Propeller or the Deriaz turbine. Peak efficiencies are similar. Poor part load efficiency not only leads to loss of output but also indicates danger of wear due to incorrect blade angles.

(*c*) **Quality of Water.**—The selection of an Impulse turbine, as against a Francis wheel is influenced by the presence of abrasive matter in the water. The efficiency of a Francis wheel may be impaired by damage to its rather elaborate sealing arrangements (see p. 961 and Fig. 23), whereas a Pelton Wheel will continue to operate successfully even after considerable wear has occurred, and worn parts are more readily replaceable.

(*d*) **Runaway Speed.**—Generating units are designed to withstand full 'runaway' speed although this adds to the generator cost. Runaway speeds are given below:

Runner type	Runaway speed % of normal speed	Remarks
Pelton Wheel	175%	Speeds stated are for rated net head
Turgo Wheel	180%	
Francis	180—190%	
Propeller, fixed	200—250%	
Propeller, feathering	250—300%	'Off-cam' runaway, i.e., runner vanes and guide vanes not linked.
Propeller, feathering (with anti-racing brake)	170—200%	'On-cam' runaway speed 25% lower
Deriaz	200%	

It will be seen that some of the economy due to the higher operating speed of the Fixed or Feathering Propeller is offset by a higher runaway speed. This can be limited by means of a hydro-brake (see Bibliography, ref. 7).

(*e*) **Hydraulic Thrust.**—The thrust bearing for a Propeller runner is more heavily loaded than that for the corresponding Francis runner, and is therefore more expensive.

IMPULSE TURBINES

Definition.—In an impulse turbine the water is supplied to the runner at atmospheric pressure, possessing kinetic energy only. The flow through the runner is entirely at atmospheric pressure, the force exerted by the water being due to changes in the direction of flow only.

THE PELTON WHEEL

This is the most common form of impulse turbine now manufactured. Pelton turbines are in operation under heads as high as 5,800 ft. (Reisseck, Austria. See Appendix A). A single wheel, single jet machine with an output of 60,000 h.p. has been built. This turbine has the exceptionally high specific speed for a single jet of 4·7 r.p.m. at 3,380 ft. (Avise plant, Italy. See Appendix A). A multi-jet set delivering 140,000 h.p. is in service. (Kemano station, British Columbia. See Appendix A). Efficiencies reach 90%.

The turbine consists essentially of a nozzle or nozzles directing a jet of water onto a number of buckets attached to the periphery of the runner (Fig. 5). The buckets are symmetrical relative to the centre line of the jet, having a central splitter edge, which divides the jet equally (Fig. 6). This eliminates side thrust on the runner and a thrust bearing is consequently not required. Pelton Wheels may be arranged with either vertical or horizontal axis.

Horizontal Shaft Machines.—These are frequently provided with two runners, overhung on either side of the generator (Fig. 5). The number of jets per wheel is normally limited to two.

Vertical Shaft Machines.—These are nowadays preferred for large outputs and where space economy is a consideration. The bearing arrangement simplifies design of the alternator, and a higher speed is made possible by an increased number of nozzles per wheel. Up to six jets have been used on a single vertical shaft runner (Bridge River Development, British Columbia. See Appendix A).

Runner Construction.—High specific speed wheels are integrally cast in steel, stainless steel or bronze, Low speed wheels frequently have the buckets bolted to the wheel. The buckets can be cast, forged or fabricated.

PROPORTIONS OF NOZZLE, BUCKETS AND WHEEL.

Nozzle and Jet Data.—The section of all modern nozzles is circular. The size of the jet and hence the flow to the wheel is adjusted by a spear moving axially within the nozzle under hand or servomotor control.

Considerable experiment is necessary to arrive at the best form of nozzle and spear to give a compact parallel jet, particularly at the higher heads. It is most important that the area of the water passage should decrease steadily towards the outlet. With reference to Fig. 4, typical proportions are as below:

d = maximum jet dia., i.e., spear fully retracted as shown.

$d_1/d = 1{\cdot}2$ to $1{\cdot}4$. $\alpha = 60°$ to $90°$.

$d_2/d = 3{\cdot}0$ to $4{\cdot}0$. $\beta = 40°$ to $60°$.

$d_3/d = 1{\cdot}25$ to $1{\cdot}5$.

Velocity of jet, $v = C_V \sqrt{(2gH)}$ . . . . (4)

where H = Head behind nozzle,

C_V = Velocity Coefficient of nozzle = 0·95 to 0·98.

Discharge $Q = \pi d^2/4 \times v = 0{\cdot}75$ to $0{\cdot}77 d^2 \times \sqrt{(2gH)}$ . . . (5)

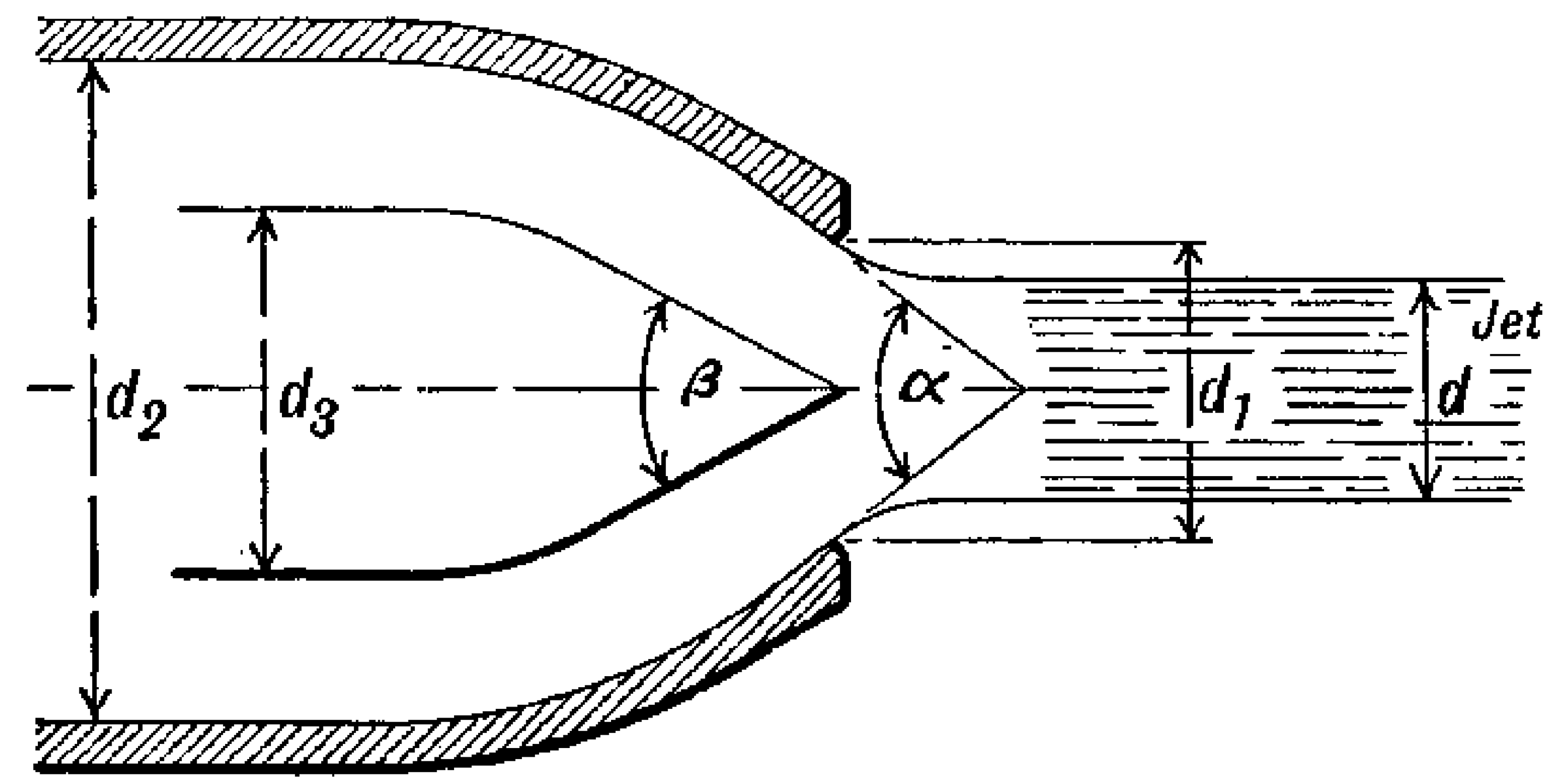

Fig. 4.—Proportions of Nozzles and Spear.

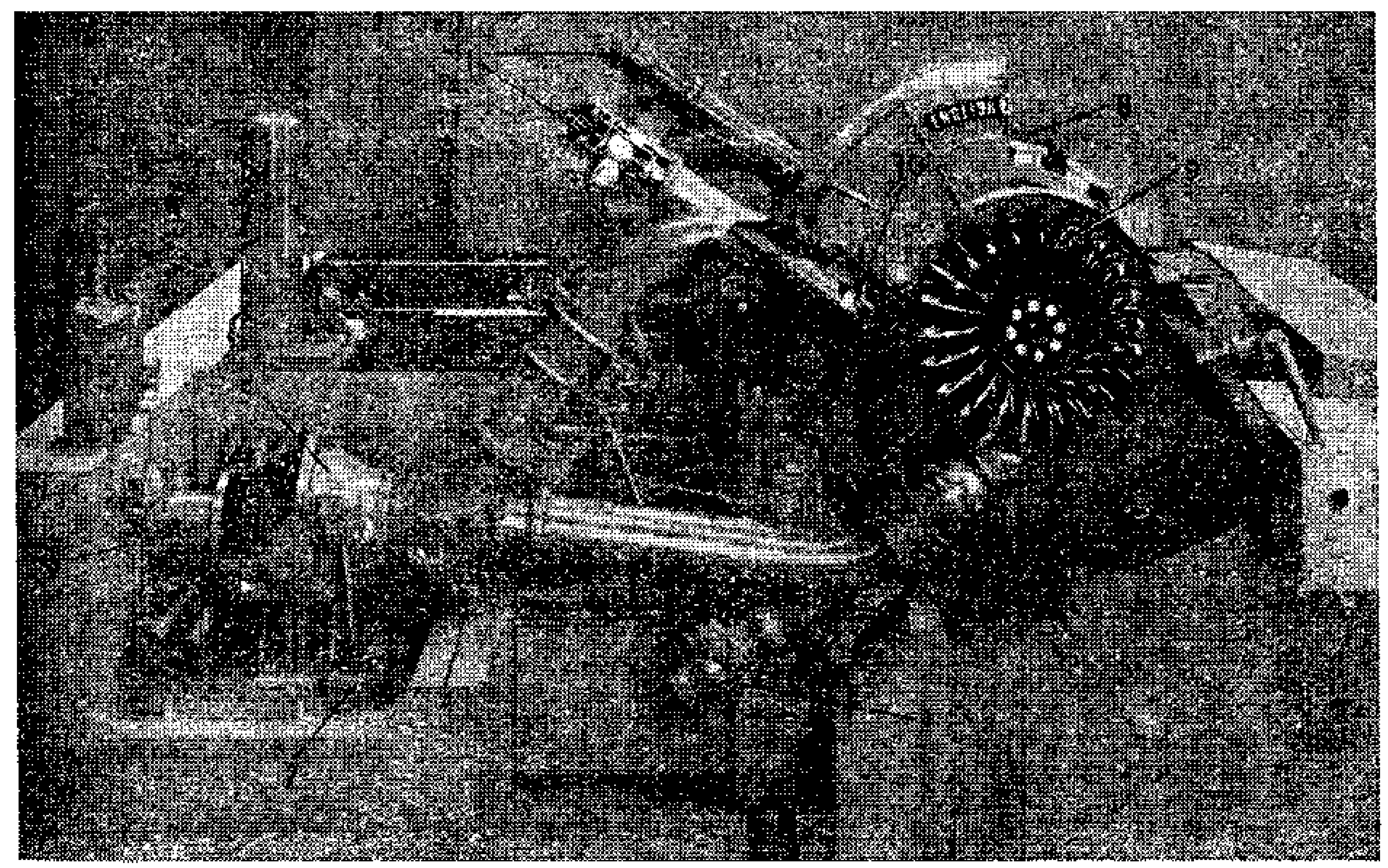

Fig. 5.—Pelton Wheel, 39,000 h.p. twin overhung, 428 r.p.m. under 1,230 ft. head. (Cavado station, Portugal; *English Electric*).

Key: 1. Spear and Diffuser Servomotor. 2. Pressure Receiver. 3. Oil Pressure Pumping Set. 4. Bifurcation. 5. Straightflow Type Inlet Valve. 6. Valve Door. 7. Valve Servomotor. 8. Generator Rotor. 9. Integral Runner. 10. Diffuser. 11. Nozzle. 12. Operating Shaft.

Buckets.—While the exact proportions of the buckets vary considerably, the following figures may be taken as a guide (see Fig. 6):

a/d = 3·0 to 3·5 $\quad$ c/d = 0·8 to 0·95
b/d = 2·4 to 2·8 $\quad$ w/d = 1·2.

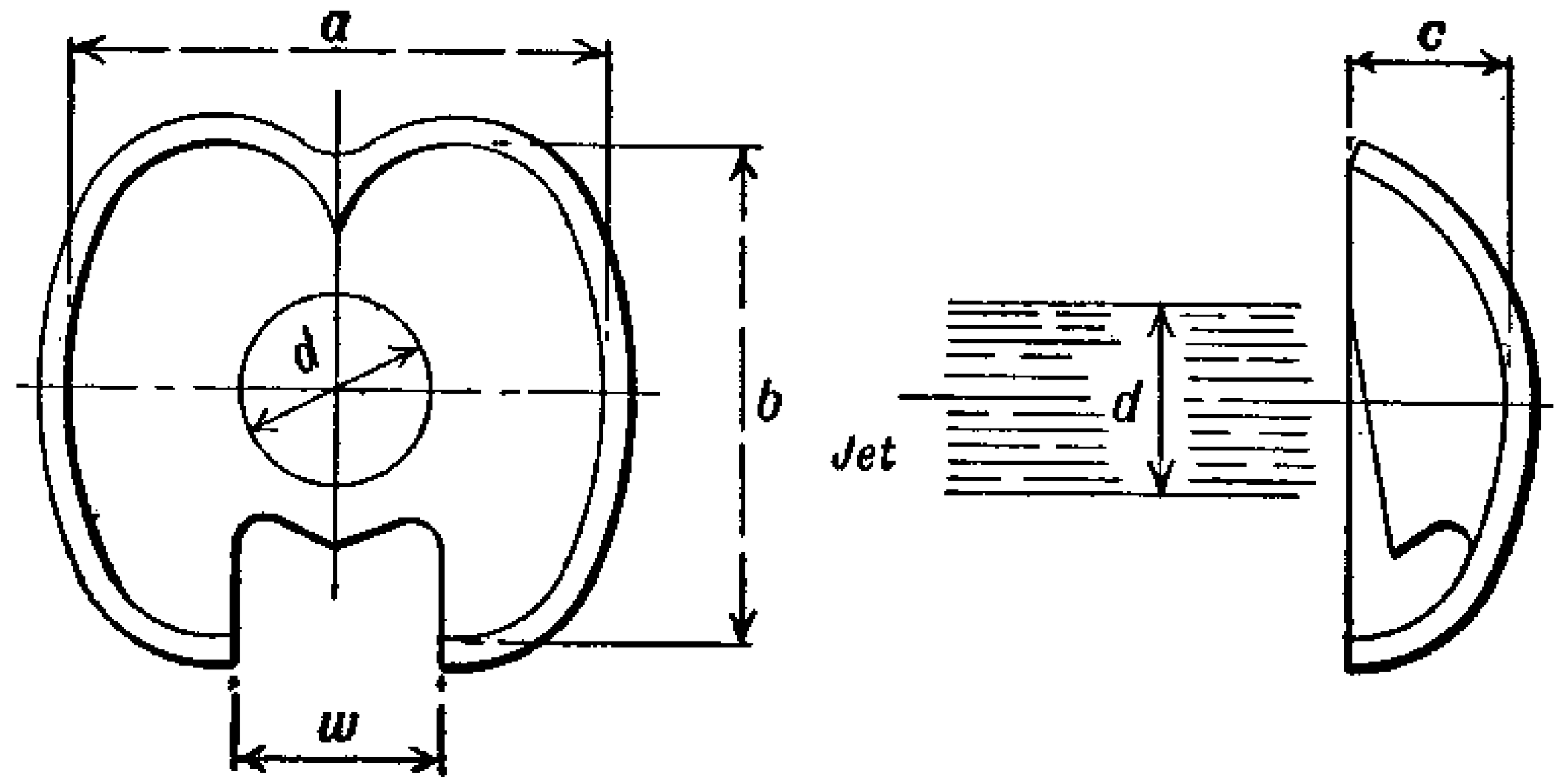

FIG. 6.—Proportions of Pelton Bucket.

Wheel.—With reference to Fig. 7, for best efficiency:

Peripheral velocity, u = 0·46 to 0·5v . . . . (6)
= 0·44 to 0·49 $\sqrt{(2gH)}$ . . . . (7)

(For the theoretical value see paragraph 'Calculation of Power').

Whence, speed, $n = 8{\cdot}4 \text{ to } 9{\cdot}35 \dfrac{\sqrt{(2gH)}}{D}$ r.p.m. . . . . (8)

Also, $N = \dfrac{\varepsilon.W.Q.H}{550}$ b.h.p. . . . . (9)

where ε = overall efficiency of turbine = say, 85%
W = density of water = 62·4 lb. per cu. ft.

Hence, taking mean values of coefficients,

$$n_s = \frac{8{\cdot}9\sqrt{(2gH)}}{D} \times \sqrt{\left\{\frac{0{\cdot}85 \times 62{\cdot}4 \times [0{\cdot}76\, d^2 \sqrt{(2gH)}]H}{550}\right\}} \div H^{5/4}$$

$= 55d/D$ . . . . (10)
or $D/d = 55/n_s$ (British) . . . . (11)

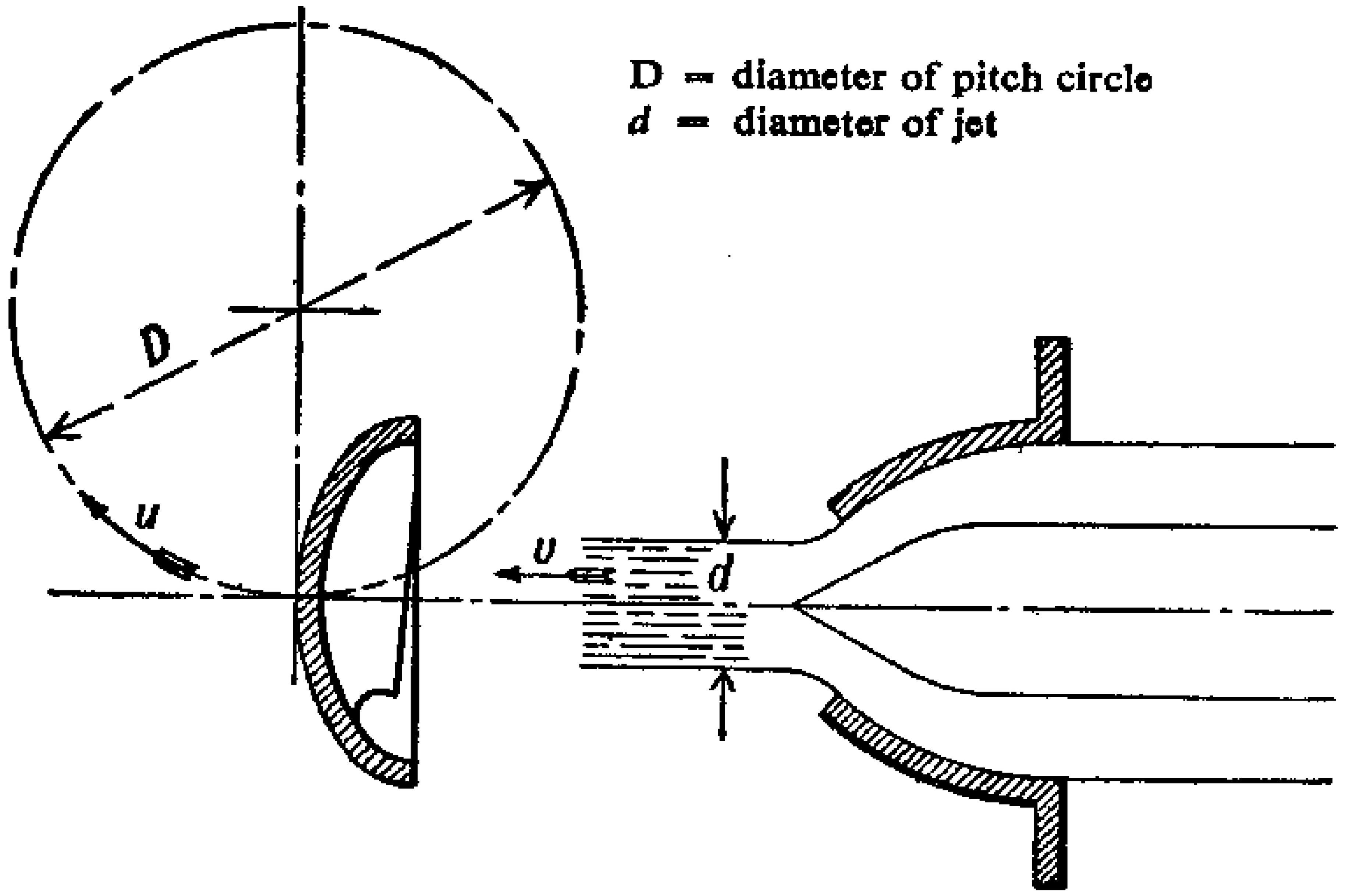

FIG. 7.—Wheel dimensions for Pelton Wheel.

This result is plotted graphically in Fig. 8.

For values of D/d less than 10 : 1, particularly careful design is required to achieve good efficiencies.

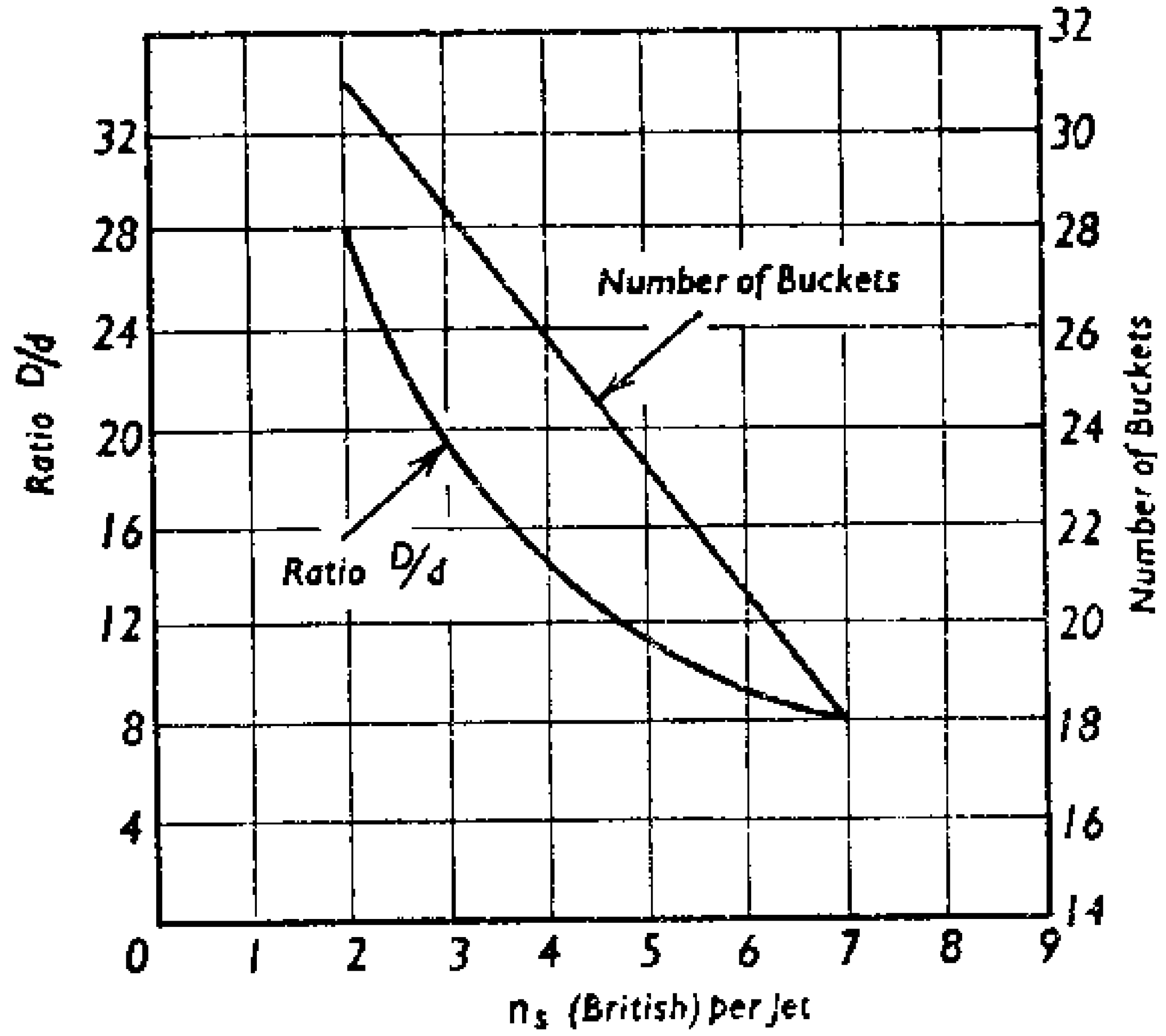

FIG. 8.—Variation of D/d and Bucket Number with Specific Speed for Pelton Wheel.

Number of Buckets.—There should be sufficient buckets to intercept the entire jet. Modern practice is shown in Fig. 8, though some deviation from the numbers indicated would not appreciably affect the wheel efficiency.

EXAMPLE OF PELTON WHEEL CALCULATION.—The determination of the leading dimensions of a Pelton Wheel had been illustrated earlier in this chapter (see 'Examples of Speed and Type Selection'—Case (2), p. 947)

THE VELOCITY DIAGRAM.—The velocity diagram for inlet and outlet of a Pelton bucket section is shown in Fig. 9. Symbols are defined as follows:

v = Absolute water velocity $\quad$ u = Bucket velocity
w = Relative water velocity $\quad$ θ = Bucket angle.

Suffixes 1 and 2 refer to inlet and outlet respectively.

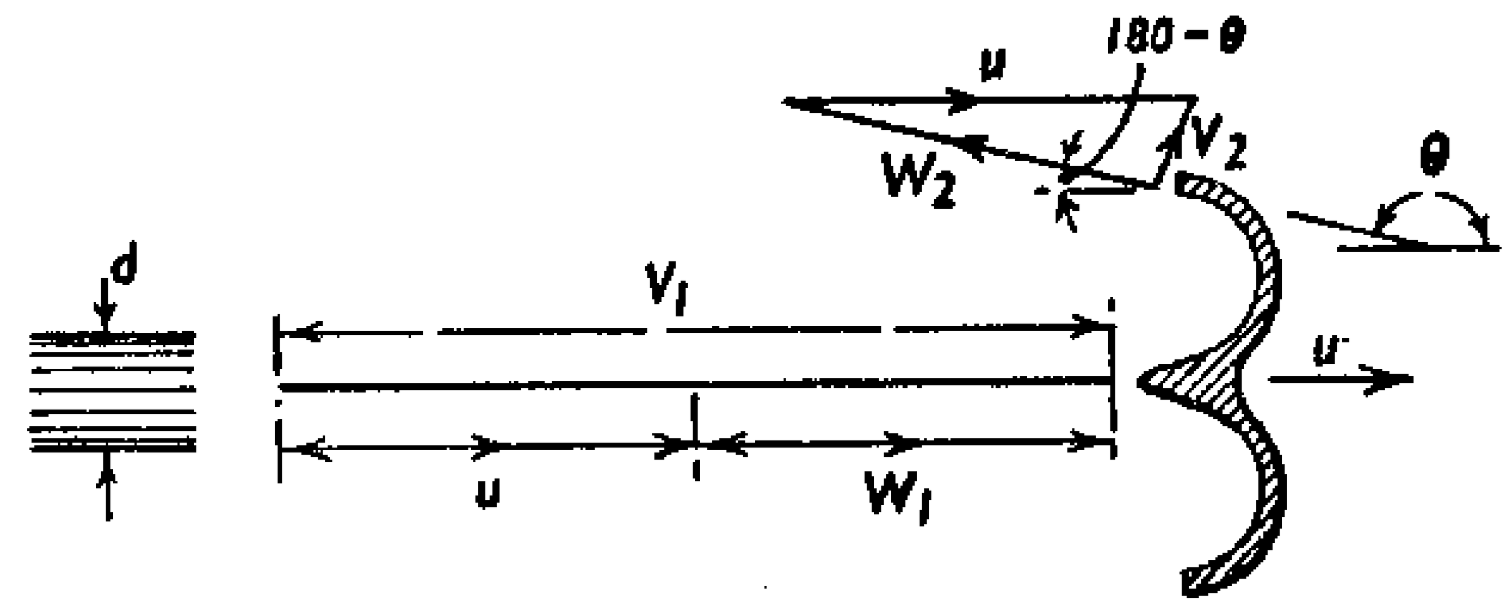

FIG. 9.—Velocity Diagram for Pelton Bucket.

TURBINE EFFICIENCIES.

Hydraulic Efficiency, $\varepsilon_H = \dfrac{\text{Work done per sec. by water}}{\text{Energy input to turbine}}$ . . . (12)

Mechanical Efficiency, $\varepsilon_M = \dfrac{\text{Power output of turbine}}{\text{Work done per sec. by water}}$ . . . (13)

Overall Efficiency, $\varepsilon = \dfrac{\text{Power output of turbine}}{\text{Energy input to turbine}}$ . . . . . (14)

$= \varepsilon_M \times \varepsilon_H$ . . . . (15)

CALCULATION OF POWER.

Work done on runner per lb. of water $= \varepsilon_H . H$ . . . . . (16)

$= 1/g \times u(v_1 - u) \times [1 + K\cos(180 - \theta)]$ ft. lb. . . . . (17)

where $K = w_2/w_1$ . . . . (18)

$= 0{\cdot}9$ to $0{\cdot}95$ approximately.

g = acceleration of gravity = 32·2 ft./sec.^{2}

Flow through runner per sec $= W \times \pi d^2/4 \times v_1$ lb./sec. . . . . (19)

Hence, power output of turbine:

$= \varepsilon_M \times W\pi d^2/4g \times v_1 u(v_1 - u) \times [1 + K\cos(180 - \theta)]$ . . . (20)

Theoretically this is a maximum when $\theta = 180°$, and $u = 0{\cdot}5\, v_1$.

In practice θ must be somewhat smaller, to prevent water from one bucket impinging on the back of the next. Normal values are 165° to 175°.

REGULATION.—It is the function of the spear valve to match the input of the turbine to the load, in order to maintain a sensibly constant speed. For turbines subject only to gradual load changes, and where small fluctuations of speed are not detrimental, a hand-operated spear is satisfactory.

When accurate control of speed is of importance, such as for turbines driving generating equipment, rapid and accurate control of the water quantity reaching the wheel must be ensured. This can be achieved by operating the spear by means of an hydraulic servomotor controlled by a speed governor. However, unless the pipeline is very short compared to the head, direct regulation by means of the spear will cause severe water hammer when large loads are thrown off suddenly. To prevent this the spear is usually arranged to move so that the velocity of the water in the pipe is changed only very slowly, and special devices are used to cut the water off from the wheel when load is thrown off until the quantity of water flowing down the pipe is correct for the new load. This diversion of the water can be achieved in three ways, and either (2) or (3) below is the usual European practice.

(1) *Relief Valve Device.*—An auxiliary nozzle is arranged to open simultaneously as the main nozzle closes, and then this nozzle is closed very slowly under the control of a dashpot.

(2) *Deflector Device.*—A deflector is arranged in front of the nozzle which moves to cut off the jet from the wheel until the spear, which moves slowly under the control of a dashpot, has reached the position corresponding to the new jet. The link gear between the deflector and spear is so arranged that the deflector just clears the jet when the spear reaches its final position.

(3) *Diffusing Device.*—Small, inclined blades are made to protrude from the spear, and cause the jet to whirl and break up into spray, until the spear, moving slowly under the control of a dashpot, reaches the position corresponding to the new jet. These blades lie just flush with the spear in the final position.

For small sets, a governor-operated deflector may be used in conjunction with a hand-operated spear valve.

In a well-designed system the governor can be arranged to operate a deflector or spear and relief nozzle in 1·8 to 2 secs., and a Seewer diffuser in 0·5 to 1 sec. The speed rise will depend on the 'flywheel effect' of the set (see 'Stability', p. 969), the following figures are usual:

Load thrown off	Momentary speed rise above normal steady speed after drop in load, in % of normal speed	
% of full load	Deflector or spear and relief spear	Diffuser
100%	15% to 25%	5% to 10%
75%	12% to 19%	4% to 8%
50%	8% to 13%	3% to 6%
25%	4% to 6%	1% to 3%

For load thrown on the conditions are dictated entirely by the design of the pipeline, since any attempt to cause the water column in the pipe to accelerate suddenly will cause so great a drop of head that no greater power is available at the jet, and dangerous pressure waves are set up. Unless the conditions of operation are studied very carefully in the design of the pipeline it will be impossible to throw load on the set quickly, and any attempt to adjust the governor to enable this to be done will only result in hunting and dangerous surges in the pipeline.

THE TURGO WHEEL

This form of impulse turbine has been used for heads up to 1,000 ft. and outputs up to 5,000 h.p., in place of a multi-jet Pelton Wheel, to which it has a similiar specific speed (see Fig. 1). The buckets are non-symmetrical, the jet entering at an angle to the wheel plane, as shown in Fig. 10. This arrangement leads to a smaller D/d ratio than that attainable with the Pelton Wheel, and hence to a higher specific speed per jet (see formula (10), p. 950).

Turgo wheels are normally arranged with one or two runners mounted on a horizontal shaft and with one jet per runner. Regulation is substantially similar to that for the Pelton Wheel, to which reference is made.

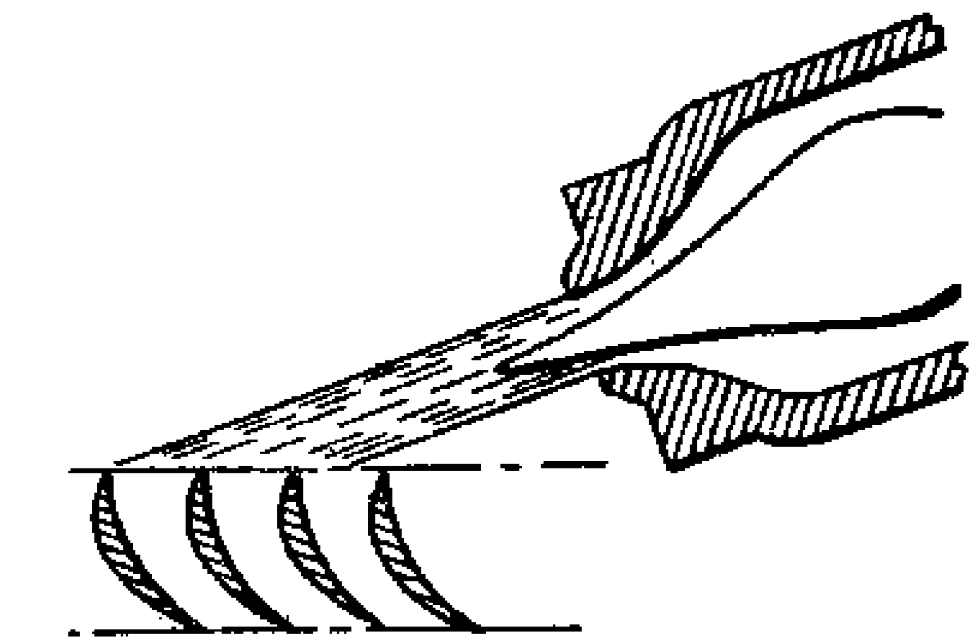

Fig. 10.—Jet arrangement for Turgo Wheel.

REACTION TURBINES

Definition.—In a reaction turbine the water supplied to the runner possesses energy which is partly kinetic and partly pressure. Both types of energy are converted into work in the runner, resulting in a drop of pressure and of absolute velocity of the water.

BASIC FEATURES.—The reaction turbine consists fundamentally of four main sections; namely the casing or flume, the gate apparatus, the runner, and the suction or draft tube (see Fig. 11). The proportious and arrangement of these differ for various conditions of speed and head. Reaction turbines may be arranged with either horizontal or vertical shaft. Large modern sets are of the vertical shaft type, with one runner per turbine.

The Casing.—All large modern reaction turbines are provided with a volute or spiral casing, the function of which is to distribute the water equally to all parts of the gate apparatus, and to impart to it a whirl (or tangential) component of velocity.

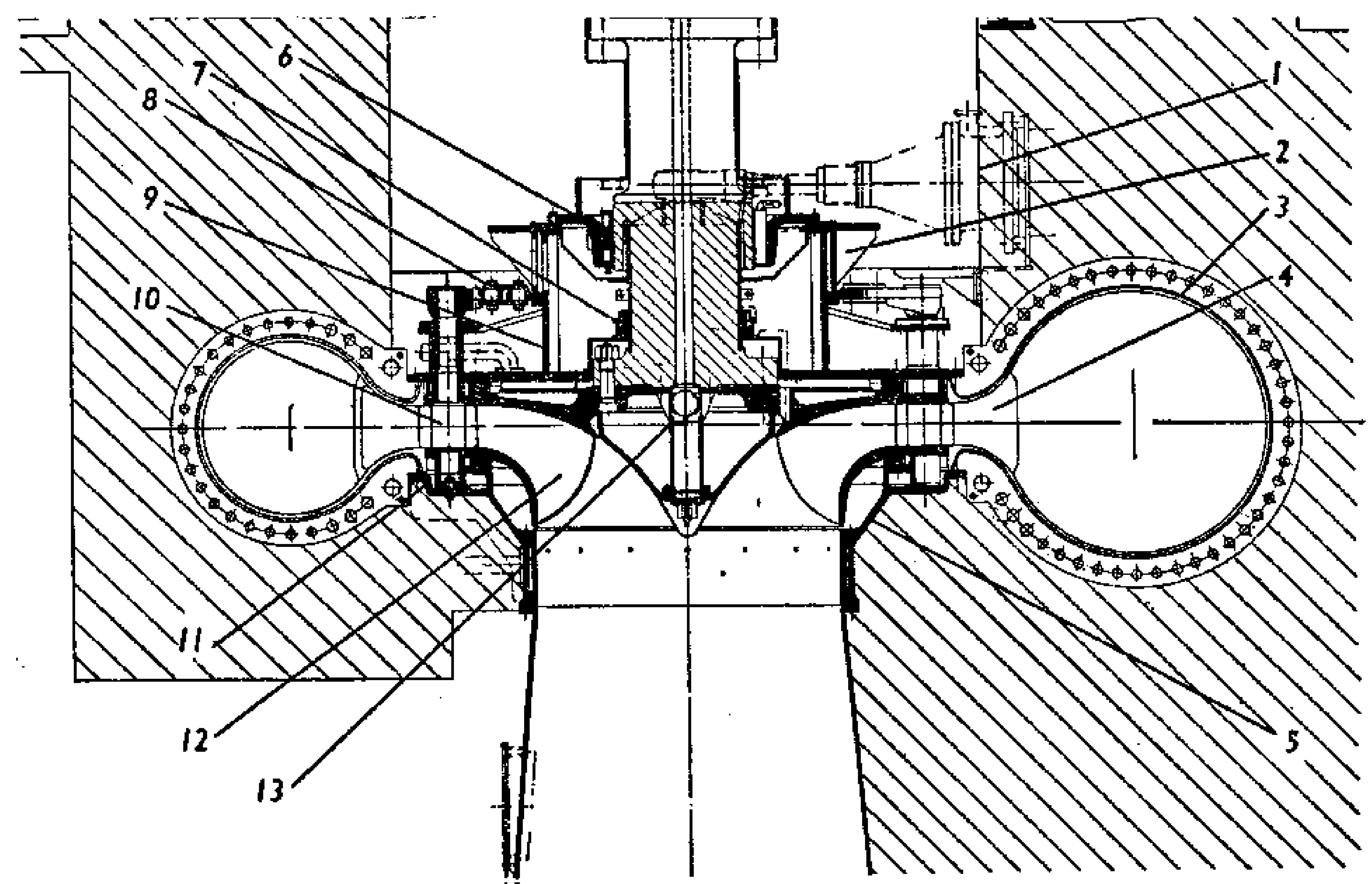

Fig. 11.—Francis Turbine, 200,000 h.p., 277 r.p.m.; 875 ft. head. Bersimis, Canada (*English Electric.*)

Key: 1. Guide Vane Servomotor. 2. Regulating Ring. 3. Spiral Case. 4. Stay Vane. 5. Foundation Ring. 6. Guide Bearing. 7. Shaft Gland. 8. Guide Vane Linkage. 9. Top Cover. 10. Guide Vane. 11. Pivot Ring. 12. Runner. 13. Air Valve.