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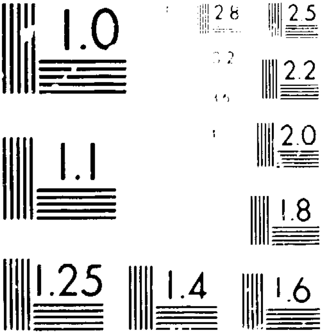
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LOW-HEAD HYDROELECTRIC UNIT FUNDAMENTALS*

by

Howard A. Mayo Jr.**

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** Manager, Market Development, Allis-Chalmers, Hydro-Turbine Division, York, PA 17405, U.S.A.

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LOW HEAD HYDROELECTRIC UNIT FUNDAMENTALS

The development of thousands of existing low head dams in the United States is once again becoming economical as nonrenewable energy resources are rapidly increasing in cost. For almost two generations the development of low head hydroelectric sites had been all but stopped. As a result, a very limited number of people today is familiar with the basic technology and background. Not only has the terminology changed but so has equipment technology.

Low head hydro opportunities in USA are gradually being defined (Figure 1) as a result of efforts by the Department of Energy and the Corps of Engineers, plus several other federal, state and local agencies. The Corps of Engineers has identified 59,000 existing dams in the USA conservatively 10% of which may be economically developable for power. The Department of Energy (DOE) has funded 54 low head site feasibility studies and seven projects will receive partial funding for construction. The recent energy bill (Figure 2) includes 10 million dollars per year for 3 years for low interest rate feasibility study loans. Also. 100 million dollars per year for 3 years is authorized for low interest rate construction loans. The DOE has funded several study projects and some may be helpful.

The Federal Energy Regulatory Commission (FERC), formerly Federal Power Commission (FPC), has instituted new procedures for minor plant licenses (under 1500 kW) and is planning to soon issue new procedures for hydroprojects, using existing dams. This may substantially expedite related permits and licenses.

Internationally low head sites have been developed to a somewhat greater extent because of significantly higher costs for alternative sources of energy and in some cases is due to lesser environmental and/or regulatory restraints. While U. S. manufacturers are prevented from selling hydro generation equipment to foreign countries which have their own hydroturbine industry, there are developing areas with significant low head hydro potential without indigenous industries to satisfy their needs.

U. S. industry clearly has the technology and hardware to economically develop hydro sites. The fundamentals, however, are not widely understood, therefore we would like to review several fundamental considerations and explain what has been done to meet present project needs.

Head

To provide an introductory background for discussions of specific equipment types it is appropriate to start with head and flow. Some people find it rather shocking when it is pointed out "hydraulic turbines do not use water". Stated more precisely, hydraulic turbines do not consume water. The same amount of water is discharged from the turbine as enters the turbine entrance.

On the other hand, the head is "used" and the degree to which some is left over in terms of the discharge velocity is directly related to the efficiency of energy conversion.

The distance from the forebay water surface to the tailwater surface (Figure 3) is the gross head available at any particular site and at any particular time. Hydraulic turbine models, on the other hand, are tested under net head conditions so that this test information may be applied to any number of different site conditions. The net effective head on the turbine is determined by deducting losses as the water flows to the turbine and as it leaves the turbine. These losses include such items as trash rack losses, intake losses, penstock loss, bend and sudden expansion or contraction losses upstream of the turbine. For a reaction turbine the discharge velocity head loss is not deducted while if an impulse turbine is used, the distance between the nozzle centerline and the tailwater elevation must be deducted since this cannot be recovered.

As a result, an impulse turbine at a given site will have a lower net head than a reaction turbine since the impulse turbine must be set above the tailwater elevation. If there is a substantial change in tailwater surface elevation due to changes in stream flow or turbine discharge then the impulse turbine may have to be set relatively high above tailwater. For low head applications this can be a substantial loss in head or system efficiency.

For the old style open flume installations the power plant owner generally was only familiar with the gross head on the hydraulic turbine. The difference between gross head and net head frequently was very small since the intake and flume was large with low velocities and the hydraulic turbines were of relatively low specific speed types resulting in low discharge velocities. Today when we are considering high specific speed runners in order to minimize the equipment costs it becomes extremely important that careful consideration be given to head losses on a specific project basis.

Flow

The water supply to most hydroelectric installations is not constant. (Figure 4) Most rivers, even when they have large reservoirs, are subject to periods of drougth as well as periods of heavy rains and flood flows. These natural characteristics are a major consideration when selecting hydroelectric equipment and are site specific as is the head available. Heavy rain which causes flood runoffs may result in the actual gross head at the project being reduced to almost nothing. On the other hand, periods of drouth may reduce the water supply to minimum amounts.

In order to attempt to predict the power available from a particular hydroelectric site, the historical water flow records need to be put into usable form. The usual approach is to prepare a flow duration curve based on at least a 10 year average of river flows adjusted to the drainage area at the particular dam site. In USA this information usually is obtained from United States Geological Survey gauging station data. The most reliable data is obtained when the gauging station is close to the power plant site. With appropriate adjustments reasonable approximations may be made using gauging station information from a site within the same general rainfall area. In addition, head duration information should be developed which will correspond to the flow duration characteristics in order to more reasonably predict the kilowatt hour output of the proposed project. The area under the flow duration curve, limited by the turbine-generator maximum output is proportional to kilowatt hours. Adjustments for flood flows, reduced head and dry periods provide a reasonably accurate historical representation useable for predicting future averages.

The older sites were frequently developed for the average flow available to more nearly assure operation during a 10 or 12 hour workday. Today where the hydroelectric unit will usually be interconnected with a large system, it may be far more economical to develop for flows available 20% to 30% of the time. This, therefore, is usually a good starting place for sizing generating equipment.

Rules of Thumb

Rules of thumb (Figure 5) based on actual experience at thousands of previous installations can provide a starting place for sizing equipment. From experience we know that average rainfall information is directly related to the streamflow based on the drainage area at a particular site. For example, in New England where the rainfall may average from 20" to 30" per year, the drainage area in square miles may be doubled to obtain approximately the flow available 20% to 30% of the year. This can provide a starting place for sizing the turbine on a very preliminary, initial basis.

On the other hand, if there are existing structures the sizing of an individual turbine may be determined by the width of an existing tailrace or the area of the tailrace outlet. Since modern tubular turbines have draft tube widths approximately twice the runner diameter, the runner size may be approximated on this basis. If, on the other hand, this size turbine runner provides a discharge so high that the tailrace velocity is excessive in terms of velocity head loss, it may be necessary to reduce the runner size.

Other simplified calculations such as multiplying the stream flow in cubic feet per second by one tenth of the head in feet to obtain the horsepower and the horsepower by seven tenths to obtain generator output in kilowatts can simplify approximation of the capacity available at a particular site. These rules of thumb and simplified calculations help to provide a quick and economical estimate of a particular site's potential. With such information and a basic knowledge of equipment alternatives as well as approximate costs, an initial approximation of site feasibility may be developed.

The first question asked by most potential hydro site developers is "Do I have an economical site?" or "Under how low a head will a turbine operate?". For the first question we can usually provide a reasonable answer? However, the second question reflects a lack of understanding that low head hydro is a question of economics and not whether or not the equipment will operate. For preliminary purposes the cost of developing a particular site as it relates to the kilowatt output is an important guideline. It must be recognized that in comparing various sites with different heads, the cost per kilowatt of a site with zero head is infinite. Therefore, at progressively lower heads there is some point at which one cannot afford to develop the site; yet machinery can be provided which can develop power.

Setting

A third factor must be considered prior to equipment selection. Where will the turbine be located with respect to tailwater elevations? Hydraulic turbines are subject to pitting due to cavitation which is damage from localized metal removal. It is a result of irregularities in the water flow passages and excessively low pressures on the runner buckets or blades, throat ring, gates, etc. Cavitation resulting from the formation of partial vacuums in the flowing liquids is the primary cause of pitting damage. It is not related to erosion but may be accelerated by both corrosion and erosion.

For a given head a smaller, lower cost, high speed runner must be set lower (i.e., closer to tailwater or even below tailwater) than a larger, higher cost, low speed turbine runner. (Figure 6) Also atmospheric pressure or plant elevation above sea level is a factor as are tailwater elevation variations and operating requirements. This is a complex subject which can only be accurately resolved by model tests. Every runner design will have different cavitation characteristics, therefore, the anticipated turbine location or setting with respect to tailwater elevations is important to turbine selection.

Open Flume and Pressure Case

Most of the early hydraulic turbine installations were either in an open flume or a pressure case. (Figure 7) The turbines were arranged either with a vertical or horizontal shaft and either a single runner or several runners were mounted on the shaft with their respective gate cases. Simplified illustrations show representative open flume and pressure case settings with a straight conical draft tube extending below the tailwater elevation. Many of the earliest installations actually did not have an effective draft tube so that they had to be set with the turbine right at tailwater or the velocity head from the turbine was lost. Where there are existing structures they most frequently are of this general configuration. This may become very important in selecting a suitable hydroelectric unit which will provide most economical civil construction.

Intakes

Most modern installations, (Figure 8) particularly those with the higher capacity hydroelectric units, have either a semispiral case for the lower heads or a full spiral case for higher heads. It is important to be aware that the spiral case water passageway widths are typically three (3) times the runner diameter.

In the more modern low head installations, where tubular turbines have been applied, the intake water passageways are generally only twice (2) the runner diameter in width.

In comparing two basic types of tubular turbine intakes, it should be noted that Bulb unit intakes are generally approximately three (3) times the runner diameter in height in order to obtain the necessary cross-sectional area for the water to pass around the generator bulb. This is also generally true with pit type tubular unit installations. On the other hand, other types of tubular turbine installations, such as the TUBE turbine and the Harza type arrangement with the rim generator, have intakes which are only 40% to 50% larger than the runner diameter. For some applications this can be a significant factor in civil construction costs.

Draft Tubes

When low speed, large diameter Francis turbines were installed under low heads the lack of a draft tube or a very short cone resulted in a nominal velocity head loss from the runner. This was not particularly critical for installations which were underdeveloped based on today's standards since they spilled water over the dam most of the year. However, today when we generally are trying to reduce the overall equipment and civil construction costs by using high specific speed propeller runners, the draft tube is extremely critical from both a stability and an efficiency viewpoint.
Since the runner diameter is small, a substantial percentage of the total energy is in the form of velocity of the water leaving the runner. To recover this efficiently this velocity must be reduced gradually and pipe friction losses must be minimized.

To obtain generally acceptable draft tube outlet losses a straight conical draft tube (Figure 9) must be approximately 4 or 5 times the runner diameter in length. If set vertically, this means the hydraulic turbine must be set substantially above the tailrace floor or that tailrace floor must be excavated well below tailwater. If, on the other hand, the draft tube discharges horizontally, it is very possible that less excavation is required.

In comparing the vertical and horizontal conical draft tube arrangements, it should be noted that approximately four (4) runner diameters are needed for a tailrace width when the vertical arrangement is used. However, only two (2) runner diameters would be needed if the draft tube is arranged horizontally.

To obtain some reduced tailrace width and yet retain a vertical shaft arrangement, which is particularly suited to large hydroelectric equipment, the elbow draft tube was developed. It will be noted that the draft tube depth and width have both been reduced thereby reducing the excavation required. On the other hand, the horizontal leg of the draft tube is still approximately four (4) times the runner diameter in order to obtain discharge velocities comparable to the straight conical draft tubes and the width is approximately three (3) runner diameters.

An alternative horizontal draft tube might be described as an "S" configuration in that a reverse bend is provided in order to bring the turbine shaft out of the water passageway. From the viewpoint of velocity head recovery the straight conical draft tube minimizes hydraulic losses. A slight increase in loss is obtained when the draft tube is bent and these losses, to some degree, relate to the angle of the bend. The significance of these losses may be substantial under very low heads and very high discharges, however, they become less important for the lower capacity hydraulic installations and part load operation.

Impulse Runners

There are two (2) basic classes of hydraulic turbines. These are identified as impulse turbines and reaction turbines. The fundamental difference being that impulse turbines are driven by kinetic energy (jet action) while the reaction turbines convert both kinetic and pressure energy. The impulse turbines (Figure 10) are inherently relatively low speed, large diameter machines as compared to reaction turbines and are therefore best suited for high head applications. A low capacity, high head unit will however operate at a high RPM.

The tangential type impulse runner with a single jet will operate from 3 RPM to 10 RPM based on the runner size necessary to obtain 1 HP under 1' head. This characteristic or specific speed can be increased by providing additional jets. For horizontal shaft installations a maximum of two jets per runner will increase the speed approximately 40% as a result of the smaller physical size required for the same horsepower and head relationship. If the turbine shaft is arranged vertically, a maximum of six jets have been used and since the runner would be even smaller, the speed would be increased almost 2 1/2 times.

The Turgo or diagonal type impulse runner is, in effect, a higher speed design which would operate at 11 RPM to 12 RPM. The Michell or cross-flow type impulse runner has even a higher operating speed which is approximately 20 RPM to 25 RPM again for a 1 HP unit under 1' head.

It should be noted that impulse runners must operate in air to be efficient. This means that they must either be located above the maximum tailwater elevation or provisions be made for pressurizing the housing. Most installations are located above tailwater and therefore the distance from the nozzle centerline to tailwater must be deducted in addition to intake and penstock losses to obtain the net effective head on the runner. The distance above tailwater for low head applications may be a very appreciable loss so that this, in combination with the low operating speed and relatively large physical size, can make impulse turbines uneconomical for low heads. On the other hand, it must be recognized that for very low outputs, impulse turbines are being offered for heads as low as 46' and capacities as low as 100 watts.

Reaction Runners

Reaction turbine runners include two (2) basic types identified as Francis and propeller. (Figure 11) The general physical difference is that Francis runners have a shroud or band located circumferentially around the runner discharge and attached to the runner buckets while a propeller runner does not. There is one exception to this description which we will describe later under generators.

High head Francis runners are characterized by a large inlet diameter with low entrance height and a small discharge diameter. Their characteristic operating speed for 1' head and 1 HP output would be in the order of 20 RPM. Such runner designs have been used for heads in excess of 1.500', however, for such high heads the runner is generally located well below tailwater elevations. This is necessary in order to minimize pitting damage.

For medium heads and a characteristic speed of approximately 50 RPM, the runner inlet and discharge diameters are almost the same. For the low head Francis type runners, the inlet diameter is substantially smaller than the discharge diameter and the entrance height has increased substantially to provide a greater entrance area. These designs may operate at a characteristic speed of 100 RPM and again must be properly set with respect to tailwater to minimize cavitation and the resulting pitting damage.

It should be recognized that an experienced manufacturer will have a whole series or family of Francis runner designs over this characteristic speed range. On the other hand, because usually these designs have been developed based on specific projects and needs, the operating or performance characteristics are not always consistent with the physical proportions and there can be very substantial differences in performance for given runner configurations.

The early low head hydraulic turbine installations generally used low speed runner designs (what we would consider as high head runner proportions) which were not subject to pitting damage if their water passageway and bucket designs were reasonably well shaped. As the technology improved, there were increasing efforts to increase the runner speed and to increase the runner output for a given head. With this came cavitation with pitting damage and the recognition that a high speed runner had to be set closer to tailwater elevations. Some of the older installations had runners set extremely high with respect to tailwater and because of a relatively poor draft tube design, they did not experience excessive cavitation. For many of the old runner designs the only cavitation information available is based on experience. Modern runner designs, however, are model tested, not only for efficiency, but also cavitation and other operating characteristics.

Propeller runner blades may be shaped very similar to the buckets of a Francis runner for mixed flow designs or substantially different for axial flow designs. Also, the number of propeller runner blades is generally substantially less than any of the Francis runner designs. While the fewer number of blades provides a higher speed and higher output for a given size and head, it also results in a greater blade loading and therefore more critical cavitation characteristics. Cavitation test data is therefore extremely important for low head, high speed propeller runner designs.

The mixed flow propeller runners are most commonly used under medium heads up to approximately 200' and may have a characteristic speed of approximately 75 RPM depending upon the number of blades and their shape. The axial flow runners, on the other hand, will have characteristic speeds up to approximately 200 RPM and while most installations for low heads have a minimum of four blades, some designs have used two or three blade for extremely low heads. Due to the high rotational speed, high capacity or discharge for a given size and potentially simple water passageway, propeller runners are particularly suited to low head applications.

While the early propeller runners had fixed position blades, it was not long before the advantages of being able to adjust the blade angles became recognized. Both mixed flow and axial flow propeller runners have been built with adjustable runner blades. The blade configuration changes somewhat for the mixed flow designs due to the need for a larger hub to contain the blade operating mechanism. However, this change is less noticeable in the very low head axial flow runners. The advantages of coordinating runner blade angle with wicket gate angle was recognized and patented by Dr. Kaplan in the early 1900's and today his name is perpetuated as a designation for this specific type of construction. This, however, was only one of his many patents but it was a particularly significant patent in the United States. Although Dr. Kaplan disclosed mixed flow propeller runners as well as axial flow turbine intakes, it is Deriaz's name which is frequently applied to mixed flow propeller runners with adjustable blades.

We will get into the performance characteristics of fixed and adjustable blade runners later; however, it is important to realize that the coordination of runner blade position and wicket gate position provides optimum hydraulic performance over a very wide range of flow and head thereby making this an extremely desirable design for low head applications.

Distributors

Many different types of water control devices have been developed over the years to control the amount of water entering the hydraulic turbine. The objective is to control the water volume with minimum turbulence and head loss at the various control device positions. Any of the control devices illustrated (Figure 12) may be used with a propeller runner, however, due to the radially inward nature of the flow to Francis runners the more axial types of gate mechanisms are not particularly suited to Francis runner installations.

Among the many early designs are the register and cylinder gate devices. These were normally operated by gear mechanisms, were relatively slow moving and introduced substantial turbulence thereby reducing part load efficiency. The register gate is basically a cylinder with intermittent rectangular openings. It is moved circumferentially so that these openings either are in alignment with corresponding openings in the stationary structure or are more or less blocked by the stationary structure. The cylinder gate is like a section of pipe which is moved axially to open up more or less of the area between stationary guide vanes which are usually located externally to the cylinder. Usually the cylinder gate is housed within an extension to the intake vane structure making the distributor assembly twice as long as that of a register gate distributor assembly.

Improved part load efficiency was obtained with the development of wicket gates. Such gates pivot about an axis either near one end or near the middle of the gate itself. Early designs provided a lever or link attached to the gate and then to a gate ring and the gate ring operating mechanism, all of which was in the water passageway.

A more modern refinement is the extension of the wicket gate by making the trunnion integral with the gate or rigidly attached to the gate. A lever could then be attached to the gate trunnion or stem and by using links and pins be connected to the gate ring and its operating mechanism. This outside type gate mechanism could either be located on the turbine head cover or around the turbine throat or discharge barrel. The mechanism could be kept in the dry where it was accessible by either the addition of a spiral case to distribute the water evenly around the runner or by a pit liner attached to the periphery of the head cover flange. This so called outside gate mechanism could also be submerged within the water passageway.
More recently for propeller runner applications, both conical and radial wicket gate arrangements have been used. These have the advantage that the large diameter, rigid stay ring or column bolt construction needed to support the head cover on a conventional outside type gate mechanism is largely eliminated and the flow to the hydraulic turbine is brought in more nearly axially. Some slight improvements in performance, particularly in the high capacity areas may be attributed to these arrangements, however, the conical gate arrangement is relatively expensive due to the contour machining that is required to obtain minimum leakage when

the gates are closed. Special provisions must also be made to provide accurate alignment of the gate stem bushings in the conical arrangement.

Any of these distributor assemblies is suitable for use on hydraulic turbine runners having a horizontal or inclined shaft in addition to those having vertical shafts. Additionally, any of these basic distributor assembly configurations may be built with stationary wicket gates (fixed position vanes) rather than adjustable wicket gates. When this is done the need for stay vanes for structural support and rigidity may be eliminated.

Generators

Hydroelectric unit generators can be provided for horizontal, inclined or vertical shaft arrangements; can be provided with speed increasers or can be located within or external to the water passageways. In the smaller capacities the generators may be of the induction type, may be direct current or of the more conventional higher capacity synchronous type. There are, however, some overall characteristics that should be recognized. (Figure 13)

Conventional directconnected synchronous generators have an optimized pole length to diameter relationship which has been developed over many years. Such generators provide what is generally considered standard flywheel effect, conventional short circuit ratios and other electrical characteristics. Their power factor, voltage and insulation levels can be selected to meet system requirements. However, 80% power factor and Type "B" insulation have been relatively typical. For the lower speeds and lower capacity applications, such generators are usually air cooled and are physically designed to withstand the full hydraulic turbine runaway speed under the highest head conditions. The vertical generators also usually incorporate a thrust bearing designed to carry all of the rotating weight plus turbine hydraulic thrust. Frequently static excitation equipment is used although brushless exciters may be more applicable to the lower capacity, high speed installations.

A speed increaser in conjunction with a high speed generator may be more economical for some applications. Since the speed increaser adds many more mechanical components which may eventually be subject to wear and maintenance and will have an efficiency loss of at least 1% for the first reduction stage (maximum ratio of approximately 5/1) and an additional loss of approximately 1% for each additional stage, there must be a sufficient reduction in total capital investment cost and delivery time to justify the disadvantages of a speed increaser. Such an arrangement may be particularly advantageous when an indiction generator can be accommodated within the electrical system. This means that the unit must be interconnected with a system from which it can obtain excitation energy.

One of the advantages of using a speed increaser is that the turbine can be operated at its optimum speed and the stepup ratio established to provide a relatively high synchronous speed. In the range of higher speed, low capacity generators there are not only many more sources of supply but also a great many more motors in this general frame size are routinely being manufactured. Hydraulic turbine overspeeds normally are at least 80% above synchronous speed for Francis turbines and in some cases for propeller turbines can go as high as 200% above synchronous speed. Design of the generator with respect to overspeed can therefore become an important factor in power plant equipment cost evaluations.

Bulb generators are designed to fit within the water passageway. Generally their outside diameter is approximately equal to the turbine runner diameter to minimize head losses and unit spacing. The reduced stator and rotor diameter results in longer poles. This generator configuration has application for units with capacities greater than standardized units.

Bulb unit designs offered by American manufacturers have been modified based on European experience. Advantages of the Bulb unit should be most effective for the higher capacity installations where the custom engineering is less critical to the total project cost.

The Rim generating unit, patented by L. F. Harza (about 1920) was promoted in Europe during World War II to provide hydrogenerating units within a dam that could be over topped by water so that it was not readily visable from the air. For these installations the generator rotor is mechanically attached to the periphery of the propeller runner blades. Comparisons of conventional generator proportions related to hydraulic turbine runner diameters, heads and speeds show there is a rather wide range where very nearly conventional generator proportions are applicable. The historical problem with this basic design has been the difficulty of providing a runner seal at the periphery of the runner blades that will have a reasonable life. Improved seal technology may gradually minimize this problem providing the water does not contain sand and additional work is being performed to develop techniques for permitting adjustment of the runner blades. Present designs are generally unproven and rather complex. Adjustable runner blades also complicate keeping the generator rotor concentric.

On the assumption that seal, rotor and runner support problems can be resolved this generator arrangement would have the advantage that only a single powerhouse crane is needed to handle both the turbine and the generator. A straight conical draft tube and simplified intake can be used. On the other hand, this is still basically a custom designed generating unit which must be capable of withstanding the full turbine runaway speed.

As with other components of a low head hydroelectric project, there is no single design, type or physical arrangement which provides an economical answer for all sites. Hydroelectric power equipment is site specific.

Cost Reduction

The challenge facing developers of low head hydroelectric sites is not whether or not technology is available or whether or not equipment will work. The challenge is to find means to reduce project costs so that the lower capacity and lower head hydroelectric sites will be economical. A fundamental approach to lower cost projects is standardization. The challenge is to standardize yet accommodate site specific requirements.

Costs are most effectively reduced by examining the largest increments of cost. Custom design and engineering costs are roughly equal to the manufacturing costs of small turbines. Therefore, standardization is the single most productive area of cost reduction. This, of course, becomes practical only if a market of sufficient magnitude to recover the standardization costs can reasonably be expected to develop.

The benefits of standardization include:

More economical development of lower head sites.

Spreading of design costs over multiple units.

Utilize available components. Eliminate respecifying individual components.

Simplify feasibility studies.

Simplify purchasing for customers.

Obtain economies of scale in manufacturing and purchasing.

Obtain quicker delivery.

Provide predictable, reliable installations at lower cost per kw.

In deciding what should be standardized there are several fundamental parameters that must be recognized.

1. A pipe is the simplest and most economical means for moving water from forebay to tailwater.

2. The propeller type runner provides smallest physical diameter with the maximum output and speed for low head applications.

3. Speed increasers, generators, valves and control components are generally available and are essentially already standardized.

4. By bending the turbine intake or draft tube other standardized components can be accommodated with minimum loss of equipment performance.

5. A complete unit from water intake to electrical transmission is needed to further minimize custom engineering and project costs.

6. Custom designed units incorporating most of these fundamentals have been designed and manufactured beginning back in the 1930's. No new technology is needed, however, standardization of the hydraulic turbine components and electrical systems is needed to reduce costs.

Performance

Since low cost is one of the primary objectives it is appropriate that the runner and distributor assembly be evaluated regarding their individual benefits as compared to their costs. It will be recognized that if a hydraulic turbine has fixed position blades and fixed wicket gate (vane) positions, it will basically have one point of operation for a given head. This is the simplest and lowest cost arrangement. (Figure 14)

Another approach would be the addition of adjustable wicket gates, however, this involves anywhere from 12 to 24 gates with the corresponding number of levers, links, and pins connecting them to the gate ring plus push and pull rods etc., which substantially increases the turbine cost but provides only a narrow range of good efficiency.

The next most economical increment is therefore adjustable runner blades where we are dealing with only 4 or 5 basic adjustable components. While this incremental cost varies with the equipment size to some extent, it represents an increase in basic turbine cost of approximately 25%. On the other hand, a very wide range of good efficiency is obtained by using the adjustable blade runner with fixed position gates (vanes).

Contrast this with the incremental cost of approximately 50% for the addition of adjustable wicket gates which then only provide a relatively narrow range of reasonable good efficiency. In general, the addition of adjustable runner blades results in a minor cost increase but a very major improvement in unit flexibility and operating range.

The point may very reasonably be made that adjustable wicket gates will close off the flow while adjustable blades do not. On the other hand, even when adjustable wicket gates are provided, a backup closure device at the intake is conventionally used to permit maintenance, repair and adjustment of the wicket gates. Generally a standard intake closure device can be provided more economically at or near the turbine. The objective of reduced project costs and operating simplicity is served to maximum advantage by this approach for a maximum number of applications within the low head, lower capacity ranges. The combination of adjustable runner blades and and adjustable wicket gates (Kaplan turbine) with its approximately 75% increase in turbine cost does not appear to be justified for most of the lower capacity applications.

As a result, the present standardization program incorporates 2 or 3 stationary guide vane shapes and fixed or adjustable blade runners with either 3, 4 or 5 runner blades. These all fit within 10 standard sizes of basic water passageways. This approach provides a very high degree of flexibility over a reasonably wide range of unit sizes. As more details develop with respect to specific sites, there is, of course, the possibility of extending this basic concept in areas of eq ipment size, applicable heads and necessary setting with respect to tailwater. The ability to capitalize on the many existing sources of largely standardized motors and generators as well as gear units and valves makes this a particularly practical and flexible standardization program. It is an approach based on more than 100 years experience in the design and application of hydroelectric equipment and the capability of designing and manufacturing all of the basic types of equipment. It is founded on extremely basic fundamentals.

Optimized Project Cost

To summarize our objective of having the maximum benefits at minimum costs, we have listed eight (8) specific advantages of the "TUBE" unit. These superlatives are valid in comparing this unit with any other equipment combination or arrangement regardless whether it was equipment manufactured in the late 1800's or whether it is the latest, most imaginative, exotic design proposed.

To provide optimum project cost, the TUBE unit provides:

1. Highest runner speed for given head, output and setting above tailwater.

2. Maximum application flexibility.

3. Maximum use of available standard components.

4. Smallest and simplest water passageways.

5. Minimum foundation and building needs.

6. Simplest maintenance through maximum accessibility to all components.

7. Coordinated water intake to electrical output with controls, a unit concept.

8. Predesign to standard specifications and manufacturing procedures to provide:
   - Low Cost
   - Fast Delivery
   - Economical Installation

Standard Unit

We would like to briefly describe the standard TUBE unit's extent of equipment supply. (Figure 15) More detail is provided in published literature and the standard specifications.

Tight closure is provided in the intake water passageway by a closure device such as standard butterfly valves or an intake gate. The TUBE turbine itself has fabricated steel stationary guide vanes to provide the proper water flow to the runner blades. These vanes support the upstream bearing housing which contains an oil lubricated antifriction bearing. The runner hub contains the blade operating mechanism for the adjustable blade runners and is also of steel as are the runner blades. This hub is bolted to a tubular shaft which provides stiffness as well as low weight and avoids the cost and delays frequently incurred with forgings.

The fabricated steel water passageway optimizes the velocity head recovery as the water is guided from the runner to the tailrace. This water passageway is extended to provide a seal between tailwater and the powerhouse generator room. A floating packing box is provided where the turbine shaft extends through the water passageway. When the turbine is directly connected to a conventional generator, a combination outboard guide and thrust bearing is provided to support the turbine shaft. An air operated clutch may be incorporated between the turbine and generator or between the speed increaser and generator if the latter proves to be a suitable alternative.

When an adjustable blade runner is used the blade operating rod is extended either through the speed increaser or through the generator if direct connected, to a blade positioner. This blade positioner may be controlled either manually, remotely, automatically from water level or may be provided with a simple governor.

The necessary oil pressure system with standard commercial reservoir and accumulators provide reliable operation of the blade positioner and/or inlet closure device. It is included along with the necessary control equipment and instrumentation to provide basic equipment control and protective devices for reliable operation. Generator grounding components, excitation equipment, instrumentation, switch gear, breaker, transformer and switches are available up to and including the substation if their supply is advantageous to the project.

Complete projects will be considered for a coordinated turnkey approach on a case by case basis. This may include the supply of financing, project engineering, civil construction, equipment installation, operation and testing. At the present time, units are being manufactured to standardized designs including procurement and manufacturing procedures.

One of the objectives is to be able to provide machinery within six months from receiving an order and in most cases have it in operation within the next three months. This in itself should appreciably reduce project costs and help to meet national objectives of increasing use of renewable energy resources.

Experience

Most of the modern low head installations in the United States have included TUBE units. These installations have incorporated custom designed turbines with runner diameters as small as 30" (750 mm) and as large as 315" (8 meters) in diameter. These latter units are the largest tubular turbines in the world and were purchased by the U.S. Corps of Engineers. Within the standardized TUBE unit size range there are five installations in operation of which one is located in Canada. Each is generally similar to the standardized unit. (Figure 16)

The purchasers include a utility, a paper company, an irrigation district and two municipal installations, one each in Canada and the United States. These installations include both fixed and adjustable blade runners, a unit with a speed increaser, both induction and synchronous generators, both intake valves and gates and all have been in successful operation for more than 10 years. One installation has black start capability, two others have head water level control instead of a governor and two are semiautomatic or automatic with remote control. One has no powerhouse. Three of the contracts were obtained as a result of competitive bids while at least one of the other two were negotiated contracts. All were handled as completely coordinated units.

Descriptive literature (Figure 17) is now available for these standardized hydroelectric generating units. This bulletin includes a sizing chart so that based on net head and discharge or desired kilowatt output, a runner size can be established subject to modifications which might be necessary to compensate for higher settings above tailwater elevation. Based on the various standard runner sizes, preliminary overall dimensions are provided as ratios relating to the runner size. A brief specification is provided for each of the major components as are basic singleline diagrams for the electrical and control systems used with both induction and synchronous generators. A representative performance curve is provided for purposes of comparing full load and part load operation.

The back cover of the bulletin provides a list describing typical information which is needed in order to provide a more detailed equipment sizing and site evaluation. Application Engineers are available to assist potential low head hydro site developers in evaluating the equipment alternatives for a particular site regardless whether it is a standard TUBE unit or whether any other equipment arrangement may better suit the particular site requirements.

This service is provided as part of the continuing effort to help hydroelectric equipment users evaluate their project potential and economic feasibility. It is a service which has been provided for more than 100 years to potential hydroelectric equipment users and their engineers. We are looking forward to your taking advantage of the most modern technology and most r adily available engineering and economic assistance. Hopefully you too can justify a modern low head hydroelectric installation to help recover this renewable energy resource which is currently being wasted at many sites.

What are the Dams being used for?

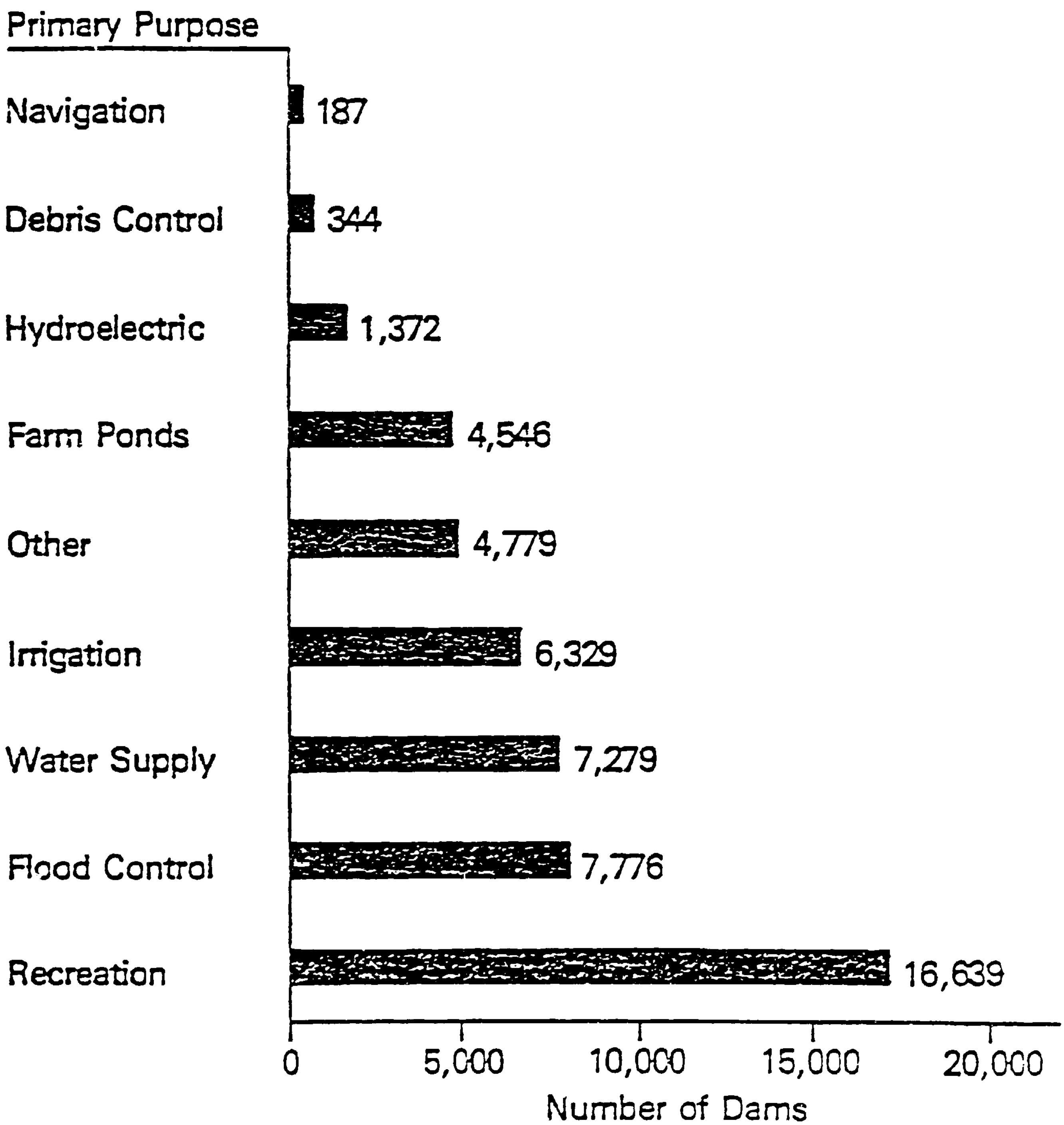


Figure 1

THE NATIONAL ENERGY ACT

LOW INTEREST LOANS

$10 MILLION/YEAR FOR 3 YEARS

FOR FEASIBILITY STUDIES

(FORGIVEABLE IF SITE NOT ECONOMICAL)

$100 MILLION/YEAR FOR 3 YEARS

FOR CONSTRUCTION

FOR EXISTING DAMS

POWERHOUSE PART OF DAM

OMB PROPOSING TO FUND ONLY 18 MILLION IN FISCAL YEAR 1979

Figure 2

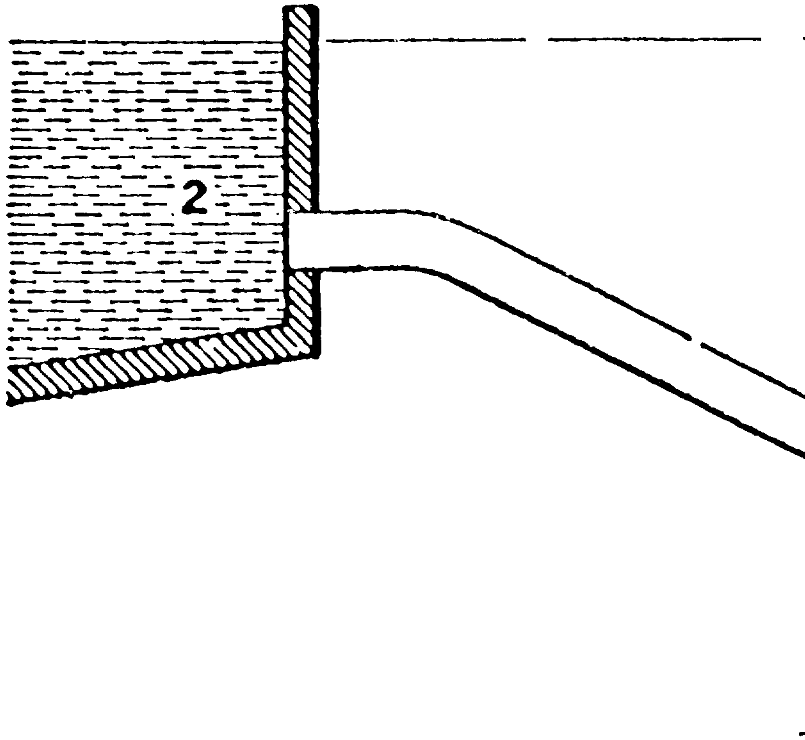
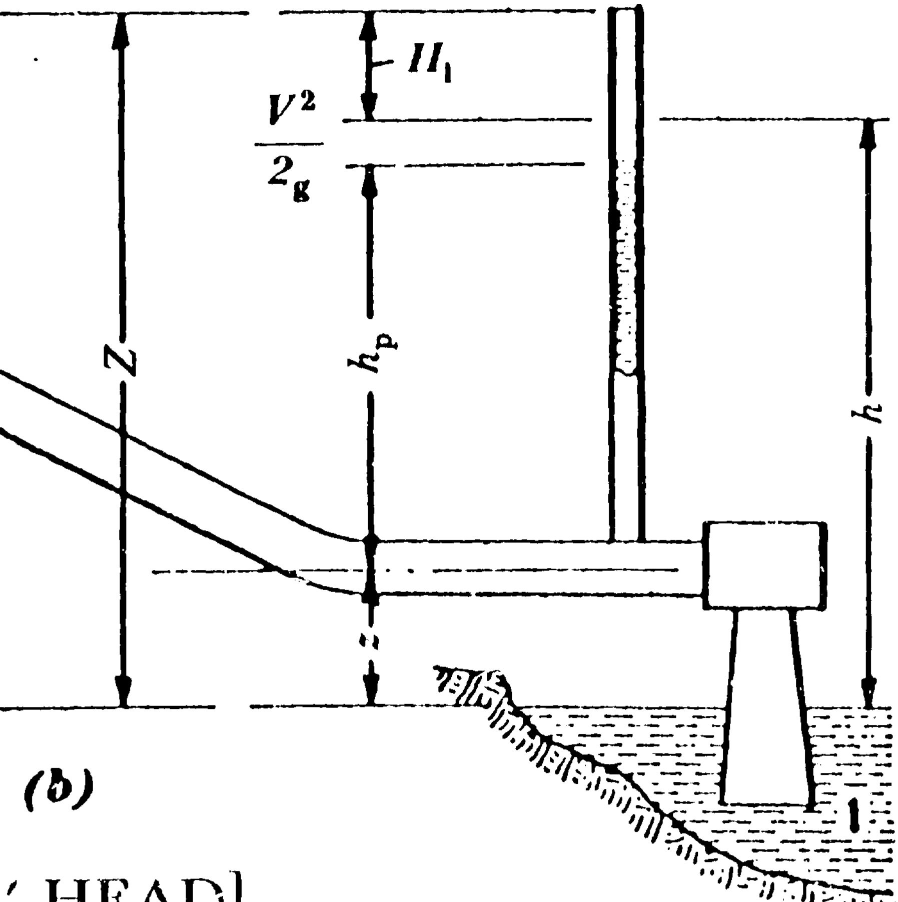


Figure 3

[V = 8⅕ = 1

2. forebay



(b)

′ HEAD]

1. tailwater

(*b*) Reaction turbine

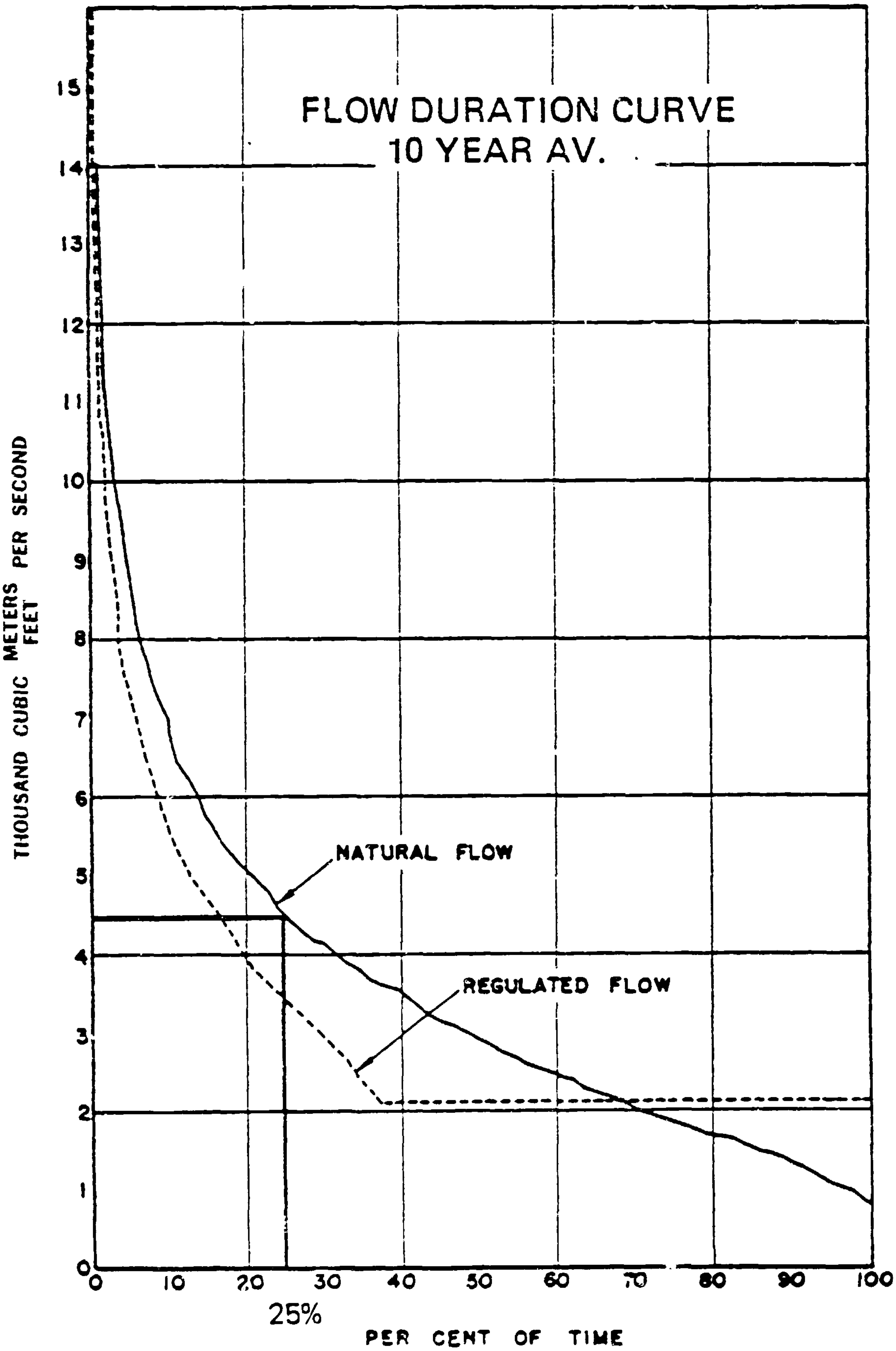

FLOW DURATION CURVE
10 YEAR AV.
THOUSAND CUBIC METERS FEET PER SECOND
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
NATURAL FLOW
REGULATED FLOW
0
10
20
30
40
50
60
70
80
90
100
25%
PER CENT OF TIME

Figure 4

Rules of Thumb

Rainfall $\approx$ CFS runoff/Square Mile

Example

New England 20" to 30" $\approx$ 2CFS/Sq. Mi. $\approx$

Flow available 20% to 30% of year

CFS available 25% of Time is a starting place for turbine sizing

1/2 Tailrace width is a starting place for turbine sizing.

$$\text{Horsepower} = \text{Flow(CFS)} \times \frac{\text{Head (Feet)}}{10}$$

(Assumes Turbine Efficiency of 88.1%)

KW Generator Output = HP x 0.7

(Assumes Generator x Gear Eff. = 93.8%)

Figure 5

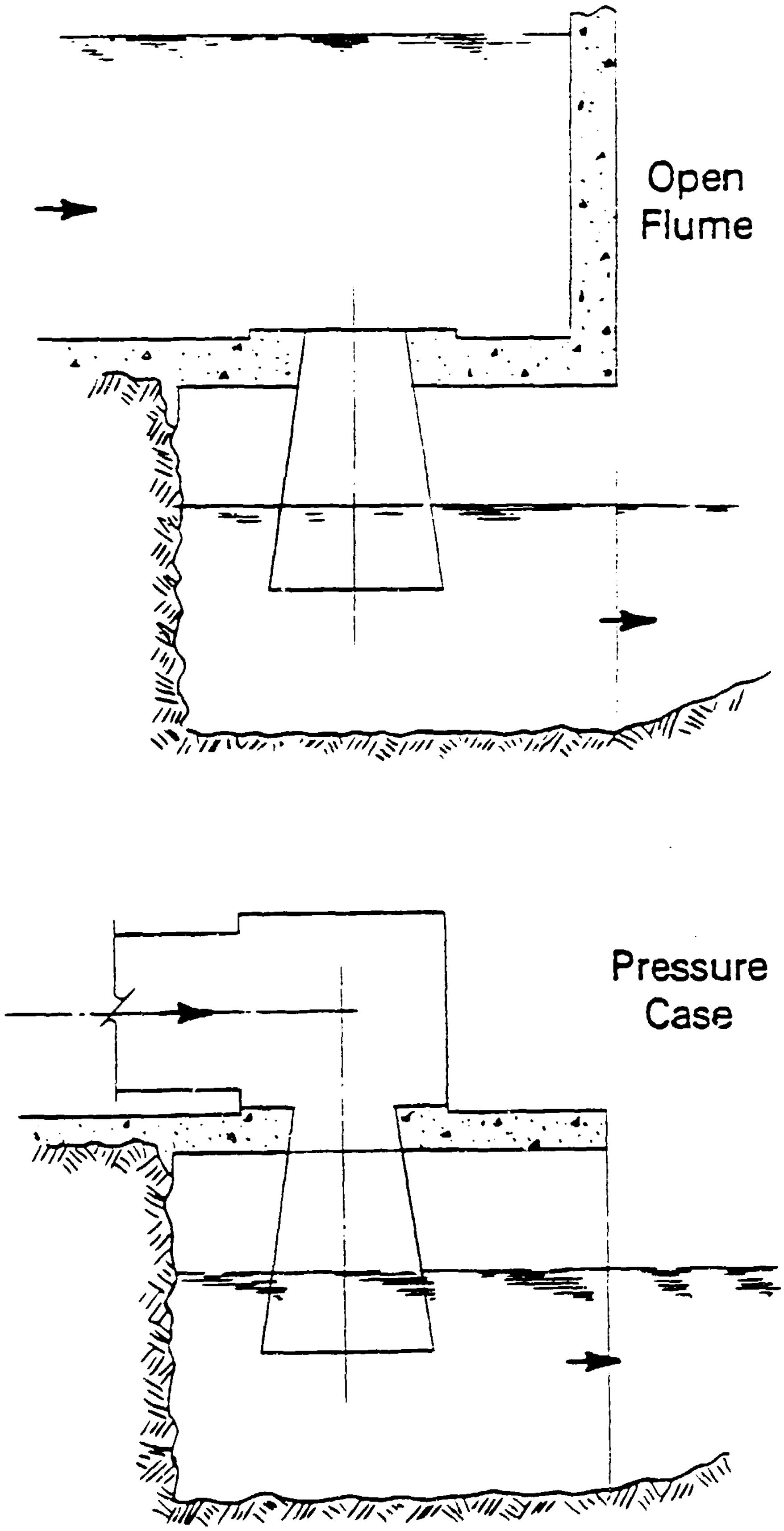


Figure 7

INTAKES & CASES

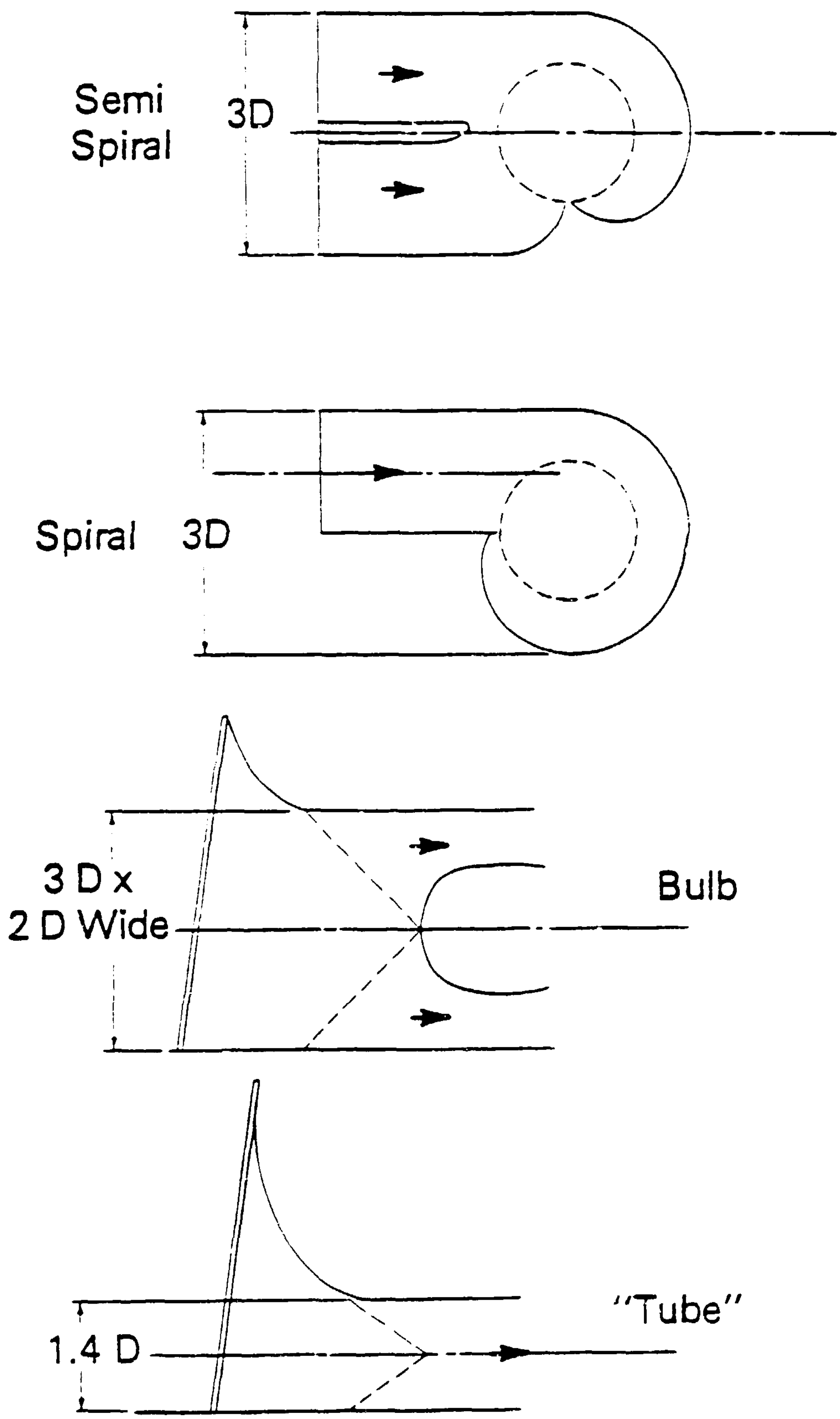


Figure 8

DRAFT TUBES

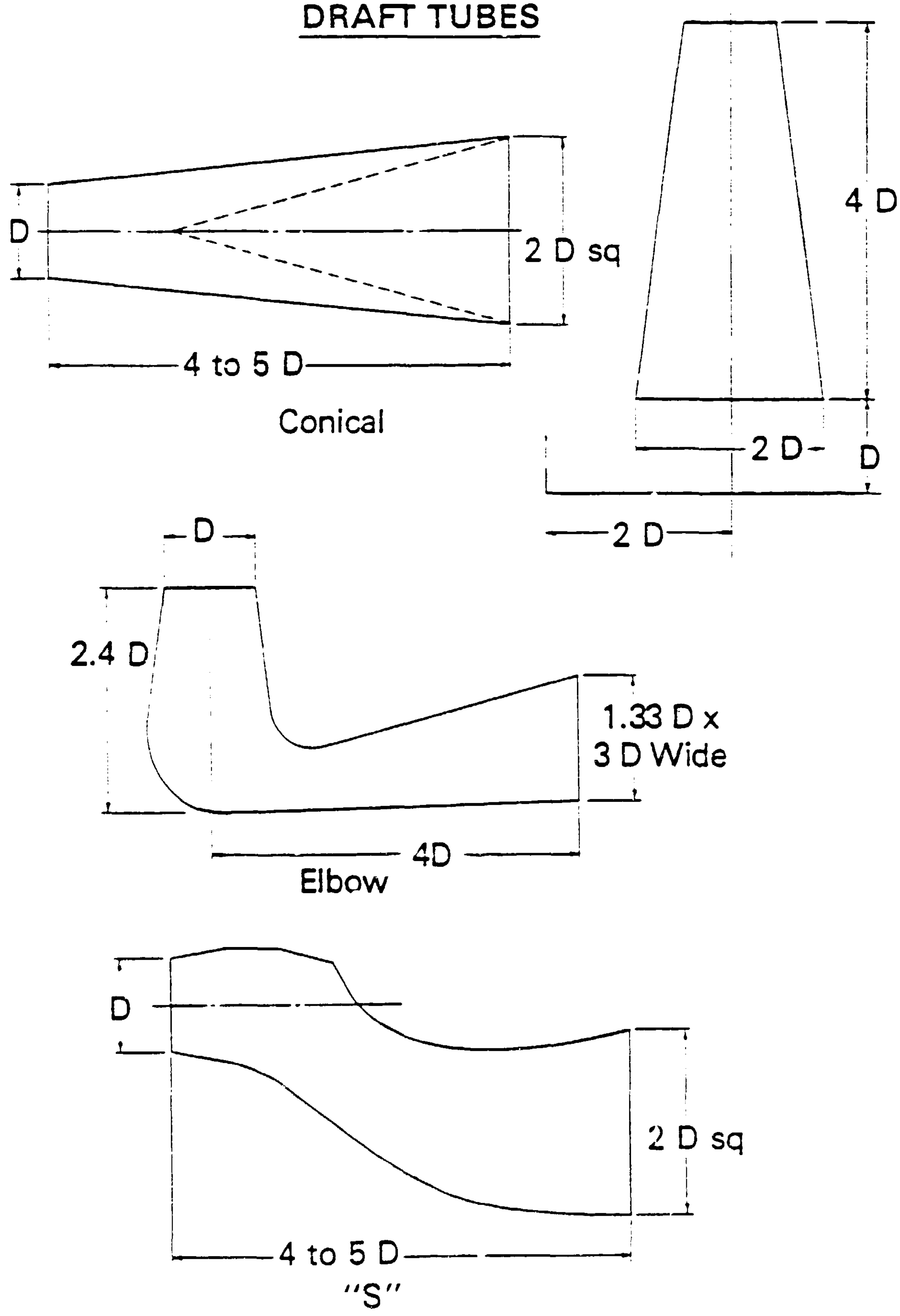
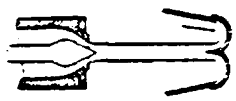


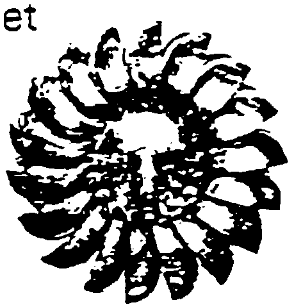
Figure 9

IMPULSE RUNNERS

Pelton, Doble
(Tangential)

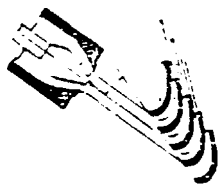
Low Speed

Nozzle  Bucket

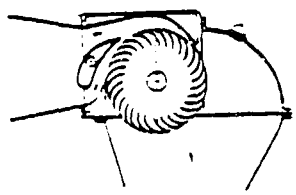


High Speed

Turgo
(Diagonal)

Nozzle  Buckets

Michell, Banki
(Crossflow)



High Head - Low Volume
Low RPM For Given Head
Head Measured To Nozzle or Centerline
Do Not Recover "Suction" Head

Figure 10

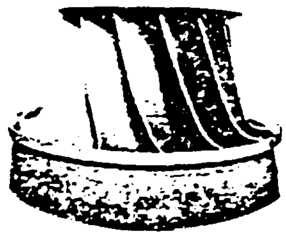
REACTION RUNNERS

Francis

High Head

Medium Head

Low Head



Propeller

Mixed Flow

Dariez

Medium Head

Adjustable Blades ↔ Fixed Blades

Low Head

Axial Flow

Kaplan = Coordinated Blades & Gates

Low Head - High Volume
Higher RPM For Given Head
Output Limited By Cavitation

Figure 11

DISTRIBUTOR ASSEMBLY

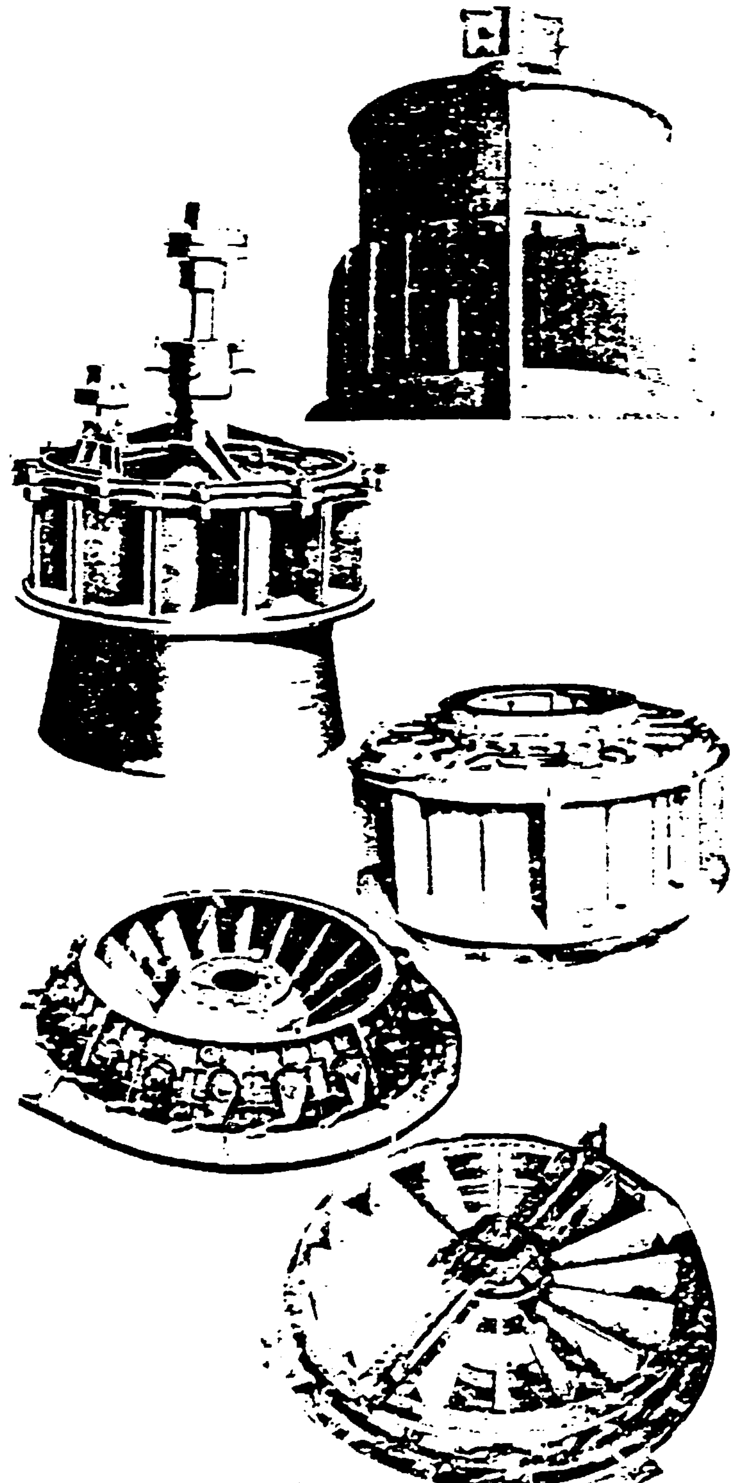
Cylinder Gate
Francis or Propeller

Inside Mechanism
Francis or Propeller

Outside Mechanism
Francis or Propeller

Conical Gates
Propeller

Radial Gates
Propeller

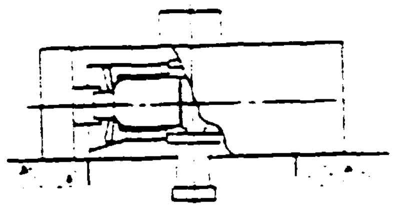


Shaft May Also Be Horizontal
Or Inclined

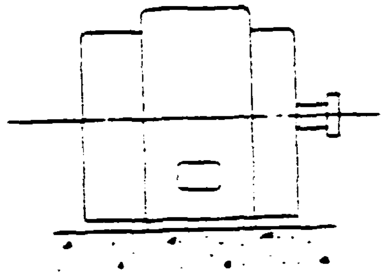
Fixed Position (Vanes) Gates May Be Used

Figure 12

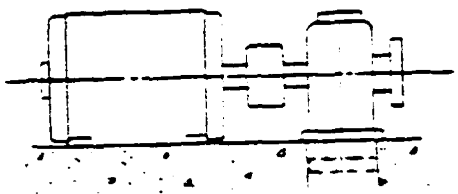
Vertical
Direct



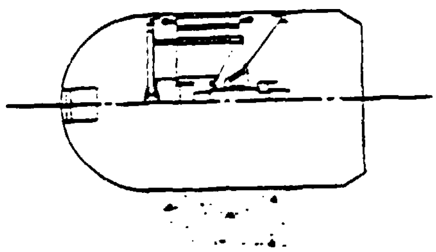
Horizontal
Direct



Horizontal
With Speed
Increaser



Bulb



Rim
(Harza)

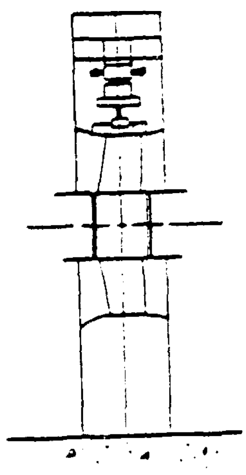


Figure 13

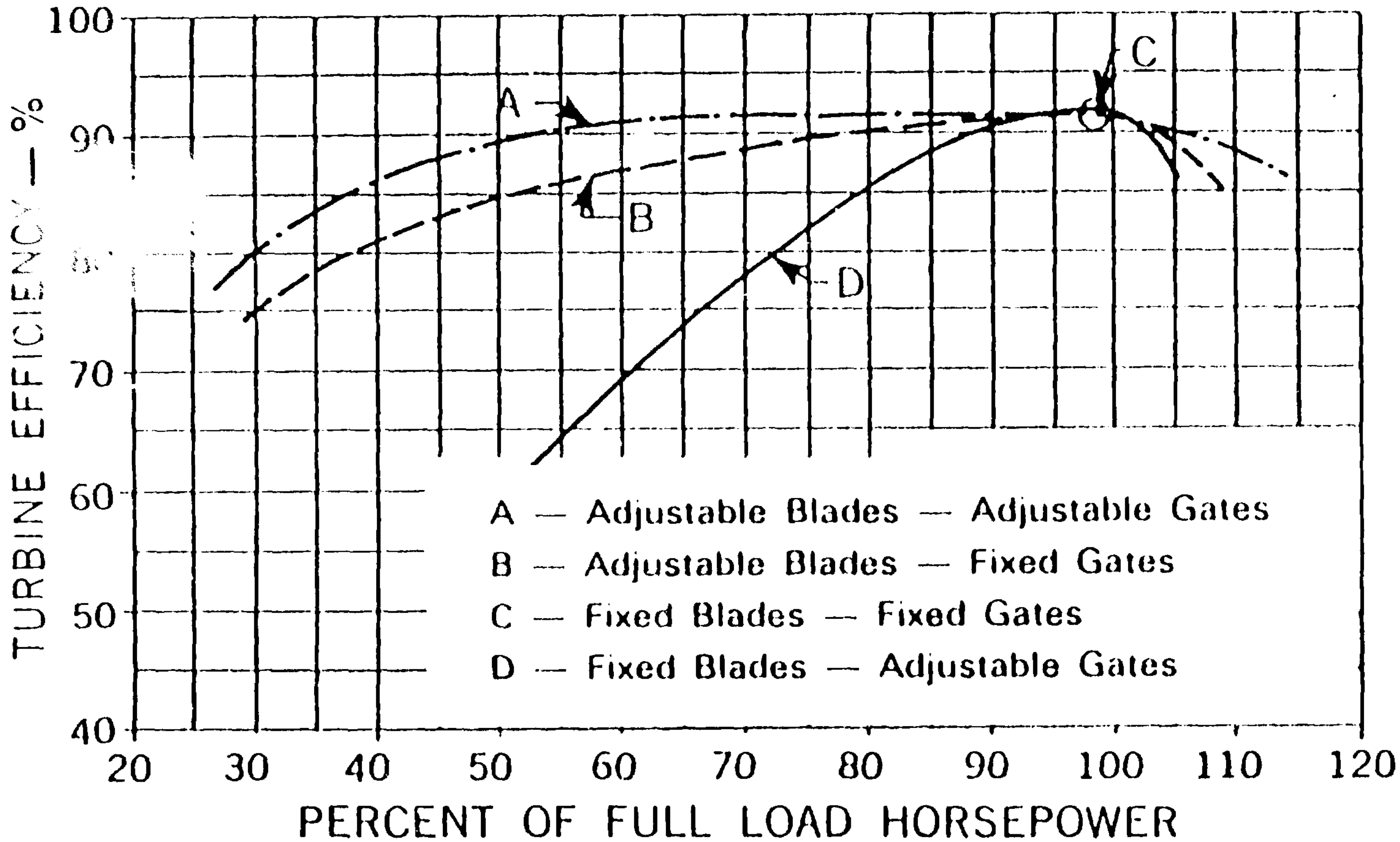

TURBINE EFFICIENCY — %
PERCENT OF FULL LOAD HORSEPOWER
100
90
70
60
50
40
20
30
40
50
60
70
80
90
100
110
120
A
B
C
D
A — Adjustable Blades — Adjustable Gates
B — Adjustable Blades — Fixed Gates
C — Fixed Blades — Fixed Gates
D — Fixed Blades — Adjustable Gates

Figure 14

TUBE UNIT INSTALLATIONS

Custom Designed

(Horizontal Shaft, Up To 3,000 mm Runner)

Plant Name & Owner	No. Units	Size/Type	Head	KW Output	RPM	Type Generator	Shutoff Device	Year Ordered
Lower Paint Wisc. -Mich. Power Co.	1	750 mm (30") 4X	6.1 M (20')	100	514	Induction	Slide Gate	1951
Wisconsin River. Div. 1 Consolidated Papers, Inc.	1	2,750 mm (110") 4XA	6.7 M (22')	2,000	150	Synchronous	Special B.F. Valve	1962
Turnip Check Imperial Irrig. Dist.	1	1,500 mm (60") 4XA	5.0 M (16.5')	420	218/900	Induction	Tainter Gate	1963
Swift Rapids City of Orillia	2	2,000 mm (77") 5XA	14.3 M (47')	2,500	277	Synchronous	F.W. Gate	1964
10th St. Hydro Sta. City of Norwich, Conn.	1	2,750 mm (110") 4XA	4.7 M (15.5')	1,440	128.6	Synchronous	F.W. Gate	1965

*Metric dimensions are approximate

Figure 16

standardized hydroelectric generating units

- Low-head
- Modern
- Pre-designed
- Heads up to 15m (50')
- Capacities to 5000 KW

Hydro-Turbine Division
York, Pennsylvania

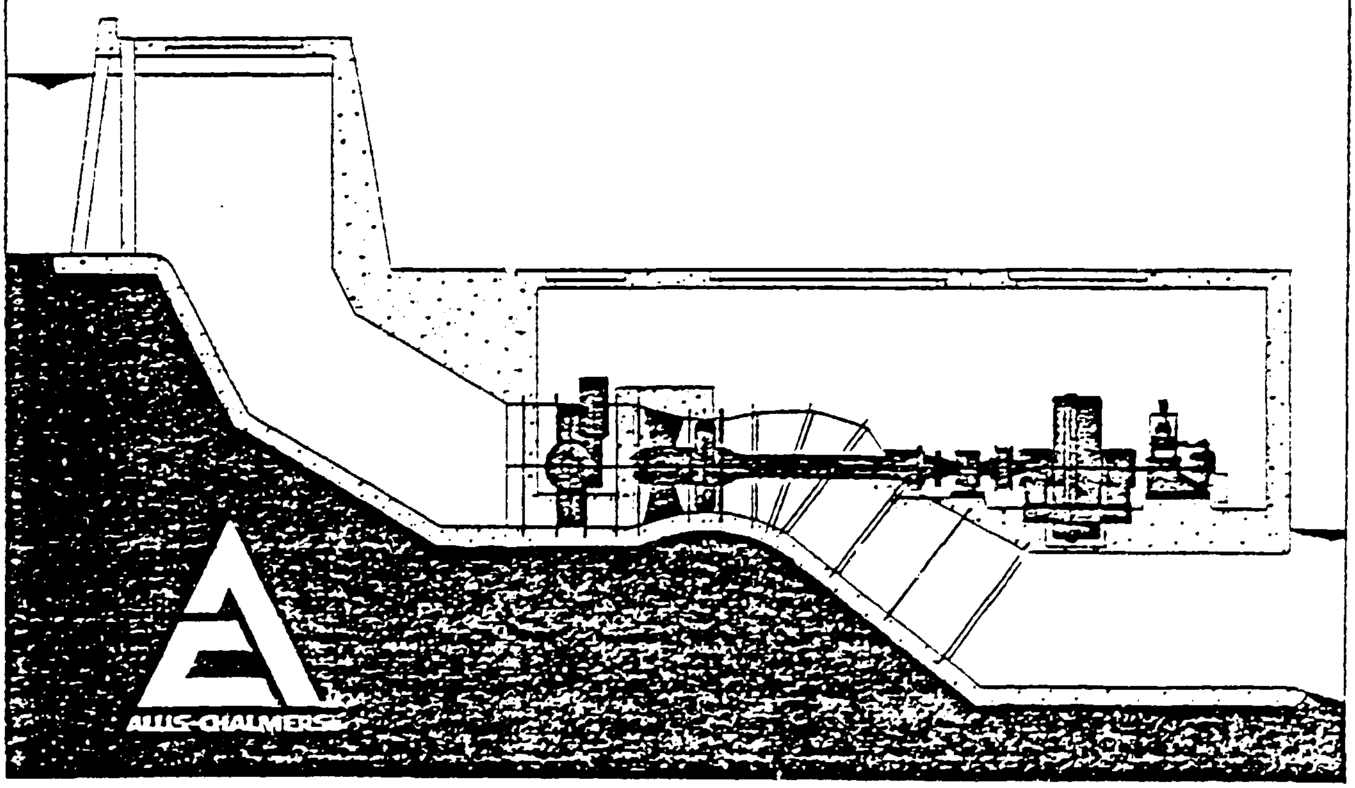


Figure 17

7