine at the base, and discharges it from the blade tips. The generator is attached to the base turbine which runs at much higher speeds than the main wind turbine. Since the main turbine is not directly connected to the generator, it can run at any speed suitable for the wind at a given moment. This principle might be applied with advantage to low head water turbines and even to river wheels.

III. GOVERNING PHYSICAL LAWS

A. Capacity of Low Head Plants

The physical laws governing the generation of electricity from water power are fairly elementary. Energy is extracted from water as it flows through hydraulic turbines in a hydroelectric plant from a high level pool to a low level pool. The difference in pool levels is called the gross head and is represented by the letter H.

The volume of water passing through the plant each second is called the discharge, represented by Q. The energy available each second, (horsepower), disregarding all energy losses, depends on H and Q, according to the equation

$$HP = \frac{Q\gamma H}{550} \tag{1}$$

where γ is the specific weight of water in pounds per cubic foot.

The capacity of a plant to generate electricity is more commonly expressed in terms of electrical power using the unit of a kilowatt or kw. Kilowatts are related to horsepower by the equation

$$kw = .746\ HP \tag{2}$$

A hydroelectric plant is most valuable if its capacity can be depended upon during periods of peak demand. This capacity may be required only for several peak hours on several peak days during the year.

The dependable capacity, however, will be less than the rated capacity if either the head or the discharge is likely to be less than the rated value during these peak periods. As explained earlier, head deficiency, a major problem for very low head installations, usually arises during periods of high river flows. Fortunately, in most areas of the country, periods of high river flows do not coincide seasonally with periods of peak demand. If they do, the use of head increasers should be given serious consideration.

Discharge deficiency is another matter. In northern areas of the country, low river flows normally occur in the winter when electrical usage is highest. In southern areas, the rivers can be lowest in the summer coinciding with heavy irrigation pumping or air conditioning loads.

If the river discharge is less than required to operate the hydroelectric units of a plant at full load, several methods of operation are possible. One method is to run the plant at part capacity, using the water as it comes. Another method is to run the plant at full capacity during the peak load hours of the day. This causes the upper pond to drop as stored water is consumed. The plant is then operated at much reduced load during offpeak allowing the upper pond to refill. The problem is that lowering the pond level reduces the head on the plant that reduces the generating capacity. With low head plants, the storage in the upper pond is usually small so that the ability to run at full capacity for any length of time is limited during periods of flow deficiency.

The problem of water deficiency is a serious one for low head plants and can influence their feasibility. It will generally result in the optimum installed capacity being less than might be indicated by the average available discharge.

The size of units constructed in a low head plant to meet the planned installed capacity is usually determined from a cost comparison of plants with different numbers of units of different size. A number of variables affect this determination. Larger units usually result in lower turbine and generator costs but require heavier gantries and bigger erection facilities.

For larger units, the powerhouse is generally more compact but excavation is usually deeper. Also, larger units cause high concentrations of flow in the river so that intake channel and tailrace channel improvement costs may be higher. It is usually possible, however, to install any size of turbine desired up to the limit of the available discharge or the limits imposed by manufacturing or transporting problems. Tubular turbines with runners up to 26 feet in diameter are being built.

B. Capacity of River Wheel Plants

The only energy available to a hypothetical river wheel plant, consisting presumably of a propeller similar to a wind turbine, is the kinetic energy of the flowing water. If all the kinetic energy of the water passing through a plant could be extracted, the capacity of the plant would be designated by

$$HP = \frac{Q\gamma}{550} \frac{V^2}{2g} \qquad (3)$$

where V is the river velocity and $V^2/2g$ is the velocity head. Not all of the kinetic energy of the water can be removed for the simple reason that the water leaving the plant must have energy left due to its exit velocity. The amount of energy lost to the exit water will be discussed later along with other losses.

The discharge applicable for a river wheel plant is not well defined since there is no conduit separating the plant flow from the rest of the flow. Following wind turbine practice, it is convenient to define Q as the product of the undisturbed river velocity and the area swept by the turbine. Equation 3 then becomes

$$HP = \frac{A\gamma}{550} \frac{V^3}{2g} \qquad (4)$$

This equation shows the strong effect of river velocity variation on generating capacity. If a river that normally ran at five fps slowed down to three fps during a low flow period, the capacity of a river wheel would be reduced to almost one-fifth of its rated capacity. This factor would make it difficult to develop dependable capacity through use of river wheel plants unless high flow periods coincided seasonally with the peak load periods. Admittedly, the problem of velocity variation would not be as severe as for wind turbines.

The size of a river wheel, which is the factor other than river velocity affecting its capacity, would be limited by the natural river depth. Any attempt to increase the depth near the river wheel would be self-defeating for two reasons. First, the velocity would be reduced locally with appreciable reduction in available energy. Second, the excavation would tend to fill again with transported sediments.

The depth of a river usually varies more than its velocity. Both the water surface level and the bed level fluctuate with discharge. In addition, large bed waves, which migrate down the river, are common occurrences. Very little data have been uncovered on river depths. It is unlikely that there are many sites in fast flowing rivers where substantial numbers of wheels larger than ten feet in diameter could be installed without a sizable part of the wheel being exposed during the low-flow season.

The generating capacity of a ten-foot diameter river wheel depends, of course, on the river velocity. River velocities have been extensively measured, especially by the USGS. According to their records [13], there are very few rivers with velocities exceeding five fps, except during times of flood when velocities can reach six to ten fps. Table II shows the kw output of a ten-foot diameter river wheel operating with an overall efficiency of 40 percent.

The amounts of power indicated in Table II are very small indeed.

TABLE II. GENERATING CAPACITY OF A 10-FOOT DIAMETER RIVER WHEEL AT 40 PERCENT OVERALL EFFICIENCY

River Velocity in fps	Capacity in kw
4	3
5	5
6	9
8	25
10	41

C. Losses in Low Head Plants

The energy available from a hydropower plant is decreased by energy losses from one source or another. It is probably true that these losses can be reduced by building the components large enough and elaborate enough, but the cost quickly mounts. When the cost of reducing losses balances the benefits of increased energy output, the optimum arrangement is achieved. For low head plants, this optimum results in rather low overall efficiencies.

The losses in a hydropower plant can be expressed in terms of efficiencies for the separate components. For this study, the components are grouped into three systems with an efficiency for each system. The first system involves the flow conduit which, in this study, includes the draft tube even though usual hydropower practice is to include the draft tube losses with the turbine losses. This seems to be the most logical approach since the draft tube losses become very important for low head units. The effect of conduit losses is to make the net head on the turbine, h, less than the gross head on the plant. The conduit efficiency, e_c, can be defined by the expression

$$e_c = \frac{h}{H} \qquad (5)$$

The second system for determining efficiency is hydromechanical which includes the turbine, the shaft and any mechanical gearing required for speed increasing. The efficiency of this system, e_m, can be defined by

$$e_m = \frac{T\omega}{Q\gamma h} \qquad (6)$$

where T is the torque in the generator shaft in ft lbs and ω is the shaft speed in radians per second. The third system is electrical and includes the generators, the low-voltage buses and the transformers. The efficiency of the electrical system, e_e, becomes

$$e_e = \frac{kw}{T\omega} \frac{550}{.746} \qquad (7)$$

Finally, Eqs. 5, 6 and 7 can be combined to give the complete expression for kilowatt output in terms of the above efficiencies,

$$kw = \frac{0.746}{550} Q\gamma H\, e_c\, e_m\, e_e \qquad (8)$$

How these efficiencies are influenced by head is discussed briefly in the following paragraphs.

Head is an unimportant factor affecting the efficiency of the electrical system because its characteristics are fairly well divorced from the flow. This is especially true when speed increasing gears are used.

Capacity is a factor, however, since large capacity electrical systems tend to be more efficient than small ones [15, p. 952]. The electrical efficiency of a 100 kw unit is typically about 90 percent but it may be as high as 96 percent for a 10,000 kw unit. Once again, efficiency is a matter of economics and equipment could be made more efficient at greater expense.

The losses in the hydromechanical system result largely from the interaction of the fluid and the turbine blades. Losses in bearings, gears and seals total about one percent and would probably not exceed two percent [8, p. 6].

The hydraulic efficiency of a turbine depends upon the relationship of the runner diameter and the runner speed to the head and discharge. This relationship limits the speeds and diameters to a fairly narrow range as shown by the plots in Figs. 4 and 5.

Figure 4 is a plot of a number of existing low head units showing, with the aid of dimensionless parameters, how diameter, d , is related to head and discharge. Figure 5 shows the relationship of runner speed (ω in rad/sec) to head and discharge. A number of wind turbines are represented on these two figures for comparison purposes.

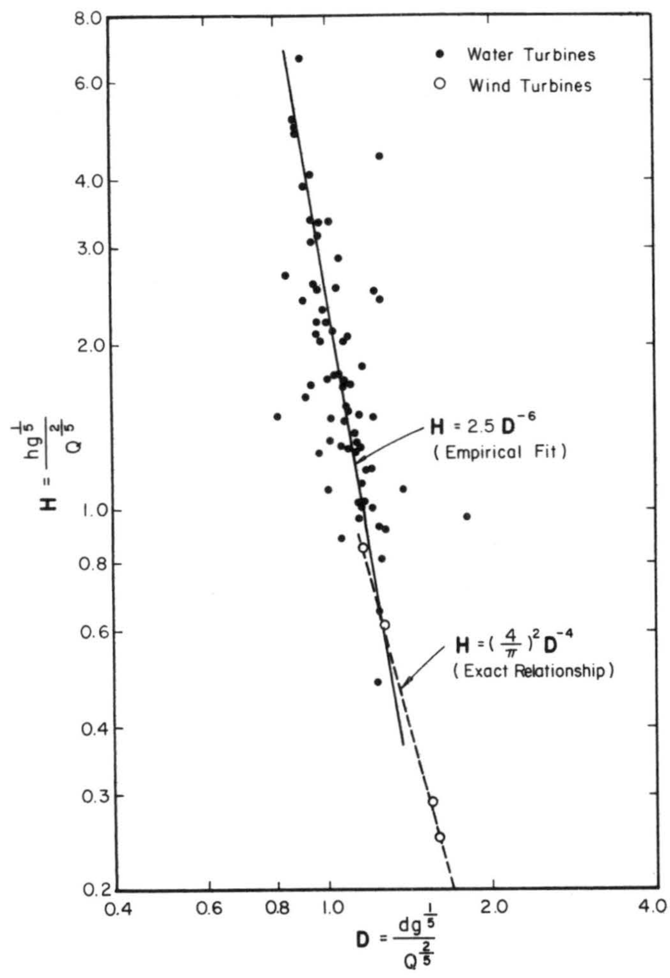

Fig. 4 Runner diameter as a dimensionless function of head and discharge

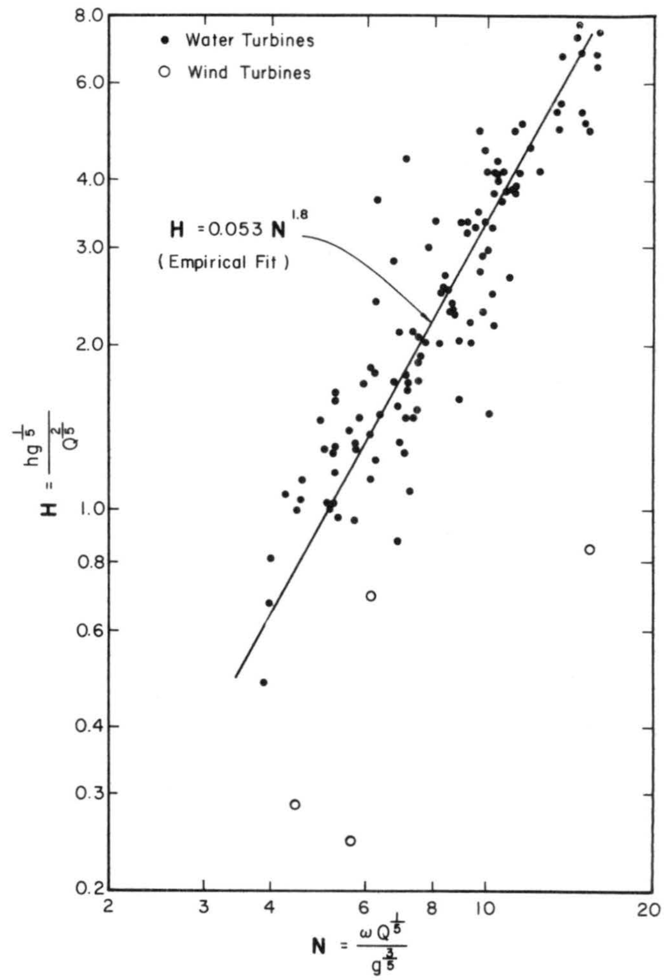

Fig. 5 Runner speed as a dimensionless function of head and discharge

Figure 4 shows a rather narrow band of scatter for the dimensionless parameters chosen and a surprising correspondence between water turbines with their more or less complex flow passages and wind turbines with no flow conduit at all. The data for wind turbines plot on a single line because the coordinate parameters are interdependent since head, discharge and diameter are related. It is also somewhat surprising that the data overlap for the two types of turbines. The reason is that the heads for wind turbines are feet of air rather than feet of water. River wheels would plot far below the range of this chart. The main point shown in Fig. 4 is that the diameters of turbines with the same discharge capacity tend to be larger for lower heads even though the energy output is smaller.

The data for turbine speed shown on Fig. 5 have much more scatter than the data for turbine diameter. This is probably because efficiency and cost are not affected as much by speed as by diameter. The parameter chosen for speed is not the specific speed usually used for turbine data. Plots relating specific speed to head are often employed [3, p. 33; 1, p. 712] but the plot of Fig. 5 produced less scatter than the same data plotted in the more usual terms. As a frame of reference, **H** = 1.0 could apply either to a 100 kw unit with a head of four feet or to a 10,000 kw unit with 16 feet of head, both very near the lower limit of existing plants as shown in Fig. 3. According to Fig. 5, the design turbine speed drops rapidly with head. This emphasizes the need for speed increasers for low head units.

Turbine efficiency can be shown to depend upon runner diameter and speed as well as head. Analytical determinations of efficiency based on airfoil theory substantiate the results of Figs. 4 and 5 by indicating optimum efficiencies for turbines that plot in the areas where most of the data is concentrated. For these turbines, the effect of head on efficiency is not as great as might be expected. Calculations based on airfoil theory gives peak efficiencies of about 91 percent for **H** = 1.5 and 90 percent for **H** = 0.5.

Turbines cannot always operate at peak efficiency. Variable pitch runner blades and/or guide vanes are commonly provided to keep offpeak efficiencies as high as possible. If both guide vanes and runner blades are variable, as with Kaplan turbines, efficiency can be maintained consistently high over a wide range of operating conditions. Propeller turbines, with fixed runner blades and variable pitch guide vanes have, on the other hand, rather poor efficiencies at offpeak conditions. A reasonably flat efficiency curve can be achieved in the American-type tube turbine if it has variable runner blades and fixed guide vanes [8, p. 6]. Since there are usually many more guide vanes than runner blades in a unit, this represents a considerable saving in costs.

Adjustable runner blades would not be required if the turbine speed could be varied with head and if the turbine could be operated at the optimum power output for each speed. Connected to a large system, low head plants can operate continuously at optimum output but speed variation cannot be allowed because of the required A.C. synchronization. The use of D.C. generators with appropriate rectifying equipment might be a partial solution for the future, but other approaches discussed later are available.

While the efficiencies of the electrical system and the hydromechanical system are not greatly affected by head, the efficiency of the conduit is. Losses in the flow conduit arise as a result of entrance losses including trashrack drag, wall friction and exit losses. Of these, the exit loss is by far the greatest and would be even more dominant were it not for the energy recovery of the expanding or diffuser section of the draft tube. To be effective, the expansion of a draft tube must be gradual enough so that the flow will expand with the walls and not separate away to form eddies. However, it must not be so gradual that the structure becomes so long that wall friction is appreciable. The superiority of straight conical draft tubes, possible with tubular turbines, over elbow draft tubes, required for spiral case arrangements, is evident.

According to laboratory tests [16], the most efficient conical draft tube would be about ten turbine diameters long with a total included angle of divergence of about seven degrees. This draft tube would recover about 91 percent of the kinetic energy possessed by the water as it leaves the turbine. Economics, however, usually limits the length of the expanding section to the order of four turbine diameters or less. For this length, the optimum angle of divergence is about 12 degrees and the energy recovery is about 78 percent. The amount of energy lost to the exit flow is then about 22 percent of the kinetic energy of the water leaving the turbine. This figure can be converted to conduit efficiency assuming that turbine diameters follow the trend of Fig. 4. With allowances for other minor conduit losses, a representative conduit efficiency of 90 percent can be arrived at for **H** = 1.5 and 86 percent for **H** = 0.5.

The overall efficiency of typical low head plants obtained from the electrical, hydromechanical and conduit efficiencies described above is shown in Fig. 6 as a function of head and discharge. According to this figure, overall efficiencies for low head installations ($H < 50$ ft) range from 75 to 85 percent. These values seem low compared to published data, but the fact remains that efficiencies for low head plants can be expected to be appreciably lower than for higher head plants.

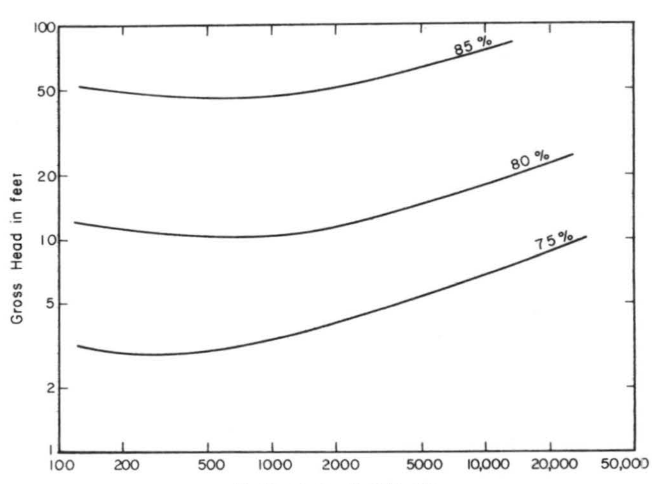

Fig. 6 Estimated overall peak efficiency for units of different rated head and discharge

D. Losses in River Wheel Plants

The losses in a hypothetical river wheel plant can be grouped under the same three general categories used for low head plants, specifically, conduit, hydromechanical and electrical. Equations 5 through 8 can be applied. The hydromechanical and electrical losses are much the same as discussed under low head plants but the concept of conduit losses requires special elaboration.

The water which passes through a wind turbine or river wheel is confined by a pseudo-conduit formed by the boundary of the outside flow, shown in Fig. 7. The water upstream of the river wheel is moving at the speed of the river, but it slows down as it passes through the wheel. The axial velocity of the water passing through the wheel, U_p , is controlled by the speed of the wheel and the angle of the blades. According to a commonly accepted theory originally developed for aircraft propellers, the flow will continue to decelerate downstream for some distance providing a wake of low velocity, U_w , having a diameter somewhat larger than the wheel itself. This, in effect, produces a natural diffuser action.

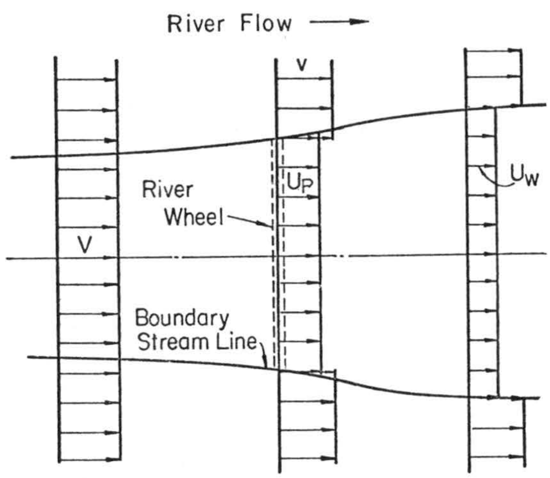

Fig. 7 Definition diagram for river wheel theory

According to the theory, the velocity through the wheel is the average of V and U_w . The amount of energy available to the wheel depends upon the value of U_p at which the wheel operates. If U_p is small, the discharge through the wheel is correspondingly small so that the energy extraction is small. If U_p is large, the energy remaining in the wake is large but again the energy extraction is small. The optimum value of U_p turns out to be .67V and the maximum energy available turns out to be 59 percent of that given by Eq. 4. This loss of energy can be attributed to the conveyance of fluid to and from the propeller and in this sense is a conduit loss. The theoretical conduit efficiency for river wheels is, therefore, 59 percent. This analysis has received considerable criticism [12, p. 191], but a value of 59 percent is used by most references.

Efficiency for wind turbines can be estimated analytically by airfoil theory the same as for low head runners. The main difference is the lack of guide vanes that give the wind an initial whirling motion before it reaches the turbine. The result is lower theoretical peak efficiencies reached at somewhat higher runner speeds. The higher runner speeds are evidenced in the data of Fig. 5. Theoretically, the peak efficiency should be about 81 percent for a tip speed ratio of about 4.0. The tip speed ratio is the ratio of the velocity of the tips of the turbine blade to the undisturbed velocity of the flow. As shown in Table I, wind turbines are designed with tip speed ratios somewhat higher than 4.0. This is necessary to keep generator speeds as high as possible. The best efficiencies found in the literature are for the SEAS wind turbine [17, p. 66] where the efficiency is stated as 80 percent for a tip speed ratio of 5.0.

A reasonable estimate of overall efficiency for a wind or river turbine would be about 40 percent based on a conduit efficiency of 59 percent, turbine efficiency (including gearing) of 78 percent and an electrical efficiency of 90 percent.

IV. ECONOMIC CONSIDERATIONS

There are several ways of looking at the value of a proposed hydropower plant, but a revealing comparison is the relationship between annual cost and load factor. The annual costs of any generating plant, hydro or otherwise, include the following:

1. Interest on the initial capital investment.
2. Payment to an amortization fund.
3. Maintenance and operating costs.
4. Taxes, licenses and fees.
5. Cost of fuel and fuel handling.

The load factor of any plant is defined, for this report, as the ratio of the amount of energy that was produced at the plant over a period of time to the amount of energy that would be produced if the plant were operated continuously at its level of dependable power output. Since most plants are operating at less than their dependable output some of the time, load factors are usually less than one. But some plants, particularly low head plants, have a dependable output less than their rated output so that their load factor could be greater than one falling under the above definition.

The annual costs for fossil fuel plants, or nuclear plants for that matter, depend upon load factor mainly because higher load factors require more fuel. Figure 8 shows estimated annual cost/load factor relationships for several different plants.

Plant A is a diesel-electric station having a low capital investment but comparatively high fuel costs. Plant B is a modern steam plant located close to the source of fuel. In this case, the capital investment is higher but the fuel costs are lower. If these two plants were connected to the same system, it would be most economical to run the steam plants as much as possible to keep its load factor high. The diesel plant, then, should be run as little as possible for a low load factor. The load factor curves go beyond a value of one for Plant B as might occur in a plant in which the dependable capacity was judged less than the rated capacity because of the possibility of a partial shutdown for repairs.

A comparison of hydropower plants with fossil fuel plants is provided by curves C and D on Fig. 8. Curve C is typical of a hydropower plant with considerable capital invested in non-productive features such as the dam and spillway which are nevertheless charged to the production of electricity. The curve can be thought of as the results of a design study, which determines how much generation capacity to install. Increasing the installed capacity decreases the cost of the dam, etc., and lowers the capital cost per kw. However, it also lowers the amount of water available per kw, thereby lowering the available load factor. On an annual basis, the Hydroplant C, would cost more than Plant B if too few units were installed. It would cost more than Plant A if too many units were installed. In this example, the most competitive plant would have enough capacity for a load factor of about 25 percent.

A low head plant, which has only its power facilities charged to electricity, is represented in Fig. 8 by curve D. For this plant, the annual cost per kw of firm capacity falls with an increase in load factor. The reason is that, because of a lack of reservoir storage, the ratio of dependable capacity to installed capacity is much lower if the plant is built with a large installed capacity (low load factor) than it is if it had a small installed capacity. This causes the annual cost based on dependable capacity to be higher for lower load factor. The low head plant appears to be feasible provided the installed capacity is not too large. It should be noted, in this example, that the two hydroelectric plants have approximately the same degree of economic advantage over the thermal plants but under much different conditions of load factor; also that the low head plant might be a better proposition than the high head plant under some conditions of load factor.

The amount of capital that can be invested in a low head hydroelectric plant depends upon the alternative sources of power available. On an average, the annual costs of a hydroplant is about 10 percent of the capital investment. A low head hydroelectric plant that would supply electricity to a power grid at 100 percent load factor would be feasible, compared with Plant B, if it could be constructed with a capital investment at \$440 per kw of firm capacity. If a low head plant serviced an isolated system having a load factor of 60 percent, which would otherwise be serviced by a diesel set similar to Plant A, up to \$650 per kw could be invested. On the other hand, if the isolated system required a load factor of 90 percent such as might occur with some industrial applications, the investment could economically reach \$1000 per kw.

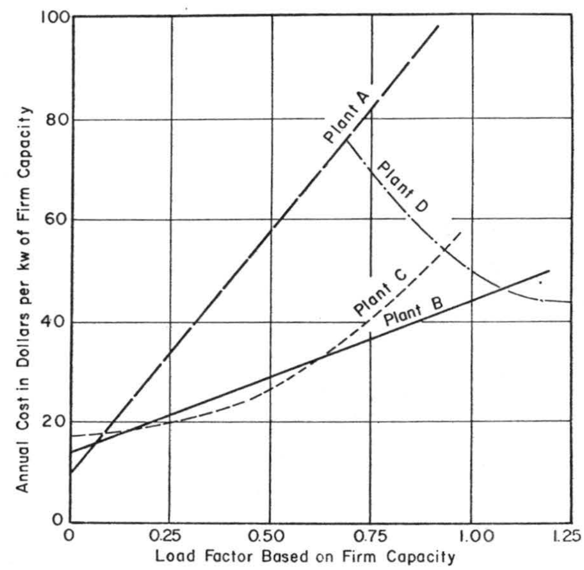

Fig. 8 Variation of annual cost for generating plants

Feasibility of a hydroelectric plant, therefore, depends upon the type of plant that would best serve as an alternative and upon the operational load factor of the plant. The values quoted are rather high and serve only to show that relatively expensive hydroelectric plants can be economically feasible under certain conditions.

The economic feasibility of a hydroelectric plant also depends upon how much of the cost of the total development must be charged to the production of electricity. Many sites are developed for their hydropower alone. The entire cost of the project, including the procurement of land for the reservoir and the site facilities, the construction of the access road, the camp, the impounding structure, the flood spillway, as well as the power facilities are all charged to power production. However, the very lowest head plants can be justified only when they are incorporated into a development built primarily for some other purpose such as flood control, navigation or irrigation. Of course, all facilities directly related to power production should be charged to the hydroelectric part of the development.

Ordinarily, head is not an overriding factor in feasibility studies. Medium low head plants may be just as attractive as high head plants because costs and benefits vary with head to some degree. However, for very low head plants, it does become important because benefits in the form of energy production do vary with head while costs do not. For instance, the size of the impounding structure becomes more a function of the depth of the river than the head and power facilities are designed according to the discharge, rather than the head. The result is that the lower the head, the less likely the plant will prove to be economically feasible.

The one attractive feature of river turbines is that they would require a very minimum of peripheral construction. Even access roads would not be required if they were built and maintained by river transport.

V. COST CHARACTERISTICS

A. Low Head Plants

To fully appreciate the significance of head for low head plants, it is necessary to make some estimate of costs. The figures presented in this section are based on data collected from several sources and interpreted by using a number of assumptions, some of which can be only partially supported. The results are intended to show only the general trend of costs and are not sufficiently reliable to be used even for preliminary cost estimates. To discourage their use in estimates, the figures are shown only as indices relative to the cost of a reference plant. This reference plant has a head of 50 feet and a capacity of 10,000 kw per generating unit.

The cost curves are shown in Figs. 9a and 9b. Figure 9a contains relative costs for 10,000 kw units with heads varying from 10 to 50 feet. The costs are divided into hydromechanical, electrical, and civil categories to show the effect of head on these components. According to Fig. 9a, a 10,000 kw unit with a head of 10 feet costs almost six times as much as one with a head of 50 feet. Figure 9b contains costs for 1,000 kw units relative to the 10,000 kw reference unit with 50 feet of head. The costs per kw are shown to be higher for the smaller units largely due to higher electrical costs.

It is assumed that all plants consist of tube turbines as developed by Allis Chalmers since these promise to be the most economical in North America, for very low heads. The costs are for a single powerhouse unit and no allowance has been made for an erection bay or a crane or gantry. Costs for foundation preparation, dewatering, or channel improvement are also neglected. It is assumed that the units are to be installed in a development for which all costs, other than those directly related to power production, are to be charged to some other purpose.

The hydromechanical costs include the turbine with its accessory equipment, the speed increasing gear, and an emergency closure gate. The costs for turbines are based on bid data published by the Federal Power Commission [18]. The lowest head reported is 37.5 feet for the North Highlands Project on the Chattahoochee River in Georgia. Extrapolation to lower heads is made by using turbine weight data in reference [1] assuming a constant cost to weight ratio. There is a great deal of scatter in the bid data, which includes both Kaplan and propeller turbines, but a definite trend is apparent. The tube turbines are assumed to cost the same as propeller turbines which, according to this data, are about 25 percent cheaper than Kaplans.

Speed increasing gears are a fairly well established product and the cost depends largely on the input torque. Lower head runners deliver more torque per kw because they run at lower speeds. The gear costs are therefore higher on a per kw basis. For heads of 10 feet, the gears cost approximately as much as the entire electrical system. There is also a trend for small capacity gears to be more expensive per unit of torque than large gears. This causes gears for small plants to be more costly per kw.

There is a wide range of opinion regarding emergency closure gates for low head plants. Conservative practice is to provide each unit with a quick operating gate. For some very low head plants, however, several units have been provided with a single gate to be transported by a crane from a storage area when needed. For this study, it is assumed that each unit will have an emergency gate.

The electrical costs include the generators and switching equipment, but not the high voltage transformers. The costs are based on the use of horizontal axis, synchronous generators operating

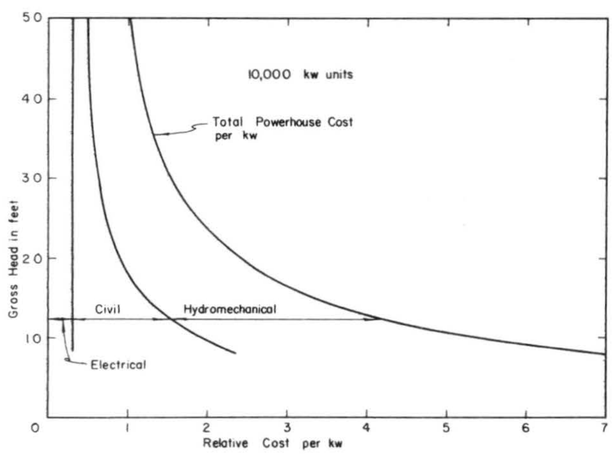

Fig. 9a Cost of 10,000 kw units relative to a 10,000 kw unit at 50' head

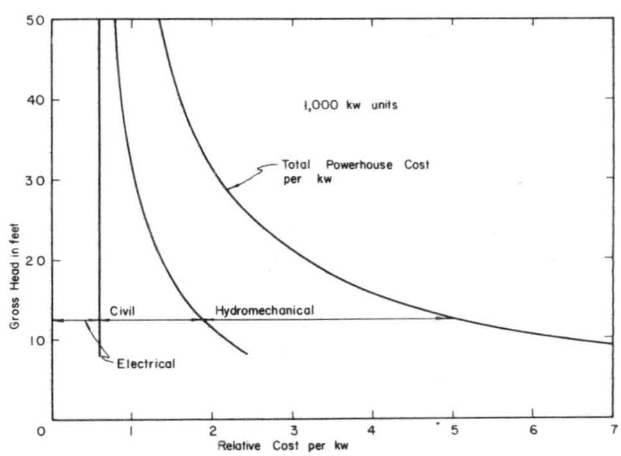

Fig. 9b Cost of 1,000 kw units relative to a 10,000 kw unit at 50' head

through gearing at 600 rpm. It is assumed that electrical costs per kw would depend upon capacity but not on head. Electrical equipment for smaller capacities costs considerably more per kw than larger capacities, as shown in Figs. 9a and 9b.

The civil costs comprise the powerhouse substructure and superstructure and include the trashracks. No allowance is made for foundation excavation or dewatering on the assumption that, if the powerhouse was not built, this work would have to be done on the alternative embankment structure. These costs vary considerably from site to site, in any case. The total civil costs are on quantities determined from preliminary powerhouse layouts based on the arrangement of Ozark Lock and Dam in Fig. 2c.

The relative costs of Figs. 9a and 9b clearly show the reason for an absence of units in the very low head range of Fig. 3. One would expect from these figures, however, that larger capacity plants could be built at lower heads, than smaller plants, which is contrary to the data of Fig. 3. The explanation must be that the smaller low head plants are in remote areas where low cost electricity is not available.

B. River Wheel Plants

There is very little likelihood that river wheel plants will ever be an economic reality. On any of the major rivers of the United States where electricity is available, river wheel plants would have to be constructed at a cost of about $200 per kw. As mentioned earlier, a ten foot diameter wheel would be close to the upper limit for rivers flowing five fps or greater and, according to Table II, it would have a capacity of only five kw. This would limit the cost of such a wheel to approximately $1000. It would cost this much merely to place a concrete pile into the river bed to support the wheel.

One could imagine very remote locations, especially unattended ones, where dependable power in modest quantities would be needed to operate some sort of equipment. Here, river wheels might be attractive if they were commercially available. However, the kinetic energy of rivers does not appear to a variable source of energy of national scope.

VI. POSSIBLE FUTURE TECHNOLOGICAL DEVELOPMENTS

A. Turbines

The science of turbine design constantly is being refined and many subtle improvements have been made to basic arrangements. However, major changes, such as the tubular turbine, are much more rare and represent years of expensive development and promotion. After discussions with designers working for the leading turbine manufacturers, the writer is not aware of any forthcoming new designs for low head turbines.

The greatest expense of turbine manufacture is in the close tolerance machining of moving parts. Figure 10 shows a futuristic arrangement based on the hollow bladed Enfield-Andreau wind turbine and having few machined moving parts. The runner is supported at the center by a short shaft connected to the guide vanes and is free-running with no generator attached. As water flows past the blades causing the turbine to rotate, it operates as a centrifugal pump. Water is drawn into the runner at the hub and discharged into the peripheral pumping volute at a higher pressure. The high pressure water from all of the units at a particular site is collected and passed through a single conventional turbine generator to produce electricity.

As an example, imagine that five hollow blade runners, each 20 feet in diameter operating with ten feet of head, pump water to a single turbine generator. These runners each have a flow through capacity of 5000 cfs and can pump 350 cfs against a head of 135 feet. The single turbine generator is a 15,000 kw unit with a conventional Francis runner. The runner operates with a capacity of 1,750 cfs against the head of 135 feet. The Francis runner has a speed of 360 rpm and is directly coupled to the generator.

This arrangement would eliminate five governors, gear sets and generators but would add five pumping volutes, a manifold collecting penstock, and a conventional generating unit. Careful technical and economic feasibility studies would be required to determine if there is any advantage to such an arrangement.

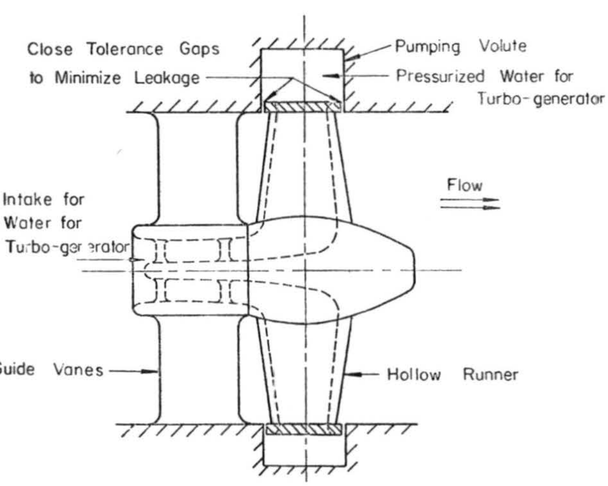

Fig. 10 Hollow runner propeller turbine

An extension of this concept is to cause these hollow blade runners to pump water to a higher level reservoir for water supply needs or irrigation use or for generation of electricity during peak hours. It might be possible to connect several runners in series to obtain higher pumping heads, but this would make sealing problems more difficult.

B. Electrical Equipment

The electrical equipment represents only a small part of the cost of very low head units. Therefore, electrical improvements would have small impact on feasibility. The only improvement that would seem to be significant would be one that allowed variable speed turbine operation, as with D.C. generators. High voltage D.C. transmission offers some economy over A.C. transmission under certain conditions, but the problem of economically obtaining high voltage from a D.C. generator has not been solved.

C. Civil Structure

The section of the civil structure where improvement would be most significant is the draft tube. In tubular turbines, the draft tube represents a major extension of the civil structure and accounts for about 30 percent of its cost. There are several arrangements that could be explored to reduce the length and, perhaps, the cost of diffusers.

Considerable research has been devoted to draft tube design for other than low head plants, and some sophisticated arrangements with control vanes have been proposed. Simple designs have proven best, however, mainly because of the complex whirling motion that occurs in draft tube flow. Low head plants, on the other hand, produce relatively little whirling motion especially with variable pitch guide vanes and propeller blades. When this is the case, more sophisticated draft tubes may be beneficial.

The key to proper diffuser action is in preventing the boundary layer of the flow from separating from the diffuser walls. Control vanes near the boundary have been used successfully in some situations to prevent separation, and they may be used to shorten the diffuser as shown in Fig. 11a. Another possible method is boundary layer suction, as shown in Fig. 11b. Here the slow moving boundary fluid that tends to cause separation is withdrawn from the flow. A third possibility is a multiple cone diffuser, as shown in Fig. 11c. This arrangement would provide the shortest draft tube but would present the greatest structural problems and would be relatively expensive to build.

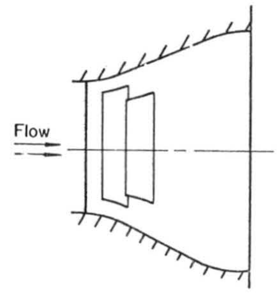

Fig. 11a Short diffuser with control vanes

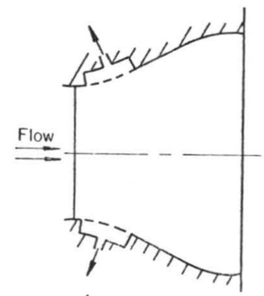

Fig. 11b Short diffuser with boundary layer suction

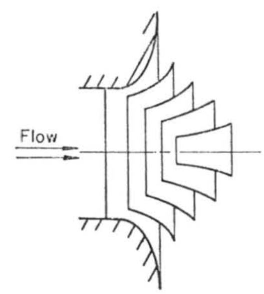

Fig. 11c Multiple cone diffuser

VII. SECONDARY CONSIDERATIONS

One of the outstanding advantages of very low head hydroelectric development is its compatibility with the natural environment. Aesthetically, low head plants can be very attractive. Tubular turbines can be fitted into a powerhouse with a very compact, low, unobtrusive profile. There is virtually no pollution associated with hydroelectric plants either in the form of sound, heat, or smoke. The level of activity around a hydroplant is also low. The trend is to automatic control with very few people in attendance and a minimum of maintenance personnel. As a result, low head plants can be located in areas, such as lakeside or riverside parks where aesthetics are important, without introducing an obvious industrial atmosphere to the area. This is in sharp contrast to steam plants with prominent industrial type buildings, high stacks, and cooling towers.

Since these plants presumably would be built only at sites where impoundments are to be created anyway, there is no question of effects on river profile. The only apparent drawback to developing hydropower at an existing impoundment is that there would be somewhat less aeration of the water if it goes through turbines rather than over a spillway. This may have a bearing on the ability of the river to absorb pollution.

Another consideration that affects the development of low head sites is the natural tendency for planners of power organizations to look to sources of large blocks of power to meet the rapid load growth. They ignore places that would develop only small amounts of power because these small sites do not solve the problem of the moment. The growth of small capacity sites would probably require separate departments or organizations charged solely with locating and developing them as they prove feasible.

The main effect of a large scale development of a river with batteries of river wheels would be in making the river flow deeper, particularly for low flows. At discharge high enough to threaten the capacity of the river channel, these units would have a minimum affect since the proportion of energy withdrawal would become negligible.

The deeper, slower flow caused by a set of river wheels may affect the river in several ways. The obvious affect would be in the reduction of the sediment transporting capacity of the river in the stretch where the river wheels were located. This probably would result in an aggrading of the river bed upstream of the stretch and a degrading downstream. The extent of these affects could be computed fairly accurately before the units were installed, based on a study of the individual river. The water temperature might also be influenced by a change in depth, but the effect of deeper water would be opposite to the effect of slower velocity and longer detention. The change, if any, would not be clearly predictable.

VIII. CONCLUSIONS AND COMMENTS

As a result of this study it is possible to draw the following conclusions:

1. Hydraulic turbine manufacturers in the past have been actively engaged in the development of special turbines for low head application. This effort has culminated in bulb type units common in Europe and tube turbines which are finding application in North America.

2. The countries of Europe have made extensive use of navigation control structures for the generation of electricity and have built many units with heads less than 25 feet, whereas there have been very few units built in North America with heads of 25 feet or less.

3. The wind as a source of energy for the generation of electricity has been the subject of considerable study and a number of modern airfoil wind turbines have been built on an experimental basis.

4. Flowing water in rivers can also be used to generate electricity but interest in this source of energy has been minimal, chiefly because of the high cost of the required equipment relative to the benefits.

5. The generation of electricity from flowing water of rivers is not economically justifiable except possibly in small quantities at very remote locations.

6. The available head is the most important factor affecting the feasibility of low head hydroelectric plants. Considering well designed low head plants of equal discharge capacity but different heads, the lower head plant will have:

   a. lower kw capacity

   b. larger, slower turning turbines

   c. heavier, slower turning generators (alternatively more expensive speed increasing gears)

   d. larger flow conduits

   e. lower overall efficiency

   f. higher total cost

   g. higher cost per kw

   h. lower benefit/cost ratio.

7. Low head generating units can be located in low profile structures with high aesthetic qualities and function without contributing to the pollution of the environment.

8. Hollow blade turbine runners, based on a principle used in a British wind turbine, are a possibility for reducing the cost of low head developments.

9. There appears to be a need for research in the design of draft tubes for tubular turbines to apply modern principles of boundary layer control to reduce the length of draft tube diffusers.

In addition to the above direct conclusions there are a few comments that should be made regarding low head hydrogeneration. It is not easy to understand why there are so few low head units in North America compared to Europe. In the beginning of this century a great many small, low head units were installed on this continent, mostly by small utility and industrial organizations. With the development of large improved thermal and hydroelectric plants, most of these small plants were shut down as they wore out. In Europe, however, low head hydrogeneration has continued to develop. Some of this development may have been due to unsettled political climates, whereby governments would look to hydropower as being insurance against a loss of fossil fuel supplies. Some is undoubtedly economic reflecting differences in the value of resources, including manpower, in the two continents. However, the impression is that low head development has been bypassed in North America by planners who are pressed to develop large blocks of power to meet rapidly growing load demand. This tendency is likely to continue, even as the pollution problem associated with thermal and nuclear plants increases, because the development of low head hydropower will never make a sizeable dent in the needs for thermal and nuclear power. The development of low head power, where economically justifiable, will seem to depend on the action of persons conscious of the waste of an untapped non-depletable national resource rather than on persons looking to meet power demands.

The manufacturers of low head turbines, in the face of the limited demand for these units, do not appear to be able to support the research that would help to make low head power generation more attractive. If a program to develop low head sites is desirable, extensive research in many areas of powerhouse design would be certain to bring about savings in the cost of the development program. In this connection, it is worth commenting on the similarity between low head hydrogeneration and low head pumping. Much of what would be learned regarding low head generation would apply to pumping as well.

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APPENDIX A

LOW HEAD TURBINES

APPENDIX A

LOW HEAD TURBINES

(1) Ref. No.	(2) Name	(3) River	(4) Country	(5) Mfr.	(6) Year Built	(7) No. of Units	(8) Rated m	(9) Head ft
1	Rostin	Parsenta	Poland	EW	1936	2	3.75	12.3
2	Iller VII	Ill	Germany	EW	1937	4	9.0	29.5
3	Iller VI	Ill	Germany	EW	1939	3	9.2	30.1
4	Iller V	Ill	Germany	EW	1940	3	8.1	26.5
5	Lech (9 plants)	Lech	Germany	EW	1940	54	8.2	26.9
6	Iller VIII	Ill	Germany	EW	1942	3	8.6	28.1
7	Saalach	Saalach	Austria	EW	1943	2	8.4	27.5
8	Saalach	Saalach	Austria	EW	1943	1	8.4	27.5
9	Iller V	Ill	Germany	EW	1949	1	8.1	26.5
10	Iller VI	Ill	Germany	EW	1949	1	9.2	30.1
11	Iller VIII	Ill	Germany	EW	1949	1	8.6	28.1
12	Castet	Gave d'Ossau	France	N	1953	2	7.0	23.0
13	Wadrinau		France	N	1956		4.6	15.1
14	Burglen	Thur	Switz.	EW	1956	1	3.1	10.2
15	Reutte	Lech	Austria	EW	1956	1	6.1	20.0
16	Cambeyrac	Truyere	France	N	1957	1	10.7	35.0
17	Ruhmemuhle	Rhume-Leine	Germany	V	1957	1	3.8	12.4
18	Sylvenstein	Isar	Germany	V	1957	1	25.8	84.5
19	Argentat (main)	Dordogne	France	N&CA	1958	2	16.5	54.0
20	Argentat (compensation)	Dordogne	France	N	1958	1	16.5	54.0
21	Beaumont-Monteux	Isere	France	N	1958	1	12.5	41.0
22	Trier	Moselle	Germany	EW	1958	4	5.1	16.7
23	Gaggenau	Murg	Germany	V	1958	1	3.0	9.8
24	Hitokita		Japan	EW	1958	1	12.0	39.3
25	Finsing		Germany	EW	1958	1	8.6	28.2
26	St. Malo		France	N	1959	1	4.8	15.7
27	Detzem	Moselle	Germany	EW	1959	4	7.0	23.0
28	Koshi		Japan	EW	1959	1	8.5	27.8
29	Altenburg	Lippe	Germany	V	1960	1	3.5	11.5
30	Haslach		Germany	V	1960	2	15.0	49.1
31	Altbach	Neckar	Germany	V	1960	2	5.1	16.7
32	Puhos		Finland	EW	1960	1	4.5	14.7
33	Weilheim		Germany	EW	1960	1	4.35	14.2
34	Saikawa		Japan	EW	1960	1	18.3	60.0
35	Buckenhofen		Germany	EW	1960	2	5.2	17.0
36	Finsing Kanal		Germany	V	1961	1	10.6	34.7
37	Omata		Japan	V	1961	1		
38	Joganjigawa	Joganji	Japan	V	1961	3	15.1	49.5
39	Shimoaka		Japan	V	1961	1	10.7	35.0
40	Herrfors		Finland	EW	1961	1	3.5	11.5
41	Akirashima		Japan	EW	1961	1	13.7	45.0
42	Hausen		Germany	V	1962	2	5.0	17.4
43	Partensteinrohr		Austria	V	1962	1	10.9	35.7
44	Thunsdorf		Austria	EW	1962	1	10.3	33.7
45	Neuville		Belgium	EW	1962	4	4.0	13.1
46	Rüchlig		Switz.	EW	1962	4	3.3	10.8
47	Muden	Moselle	Germany	V	1962	4	4.13	13.5
48	Fankel	Moselle	Germany	V	1962	4	4.13	13.5
49	Grevenmacher	Moselle	Germany	EW	1962	3	5.5	18.0
50	Urspring	Moselle	Germany	V	1963	3	8.15	26.7

Notes: This listing is an expansion of one which originally appeared in reference (3) of the List of References. The original contained references 1 to 94 which are all tubular turbines.

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Ref. No.	Turbine Rated Output H.P.	M.W.	Speed rpm Turbine	Generator	Wheel dia m	Specific Speed Metric	cfs units	Remarks
1	259	0.19	250	250		882	176	Bulb unit-submerged
2	2380	1.75	250	250		1030	235	Ring units
3	2550	1.87	214.3	214.3		677	153	
4	2140	1.57	214.3	214.3		728	165	
5	1850	1.36	214.3	214.3		665	151	
6	2380	1.75	214.3	214.3		710	161	
7	1860	1.37	214.3	214.3		645	146	Submerged
8	1420	1.04	214.3	214.3		565	128	Submerged
9	1020	1.39	214.3	214.3		502	114	
10	2210	1.63	214.3	214.3		630	145	
11	2030	1.49	214.3	214.3		656	149	Last ring unit by EW
12	1120	0.82	250	250	1.65	735	167	
13	2020	1.48	107	750	3.05	712	162	Pit type
14	610	0.45	113	1000		680	154	
15	1790	1.24	165	1000	1.95	729	165	Submerged plant
16	7000	5.15	150	150	3.1	645	147	
17	688	0.5	177	750		875	199	
18	3800	2.8	452	1000		480	109	
19	19250	14.2	150	150	3.8	627	142	
20	4100	3.0	300	1500		576	131	
21	12000	8.8	150	150	3.8	700	159	
22	6000	4.42	78	750	4.6	790	180	
23	655	0.48	148	765	2.09	960	218	Asynch. gen.
24	1800	1.32	333.3	1000		628	142	
25	1020	0.75	345	345		750	170	
26	12200	9.0	88.2	88.2	5.8	1370	310	
27	7840	5.88	92.5	750	4.2	720	164	5 blades
28	2230	1.64	225	225		732	166	
29	992	0.73	135	750		888	202	
30	783	0.58	600	600		568	129	
31	1370	1.01	175	750		844	192	
32	1087	0.8	150	750	2.2	752	171	
33	790	.58	186	600		832	189	
34	2950	2.16	450	450		646	147	
35	1990	1.46	166.7	166.7		946	215	
36	4130	3.04	214.3	214.3		720	163	
37	4760	3.5						
38	7230	5.32	240	240		685	156	
39	2500	1.84	240	240		620	141	
40	586	.43	165	600		835	190	
41	6520	4.8	240	240		736	167	
42	1275	0.93	200	200		955	217	
43	3410	2.5	234	234		690	157	
44	1222	0.9	375	375		710	161	
45	3290	2.41	97.5	750		990	225	
46	2200	1.62	75	1000		790	180	
47	4860	3.57	77	750	4.72	912	207	
48	5000	3.67	77	750	4.72	925	210	
49	3560	2.62	120	750	3.2	850	193	Asynchronous
50	4600	3.39	166.7	166.7		820	186	

EW = Escher Wyss, V = Voith, M = Maier, AC = Allis Chalmers, N = Neyrpic, A = Alsthom, T = Tampella, C = Charmilles, R = Riva, LMZ = Russian Turbine Works.

APPENDIX A (Cont'd.)

LOW HEAD TURBINES

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Ref. No.	Name	River	Country	Mfr.	Year Built	No. of Units	Rated m	Head ft
51	Aue	Limmat	Switz.	EW	1963	2	5.55	18.2
52	Tamayado		Japan	EW	1963	1	16.8	55.0
53	Lech Stufe IV	Lech	Germany	EW	1963	3	9.2	30.1
54	Awe		Scotland	N	1963	1	6.9	22.6
55	Wintrich	Moselle	Germany	EW	1963	4	5.6	18.4
56	Neef	Moselle	Germany	EW	1964	4	5.5	18.0
57	Zeltingen	Moselle	Germany	M	1964	4	4.0	13.1
58	Palzem	Moselle	Germany	M	1964	3	3.4	11.1
59	Enkirch	Moselle	Germany	M	1965	4	5.1	16.7
60	Kislogubskaya		USSR	N	1965	1	1.28	4.2
61	Taguchi		Japan	EW	1965	1	12.4	40.0
62	Forbachrohr		Germany	V	1965	2	10.2	33.5
63	Neu Bannwill		Switz.	EW	1965	3	8.1	26.5
64	Santiago del Sil		Spain	EW	1965	2	12.0	39.3
65	Flumenthal		Switz.	EW	1965	3	7.5	24.5
66	Koide		Japan	EW	1966	1	12.9	42.2
67	Gandak		India	EW	1966	3	6.1	20.0
68	Deisisau	Neckar	Germany	V	1966	2	5.1	16.7
69	Kiev	Dnieper	USSR	USSR	1966	20	7.8	25.5
70	Pierre Benite (Main)	Rhone	France	N	1966	4	7.9	25.9
71	" (compensation)		France	N	1966	1	7.9	25.9
72	Gerstheim	Rhine	France	NCA	1966	4	9.8	32.0
73	Markolsheim (comp.)	Rhine	France	C	1966	1	9.5	31.1
74	Rance	Tidal	France	N et al	1966	24	5.75	18.8
75	Siikakoski		Finland	T	1966	2	3.4	11.2
76	San Floriano Nuovo	Piave	Italy	R	1966	1	16.5	54.0
77	Vallabregues	Rhone	France		1966	6	14.4	47.1
78	Lehmen	Moselle	Germany	V	1966	4	5.3	17.3
79	Kanev		USSR		1967	24	8.4	27.5
80	Paldang	Han	S. Korea	N et al	1967	4	11.8	38.6
81	Khasm el Girba	Atbara	Sudan	R	1967	3	7.0	23.0
82	Ozark Lock	Arkansas	USA	AC	1969-70	5	7.9	26.0
83	Chaudière	Ottawa	Canada	Can. AC	1966	1	11.6	38.0
84	Beaucaire	Rhone	France	NA	1968	6	11.25	36.8
85	Strasbourg	Rhine	France	NCA	1968	6	12.0	39.2
86	Kama		USSR	LMZ	1968	?	16.0	52.2
87	Ortachalskaya		USSR	LMZ	1964	1	10.5	34.3
88	Kaysinger Bluff	Osage	USA	AC	1970	6	21.3	70.0
89	Traicao	Tiete	Brazil	AC	1938-57	3	7.05	23.0
90	Stevens Point	Wisconsin	USA	AC	1963	1	6.7	22.0
91	Turnip Check	Irrig. Canal	USA	AC	1964	1	5.03	16.5
92	Orillia	Severn	Canada	Can. AC	1965	2	14.3	47.0
93	City of Norwich	Shetucket	USA	AC	1967	1	4.7	15.5
94	Webbers Falls	Arkansas	USA	AC	1968-71	3	6.7	22.0
95	Lower Paint	Paint	USA	AC	1952	1	6.1	20.0
96	Grifte			NV	1959	2	2.4	8.0
97	Aubas		France	SFAC	1961	3	3.3	11.0
98	Ambialet	Tarn	France	SFAC	1961	2	6.6	21.7
99	Buanameson		Spain	SFAC	1962	1	4.3	14
100	Brunnenmühle		Germany	V	1962	1	2.3	7.5

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Ref. No.	Turbine Rated Output H.P.	M.W.	Speed rpm Turbine	Generator	Wheel dia m	Specific Speed Metric	cfs units	Remarks
51	2370	1.74	136.4	1000		780	177	
52	5980	4.38	300	300		682	155	
53	5750	4.21	166.7	166.7		790	179	
54	600	.44	386	386	1.25	845	192	
55	6690	4.9	83	750	4.6	788	178	
56	5420	3.98	76	750	4.6	665	151	
57	4540	3.3	67	750	4.8	800	182	
58	2010	1.48	78	750	3.6	760	172	Asynch. gen.
59	5780	4.25	79	750	4.6	781	177	May also pump
60	545	0.4	72	600	3.3	1230	279	
61	8650	6.34	187.5	187.5		750	170	
62	1725	1.27	300	300		685	155	
63	11500	8.42	107.1	107.1		840	191	
64	11400	8.32	157.9	157.9		755	171	
65	11000	8.02	107.1	107.1		905	205	
66	12000	8.8	150	150		673	153	
67	7520	5.52	107.1	107.1		970	220	
68	1360	1.0	175	750	2.19	840	191	Also pumps
69	23400	17.2	85.7	85.7	6.0	1000	227	Submerged
70	28200	20.7	83.3	83.3	6.10	1050	238	
71	2050	1.5						
72	32800	24.0	107	107	5.6	1115	253	
73	1640	1.2	333	333	1.6	807	183	
74	13600	10.0	93.75	93.75	5.35	1228	279	Also pumps
75	1380	1.0	105	1000	2.8	845	192	
76	12250	9.0	187.5	187.5	3.0	623	142	1st of type in Italy,
77	16200	11.85	93.7	93.7		426	97	5 blades
78	6300	4.62	85	750	4.6	840	191	May also pump
79	24800	18.2						
80	28800	21.1	120	120	5.2	932	211	
81	3800	2.79	150	750	2.7±	870	197	
82	33800	24.8	60	514	8.0	830	188	
83	14000	10.2	100		4.33	560	125	
84	47700	35.0			6.25			
85	34000	25.0			5.6			
86	28400	20.8	125	125	4.5	652	148	
87	8600	6.3	125	125	3.3	614	139	Annular type with adj. blades. Also pumps
88	44600	33.2	94.7	94.7	6.5	436	99	
89	3450	2.58	150	150	3.51	770	175	
90	2800	2.1	150	150	2.8	730	167	
91	570	.42	218	900	1.53	690	156	
92	3500	2.61	277	277	1.96	590	133	
93	1999	1.5	128.6	128.6	2.8	825	187	
94	30900	23.0	60	514	8.0	975	221	
95	130	0.10	533	533		740	172	Tube type
96	350	.25	137	765		880	200	Bulb
97	410	.30	218	218	1.60	960	218	Bulb
98	2800	2.0	187.5	187.5	2.55	930	210	Bulb
99	860	.63	220	220	2.00	1040	235	Bulb
100	60	.045	350	1000		970	221	Bulb

APPENDIX A (Cont'd.)

LOW HEAD TURBINES

(1) Ref. No.	(2) Name	(3) River	(4) Country	(5) Mfr.	(6) Year Built	(7) No. of Units	(8) Rated m	(9) Head ft
101	Kosi East	Kosi East Canal	India	H	1966		6.1	20
102	Chateau du Brevil	Touques	France	SFAC	1968	1	2.3	7.5
103	Ajanruez		Spain	ASFAC		1	3.1	10
104	Dorlar		Germany	V	1945	1	1.65	5.4
105	Hessenthaler		Germany	V	1946	1	1.1	3.6
106	Randersacker	Main	Germany	V	1948	2	2.75	9.0
107	Wipfield		Germany	V	1948	2	3.15	10.3
108	Gossmannsdorf	Main	Germany	V	1948	2	2.66	8.7
109	Klettham		Germany	V	1951	1	1.28	4.2
110	Bruckmühlwehr		Germany	V	1952	1	2.0	6.6
111	Petershagen		Germany	V	1952	3	2.5	8
112	Birsfelden	Rhine	Switz.		1954	4	6.0	20
113	McArthur Falls	Winnepeg	Canada		1954	8	7.0	23
114	Schlüsselburg		Germany	V	1954	3	2.7	8.9
115	Kitzingen		Germany	V	1954	2	3.1	10
116	Birner		Germany	V	1956	1	1.5	5.0
117	Landesbergen		Germany	V	1957	3	3.6	12
118	Ruaes		Portugal	V	1959	2	2.5	8
119	Berchtesgadenwerk		Germany	V	1960	1	1.7	5.6
120	Artelshofen		Germany	V	1960	1	1.6	5.4
121	Schweinfurtwerk		Germany	V	1960	2	4.0	13
122	Aschach		Austria	V	1960	2	15.5	51
123	Rust			V	1961	1	2.0	65
124	Untere Hopfau		Germany	V	1961	1	2.0	6.5
125	Passau		Germany	V	1962	4	10	33
126	Prexlmühle		Germany	V	1963	1	2.2	7
127	Widdert		Germany	V	1964	1	3.1	10
128	Bertoldsheim		Germany	V	1965	3	4.9	16
129	Wallsee		Austria	V	1965	4	9.6	31
130	Bittenbrunn		Germany	V	1965	3	5.2	17
131	Sontheim		Germany	V	1967	1	2.1	7.0
132	Thiess		Germany	V	1967	1	3.35	11
133	Vargön	Gota-Alv	Sweden	KMW	1946	2	4.3	14
134	Stugun	Indal	Sweden			2	7.1	23
135	Bourg-les-Valence	Rhone	France	SFAC		6	11	36
136	Seyssel	Rhone	France	SFAC		3	8.0	26
137	Mauzac	Dordogne	France	SFAC		1	6.7	22
138	Jarmenil	Moselle	France	SFAC		1	5.5	18
139	La Vanelle	Isere	France	SFAC		3	7.7	25
140	St. Mary's Falls	St. Mary's Canal	USA	AC		4	6.4	2.1
141	St. Jory		France	E.de F.		1	2.4	8
142	Ambre	L'Agout	France	E.de F.		1	3	10
143	Les Albaredes	Tarn	France	SFAC		2	2.30	8
144	Tiszalök	Tisza	Hungary		1946	3	3.0	10
145	Monsin	Meuse	Belgium		1954	3	3.0	10
146	Isola Serafini	Po	Italy		1960		6.00	20
147	Säckingen	Rhine	Swiss-German		1962	4	6.6	22
148	St. Anthony Falls	Mississippi	USA	Leffel	1952	10	7.0	23.5
149	Ba. Mills		USA	Leffel	1957	2	6.0	20
150	Girishk		Afghanistan	Leffel	1958	2	7.5	25

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Ref. No.	Turbine Rated Output H.P.	M.W.	Speed rpm Turbine	Generator	Wheel dia m	Specific Speed Metric	cfs units	Remarks
101	7500	5.6	93.8	93.8	4.5	860	196	Bulb
102	250	.18	242	750	1.25	1340	305	Bulb
103	670	.49	155	155	2.24	1390	315	Bulb (under study)
104	200	.15						Kaplan
105	82	.06						Kaplan
106	1600	1.18			3.80			Kaplan
107	187	1.38						Kaplan
108	1400	1.03			3.70			Kaplan
109	50	.37						Kaplan
110	320	.23						Kaplan
111	1510	1.10	68	500	3.89	860	196	Kaplan
112	21200	15.6	68.2	68.2	11.25	1040	236	Kaplan
113	10000	7.4						Vertical propellor
114	2250	1.65						Kaplan
115	2040	1.50						Kaplan
116	62	.045						Kaplan
117	3200	2.35						Kaplan
118	700	.52						Kaplan
119	110	.08						Kaplan
120	80	.06						Kaplan
121	2600	1.9						Kaplan
122	95000	70.0			8.4			Kaplan
123	250	.18						Kaplan
124	70	.05						Kaplan
125	30000	22						Kaplan
126	75	.05						
127	440	.32						Kaplan with bevel gear
128	9100	6.7						Kaplan
129	57000	42.0						Kaplan
130	9800	7.2						Kaplan
131	160	12						Kaplan
132	240	.18						Kaplan
133	16300	12.0	46.9	46.9		980	222	Kaplan
134	24000	17.5			7.3			Kaplan
135	42000	30.70	79	79	7.00	800	180	Kaplan
136	20000	14.85	75	75	6.30	800	182	Kaplan
137	6250	4.58	94	94	4.30	690	158	Kaplan
138	1430	1.05	167	167	2.15	775	176	Kaplan
139	12800	9.43	100	100	5.00	880	200	Kaplan
140	7000	5200	80	80	1.63	650	148	Vertical propellor
141	130	.10	214	214	1.30	925	210	Vertical propellor with syphon
142	190	.26	167	167	1.60	565	128	Vertical propellor with syphon
143	400	0.30	136.5	136.5	2.06	920	210	Vertical
144	5500	4.0	75	75	6.0	1460	310	Kaplan
145	7100	5.25						Kaplan
146	16000	11.8	53.57	53.57	7.80	690	158	Kaplan
147	25000	18.3	60	60	7.40	860	196	Kaplan
148	1160	0.85	225	225		645	147	Vertical propellor
149	3000	2.20	120	120		690	157	Vertical propellor
150	2200	1.60	187.5	187.5		680	155	Vertical propellor

Mercer, Albert G.

STUDY OF FACTORS AFFECTING FEASIBILITY OF LOW HEAD HYDROELECTRIC GENERATION

Report No. CER68-69AGM26, Civil Engineering Dept., Colorado State University, Fort Collins, Colo., 80521, 23 p, 11 fig, 23 ref, March 1969

DESCRIPTORS--*hydroelectric plants/structures/low head/costs/efficiencies/*hydraulic turbines/axial flow turbines/bulb turbines/tube turbines/*draft tubes

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The feasibility of generating electricity from hydropower developments having low heads depends on the characteristics and the costs of the available equipment as well as the cost of producing electricity from alternative sources. The recent development of the tubular turbine has resulted in many advantages for the economical development of low head hydropower. Many units with heads as low as 10 feet have been built in Europe. Twenty five feet appears to be the practical lower limit in North America.

The flowing waters of rivers provides a possible source of energy for generating electricity. This energy could be developed using turbines similar to some modern airfoil wind turbines but the economics are such that this source will probably never be exploited.

Head, itself, is the most important factor affecting the feasibility of low head hydropower. Given two well designed low head plants of equal discharge capacity, the lower head plant will be less feasible because the kw output will be lower but the costs will be higher. The lower head plant will have larger, slower turning turbines and larger inlet and outlet passages.

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