HYDROELECTRIC POWER GENERATION

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December 2011

Sources:
1 STANDARD HANDBOOK FOR ELECTRICAL ENGINEERS-*Section 09*
2 www.digitalengineeringlibrary.com Source:
3 http://en.wikipedia.org/wiki/Hydroelectricity
4 http://www.google.iq/search?q=HYDROELECTRIC+POWER+GENERATION&hl
5 http://en.wikipedia.org/wiki/Hydraulic_head

CONTENTS

1 GENERAL

1.1 Introduction

Articles and researches about this topic are not new and might be too many, but I see it as an important knowledge for power engineers. Choosing this field for my paper for consultancy degree in Electric Engineer was one of the proposals of Kurdistan Engineering Union.
My thanks and appreciations to Mr. Hussamaddin Mohammed, Consultant Engineer and Deputy Chairman of Kurdistan Engineering Union. He was a big support in preparing this paper.

Hydropower is produced when kinetic energy in flowing water is converted into electricity.
Hydropower has been a significant source of electrical energy in the United States, Europe and many other industrial countries. Iraq was concerned with Hydropower as an efficient source for generating electric power since the 1950s. Iraq now has five large dams containing hydro power stations and the first completed projects in this field are ***Dokan*** and ***Darbandikhan*** Dams in Kurdistan Region in Sulaimaniyah province. The other three are **Mosul Dam** as the largest dam in Iraq**, Haditha Barrage** and **Al Hindiya Barrage.** Traditionally, hydropower has been a low-cost, reliable energy source. It utilizes a renewable fuel (water) that can be sustained indefinitely, and is free of fossil fuel emissions. And because hydroelectric generators are especially suited for providing peaking power, hydropower complements thermal generation and improves overall power production efficiency.

It was not easy to make a shorter work, as almost all the detailed wordings are necessary information, so please be patient in reading the instruments.

1.2 Abbreviations

a _ celerity or speed of sound in water, feet/second
BOD _ biological oxygen demand, parts per million/day
D _ Winter-Kennedy **piezometric head** pressure differential, feet **piezometric head** is a specific measurement of water pressure above a geodetic datum (http://en.wikipedia.org/wiki/Hydraulic_head)
DO _ dissolved oxygen, parts per million
E _ specific energy, foot-pounds (force)/pound (force)
Erel _ relative efficiency, kilowatts/feet1/2
Et _ turbine efficiency, percent or decimal
Et-g _ combined turbine-generator efficiency, percent or decimal
G _ local acceleration of gravity, feet/second2
H _ total net head or total dynamic head, feet
Hb _ barometric pressure head, feet
Hd _ design head (head of best efficiency), feet
HP _ turbine output, horsepower
*H*0 _ initial piezometric head, feet
K _ radius of gyration, feet
kW _ generator output, kilowatts
L _ length of water conduit, feet
MW _ generator output, megawatts
MVA _ generator or transformer capacity, megavolts-amperes
MVAR _ generator output, reactive, megavars
N _ rotational speed, revolutions/minute
Ns _ specific speed, revolutions/minute-horsepower1/2/head5/4
Q _ volumetric flow rate, feet3/second
*Q*20 _ 20 percent flow exceeded (time flow value is exceeded), percent
*Q*30 _ 30 percent flow exceeded (time flow value is exceeded), percent

T or *t* _ time, seconds
V _ flow velocity, feet/second
*V*0 _ initial flow velocity, feet/second
W _ weight, pounds (force)
WK2 _ angular inertia, pound-feet2
- specific weight of water, pounds/foot3

1.3 Nomenclature

The following terms are commonly used to describe hydroelectric equipment, facilities, and production:

Afterbay (tailrace): The body of water immediately downstream from a power plant or pumping plant.

Appurtenant structures: Intakes, outlet works, spillways, bridges, drain systems, tunnels, towers, etc.

Auxiliary power: The electric system supply to motors and other auxiliary electrical equipment required for operation of a generating station.

Base loading: Running water through a power plant at a roughly steady rate, thereby producing power at a steady rate.

Base load plant: Powerplant normally operated to take all or part of the minimum load of a system, and which consequently runs continuously and produces electricity at an essentially constant rate. Operated to maximize system mechanical and thermal efficiency and minimize operating costs.

Bulkhead: A one-piece fabricated steel unit that is lowered into guides and seals against a frame to close a water passage in a dam, conduit, spillway, etc.

Bulkhead gate: A gate used either for temporary closure of a channel or conduit before dewatering it for inspection or maintenance or for closure against flowing water. Bulkhead gates nearly always operate under balanced pressures.

Cavitation damage: Pitting and wear damage to solid surfaces (e.g., the blades of a hydraulic turbine) caused by the implosion of bubbles of water vapor in fast-flowing water.

(FIGURE-01) Cavitating propeller model in a water tunnel experiment.

Cofferdam: A temporary barrier, usually an earthen dike, constructed around a worksite in a reservoir or on a stream. The cofferdam allows the worksite to be dewatered so that construction can proceed under dry conditions.

Crest: The top surface of a dam or high point of a spillway control section.

Dam: A concrete and/or earthen barrier constructed across a river and designed to control water flow or create a reservoir.

Dewater (unwater): To drain the water passages and expose the turbine runner. Generally requires closing of an isolation valve or lowering of the head gates, and opening of the penstock drain valves.

Draft tube: Part of the powerhouse structure designed to carry the water away from the turbine runner.

Fish bypass system: A system for intercepting and moving fish around a dam as they travel downriver.

Fish ladders: A series of ascending pools constructed to enable salmon or other fish to swim upstream around or over a dam.

Fish screen: A screen across the turbine intake of a dam, designed to divert the fish into a bypass system.

Fish passage facilities: Features of a dam that enable fish to move around, through, or over without harm. Generally an upstream fish ladder or a downstream bypass system.

Forebay (headrace)*:* The body of water immediately upstream from a dam or hydroelectric plant intake structure.

Generator*:* The machine that converts mechanical energy into electrical energy.

Head*:* The difference in elevation between two specified points, for example, the vertical height of water in a reservoir above the turbine.

High-head plant*:* A powerplant with a head over 800 ft (over 250m).

Hydraulic losses. Energy loss in water passages primarily due to velocity losses at trash racks, intakes, transitions, and bends, and friction losses in pipes.

Intake*:* The entrance to a conduit through a dam or a water conveyance facility.

Intake structure: The concrete portion of an outlet works including trash racks and/or fish screens,

Upstream: from the tunnel or conduit portions. The entrance to an outlet works.

Low-head plant: A powerplant with a head less than 100 ft (30m).

Medium-head plant: A powerplant with a head between 100 and 800 ft.

Multipurpose project: A project designed for two or more water-use purposes. For example, any combination of power generation, irrigation, flood control, municipal and/or industrial water supply, navigation, recreation, and fish and wildlife enhancement.

Operating rule curve: A curve, or family of curves, indicating how a reservoir is to be operated under specific conditions and for specific purposes.

Outlet works: A combination of structures and equipment located in a dam through which controlled releases from the reservoir are made.

Peaking plant: A powerplant in which the electrical production capacity is used to meet peak energy demands. The site must be developed to provide storage of the water supply and such that the volume of water discharged through the units can be changed readily.

Penstock: A pipeline or conduit used to convey water under pressure from the supply source to the turbine(s) of a hydroelectric plant.

Pool: A reach of stream that is characterized by deep, low velocity water and a smooth surface.

Powerhouse: Primary structure of a hydroelectric dam containing turbines, generators, and auxiliary equipment.

Pumped storage plant: Powerplant designed to generate electric energy for peak load use by pumping water from a lower reservoir to a higher reservoir during periods of low energy demand using inexpensive power, and then releasing the stored water to produce power during peak demand periods.

Reservoir: A body of water impounded in an artificial lake behind a dam.

Runoff: Water that flows over the ground and reaches a stream as a result of rainfall or snowmelt.

Run-of-the-river plant: A hydroelectric powerplant that operates using the flow of a stream as it occurs and having little or no reservoir capacity for storage or regulation.

Single-purpose project: A project in which the water is used for only one purpose, such as irrigation, municipal water, or electricity production.

Spill: Water passed over a spillway without going through turbines to produce electricity. Spill can be forced, when there is no storage capability and stream flows exceed turbine capacity, or planned, for example, when water is spilled to enhance downstream fish passage.

Spillway**:** The channel or passageway around or over a dam that passes normal and/or flood flows in a manner that protects the structural integrity of the dam.

Standby power: Frequently provided as a backup for operating gates and valves in the event the principal power supply (usually electrical) fails. Includes engine-driven-generators or hydraulic oil pumps, each of which could be powered by gasoline, diesel, or propane, and power takeoffs on trucks or tractors. On small-sized gates or valves, the standby power is often hand-operated, such as a hand pump or crank.

Stop-logs: Large logs, planks, steel or concrete beams placed on top of each other with their ends held in guides between walls or piers to close an opening in a dam, conduit, spillway, etc., to the **passage of water**. Used to provide a cheaper or more easily handled means of temporary closure than a bulkhead gate.

Storage reservoir*:* A reservoir having the capacity to collect and hold water from spring time

Snowmelts: Retained water is released as necessary for multiple uses such as power production, fish passage, irrigation, and navigation.

Surge tank*:* A large tank, connected to the penstock, used to prevent excessive pressure rises and drops during sudden load changes in plants with long penstocks.

Switchyard: An outdoor facility comprised of transformers, circuit breakers, disconnect switches, and other equipment necessary to connect the generating station to the electric power system.

Tailrace: See Afterbay.

Tailwater*:* The water in the natural stream immediately downstream from a dam.

Transformer*:* An electromagnetic device used to change the magnitude of voltage or current of alternating current electricity or to electrically isolate a portion of a circuit.

Trashrack: A metal or reinforced concrete structure placed at the intake of a conduit, pipe, or tunnel that prevents large debris from entering the intake.

Trashrake (trash rake): A device that is used to remove debris, which is collected on a trashrack to prevent blocking the associated intake.

Turbine, hydraulic: An enclosed, rotary-type prime mover in which mechanical energy is produced by the force of water directed against blades or buckets fastened in an array around a vertical or horizontal shaft.

Turbine runner (water wheel): The rotor-blade assembly portion of the hydraulic turbine where moving water acts on the blades to spin them and impart energy to the rotor.

Unwater: Sea Dewater.

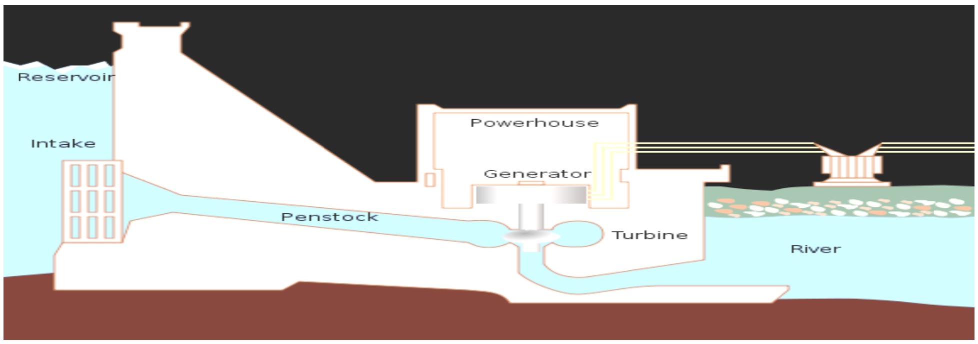
Wicket gates: Adjustable gates that pivot open around the periphery of a hydraulic turbine to control the amount of water admitted to the turbine.

2 - HYDROELECTRIC POWERPLANTS

To determine the optimal location, size, and layout of a hydroelectric powerplant, numerous factors must be considered including the local topography and geologic conditions, the amount of water and head available, power demand, accessibility to the site, and environmental concerns. The overriding consideration in the design of a hydroelectric powerplant is that it adequately performs its function and is structurally safe.

2.1 Principal Features

The principal features of a hydroelectric facility are the dam, reservoir, spillway, outlet works, penstocks, powerhouse, fish passage facilities (if fish protection is required), surge tanks, and switchyard. Most hydroelectric power plants are located at or immediately adjacent to a dam. Some plants, however, are located away from the dam, such as at the lower end of a pressure penstock, power tunnel, or power canal, or at a drop in an irrigation canal. In general, a power plant is situated so that the penstocks will be as short as practicable in order to minimize the cost of the penstocks and the associated hydraulic losses, and to avoid the necessity for surge tanks. Hydropower developments can be classified as either low, medium, or high-head projects.
Figure -1 shows in outline the most common arrangements. Other sources of hydropower involve the use of ocean waves or tidal hangs to generate electricity. These technologies are not as well developed as the more conventional hydropower sources.



(FIGURE-02) A general diagram of hydropower plant

2.2 Powerhouse Structure

The powerhouse foundation and superstructure contain the hydraulic turbine, water passages including draft tube, passageways for access to the turbine casing and draft tube, and sometimes the penstock valve. The superstructure also typically houses the generator, exciter, governor system, station service, communication and control apparatus, and protective devices for plant equipment and related auxiliaries as well as the service bay, repair shop, control room, and offices. The transformers and switchyard are usually located outdoors adjacent to the powerhouse and are not an integral part of it. Cranes are provided in the powerhouse to handle the heaviest pieces of turbine and generator and sometimes extend over the penstock valves. Alternative powerhouse designs have included separate cranes for the penstock valves. Another common powerhouse design is the outdoor type where the operating floor is placed adjacent to the turbine pits with the generator located outdoors on the roof of a one-story structure. In the outdoor type, each generator is protected by a light steel housing, which is removed by the outdoor gantry crane when access to the machine is necessary for other than routine maintenance. The erection and repair space is in the substructure and has a roof hatch for equipment access. The outdoor design reduces initial construction costs of the powerplant.
However, the choice of indoor, semi-outdoor, or outdoor type is dictated not only by consideration of the initial cost of the structure with all equipment in place, but also by the cost of maintenance of the building and equipment, and protection from the elements.

2.3 Switchyard

To provide a reliable and flexible interface between the generating equipment and the power grid, a switchyard is usually associated with a hydroelectric powerplant. Switchyards include all equipment and conductors that carry current at transmission line voltages, including their insulators, supports, switching equipment, and protective devices. The system begins with the high-voltage terminals of the step-up transformer and extends to the point where transmission lines are attached to the switchyard structure. Switchyards are typically sited to be as close to the powerplant as space permits in order to minimize the length of control circuits and power feeders, and also to enable the use of service facilities in the powerhouse.

(FIGURE-03) **Switchyard** at TVA's 500 × 404 **Wilson Dam hydroelectric plant - USA**

3 MAJOR MECHANICAL AND ELECTRICAL EQUIPMENT

Much of the major mechanical and electrical equipments installed in hydroelectric powerplants may be found in other generating, transmission, and distribution systems. In some cases, however, specialized equipment has been developed for hydropower applications.

3.1 Turbines

The word "turbine" comes from Latin and means *spinning top*. Technically, hydraulic turbines that drive electric generators are called hydraulic prime movers. Whatever name is used, all hydraulic turbines convert fluid power into mechanical power by the same physical principle. They develop their mechanical power via the rate of change of angular momentum of the fluid. In most cases, the head is used to impart an angular momentum or prewhirl to the fluid. The action of the turbine runner is to remove this angular momentum or to straighten out the fluid streamlines. The effect of this change in angular momentum is to induce a torque on the shaft of the runner. The speed of rotation is the rate at which this angular momentum is changed, and torque multiplied by rotational speed is mechanical power.

The relative proportions of power transferred by a change of static pressure and by a change in velocity provide the most basic method of classifying turbines. The ratio of this transfer by means of a change in static pressure to the total change in the runner is called the degree of reaction, or more simply reaction. Therefore, if there is any significant pressure change in the runner of a turbine, it is a *reaction* hydraulic turbine. If there is no change in pressure, only in velocity, the degree of reaction is zero and these special cases are called *impulse* hydraulic turbines.

Aside from the most basic category as reaction or impulse, hydraulic turbines are classified in two separate ways—by the ***type of runner*** and by the ***configuration of the water passages***. For reaction turbines, there are different classifications of runners— axial, radial, and mixed. These terms denote whether the flow enters the runner parallel or perpendicular to the shaft, or at some angle in between. In modern reaction turbines, the flow leaves the runner axially. For the lowest head applications, reaction turbines with propeller type runners are utilized. These may be *fixed blade* or if the pitch angle of the blades can be adjusted, they are called *Kaplans* (Fig.-04).

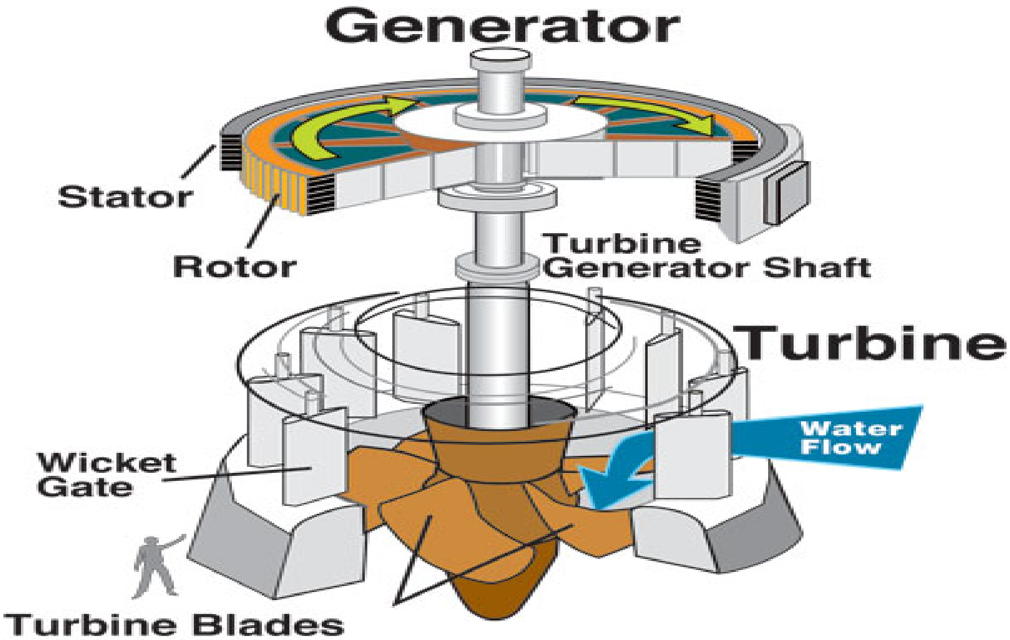


FIGURE -04 Sectional elevation of an adjustable blade propeller (Kaplan) turbine.

In propeller turbines, the fluid enters and leaves the runner axially; therefore, these are axial flow machines.
A Francis runner looks somewhat like the impeller of a centrifugal pump. It has no adjustable or moveable parts. Unlike propeller or Kaplan turbines, where flow increases with runaway speed, Francis turbines tend to choke or reduce the flow with runaway speed. This characteristic can produce unwanted pressure rises in the penstock immediately following a load rejection (i.e., the loss of an electrical load). For the highest head applications, the preferred choice is an impulse turbine. There are a number of different designs of impulse turbine runners. The most common is the *Pelton* (Fig.-06). In this design, jets discharge directly into buckets mounted around the periphery of a runner, which is housed in an atmospherically vented casing. Because the runner is at atmospheric pressure, impulse turbines are not subject to cavitations. The jet strikes a splitter in the middle of the bucket, which divides the jet in two. Each half of the jet turns almost a full 180° in the bucket and then falls free.

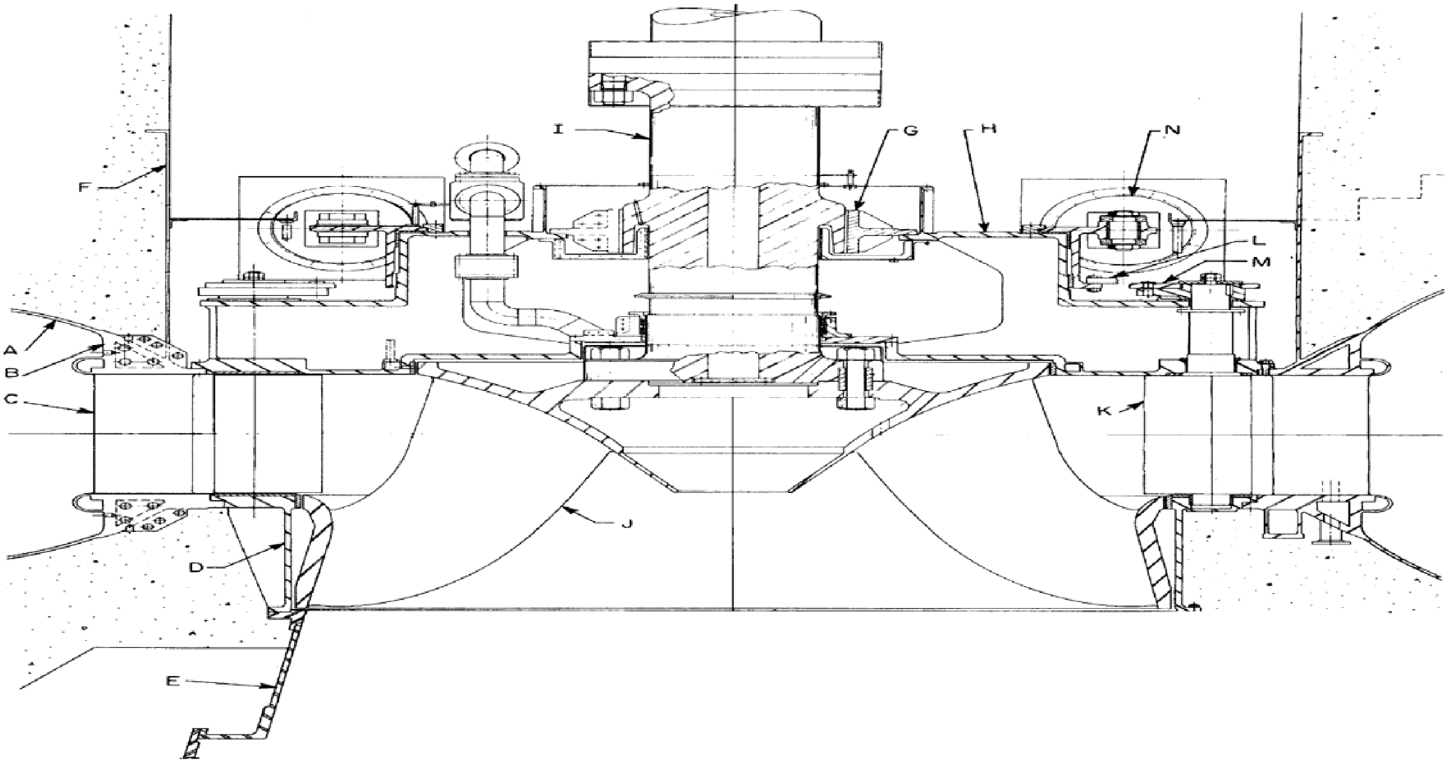


FIGURE -05 Sectional elevation of a Francis reaction turbine: A—spiral case; B—stay ring; C—stay vane; D—discharge ring; E—draft tube liner; G—main-shaft bearing; H—head cover; I—main shaft; J—runner; K—wicket gates; L—links; M—gate levers; N—servomotors.

The jet discharge is throttled or controlled by needle valves. Since this provides for a wide range of discharge from an individual nozzle and since multiple nozzles may be used on the same runner, Peltons can have a high efficiency over a very wide power range. If the shaft is mounted in the vertical, any practical number of nozzles can be used. However, if the shaft is horizontal, only two or three nozzles can be used. This is because of the need for gravity to clear the water from a bucket before the jet from the next nozzle strikes it. A variation of the basic Pelton design is the *Turgo* impulse turbine. In this design, the jets strike the buckets at a side angle and discharge out the opposite side. The buckets do not have a splitter. The advantage is that this design allows larger nozzles with higher flow rates to be used for a given diameter of wheel.
Another design of impulse turbine is the *cross-flow* turbine. Today's cross-flow designs are developed from an earlier version called the *Banki* or *Michell* turbine. The name cross-flow comes from the action of the fluid to enter the vanes on one side of the horizontally mounted cylindrical runner and purported travel across the interior center and out the vanes on the other side. In point of fact, research has shown that the water actually rides around the periphery of the runner in the vanes until it can discharge out the other side.

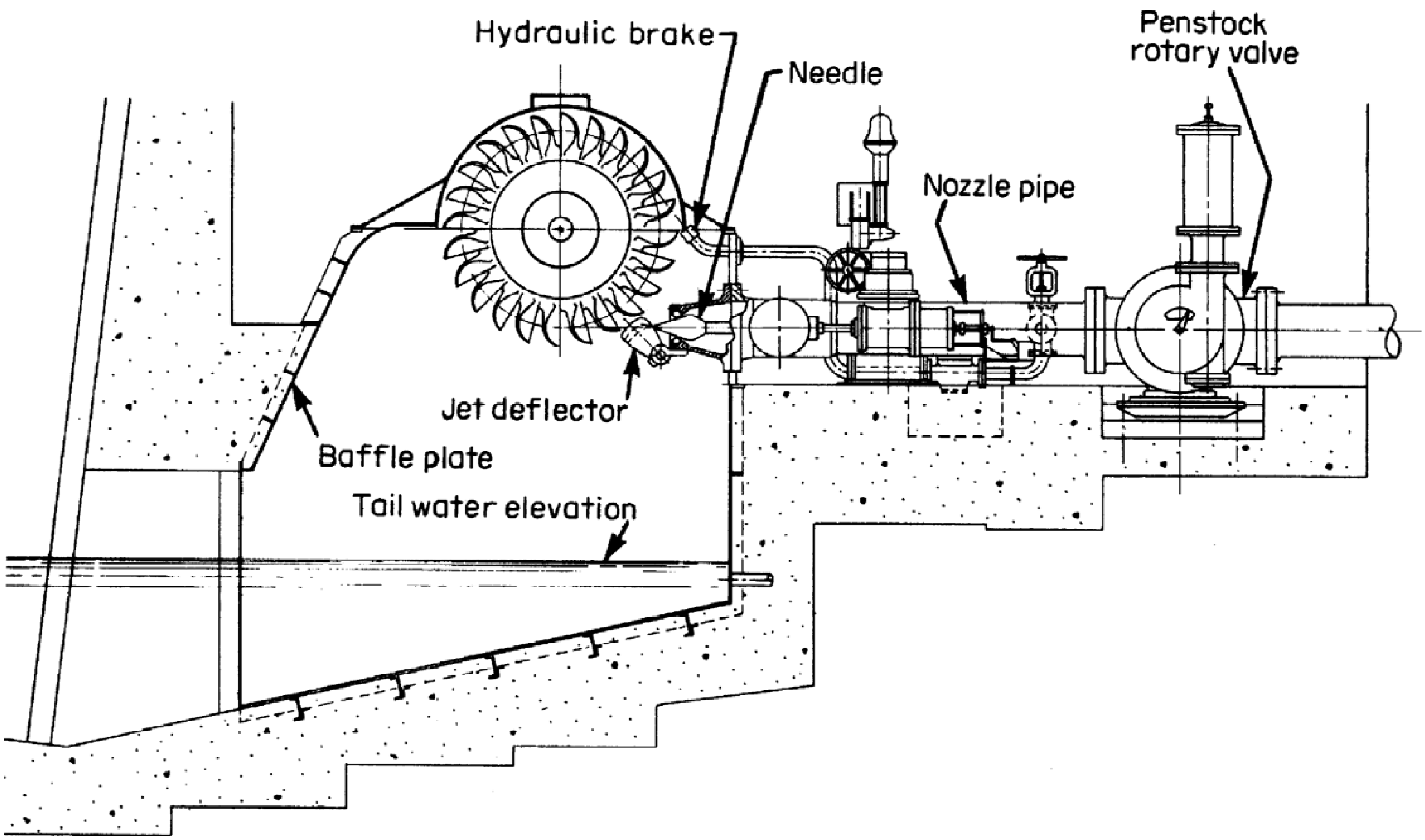


FIGURE -06 Section through a horizontal impulse turbine.

The principal advantages of this design are that it can operate at much lower heads than a Pelton and has a very wide range of flows. The wide flow range is achieved by dividing the runner into compartments. One commercial cross-flow turbine advertises a flow range of 16% to 100%. This is on the order of at least twice the flow range available from reaction turbines. One significant difference between reaction and impulse turbines is that reaction turbines have draft tubes to convey the discharge from the runner to the tailrace. The purpose of a draft tube is twofold. The first is to confine the high velocity discharge under the runner so that the static pressure may be below atmospheric. This increases the head across the runner. The second is to slow that high velocity prior to discharge into the tailrace. As a consequence of slowing the velocity, the pressure is recovered. For this latter reason, draft tubes are sometimes referred to as pressure recovery devices. Aside from the different types of runners, turbines are classified by the different configurations of their water passages. Reaction turbines typically have vertical shafts. The runners of propeller type turbines with vertical shafts are surrounded by a circular water passage called a semispiral case. This is generally formed by concrete and fed with water directly from the forebay through intake bays. Francis turbine runners are surrounded by a full spiral case and, because of the higher head and increased water pressure, this is generally formed from rolled steel plate and then embedded in concrete. Water is generally conveyed to these spiral cases through penstocks. Typically, just upstream of the turbine there is a shut-off or isolation valve in the penstock. When this valve is closed, the turbine can be dewatered. Spiral cases supply water to circular sets of wicket gates and stay vanes in what is called the distributor section. The wicket gates control the rate of flow. The principal purpose of the stay vanes, however, is structural rather than hydraulic. They are used to transfer the vertical load of the weight of the upper powerhouse structure to the powerhouse foundation. Stay vane design may improve the efficiency of the turbine by providing smooth transition of flow to the turbine runner.

With a vertical shaft, the beginning of the draft tube under the runner is pointed downward. In order to minimize the amount of required excavation, draft tubes are often constructed with an elbow to turn them horizontal about mid length and these are called elbow draft tubes. To reduce excavation and cofferdam

costs, low head units may have horizontal or inclined shafts. The water passages for horizontal or inclined shafts have less severe bends and turns and, therefore, tend to have lower hydraulic losses and higher efficiency. A common horizontal shaft configuration is to house the generator upstream of the runner in a submarine-like bulb. These are called *bulb t*urbines, even though the runners are usually conventional fixed blade propeller or Kaplan types (Fig.-04). A variation on this design is to house the upstream generator in a concrete silo with the water passages on either side. This is called a *pit* turbine. Pit turbines typically use speed-increasing gearboxes to reduce the size of the generator. Rather than the generator being upstream, the shaft may extend downstream, either horizontally or inclined at an upward angle. In these configurations, the shaft can extend through the draft tube liner so that the generator is not housed inside the water passages. Whether the shaft is horizontal or inclined, these are referred to as *tubular* turbines (Fig. -08). There is even a design where the generator is housed around the periphery of the runner, called a *rim* turbine.
Due to the higher head, water is conveyed to impulse turbines through penstocks. The runners of most impulse turbines rotate in some type of splash containing housing. Since the runners of impulse turbines are vented and operate at atmospheric pressure, they must be set at an elevation higher than the maximum tailwater elevation to avoid being flooded out. The discharge is conveyed to the tailrace through some type of open surface canal or tunnel.

.3.2 Generators

A hydraulic turbine converts the energy of flowing water into mechanical energy; a hydroelectric generator converts this mechanical energy into electricity. Almost all hydroelectric generators are synchronous alternating-current machines with stationary armatures and salient-pole rotating field structures. The stationary armature (stator) is comprised of a steel core encircled by a frame that is mounted to the powerplant foundation. A 3-phase armature winding, in which the alternating current is generated, is embedded in the stator core. The three phases of the armature winding are Yconnected at the neutral end. The rotating magnetic field is typically produced via a direct current–excited winding connected to an external excitation source through slip rings and brushes. An amortisseur winding is often mounted on the rotor poles to dampen out mechanical oscillations
that may occur during abnormal conditions. The stators of hydroelectric generators usually have a large diameter armature compared to other types of generators, and can exceed 60 ft. The capacity of hydroelectric generators may range from a fraction of an MVA to more than 800 MVA.
Hydroelectric generators are typically air-cooled, although the stator windings of the highest-capacity
machines may be directly water-cooled. The electrical and mechanical design of each hydroelectric generator must conform to the electrical requirements of the power transmission and distribution system to which it will be connected and also to the hydraulic requirements if its specific plant. Such constraints have made it impossible to standardize the size or capacity of hydroelectric generators. The rotational speeds of the generator
and turbine are usually the same because their shafts are directly connected. In some cases, however, a speed increaser (gearbox) is used to enable the generator to operate at a higher speed than that of the turbine, thus permitting a smaller and less expensive generator to be used. Hydro-generators are relatively low-speed machines, typically ranging from 50 to 600 revolutions per minute (rpm).
Large diameter units with a lower hydraulic head operate at slower speeds, whereas physically smaller units with high hydraulic head operate at higher speeds. The best speed for each type of turbine is first established, and a generator is then designed that will produce 60 cycle alternating current at that speed. For a generator operating in a 60-Hz system, the rotational speed (in rpm) times the number of field poles on the rotor is always 7200. Hydroelectric generators are normally vertical shaft machines, although some smaller units are mounted horizontally.

3.3 Governors

Almost all hydraulic turbine generator units run at a constant speed. The governor keeps each unit operating at its proper speed through a high pressure hydraulic system that operates wicket gates which control water flow into the turbine. When there are load changes or disturbances in the power grid, the governors respond by increasing or decreasing power output of the generating units to meet power demands and keep the frequency of the power grid at 50 cycles. Governor-operating characteristics will be determined from the electrical, mechanical, and hydraulic characteristics of the generator, turbine, and penstock. Older governors use mechanical speed sensing and control, interfaced to the hydraulic system to govern turbine speed. Newer systems incorporate electronic or digital speed sensing and controls with a hydraulic interface to the turbine governor.

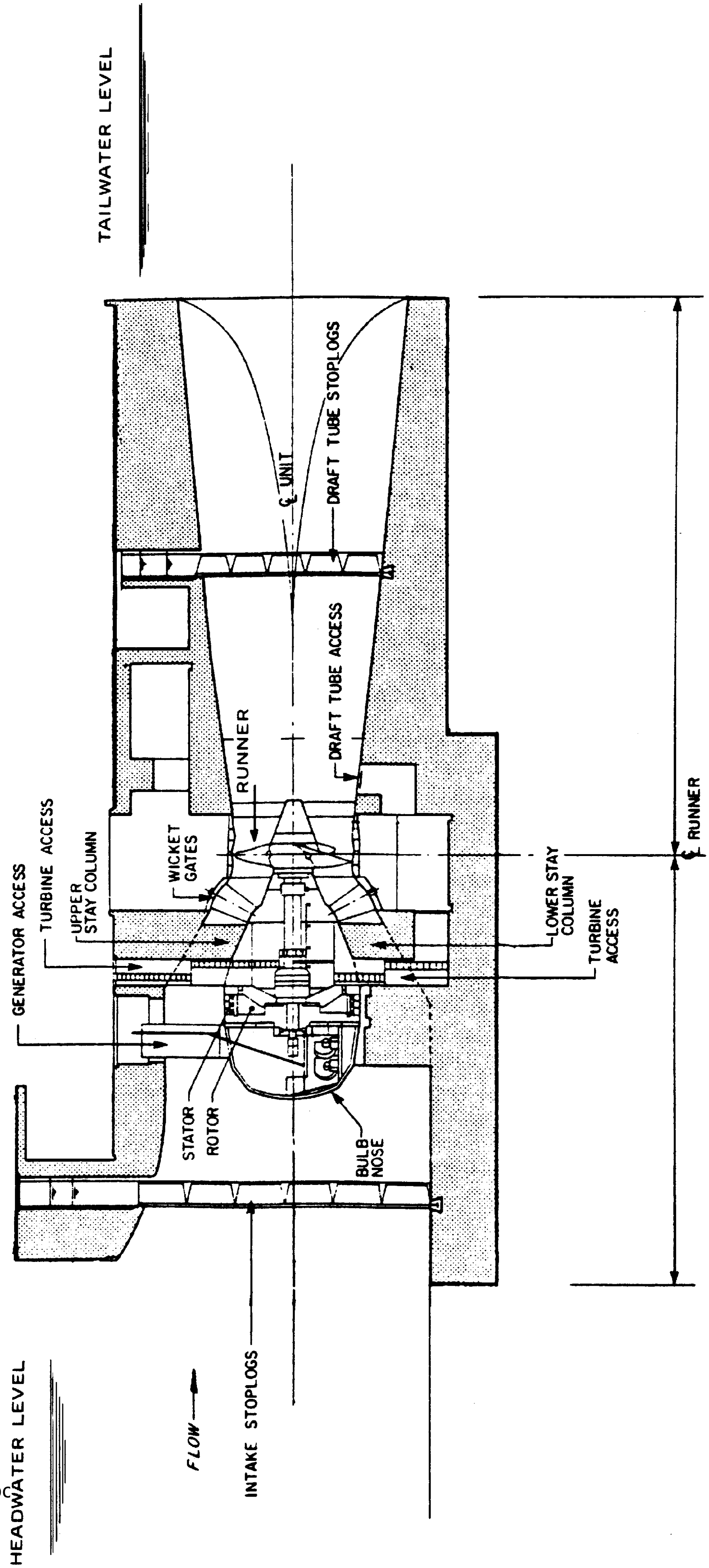

TAILWATER LEVEL
HEADWATER LEVEL
FLOW
INTAKE STOPLOGS
DRAFT TUBE STOPLOGS
℄ UNIT
DRAFT TUBE ACCESS
RUNNER
GENERATOR ACCESS
TURBINE ACCESS
UPPER STAY COLUMN
WICKET GATES
LOWER STAY COLUMN
TURBINE ACCESS
STATOR
ROTOR
BULB NOSE
℄ RUNNER

FIGURE -07 Sectional elevation of an axial-flow (bulb)

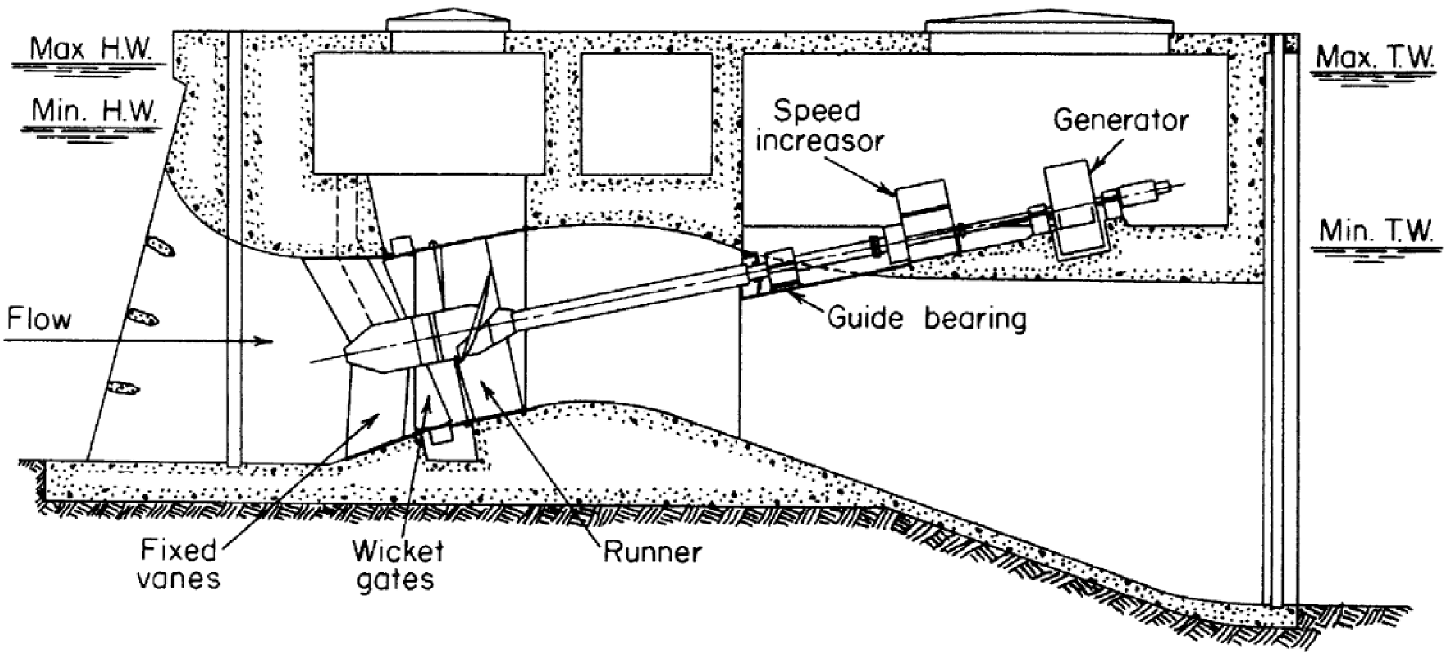


FIGURE -08 Sectional elevation of an axial-flow (tubular) turbine.

3.4 Excitation Systems

The function of the excitation system is to supply direct current to the field winding of the main generator. This current is used to create the rotating magnetic field necessary for generator action. Control of the current in the field winding must be accurate, sensitive, and reliable to allow stable and economic operation of the generator. All excitation systems include an exciter, a voltage regulator, generator voltage and current transformers, and limiters and protective circuits. The exciter may be a rotating type that is directly connected to the generator shaft or a modern static system utilizing solid-state devices fed from a high-voltage bus.

3.5 Circuit Breakers

A circuit breaker is a mechanical switching device, capable of making, carrying, and interrupting current during normal operating conditions as well as under specified abnormal conditions, such as during a short circuit. Circuit breaker ratings and location are considered during the preliminary design of a powerplant to meet the switching flexibility and protection requirements of the generators, transformers, buses, transmission lines, etc. Generators at large multi-unit powerplants are commonly configured so that a dedicated unit breaker is situated between the phase terminals of each generator and the main step-up transformer. Smaller plants may only have provision for switching via a switchyard breaker on the high voltage side of the step-up transformer, the generator and transformer being connected and disconnected to the transmission network as a unit. In some cases, circuit breakers are used to perform switching between a main and transfer bus in the switchyard. A variety of switching schemes are possible and commonly used, depending on the local requirements and economic considerations. The ratings, design, construction, and operation of circuit breakers installed at
Hydro-electric powerplants are generally similar to those used in other power system applications.

3.6 Transformers

Most dams and associated hydroelectric powerplants are located a great distance from population centers;

Therefore, the economics of transmitting power over long transmission lines must be considered. Traditionally, hydro generation has been in the medium voltage range, or about 15 kV. Power transformers step the voltage up to the 100 to 500 kV range for a more economical transmission from the powerplant by minimizing transmission line losses.
Transformers associated with hydroelectric generation may differ somewhat from those used in transmission and distribution applications. For example, it is not uncommon for a single step-up transformer to accommodate multiple hydro generators. To maintain fault isolation between generators for such a transformer-sharing arrangement, each machine may be connected to an exclusive primary winding. Multiple primary windings are often used in hydropowerplants because of the relatively small power output ratings (MVA) of a typical generating unit. Thus, a single large transformer can be sized and manufactured to meet the requirements of multiple generators, providing a substantial savings in equipment cost.

(FIGURE-09) transformer

Also unique to hydro plants is the use of the forced-oil-water (FOW) transformer cooling method. Although few, if any, new transformers are cooled this way because of environmental issues, the availability and efficiency of FOW made it the method of choice in the past. The availability and proximity to water made FOW an attractive and unique solution to step-up power transformer cooling.

4 BALANCE OF PLANT

4.1 Station Service

The station service supply and distribution system is provided to furnish power for the plant, dam auxiliaries, lighting, and other adjacent features of the project. Since hydroelectric plants are capable of starting with relatively low auxiliary power needs (compared to steam plants), they are often used to provide “black start” capability for the local transmission system. If the plant is to provide this capability, the station service system design must include an automatic start engine-driven generator to provide power to critical auxiliary powerhouse loads. This is in addition to the engine generator the plant must have to operate spillway gates and other river regulating works when offsite power is unavailable.
The complexity and operational flexibility of the station service system are related to the number of main generator units and the importance of the plant to the overall power system. Large plants with numerous

units may have two station service transformers and even dedicated station service hydro generators. Station service transformers are often fed from different main generator unit buses to allow the main units to carry station service loads upon disconnecting from the system. Smaller hydroelectric plants may have only one station service transformer and an engine-driven generator.

4.2 Switchgear

Station service systems at hydroelectric plants utilize standard metal-clad switchgear assemblies. In large plants, where the distance between the station service switchgear and the utilization equipment is large, the use of 4.16 or 13.8 kV distribution circuits is used where economically justified. Double ended switchgear, consisting of two dry-type 13.8 or 4.16 kV transformers fed from separate sources, and connected to 600 V switchgear with a normally open tiebreaker between the two sections, is often used for important load centers.


(FIGURE-10) Switchgear

4.3 Controls

Plant controls are comprised of computer-based controls, hard-wired or programmable logic, indicating and recording instruments, protective relays and similar equipments. Each generator or pair of generators often has local control panels or switchboards located near the units. For multiple unit plants, centralized controls are also used to coordinate the operation of all units within the powerhouse. The centralized control equipment is situated in a control room located at an elevation above the maximum high water levels. Centralized control is used to apportion MW and MVAR loading among multiple machines while respecting machine operating limits.


(FIGURE-11) Main control room in a plant

Small plants may not have a dedicated control room. They may have the local unit control panels integrated with the station service switchgear lineup, which usually requires additional compartments to accommodate the needed equipment.

4.4 Instrumentation

The instrumentation at hydroelectric projects has a number of unique features, most of which involve the measurement of hydraulic and mechanical parameters. There are two basic types of these parameters—performance and positional. Performance parameters include power, head, and flow. Positional parameters refer to such items as wicket gate opening, nozzle jet opening, and Kaplan blade angle position.

Head is a performance parameter that can usually be measured to a high degree of accuracy. The traditional method is by the use of stilling wells. These are vertical tubes with restricted openings under the water surface of the elevation to be measured. This restricted opening serves to dampen the effect of wave action and provides a steady water surface inside the well. Floats with counterweights or electro tapes can be used inside the stilling well to measure the water surface elevation. More modern measuring devices use radar or acoustic waves rather than stilling wells. These waves are bounced off an open water surface to measure a vertical distance between the instrument and water surface. The head measurement described above presents some challenges. Although head refers to distance or height, it is used to express the pressure resulting from the weight of a body of liquid since the weight is directly proportional to the height. Therefore, head actually represents a difference in

hydraulic energy levels. However, when water is flowing, the elevation of the water surface is not the true energy level because it does not account for the kinetic energy contained in the velocity head, $V2/2g$. Thus, measuring the elevation of a tailwater surface at a draft tube exit does not provide a correct downstream energy level. In addition, bends in the river or the operation of adjacent units may cause the head on any one individual unit to differ from the location where head is measured for the powerhouse. Thus, the location where head is measured is a unique feature of the accuracy of head measurement. Volumetric flow rate is generally the most difficult performance parameter to measure to any degree of accuracy. For projects with penstocks or at least a water passage with a constant cross section of sufficient length, there are several methods to accurately measure absolute flow. However, with large, run-of-the-river projects where the cross section of the water passage is continually changing, accurately measuring flow becomes very difficult. In such situations, relative flow may be measured instead to determine a relative efficiency. Relative flow is uniquely measured by determining

the effect that absolute flow has on another parameter that can be measured. The Winter- Kennedy piezometer system is commonly used for this purpose. This consists of two piezometer taps, one on the inside and the other on the outside of the spiral or semi-spiral case. The square root of the piezometric or pressure difference between these two taps is directly proportional to the flow rate. Therefore, a relative efficiency of the turbine-generator may be measured as $Erel$ _ kW/(H→D), where kW is the generator output in kilowatts, H is head in feet, and D is the piezometric difference, usually in feet.

With reference to the positional parameters, the actual wicket gate opening is defined as the dimension of the largest sphere that can pass between the two gates. When a turbine is unwatered, the gate opening may be calibrated with a curved scale on the wicket gate operating ring or even an angle indicator on the top of the wicket gate stems. However, in order to use a straight-line motion sensor to measure the amount of wicket gate opening, the stroke of the wicket gate servomotor reach rod is used. This measurement is often called gate opening and used directly without converting to actual gate opening, even though the two do not have a linear relation. Because of the curved shape of wicket gates, the relation between actual gate opening and servomotor stroke is a shallow “S” curve. In addition, at each end of the servomotor stroke there is an area of squeeze. This is where the reach rod is moving to take up slack in the linkages, but the gates are in contact or at their stops and

not moving. Therefore, a reading of a gate opening tends to be unique to each project. The inner oil pipe in the oil head on a Kaplan turbine is generally used as the indicating surface to measure blade angle. This provides a linear motion for a position sensor and can be calibrated from the master blade position ring on the hub when the unit is unwatered. However, each turbine manufacturer has a different trigonometric convention to define the actual blade angle. There is no industry standard or convention for this measurement. Therefore, a reading of a blade angle tends to be unique to each family of turbines in a powerhouse.

4.5 Protection

Hydroelectric plants are protected using standard generator, transformer, and distribution system protection methods and schemes. A few features or practices that may not be common to other types of plants are discussed here. On large generators, whose stator windings consist of multiple-turn coils with multiple parallel circuits per phase, split-phase differential relaying is sometimes used to provide increased sensitivity to turn-to-turn shorts. Under-frequency and over-frequency relaying is often not used, or is set very liberally compared to steam units as the hydraulic turbine and generator are not susceptible to damage due to off-nominal frequency operation. Special schemes are used to provide selectivity on isolated-phase bus ground faults in installations where multiple high resistance grounded units are tied together at the generator terminal voltage level.

.4.6 Direct Current Systems

A direct current (dc) system is used to provide independent power for auxiliary equipment and systems including controls, relaying, data acquisition, communication equipment, fire protection, inverter, generator exciter field flashing, alarm functions, and emergency lights. The DC system consists of a storage battery with its associated charger, and provides the stored energy required to ensure adequate and uninterruptible power for critical powerplant equipment. In the event of a complete loss of station service power, the dc system supplies the power needed to conduct an orderly shutdown of generating equipment which could be damaged if operated without auxiliary systems such as control power, cooling water, lubrication oil, etc. An inverter is fed from the battery for the critical alternating current loads. For plants equipped with black start capability (i.e., the ability to start up a plant when separated from the transmission system and the generators have been shut down), the dc system provides a dedicated power source for auxiliary equipment as well as field flashing of the generator exciter in order to restore a small amount of residual magnetism in the generator exciter field to allow the generator to build up voltage during start-up.

.4.7 Annunciation

Annunciation systems are used to alert someone (typically the control room operator) when a critical plant or equipment parameter falls out of tolerance and requires attention and/or action. Annunciates generally provide visual and audible signals, such as lights and flashers along with a horn, bell, or buzzer. Acknowledge and reset functions may also be provided. Annunciation systems may consist of a separate annunciator hardwired into the plant, or a software feature programmed into the central control system. Typical alarm points include turbine bearing oil trouble, unit bearing overheating, generator excitation system trip or trouble, generator cooling water flow, generator stator high temperature, governor oil trouble, transformer differential, and transformer overheating.

4.8 Miscellaneous Equipment and Systems

A wide variety of mechanical and electrical auxiliary equipment and systems may be found at hydroelectric powerplants. Of the following items, not all will be incorporated into all plants. The size, service, and general requirements of the facility will usually determine which items are needed: water supply systems for raw, treated, and cooling water; sewage disposal equipment; heating, ventilating, and air-conditioning systems; fire detection and protection systems; telephone and code call systems; elevators; intake and discharge gates and valves; penstock drainage and unwatering systems; station drainage system; air receivers for draft tube water depressing system; insulating and lubricating oil transfer, storage, and purification systems; compressed air systems for service, generator brakes, and turbine governor; emergency engine-driven generators; metal-enclosed buses, surge protection equipment; and transformer oil pumps.

.5 DESIGN ASPECTS

5.1 Criteria and Philosophy

The basic approach to designing a hydroelectric project is to first determine the rated discharge of the powerhouse. Hydrologic or other records are used to develop a historical graph of the frequency of volumetric flow rates. The flow values may be mean daily, weekly, or monthly. The period of record should be as long as possible. From this information, a flow exceedence graph is developed. This is a graph of flow versus the percent of time that a flow value exceeds. As a general rule of thumb, run-of-the-river projects (those having little reservoir storage capability) are sized to a *Q*20 and projects with storage are sized for a *Q*30. The term *Q*20 means a flow value that exceeds 20% of the time. In other words, the project could utilize all of the flow for generation 80% of the time. Similarly, *Q*30 means a flow value that exceeds 30% of the time.

Next, a design head is determined. This is different from rated head and is the head at which best efficiency is to occur. Such a determination depends on the specifics of the project, but a weighted average head is often used. With the hydraulic head and estimated hydraulic losses in the penstock, a power duration curve may be developed. Annual energy production may then be calculated from the area under this curve multiplied by an appropriate conversion factor. With the value of design head, a dimensionless parameter known as specific speed is determined from a historical experience curve of specific speed versus design head. Specific speed is defined as the speed at which a turbine would rotate if it were 1 ft in diameter and operating under 1 ft of head.

It is calculated in U.S. units as *Ns* _ *N*(HP)1/2/*Hd* 5/4, where *Ns* is the specific speed, *N* is the rotational speed in rpm, HP is the turbine output (at full gate in this instance) in horsepower, and *Hd* is design head in feet. The specific speed is used as a classifying parameter of hydraulic turbines. With the value of specific speed, the type and configuration of turbine can be determined, which historically has been found to be the best selection for the same conditions. Next, the size and number of generating units required to pass the rated discharge is determined.

Generally, a fewer number of larger units is the more economical option. For some projects, the physical size of the unit has been limited to the maximum size runner that could be shipped in one piece. This is largely due to the extra manufacturing costs involved in furnishing split runners. However, other considerations, such as flexibility of operation and minimum loss of capacity during shutdown for repair or maintenance, may dictate the use of more, smaller units.

Sometimes to achieve increased flexibility with few units, different size units are used in the same powerhouse.

5.2 Ratings

In the design of a hydroelectric plant, the generating equipment is first sized and then afterwards it is rated. Sizing refers to selecting the physical size of the equipment. Generally, hydrologic considerations of head and flow provide the basis for the determination of the type, number of units, runner diameter, setting, and synchronous speed of each hydraulic turbine selected for a particular project. Then the generator is sized to match the turbine speed and expected output at a selected head. Once the equipment is sized, it can then be rated. However, the rating is done in the reverse order. First, the purchaser usually specifies the temperature rise criteria from which the manufacturer then rates the generator. The generator is rated in terms of kVA and power factor. It is a standard practice to set such thermal limits to that power output which causes no more than a 60 or 80°C temperature rise above ambient in the generator windings. It is a “soft” limit in that it can be physically exceeded.

However, this can have a detrimental effect on the operational life of the insulation. Converting this generator output rating into a generator horsepower input gives the rating of the turbine. However, the actual turbine rating is not in units of horsepower, but in units of feet of head. This is because as head is increased a turbine can produce more power. This head is usually the net head, or the same head as used to develop the turbine performance characteristics. Therefore, the rating of a turbine is actually the lowest net head at which the turbine can drive the generator to produce its rated electrical output. This is a unique point, with the wicket gates full open. Therefore, it is also a “hard” limit since the turbine cannot physically produce more power unless the head is increased. As a consequence, if the turbine and generator are procured separately, it is not the turbine manufacturer but the purchaser who actually establishes the turbine rating. The discharge at this rated head is referred to as rated discharge.

There are a couple of notable alternatives to this rating procedure. Some owners equate the turbine rating to the generator nameplate rating at unity power factor, regardless of the nameplate power factor. This is referred to as the generator *capacity*. Seeking to reduce the cost of procuring hydroelectric generators, a number of years ago some purchasers began rating their turbines at 115% of the generator nameplate rating at nameplate power factor. They then specified that the generators must be capable of “continuous operation” at 115% of rated generator output. In other words, they rated a turbine at the generator’s overload rating and then specified the generator overload rating the way the regular nameplate rating is usually specified. (The turbines were also required to be able to produce an output of 115% of generator nameplate at unity power factor, at a higher head, without exceeding mechanical limits.) Today, the standard procedure is to use the full overload rating as the nameplate rating.

5.3 Speed Settings

Although some extremely small hydraulic turbines may power induction generators, most turbines are directly connected to synchronous ac generators. As a consequence, the speed of rotation must agree with one of the synchronous speeds required for the system frequency. The prevailing frequency for most systems in the United States is 60 Hz. In Europe and certain other parts of the world, 50 Hz is used. Synchronous speeds are determined by the formula, N= 120 X frequency (in cycles per second) / number of poles in the generator. The number of poles must be an even number since the poles are in pairs.

The need to rotate at a synchronous speed means that the turbine is constrained to rotate at a single speed as the hydraulic conditions of head and stream flow vary. This is a major constraint unique to the design of hydropower, negatively affecting the efficiency and smooth operation of the turbine.

The speed should be as high as practicable since this decreases the cost of the turbine and generator. The proper selection of the synchronous speed is usually done with reference to the specific speed of the hydraulic turbine. As defined in Sec. .5.1, specific speed is calculated as $Ns= N(\mathrm{HP})^{1/2}/H_d^{5/4}$.

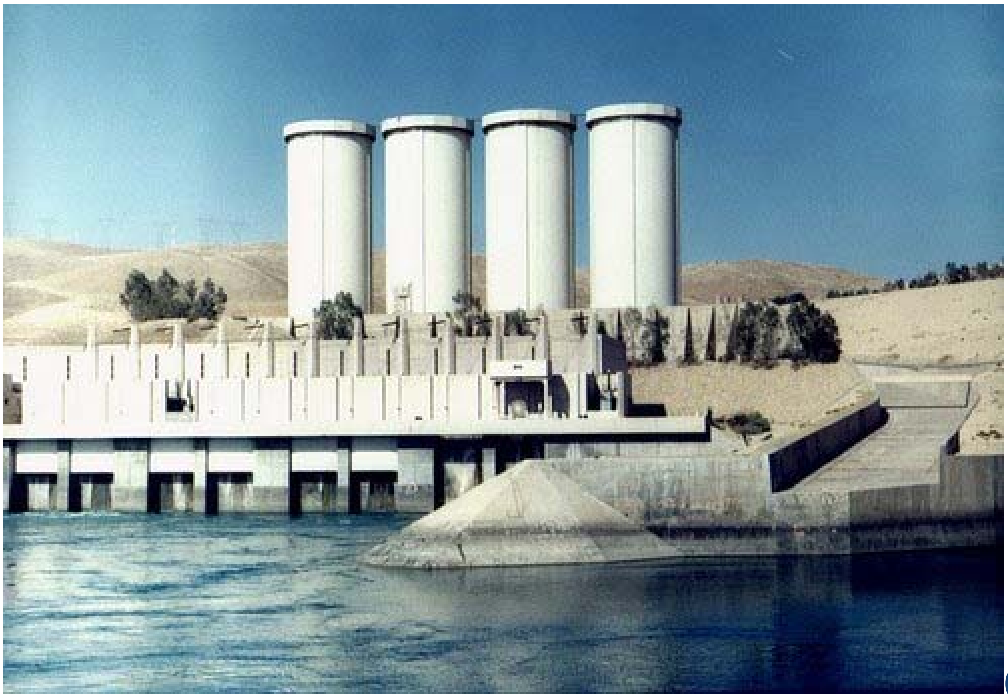
However, in this calculation, the turbine output value is the horsepower at peak efficiency at design head rather that at full gate at design head. With the values of turbine output and design head, and the turbine specific speed at peak efficiency, a trial rotational speed is calculated. This is usually rounded up to the next higher synchronous speed, and the turbine output at peak efficiency recalculated. If the turbine output at either peak efficiency or full gate or rated discharge is not as desired, the size of the turbine is changed and the speed calculation repeated.

5.4 Water Hammer and Mass Oscillations

Water hammer is a transient pressure phenomenon that can occur in moving water in a closed conduit. If there is a change of velocity, for example, due to the closing of a valve, pressure waves are created that travel up and down the conduit. Upstream of the closing valve, the fluid is progressively decelerated and compressed, causing a positive pressure transient to travel upstream. Once this wave reaches an open surface, it is reflected back toward the valve as a negative pressure wave. When it reaches the valve, it will be reflected again. This process is repeated time and again until the wave is attenuated by friction. On the downstream side of the valve, the transients are reversed with a negative wave initially traveling downstream. The greater the distance between the valve and an open surface, the higher the peak magnitude of the pressure rise. The pressure waves travel at the speed of sound or the acoustic velocity called the celerity, which is given the symbol “a.” The celerity varies
depending on the conduit boundaries, the static pressure, and the water temperature (and salinity), but is typically on the order of 2000 to 3000 ft/s.

The water passages of a hydroelectric project must be designed to withstand both the maximum positive and negative pressure transients to prevent potentially catastrophic damage to the valves or rupture of the penstock. The magnitude of the maximum transients can be controlled by the design of the dynamic elements. For example, the maximum rate of valve movement, such as the rate at which the wicket gates of a

turbine can move, can be controlled by limiting the size of the oil ports in the servomotors. Slower gate closure, however, results in higher generator overspeed when an electrical load is lost.
The magnitude of pressure transients can also be mitigated by surge tanks, accumulators, or quick acting pressure relief valves.


(FIGURE-12) Surge tanks

A surge tank has an open surface. Consequently, it provides a partial negative return wave and acts to shorten the effective length *L* of the conduit. There are a number of different types of surge tanks, such as the simple riser, restricted riser, differential, etc. The more the flow is restricted in either or both entering and leaving the surge tank, the less the pressure transients are mitigated, but the more hydraulically stable the surge tank. An accumulator does not have an open surface, but has an enclosed dome of air or gas. The quick acting valves operate in a manner analogous to safety valves.
A separate but related phenomenon to water hammer is mass oscillation. Rather than a wave within the fluid, this term denotes the actual movement or velocity of the fluid. Consequently, it is much slower and, therefore, separated from pressure transients on a time basis. Using a surge tank as an example, if the turbine wicket gates start to close, a positive pressure wave is transmitted upstream. Part of that wave continues upstream to the reservoir water surface, but a part also reaches the free surface of the surge tank and is reflected back as a negative wave. As the initial positive wave reaches the riser of the surge tank, it causes part of the flow still coming downstream to be diverted up into the surge tank and the elevation of the water surface in the tank starts to rise. Consequently, the deceleration, $\updownarrow dV/dt$, of the flow upstream of the tank is not as rapid, which serves
to mitigate the magnitude of the pressure transient upstream from that point. Another example of mass oscillation is the separation of the water column. If a valve is closed very rapidly in a high velocity flow, the momentum of the fluid downstream of the valve can cause the fluid column to separate at that point. As can be imagined, this can have dire consequences.

.6 OPERATIONAL CONSIDERATIONS

6.1 Runaway Speed

Runaway speed is the maximum rotational speed to which a generating unit can be driven with an open circuit breaker and the available hydraulic and mechanical conditions. The term usually refers to a fixed wicket gate opening, and in the case of Kaplan turbines, a fixed blade angle. During a load rejection, the water column continues to provide energy to the turbine runner. Since this energy can no longer be converted into electrical energy, a portion is mechanically stored and the rest is dissipated in turbulence before being discharged from the turbine. The energy is stored via increased angular momentum of the turbine runner, shaft, and generator rotor. The total amount of energy that can be stored is a function of the rotating inertia, or *WK*2, and the increase in rotational speed.

If the wicket gates do not move to a closed position, the speed will increase until limited by hydraulic conditions, windage, and friction. The hydraulic conditions include the available head, the turbine's performance characteristics such as off design efficiency, and cavitation, which can reduce the efficiency of the energy transfer. Windage refers to air resistance, mostly in the generator, and friction refers to mechanical "sliding" friction. Ultimately, the decreased amount of fluid energy that can be transferred from the water column is balanced by the increased windage and friction, at which point runaway speed is achieved. The higher the head, the larger the wicket gate opening, or the flatter the blades on a Kaplan turbine, the higher the runaway speed. For this latter reason, the blades on Kaplan turbines are often designed to tilt to their steepest position on loss of governor control. Francis and Kaplan turbines have different runaway speed characteristics. Francis turbines typically have less *WK*2 than Kaplans and, therefore, achieve runaway speed faster. At runaway speed, Francis turbines tend to "choke" the flow, reducing the discharge. Kaplans, on the other hand, tend to increase the flow with increasing speed at a given gate and blade angle. On Kaplan turbines, oncam

runaway speed is achieved if load is rejected, the gates do not move, and the blades are at the proper cam position for the gate opening and head and do not move. If the blades move to any other position without moving the gates, it is referred to as off-cam runaway speed. Also with Kaplans, maximum runaway discharge is when the blades are full steep.

If the wicket gates are free to move and the unit is under governor control, a shutdown sequence is initiated upon load rejection. However, since the wicket gates take a finite time to close, a transient increase in synchronous speed, known as overspeed, is achieved. In order to limit this overspeed, the wicket gates should close as quickly as possible. However, the faster they close, the higher the pressure transient of water hammer that is sent back upstream. For this reason the rate of closure, called the gate-timing element, is a compromise between overspeed and water hammer. The peak overspeed can be reduced by increasing the inertia of the rotating parts. Normally, the maximum design overspeed is 150% of synchronous speed.

6.2 Cavitation

Cavitation is a phenomenon involving the creation of bubbles containing water vapor. It occurs when the local pressure is reduced to or below the vapor pressure of water. Literally, the water boils, but at low temperature. The formation of vapor-filled bubbles is more likely to occur under conditions of high flow velocity (such as high rpm operation or high flow rates) and low pressure (such as low tailwater). Cavitation occurs in reaction hydraulic turbines, but not in impulse turbines whose runners are vented to atmospheric pressure. Minimum pressures in reaction turbines tend to occur at the trailing edge on the underside or suction side of blades or buckets. As these bubbles are carried downstream, back to higher-pressure areas, they collapse or implode. These implosions generate extremely high pressure pulses, sufficient to pit and erode the surfaces of the hardest steels. There are many types of cavitation including leading edge, areal, traveling, leakage, etc. Cavitation damage reduces turbine-operating efficiency and, if left unchecked, can lead to severe damage and extensive

repairs. Most types of cavitation, but not all, can be lessened or eliminated by increasing the submergence of the turbine runner.

Model tests are primarily used to check turbine runner, wicket gate, draft tube, casing, and sometimes inlet work designs for optimum performance. They are also used to predict the conditions under which cavitation will occur. However, their predications have a degree of uncertainty because cavitation is actually 2-phase flow and the same hydraulic model cannot have similitude with both a liquid and a gas phase. The result is that a model prediction of cavitation is usually biased. That is, if the model shows cavitation at a certain condition, the prototype will definitely cavitate at that same condition. However, if the model does not cavitate, the prototype may still experience cavitation. For this reason, turbine designers try to maximize the amount of safety margin.

Aside from submergence, controlling cavitation is best achieved through design of the runner so that velocities at critical areas do not lower the static pressure to the vapor pressure. Other control methods include welding an overlay of a cavitation-resistant material on the base metal. Sometimes, special anticavitation fins are added to turbine blades on propeller type turbines to minimize blade tip cavitation. The injection or aspiration of air bubbles has been used to cushion the action of the pressure pulses.

6.3 Turbine Efficiency

The formula for turbine efficiency is developed from the definition of fluid power. If the volumetric flow rate *Q*, in cubic feet per second (ft3/s), is multiplied by the specific weight of water *g*, in pounds (force) per cubic foot (lbsf /ft3), the weight flow rate *gQ*, in lbsf /s, passing through the turbine is obtained. This term may then be multiplied by the head *H*, in feet. (Technically, head is called the specific energy *E* and has units of ft-lbsf /lbsf .) The resulting expression, *gQH*, has units of ft-lbsf /s and represents the power available in the fluid column. Dividing this expression by 550 ft-lbsf /s per horsepower gives the power in the fluid column in units of horsepower. Since this expression represents power "in," dividing it into the horsepower "out" of the turbine yields the turbine efficiency

$E = HP/(\quad QH/550)$

If the combined turbine-generator efficiency is to be calculated, the formula may be changed to

$Et\_g = 1.3411(kW)/(\quad QH/550)$

where kW is the generator output in kilowatts.

In selecting the type of turbine for a given hydroelectric powerplant, it is important to consider the efficiency performance of the various types of turbines available for the head contemplated. Not only is this true for the value of the maximum efficiency obtainable, but also for both the percentage of full load where this maximum efficiency occurs and the efficiencies at part loads and at full load (Fig. -13).

Impulse turbines are usually a couple of percent less efficient than comparable reaction turbines. However, because of their ability to use multiple jets, they can have a flat efficiency profile over a very wide power range.

Francis turbines can have among the highest peak efficiencies. However, their runners have no mechanical adjustment and, therefore, their profiles are sharply peaked with efficiencies degrading significantly at part loads. Fixed blade propeller turbines also can have high peak efficiencies, but like Francis turbines, their profiles are sharply peaked. This latter feature is modified by Kaplan turbines, which are propeller turbines with adjustable blades. As head and flow conditions change, the pitch angle of the blades can be adjusted to maintain

a relatively flat efficiency profile over a wide range of power and head. However, Kaplan turbines do have slightly reduced peak efficiencies due to increased leakage around the ends of the blades.

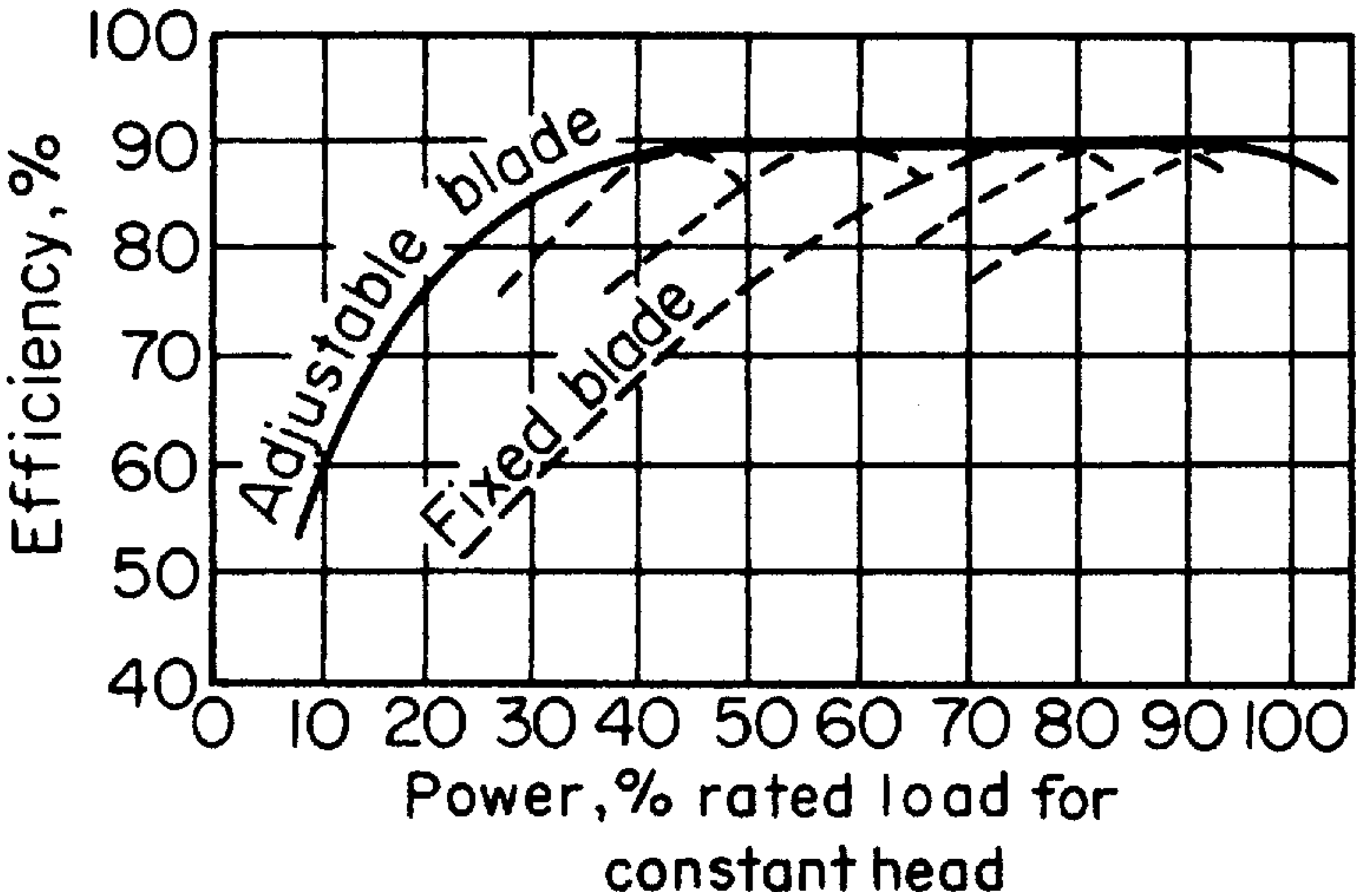


FIGURE -13 Efficiency-load relations for fixed and adjustable-blade propeller turbines.

6.4 Operating Limits

Hydroelectric projects often operate under a number of different limits or constraints. These limits may affect either generating capacity or generating efficiency, and usually originate from one of three sources—physical, contractual, or regulatory.

Physical limits are those imposed by the physical characteristics of the generating equipment or the hydraulics. For example, the maximum output of the generator may be limited such that the temperature rise above ambient within the generator insulation does not exceed a specified value. The output of the turbine may be limited to avoid operating in zones where draft tube surging occurs. Such surging causes a fluctuation in power output. The head may be limited to a minimum value to prevent the forebay from being low enough to allow air to be drawn into the penstock through a vortex at the intake. Contractual limits are imposed by the procurement specifications of the equipment. They usually apply while the equipment is under the manufacturer's warranty. For example, the specifications may limit the turbine output as a function of head to avoid cavitation damage while the turbine is under warranty. The majority of operating limits are regulatory in nature. The hydropower licensing procedure described in the following section provides ample opportunities for the imposition of operating limits.

These limits are of two types—static or time varying. An example of a static limit is a project that is in the path of ocean bound juvenile anadromous fish which may be restricted to operating within 1-percent of peak turbine efficiency during migratory seasons. (Water turbulence is at a minimum at peak turbine efficiency and, therefore, fish survival is thought to be increased.) An example of a time varying limitation is a limit on the ramp rate or the rate at which the generated power level may be changed. Such a limit may be imposed to prevent varying the elevation of the tailwater too rapidly.

6.5 Regulatory Requirements

Hydropower is regulated through three legal venues—water rights, state regulatory permits, and federal licensing. Water rights are required on all hydropower developments in the United States. These are administered through state statutes, which vary greatly from state to state. In addition, individual states have various other legal requirements, involving consultations with state agencies and permits.

Thye US Federal regulation of hydroelectric power began in 120 when Congress enacted the Federal Water Power Act and established the Federal Power Commission (FPC) to administer the Act. In 177, as part of the Department of Energy Organization Act, Congress created the Federal Energy Regulatory commission (FERC), which assumed most of the FPC's hydro regulatory responsibilities.

This commission has jurisdiction over nonfederal development of hydropower projects, constructed after 120, which meet one or more of the following criteria:

- Occupy in whole or in part lands of the United States.
- Are located on navigable waters in the United States.
- Utilize surplus water or water power from government dams.
- Affect the interests of interstate commerce.

A project's connection to the electrical grid, with transmission lines that cross state boundaries, is considered to be engaged in interstate commerce. Consequently, the vast majority of hydroelectric projects in the United States are subject to FERC jurisdiction.

Often, the first step in the licensing process is to obtain a preliminary permit from FERC. A permit simply reserves the site to the permit holder during the investigation and application phase. Permits are usually issued for a 2-year period, with extension to a third year available. Although a permit provides for a priority advantage in obtaining a fully approved license, under the FPC, municipalities are given preference to hydropower sites.

There is a provision in the licensing process called an exemption. This term may be a misnomer for it does not mean exempt from the licensing process. To achieve an exempt status, an application must still be made. Exemptions are granted to projects meeting certain criteria. One such criterion is that of a project on a man-made conduit, such as at a drop in an irrigation canal. An exemption is granted in perpetuity with no need to apply for an exemption at some future time. If a site is jurisdictional and ineligible for an exemption, it is necessary to proceed with a formal application. There are two types of licenses. A minor license is for projects under 5 MW, and a major license is for those over 5 MW. Obtaining a license requires a number of different types of studies, consultations with a number of different agencies, preparation of a license application, and can be expensive and time consuming. An FERC license conveys to the license holder the right of eminent domain. Licenses are issued for a specified period of time, usually ranging from 30 to 50 years.

Typically, new projects are issued 50-year licenses to offset major capital investments into the project. Any significant change to a project, particularly one affecting the aquatic environment, requires a reopening of the existing license. A change in generating capacity that uses more or less water can have an effect on the aquatic environment.

.7 UNIQUE FEATURES AND BENEFITS OF HYDRO

.7.1 Water Resources

Hydroelectric power generation is only one of several potential benefits of river resources development.

Multipurpose hydropower projects also provide flood control, flow augmentation, irrigation, municipal water supply, navigation, and recreation opportunities. Hydropower plants convert about 0% of the energy in falling water into electric energy. This is much more efficient than fossil-fueled powerplants, which lose more than half of the energy content of their fuel as waste heat and gases.

Hydropower is free of fossil fuel emissions and does not contribute to air pollution, acid rain, or global warming. Furthermore, no trucks, trains, barges, or pipelines are needed to bring fuel to the powerplant site. The earth's hydrologic cycle provides a continual supply of water from rainfall and snowmelt, making hydropower one of the most economic energy resources. And because hydropower is especially suited for providing peaking power, hydroelectricity complements thermal generation and improves overall power production efficiency. Hydro resources often allow utilities to delay or forego construction of additional peaking capacity.

7.2 Ancillary Services

Ancillary services comprise the resources and functions (excluding basic generation and transmission capacity) required to support the transfer of electrical energy from generating sources to loads while maintaining reliable operation of the interconnected transmission system. There are several critical ancillary services, which hydro generators are especially effective in providing. These services include the following:

Reactive Supply and Voltage Control. The provision of reactive power from generation sources to support transmission system operations, including the ability to continually adjust transmission system voltage in response to system changes. This service is required to maintain voltage control and stability. Hydroelectric generators, operating in synchronous condense mode, are capable of producing reactive power up to the nameplate capacity of the unit.

Regulation. The provision of adequate generation response capability. Under automatic generation control, supply resources are continuously balanced with minute-to-minute load variations. This service is required to maintain frequency at scheduled values and to help ensure that instantaneous tie line deviations do not cause degradation of transmission system reliability.

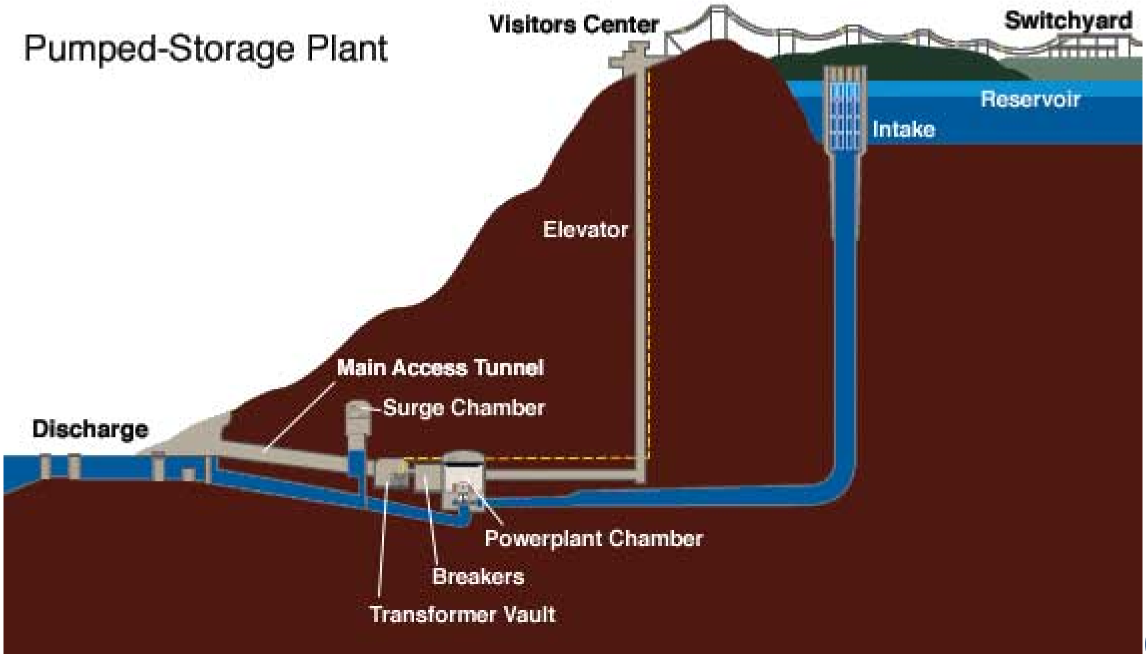
Spinning Reserve. Generation capacity is synchronized to the system but is unloaded and able to respond immediately to serve load in case of a system contingency. Capacity is fully available within 10 minutes.

Black Start. The ability of a generating unit or station, during a system restoration, to go from a complete shutdown condition to an operating condition and start delivering power without assistance from the electric system. Requires a dedicated power source for auxiliary equipment and the ability to create own field in exciter. Only required in areas that may become isolated.

.7.3 Pumped Storage

Pumped-storage plants differ from conventional hydroelectric projects. In a pumped storage scheme, the power station is located between an upper and a lower dam. During periods of high electrical demand, the plant is operated in generating mode. Water is released from the upper dam through the station's turbines and into the lower dam where it is stored. During periods when demand for electricity is low, the machines are put into pump mode to pump water from the lower dam back into the upper dam where it is stored until the station needs to generate again. Pumped storage schemes are net consumers of electricity.

Early pumped storage projects involved separate pumps and turbines. Since the economics of pumped storage favor the highest possible head, configurations included both single and multiple stage pumps and turbines. Sometimes separate motors and generators and even separate penstocks were used. Eventually, reversible pump turbines, in which the pump and turbine are the same machine, were developed. These are not turbines, but are actually pumps with centrifugal impellors, that when operated in the reverse rotational direction are capable of generating as turbines. The design process of selecting a pump turbine is similar to that of a conventional turbine. One factor of note is that specific speed for a pump is calculated from a different formula, $Ns=N(Q)^{1/2}/ H^{3/4}$,, where in U.S. units Ns is specific speed, N is rotational speed in rpm, Q is pump discharge
in gallons per minute, and H is total dynamic head in feet.



(FIGURE-13)

It is an inherent characteristic of reversible pump turbines that the peak efficiency in the generating mode occurs at a slower rotational speed than in the pumping mode. Therefore, unless a more costly 2-speed motor-generator can be used, the selected single, synchronous speed is a compromise
speed. Thus, neither the turbine nor pump can operate at their individual peak efficiency. Another factor in this compromise selection of synchronous speed is that the turbine peak efficiency is usually higher than the pump peak efficiency. This is because a pump has additional internal losses including “recirculation” losses. Additionally, the shape of the efficiency profile for the pump mode is more sharply peaked than for the turbine mode.

Generally, a pump turbine needs to spend more time out of a 24-h period in the pumping mode than in the generating mode for the same water exchange. This ratio is referred to as the *duty cycle.* For example, if a pumped storage project pumps for 16 h in order to generate at rated capacity for the remaining 8 h, it is said to have a 16-h duty cycle.

.8 ENVIRONMENTAL CONCERNS

8.1 Fish Passage

Addressing the environmental impact on rivers and maintaining a balance with the plants, fish and wildlife that also depend on the river has never been more difficult. Depending on the particular site of a hydroelectric project, providing for the passage of upstream and downstream migrants can be an important factor. While it may not be a factor for such sites as drops in man-made irrigation canals, it is a critical factor at sites on rivers with anadromous and catadromous fish. Anadromous denotes fish, such as salmon, that mature at sea, but return to fresh water to reproduce. Catadromous are the opposite in that they mature in fresh water, but reproduce at sea, such as certain types of eels.

Hydroelectric projects at such migration sites are usually required to be designed with specific upstream and downstream passage facilities.

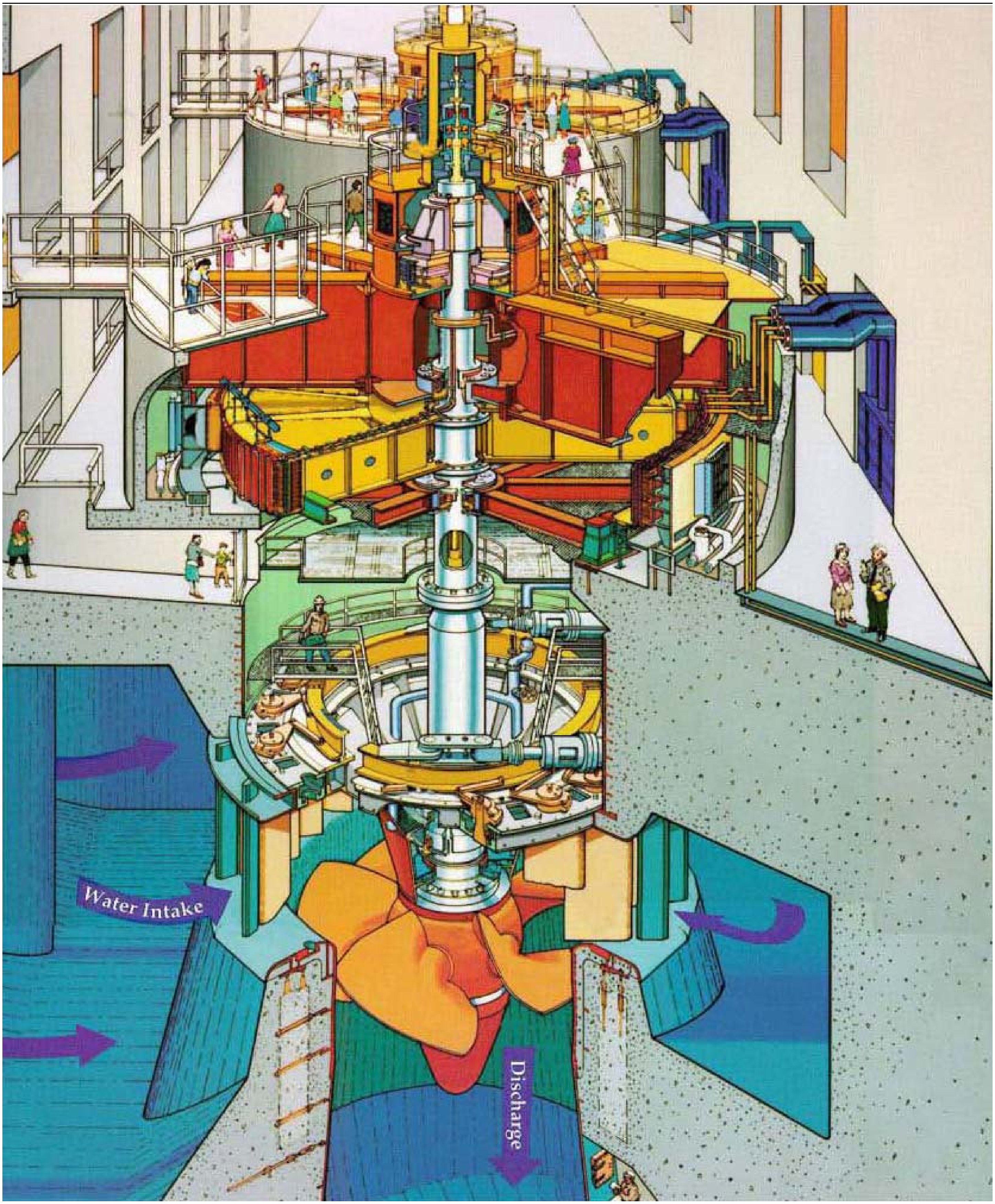


FIGURE-14 Safer Turbine for fishes

There are several different types of passage facilities for upstream migrants. The most common is a fish ladder. This is an open surface, shallow gradient, conduit with a series of small plunge pools to dissipate the hydraulic energy from the forebay to the tailwater. However, there are different designs of fish ladders for different migrant species. Salmon will climb the ladder by jumping the weirs connecting each plunge pool. However, shad will not jump, but will climb ladders that have small holes cut in the each weir at the bottom of the each plunge pool. Often extra water is released directly from the forebay as a submerged jet at the entrance to the fish ladder. This is referred to as "fish attraction water." At some powerhouses, overflow weirs are constructed along the entire downstream length for fish to migrate into and be channeled into the fish ladders. Another design of an upstream migrant facility is a fish elevator. In this design, a "crowder" is used to gather the fish into an elevator bucket that is hoisted up to the forebay elevation.

For downstream migrants, there are also a number of design options. One of the oldest is to simply open the gates on controlled spillways during the migratory season as a "fish flush." Another is to collect the downstream migrants, such as at fish hatcheries, and transport them by barges around the hydroelectric projects. Still another option is to install fish screens in the intakes to divert fish from going through the turbines, but into channels that carry them around the powerhouse. There are several different types of fish screens, including submerged bar, extended submerged bar, traveling, etc. Fish screens do disrupt the hydraulics within a turbine and decrease its overall efficiency. A unique type of fish screen called the Eicher fish screen is a wedge wire screen installed downstream of the intake in a penstock. Named after the inventor, George Eicher, it is a self-cleaning screen. This self-cleaning is achieved by simply tilting the screen on horizontal pinions so that the downstream side faces upstream.

Downstream migrants most commonly encounter lower head projects with propeller turbines. For the downstream migrants that do pass through the turbine water passages, five mechanisms of injury have been categorized and studied: strike, grinding and abrasion, decompression, shear and turbulence, and cavitation. For properly submerged lower head projects with propeller turbines, the latter three causes of injury are not as important as the first two. Consequently, to minimize strike, and grinding and abrasion, a unique design of Kaplan runner called a minimum gap runner has been developed. In this design of runner, overhangs and recesses in the runner hub hydraulically hide gaps between the inner edge of the blades and hub, and spherical rather than cylindrical cavities form the discharge ring.

.8.2 Water Temperature

The presence of a hydroelectric project can improve or degrade the temperature of the aquatic environment.

The increased cross section of a forebay or upstream reservoir of a project acts to slow the velocity of a natural river. This tends to decrease the mixing of the vertical water column and leads to stratification. Limnologists, who scientifically study bodies of fresh water, classify this stratification into three distinct layers. Upper most is the epilimnion, where the water is warmed by sunlight. Then at a depth, where sunlight no longer penetrates, there is a thermocline, where the temperature drops rapidly. Below that is the layer of cooler water called the hypolimnion. During the summer months these layers tend to be well defined. However, in winter this distinction tends to fade and may even reverse with the upper layer becoming the coolest and sinking to the bottom. Hydroelectric projects can be designed to mitigate this temperature stratification or even improve

the downstream effect of natural impoundments by two basic approaches. The first is to cause the mixing of the vertical water column. Bubbler hoses can be placed along the bottom of the reservoir to develop air curtains that set up vertical circulation patterns. Large, unhoused, mixing propellers can be used in a similar manner. Fountain-like aerators can be used to spray water from near the bottom of the reservoir into the air.

The second basic approach is to selectively withdraw water from different elevations in the reservoir into the powerhouse intakes. One way this is done is by designing thermal withdrawal towers with foundations that rest on the bottom of the reservoir. These towers have gated ports at different elevations. The water from different reservoir elevations tends to mix inside the tower before entering the penstock. A similar design is to retrofit thermal withdrawal enclosures around conventional powerhouse intakes. These also have gated ports at different elevations and the water from the different elevations tends to mix in the intake. Such structures allow hydroelectric projects to even improve the natural environment, particularly, by discharging cooler water from the bottom of the reservoir in summer.

Aside from the biological factors, water temperature has a minor effect on generation. Temperature, along with elevation and latitude, determines the specific weight of water. The heavier the water, the more electricity that can be generated by a given quantity. Typically, fresh water has a specific weight in U.S. units of about 62.4 lb/ft3. If this value is divided by the local acceleration of gravity g, in feet per second squared, the value of the density of water is obtained in slugs per cubic foot.

.8.3 Dissolved Oxygen

Hydroelectric projects can affect the dissolved oxygen (DO) content of their aquatic environment in both beneficial and detrimental ways. Among other things, DO is one of the best indicators of the health of a water ecosystem. In a natural body of water, decrease in the dissolved oxygen levels is often an indication of an influx of some type of organic pollutant. The rate at which oxygen is depleted, usually measured over a 5-day period, is the biological oxygen demand (BOD). Oxygen is consumed by plants and animals during respiration and by aerobic bacteria during the process of decomposition. As a consequence, oxygen consumption is greatest near the bottom of a reservoir, in the hypolimnion, where sunken organic matter accumulates and decomposes. Conversely, oxygen is produced by direct absorption from the atmosphere, by plant photosynthesis or is obtained from inflowing streams. Since photosynthesis requires sunlight, and the air/water interface is at the surface, the higher concentrations of DO are found in the higher elevations of a reservoir, in the epilimnion.

Physically, DO can range from 0 to 18 parts per million (ppm), but 5 to 6 ppm are needed to maintain a diverse biota population. DO concentration is most affected by water temperature. Cold water can hold more of any gas than warmer water. The DO concentrations may vary significantly at any time and place due to a number of factors besides temperature, such as barometric pressure, elevation, salinity, season, time of day, wind, and reservoir depth. Another atmospheric gas that can be of concern is nitrogen. Unlike oxygen, nitrogen is biologically inert. However, it is capable of existing in a supersaturated state for a long period of time. If

the gas is in sufficient excess, it can cause a potentially lethal condition, known as “fish bubble disease.”

This condition, similar to the bends in divers, is caused when nitrogen comes out of solution in the tissues of fish. Rivers can become supersaturated with nitrogen where the hydraulic jump at the base of spillways entraps large amounts of air in deep pools. If these deep strata are not exposed again to the atmosphere, such that the nitrogen can be “cleansed,” it will go into solution. This tends to happen when the tailwater is not free flowing, but is the reservoir of the next downstream hydroelectric project.

Although a powerhouse can do little relative to preventing oxygen depletion in the reservoir or nitrogen supersaturation in the tailrace, it can improve the environment by significantly increasing the DO level of the discharge. The most common method is by aspiration of atmospheric air immediately downstream of the runner of a reaction turbine. The area under the runner at the start of the draft tube is at a low pressure, usually sub-atmospheric. This is by design to maximize the pressure differential across the runner in order to maximize efficiency. However, by installing air pipes or using existing piping, such as vacuum breakers, atmospheric air can be drawn in or aspirated into that area. Some of the atmospheric oxygen will go into solution and increase the DO of the discharge.

The amount of DO increase depends on the water temperature, the ratio of flow rates of air to water, the size of the air bubbles, the distribution of the air in the cross section of hydraulic flow, and the contact time before the bubbles are vented to the surface of the tailwater. This aspiration process does increase the pressure under the runner and this decreases generating efficiency. Another method to increase DO is to inject commercial oxygen into the powerhouse intake. This is done only rarely because of the expense. Still another method is to use air bubbler hoses laid along the bottom of the reservoir.