SECTION 3.5

HYDRAULIC TURBINES

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INTRODUCTION

Hydraulic turbines convert potential energy to mechanical energy, which can be used as the prime mover for various types of machines and generating equipment. A generator converts the mechanical energy to electric energy. The amount of energy that can be converted depends on the available head, flow, and efficiency of the hydraulic turbine. Mechanical energy can be calculated by the following equations:

English units:

$$P = \frac{HQ\,\omega\,\eta}{550} = \frac{HQ\eta}{8.81}$$

where P = turbine output, hp [the trend is to adopt kW for turbine output (1 hp = 0.7457 kW)]
H = net head, ft
Q = turbine discharge, ft^3/s
ω = weight of water (standard conditions) = 62.4 lb/ft^3
η = turbine efficiency

Metric units:

$$\text{kW} = \frac{HQ\,\omega\,\eta}{102} = 9.8HQ\eta$$

where kW = turbine output, kW
H = net head, m
Q = turbine discharge, m^3/s
ω = weight of water (standard conditions) = 1000 kg/m^3
η = turbine efficiency

In the above equations, the following efficiencies at rated output are representative conservative values that may be used for planning and estimating in the absence of information for the selected turbine:

0.93 for Francis and propeller turbines
0.90 for Pelton and tubular turbines

Proportionality laws for homologous hydraulic turbines are shown in Table 3.5.1.

TABLE 3.5.1 Proportionality Laws*

Constant head	Constant runner and diameter	Variable runner, diameter, and head
$P \propto D^2$	$P \propto H^{3/2}$	$P \propto D^2H^{3/2}$
$n \propto \dfrac{1}{D}$	$n \propto H^{1/2}$	$n \propto \dfrac{H^{1/2}}{D}$
$Q \propto D^2$	$Q \propto H^{1/2}$	$Q \propto D^2H^{1/2}$

*P = turbine output, hp (kW)
D = runner discharge diameter, ft (m)
n = turbine rotating speed, rpm
Q = turbine discharge, ft^3/s (m^3/s)
H = net head, ft (m)

TYPES OF HYDRAULIC TURBINES

Modern hydraulic turbines evolved from crude waterwheels to today's sophisticated modern designs which were developed to accommodate a wide range of heads, flows, and operating conditions. The Francis turbine was developed by James B. Francis in the mid-1800s. The Pelton turbine was first produced in the late 1800s and is named for its developer, Lester Pelton. The fixed-blade propeller turbine was introduced in the early 1900s, and later came the adjustable-blade "Kaplan," named after Victor Kaplan, the developer of both versions. The Deriaz or diagonal turbine was developed by Paul Deriaz in the 1900s. The straight-flow type of turbine and rim generator concept was patented by Leroy F. Harza in 1919 (the modern version of this concept is manufactured under the trade name Straflo). Tubular-, bulb-, and pit-type turbines were developed in the mid-1900s. The determination of the turbine type is made in consideration of expected unit-load regulation, head and flow variations, powerhouse arrangement, headwater source and power conduit, geological conditions, necessity for a surge chamber or pressure-relief device, plant capability needed, and comparison of construction costs.

The typical range of application for the various turbine types in relation to head, flow, and output is presented in Fig. 3.5.1. The applications that each type of turbine can accommodate overlap. Consequently, for conditions in this overlap range, more than one type of turbine may be suitable. The actual operating ranges are continually being extended with the advancement of turbine design technology.

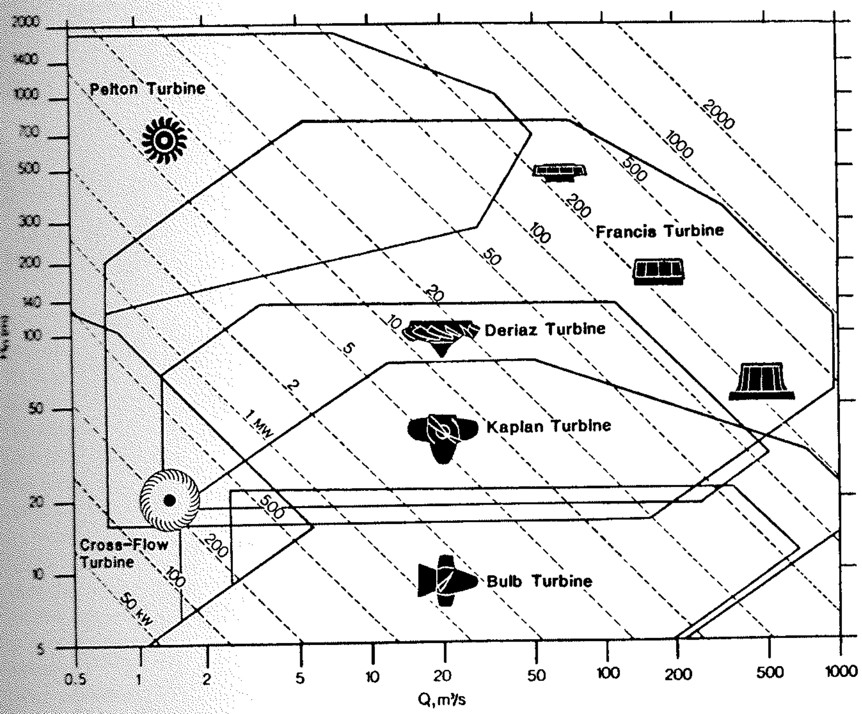

FIGURE 3.5.1 Typical range of applications for the various turbine types in relation to head, flow, and output. (*Sulzer-Escher Wyss. Ltd.*)

Hydraulic turbines are classified into two broad categories as either *reaction* (pressure type) with continuous water column from headwater to tailwater or *impulse* (pressureless type). Reaction turbines are driven by the difference in pressure between the pressure side and suction side of the runner blades. Impulse turbines are driven by one or more water jets directed tangentially into the buckets of a disk-shaped runner rotating in air. Hydraulic turbines are also classified by head: low head, below 100 ft (30.5 m); medium head, 100 to 1000 ft (30.5 to 305 m); and high head, 1000 ft (305 m) and higher. The most discriminating classification is by the type of runner and configuration of the turbine water passage. The major types of turbines are described next along with their unique features, advantages, and normal application.

Reaction Turbines

Reaction turbines are provided with a concrete semispiral case, or steel spiral case or water distributor housing, a mechanism for controlling the rate of flow and for distributing the flow equally to the runner inlet, a runner and shaft, and a draft tube for regaining part of the kinetic energy.

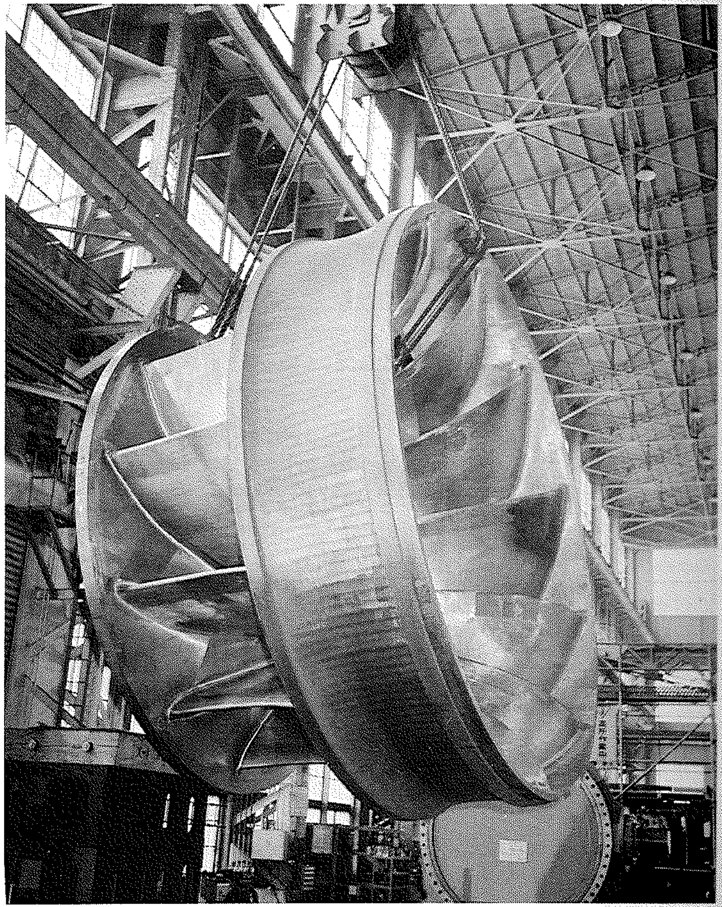

FIGURE 3.5.2 Francis turbine runner rated at 200 MW. (*Toshiba Corp.*)

Francis Turbine. The Francis type of turbine (mixed flow) was initially developed for medium-head applications; however, the head range has continually been extended with the advancement in technology (Fig. 3.5.2). The runner has multiple fixed scoop-shaped blades attached at the top to the runner crown and at the bottom to the runner band. The runner's geometry and dimensional proportions vary with its specific speed, as shown in Fig. 3.5.3. The efficiency of a Francis turbine remains relatively good down to approximately 40 percent of rated load.

Propeller Turbines. Propeller-type turbines (axial flow) were developed for relatively low-head applications. The propeller runner theoretically may have from 3 up to 10 radial blades that may be fixed or movable; however, the majority of modern propeller-type turbines have runners with three to six blades, which experience has proved to be practicable and the most favorable design range for current practice (Fig. 3.5.4).

The fixed-blade propeller turbine has a slightly higher (0.2 to 0.5 percent) peak efficiency than the adjustable-blade Kaplan turbine, because of the reduced blade-tip clearance and smaller runner hub size. However, its efficiency peak is narrower than that of the Kaplan turbine. The Kaplan turbine usually has the mechanism in the hub, which allows the blade tilt to be changed automatically with respect to the wicket gate opening while the unit is operating. A cam in the governor (mechanical or electronic) correlates the blade tilt with the gate position. The adjustable-blade runner optimizes the gate and blade position, which enables operation in its high-efficiency zone over a broad range of operating load and head conditions.

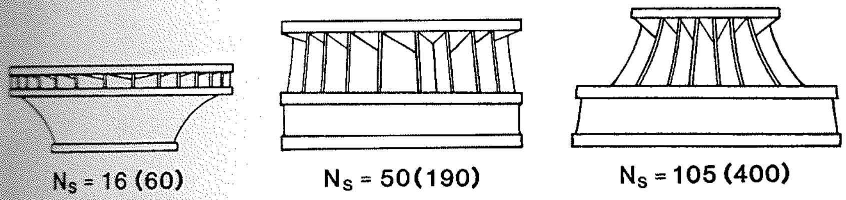

FIGURE 3.5.3 Francis runner geometry and dimensional proportions with respect to changing specific speed.

Tubular Unit. The turbine runner for the tubular unit is of the propeller type (Fig. 3.5.5). The tubular or S-type turbine is classified by its water passage configuration from the intake to the draft tube, which is S-shaped and allows the generator to be located outside the water passage. The generator may be oriented vertically or horizontally or may be inclined, and it may be direct-driven or driven at a higher speed by means of a speed-increasing gear drive. The speed increaser allows a higher operating speed and thus a smaller (and usually less expensive) generator. The tubular turbine

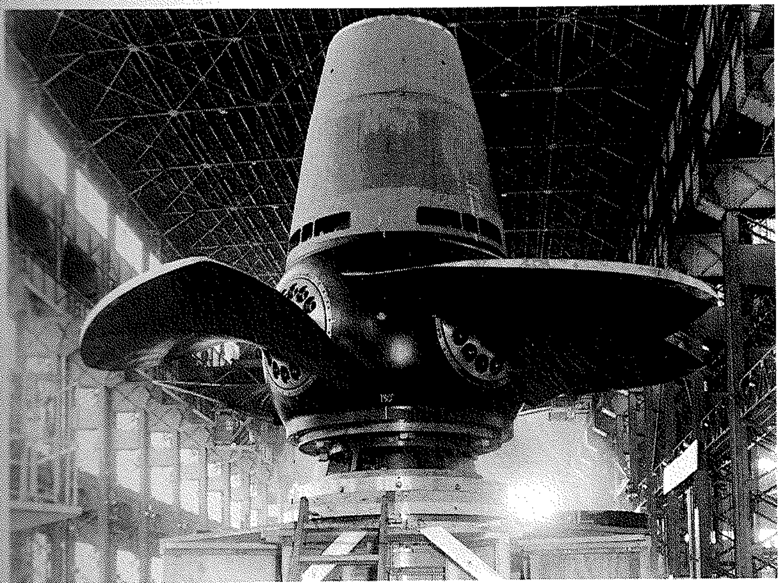

FIGURE 3.5.4 Kaplan adjustable-blade runner rated at 26.8 MW. (*Fuji Electric Co., Ltd.*)

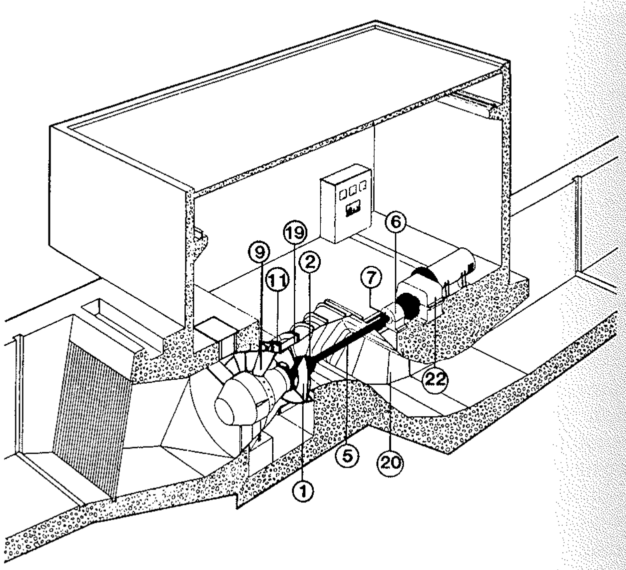

FIGURE 3.5.5 Typical tubular-type turbine arrangement. (*Voith Hydro, Inc.*)

water passage excavation is shallow and therefore much less than that required for the vertical-type turbine.

Bulb Unit. The bulb unit also utilizes a propeller-type turbine runner (Fig. 3.5.6). The bulb-type turbine configuration and arrangement locate the generator inside a watertight housing (or bulb) in the water passage. The powerhouse for a bulb unit is usually integral with the dam with a straight draft tube. The submerged and enclosed configuration makes access to the turbine and generator less inviting—with the exception of the turbine runner. The degree that accessibility to the internal parts is affected by the bulb configuration is related to physical size and whether the bulb is of the pressurized design. Inherent in the bulb unit configuration is that the mechanical inertia of the generator's rotating parts is much lower than that of a vertical unit, even with the maximum additional mechanical inertia that can be built into the machine. Consequently, the bulb unit has an inherent disadvantage for isolated operation or where a high degree of unit stability is required for speed regulation. The low inertia of the bulb unit can be compensated to some degree by the use of modern hydraulic turbine governors and a power system stabilizer (PSS).

Straflo Turbine. The Straflo turbine is designed so that the rim of the generator rotor is attached directly to the periphery of the blades of a propeller turbine runner (Fig. 3.5.7). A dependable water seal must be provided at the edge of the rotor rim, to separate the rotor poles and stator from the water passage. The water passage configuration is essentially the same as for a bulb turbine, except for external mounting of the generator. Unlike in the bulb unit generator, the mechanical inertia in the generator of the Straflo unit is equivalent to that of a conventional type of turbine generator. Consequently, the Straflo can overcome the disadvantages of the bulb unit with respect to stability and regulation.

Deriaz Turbine. This turbine (mixed axial flow) is to the Francis turbine what the Kaplan is to the fixed-blade propeller; both the Deriaz and the Kaplan configurations are

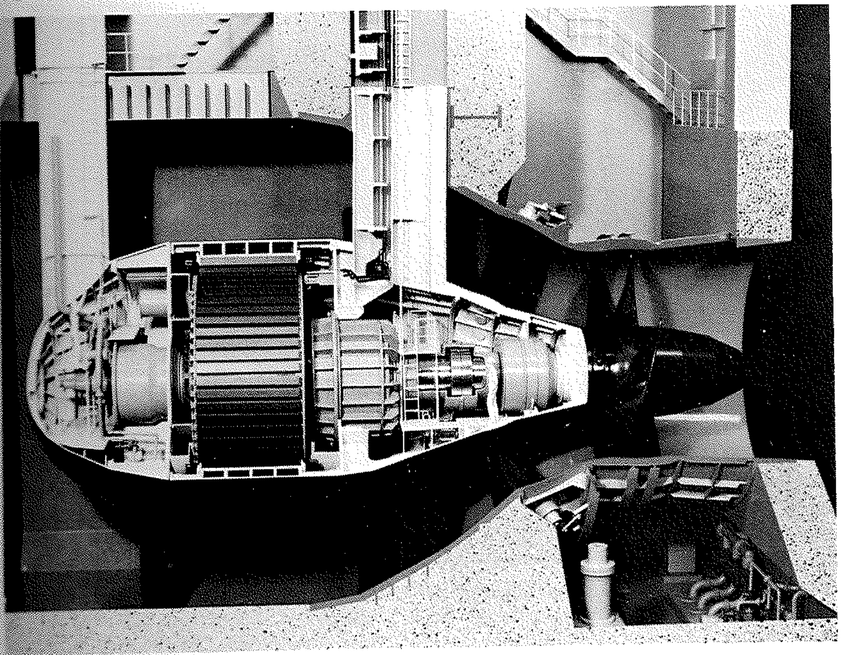

FIGURE 3.5.6 Bulb-type turbine. (*Hitachi, Ltd.*)

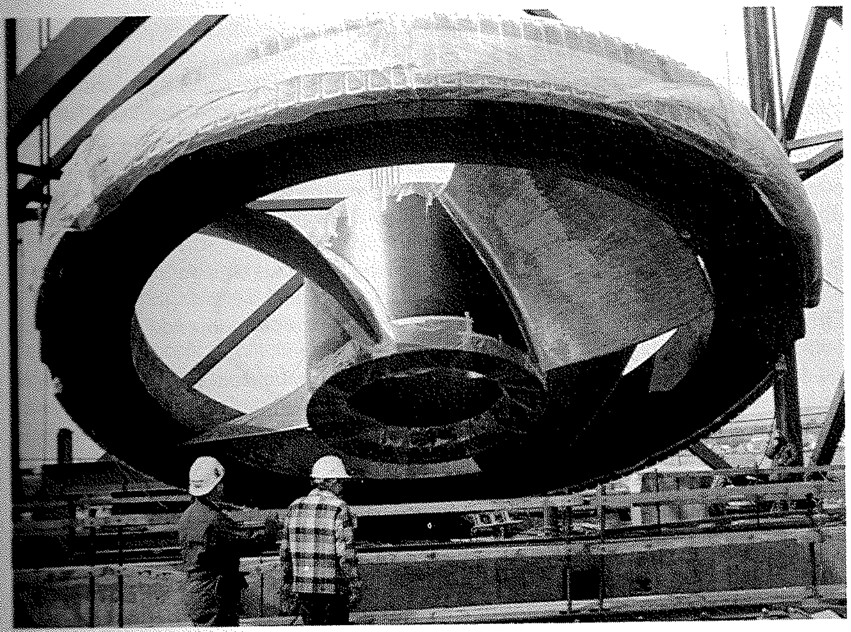

FIGURE 3.5.7 Straflo turbine. (*Sulzer-Escher Wyss. Ltd.*)

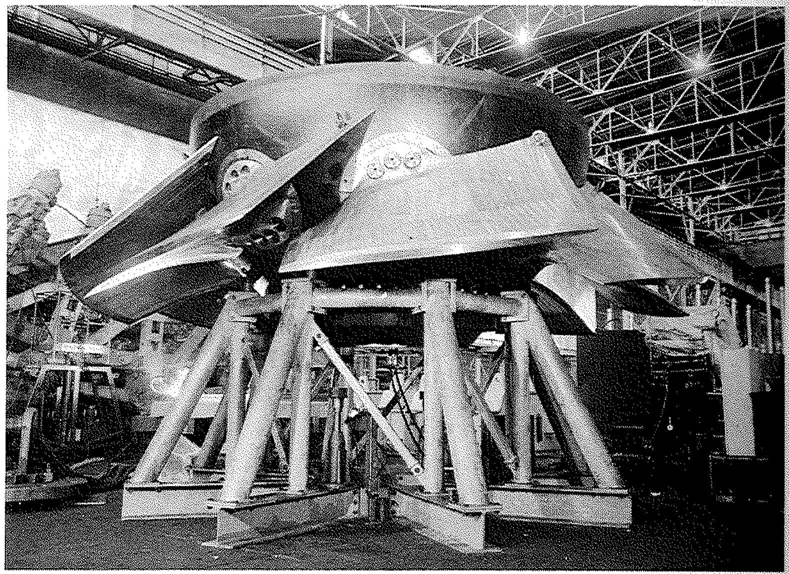

FIGURE 3.5.8 Deriaz pump-turbine runner rated at 41.7 MW. (*Voest-Alpine International Corp.*)

capable of having either adjustable or fixed blades (Fig. 3.5.8). The Deriaz adjustable-blade turbine can provide high efficiency over a broad load and head range, as can the Kaplan turbine; however, its peak efficiency may be slightly lower (1 percent) than that for a Kaplan or Francis turbine. The Deriaz turbine design has a lower specific speed, lower runaway speed, lower hydraulic thrust, higher plant sigma (cavitation coefficient), and higher operating head range than does a Kaplan turbine. Due to the hub blade configuration, a Deriaz turbine has a higher efficiency at part-load operation than a Kaplan does. Another characteristic of the Deriaz turbine is the reduced discharge at overspeed (or choking of the flow), as is characteristic of a low-specific-speed Francis runner. Deriaz-type turbines can also be designed for reversible pump-turbine service.

Pump-Turbines. A pump-turbine combines the functions of a pump and a turbine in a single machine. The stationary components of the machine are similar to those of a turbine but the impeller-runner is basically a pump impeller designed to also operate in reverse as a turbine.

A pump-turbine converts potential energy to mechanical energy in the turbine mode, and it converts mechanical energy to potential energy in the pump mode. The energy equation for the turbine mode is identical to that shown for turbines in the introduction of this section. The energy equation for the pump mode is the same at that for the turbine mode, but the efficiency term (pump efficiency in this case) is moved from the numerator to the denominator of the equation. The pump efficiency is 0.92 for planning and estimating purposes.

There are two types of pump-turbines: nonreversible and reversible. Nonreversible-type pump-turbines have seen relatively little operation and have not gained wide acceptance. The primary type of pump-turbines in operation today is the reversible type which

operates in one direction as a pump and in the opposite direction as a turbine. Pump-turbines are classified into three principal types analogous to reaction turbines and pumps:

Pump-turbine type	Approximate head range, single-stage machines
Radial-flow or Francis	75–2620 ft (23–800 m)
Mixed-flow or diagonal-flow	35–250 ft (11–76 m)
Axial-flow or propeller	3–45 ft (1–14 m)

The diagonal-flow and propeller types are subdivided into fixed-blade and adjustable-blade types. Pump-turbines are also classified according to the number of stages (single or multiple stages) and according to the orientation of the main shaft (vertical or horizontal).

The reversible Francis-type pump-turbine is the most widely used type in the industry today. The impeller runner has fewer blades than a Francis turbine runner, and the blades usually wrap from throat to tip diameter by more than 90°, sometimes up to 180°. The ratio of tip to throat diameter of a reversible impeller runner is substantially larger than that for an equivalent turbine runner. The relatively large tip diameter is approximately equal to that of an equivalent pump impeller and approximately 1.4 times that of an equivalent Francis turbine runner. Because of the comparatively large tip diameter of the impeller runner, the reversible Francis pump-turbine inherently has a lower runaway speed than a Francis turbine. Its runaway speed is generally on the order of 80 percent of that of the corresponding turbine. A further significant characteristic inherent in the hydraulic design of medium- to high-head (low-specific-speed) Francis pump-turbines is their decrease in discharge with increase in speed above synchronous speed, which can cause substantial water-hammer effects when runaway speed is reached in installations involving long water conduits.

Pump-turbines require considerably deeper settings in relation to minimum tailwater than conventional hydraulic turbines, because head losses associated with flow through the suction-draft tube in the pumping direction act to decrease the available net positive suction head, and the pump-turbine impeller is generally more sensitive to cavitation than hydraulic turbine runners designed for the same specific speed. Figure 3.5.9 shows a typical transverse section of the Rocky Mountain pumped storage powerhouse.

The economics of pumped storage generally require that the pump-turbines have a high efficiency both as a pump and as a turbine. It is also desirable, from the standpoint of design and cost of the generator-motor, that the pump-turbine have the same speed of rotation in both directions of operation. However, the hydraulic design of reversible pump-turbines with fixed blades is such that the point of best efficiency occurs at a higher value of the peripheral-speed coefficient when pumping than when operating as a turbine. This means that, for operation of such machines at a single rotating speed, the head for pumping should preferably be lower than the head for operation as a turbine. Unfortunately, except in unusual installations, the effect of head losses in the penstock and related water supply and discharge conduits is such that, for a given gross head, the total pump head will generally be higher than the net head during turbine operation by approximately twice the head losses for flow in one direction. However, through careful hydraulic design of reversible machines with fixed blades, the difference in heads required for optimum efficiency in both modes of operation at a single speed can be reduced appreciably. By use of adjustable blades, the best efficiency points for pumping and generating can be substantially brought together.

For those pump-turbines which must operate over a large range of heads, or where the pumping heads are considerably higher than the generating heads, two-speed operation to allow the maximum efficiency points for both cycles to be utilized may be jus-

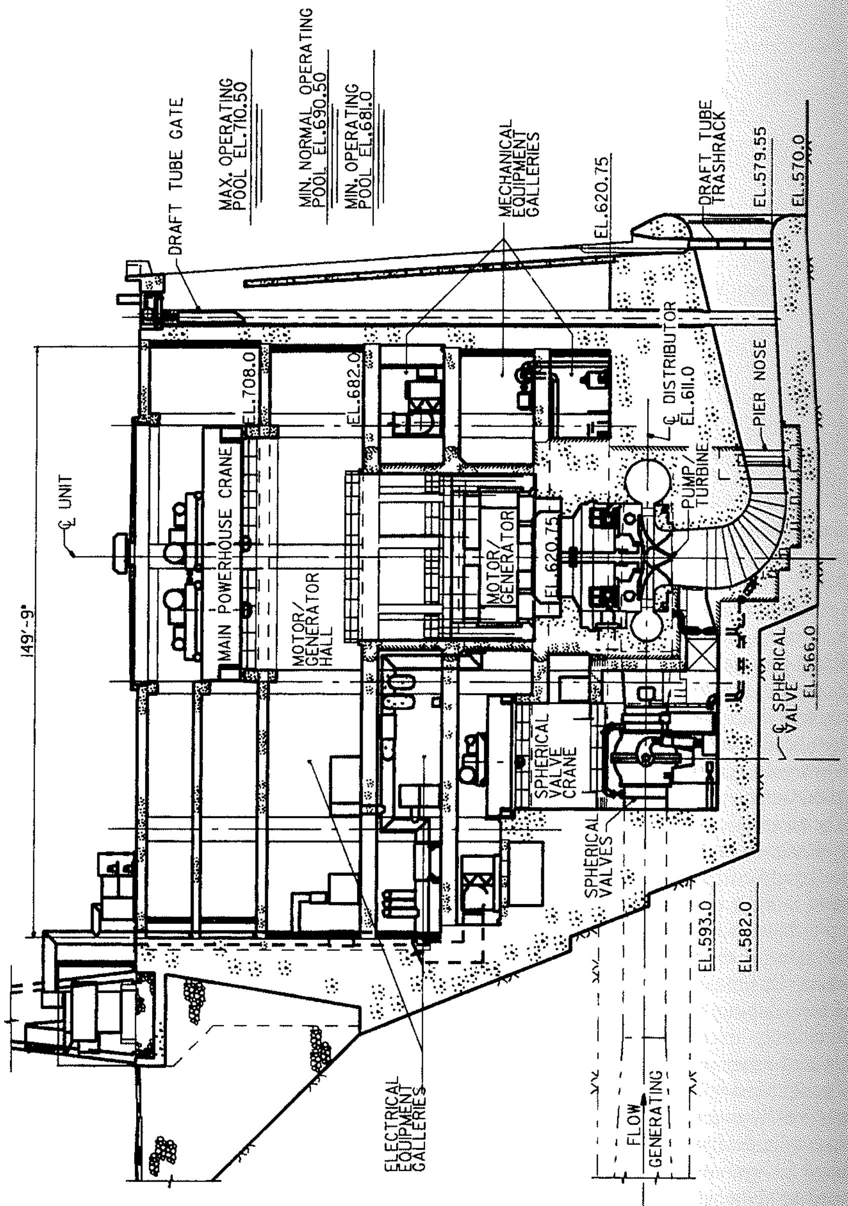

FIGURE 3.5.9 Powerhouse transverse section of Rocky Mountain pumped-storage project. (*Oglethorpe Power Corporation, GA*)

tified. Specially designed two-speed synchronous generator-motors, which electrically change the effective number of poles for generator and motor operation, have been developed for pump-turbine application.

Adjustable-speed motor-generators, which can vary the rotating speed of the unit in both the motoring and generating modes, have recently been developed, and several large prototypes have been placed into successful operation. These machines have the capability of varying the unit speed approximately plus or minus 10 percent, which permits varying the pump input at a given head. It also permits an increase in efficiency in the generating mode, and it provides improved performance over the operating head range.

Impulse Turbines

Impulse turbines are provided with a water distributor pipe and nozzles (jets), a mechanism for controlling the water jets to the runner, and a runner rotating in air.

Pelton Turbine. The Pelton turbine is designed for high-head application and has one or more nozzles, up to a maximum of six (Fig. 3.5.10). It can be arranged for operation with a single nozzle or multiple nozzles. The nozzles of a Pelton turbine are directed tangentially into the center of the runner buckets. Horizontal arrangements are typical for small units with one or two nozzles, while vertical arrangements are used for large, modern high-power units. Water is conducted and distributed to the nozzles by a spiral distributor pipe. The nozzles are fitted with adjusted needles to control flow; in addition, each nozzle can be provided with a fast-acting jet deflector to deflect the jet from the runner in the event of large load changes or emergency conditions. The deflector control feature is especially useful on long high-head penstock arrangements; it allows large changes in load without creating pressure changes in the penstock. Water discharges from the Pelton runner directly into the discharge pit and flows to the tailrace. Pelton impulse turbines discharge to the atmosphere and therefore do not regain any kinetic energy from the flow downstream of the runner.

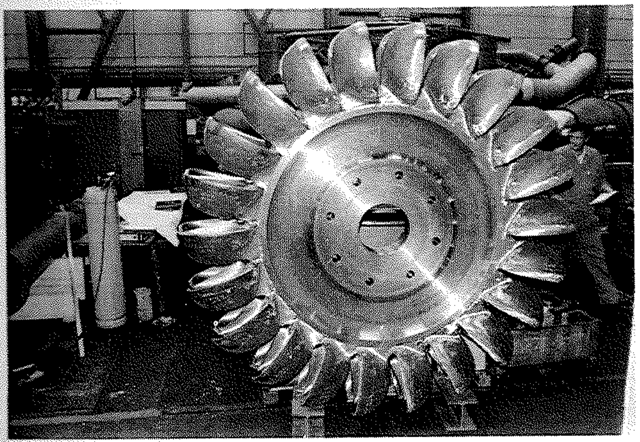

FIGURE 3.5.10 Pelton turbine runner rated at 34.2 MW. (*Sulzer-Escher Wyss, Ltd.*)

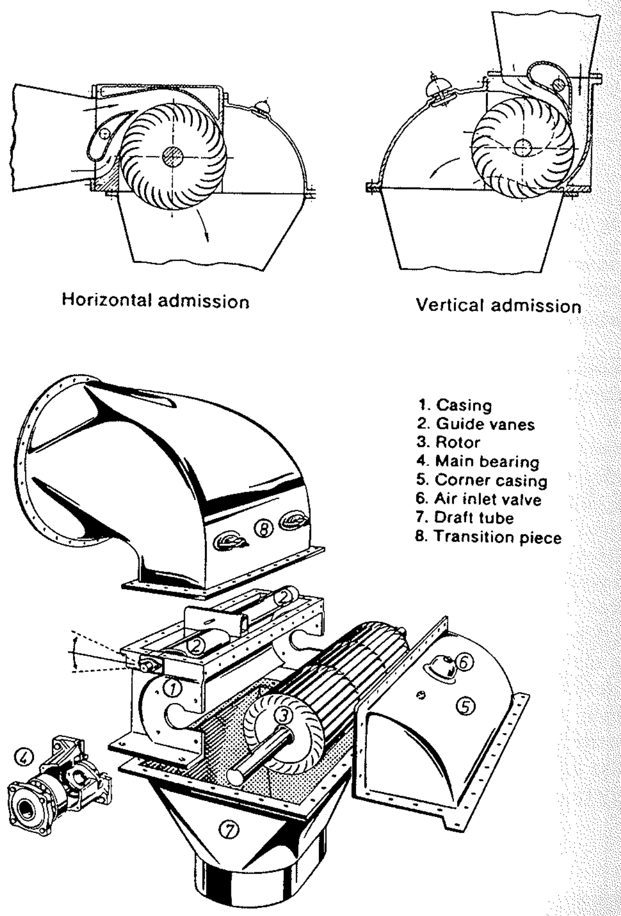

FIGURE 3.5.11 Cross-flow turbine with horizontal and vertical admission arrangement. (*Ossberger Turbines, Inc.*)

Cross-Flow Turbine. The cross-flow turbine is a variation of the impulse turbine that is sometimes described as a radial, impulse-type turbine with partial flow admission (Fig. 3.5.11). In the cross-flow turbine, the water flow path makes two passes through the runner. Flow is regulated by guide vanes, allowing the turbine to operate over a wide range of flows. Cross-flow units up to 1000 kW and heads up to 600 ft (183 m) are in service.

Turgo Turbine. The Turgo is an impulse-type turbine similar to the Pelton wheel, except that the jet enters the runner bucket and discharges free from obstruction of the buckets (Fig. 3.5.12). The Turgo impulse turbine has a higher specific speed than the Pelton unit. Turgo turbines with outputs up to 7500 kW and heads up to 770 ft (235 m) are in service.

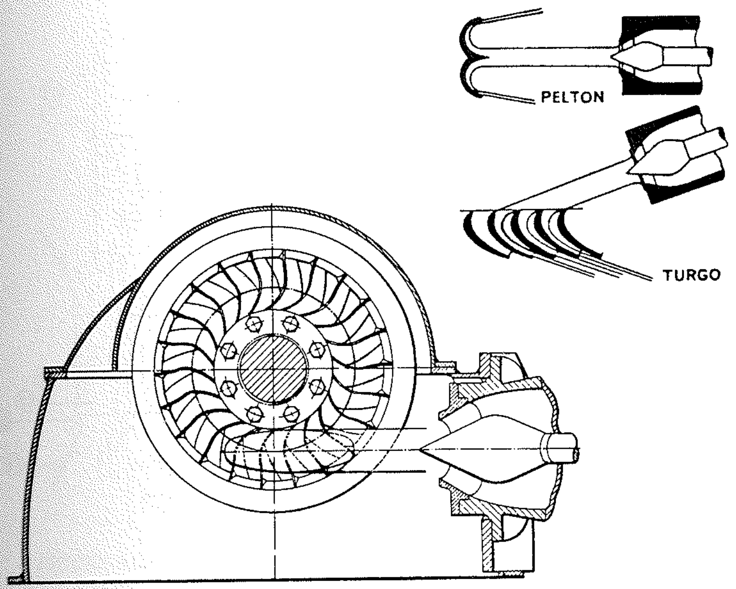

FIGURE 3.5.12 Comparison of Turgo and Pelton impulse turbines. (*Gilbert Gilkes & Gordon, LTD.*)

MAJOR TURBINE COMPONENTS

Component Definitions

The principal components of hydraulic turbines are defined in the following paragraphs. Each definition is preceded by an identification number that also appears on one or more of the accompanying drawings to assist in identifying the component (Figs. 3.5.13 to 3.5.19).

Runner Components

1. *Runner.* This is the rotating element of the turbine that converts hydraulic energy to mechanical energy. Francis-type runners consist of multiple contoured blades connected on one end by the runner crown and on the other end by the runner band. Pelton runners consist of buckets connected radially to the periphery of a disk, and propeller runners consist of blades attached to a hub.

2. *Runner cone.* This is the extension of the runner crown or hub that guides the water as it leaves the runner.

3. *Runner seals.* These are close-running clearances located between the rotating crown and the stationary head cover, and the rotating band and the stationary bottom ring. These close clearances restrict leakage from the high-pressure zone to the lower-pressure zones, which affects efficiency and hydraulic thrust.

4. *Runner wearing rings.* These rotating and stationary rings form the runner seals, which are usually designed for either one or both to be removable and replaceable.