RECENT DEVELOPMENTS IN HYDRO-ELECTRIC ENGINEERING WITH SPECIAL REFERENCE TO BRITISH PRACTICE

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In order to secure a share of the world's output of hydro-electric machinery, it was necessary for British engineers to create new features of design affording real advantages to the prospective user. It is the purpose of the paper to describe the most important of these features.

These include an automatic aerofoil flow recorder, which provides a means of operating automatically relief valves and other discharge apparatus, an automatic governor-actuator with mechanical drive, a cylindrical balanced valve and discharge regulator, and a hydraulic brake which utilizes the runner wheels as brake drums. Such a brake is desirable not only in emergency but also to protect bearings from the ill effects of slow running during deceleration.

Much attention has also been paid to the design of a satisfactory bucket fastening for impulse wheels, and welding is now extensively adopted for the fabrication of spiral casings, etc., and in conjunction with the use of alloys as a protection against cavitation.

The usual design of vertical-shaft power house involves two or more floors with many attendant disadvantages. To overcome these a new type of rigid connexion between turbine and generator was evolved which permits of a single power house floor. An important section of the paper describes the first industrial hydro-electric test plant in the country.

Extent of Water Power. No systematic and exhaustive survey of the water power at the disposal of man has yet been attempted. The calculations of a number of geological and hydrographic surveys, however, give a practical idea of the water power available over the whole world, as compared with that actually utilized up to the present time. The figures in Table 1 can be taken as the power available at ordinary minimum flow and the considerable margin due to storage which is possible in a large percentage of catchment areas is omitted altogether. The figures are, therefore, conservative.

The total available energy will be seen to be about 500,000,000 h.p. without, of course, including any contribution derived from tidal power.

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TABLE 1. AVAILABLE WATER POWER

	Probable energy disposable, h.p.	Utilized energy, h.p.	Utilized energy, per cent
Europe	58,000,000	19,500,000	33·7
America (all)	127,000,000	33,000,000	26·0
North and Central America .	73,000,000	30,000,000	42·0
Asia	90,000,000	5,400,000	6·0
Australia	17,000,000	850,000	5·0
Africa	190,000,000	380,000	0·2

Fig. 1 gives a fair idea of the situation and distribution of water power over the whole world. The extent of utilization of water power in the British Empire is, apart from the Dominion of Canada, as yet very small compared with countries like Sweden, Switzerland, Italy,

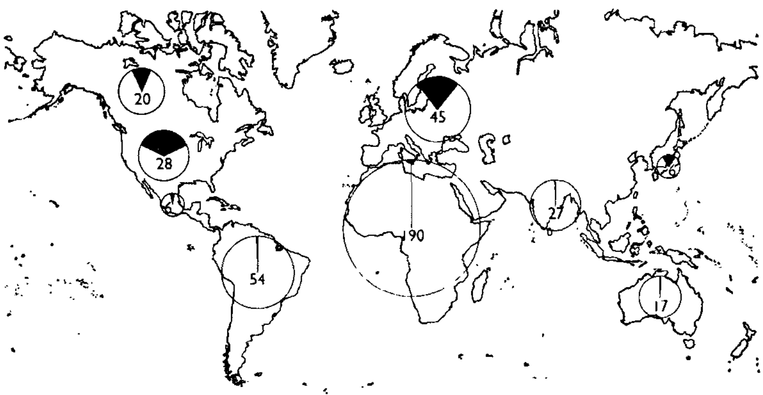


Fig. 1. Water Power of the World

Figures represent millions of horse-power. The size of the circles is proportional to the water power resources available ; the sectors represent the percentage of the available water power actually utilized for the different countries.

Germany, and France, where cheap water power is depended upon as a factor of first importance in the national economy. The importance of water power within the British Empire was recognized by the British Parliamentary Water Power Committee, which submitted the following conclusions :—

(1) The potential water power in the Empire amounts in the aggregate to at least 60,000,000 to 70,000,000 h.p.

(2) Much of this is capable of sound economic development. (It may be added that about 20 per cent of these schemes only could be classified as "high-pressure" schemes with 800–6,000 feet head; 40 per cent as "medium-pressure" schemes with 150–700 feet head; about 20 per cent as " low-pressure" schemes with about 150 feet head; and the remainder as low-head schemes, which are the least economic and require

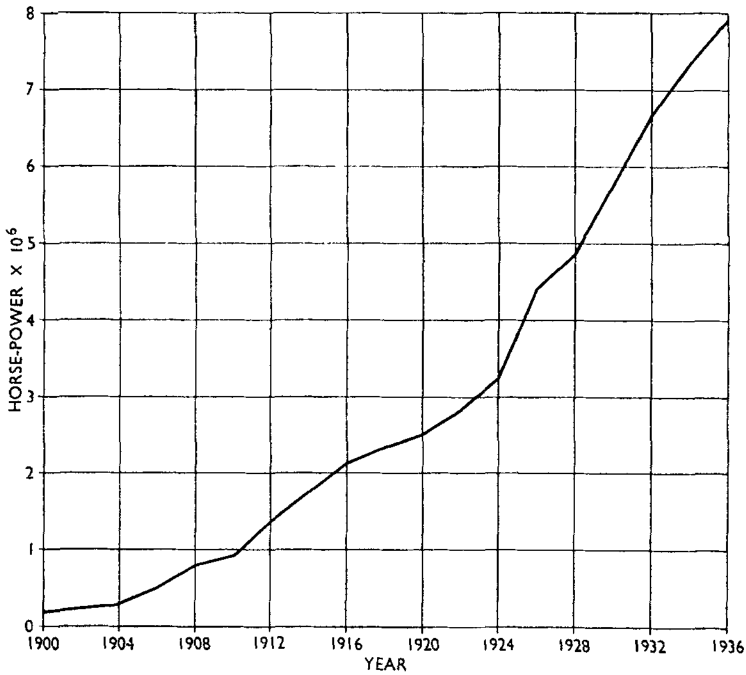


Fig. 2. Water Power Development in Canada

extensive machinery and buildings for comparatively small powers.)

(3) Except in Canada and New Zealand, and to a lesser extent in New South Wales and Tasmania, no systematic estimate has yet been made by any Government Department to ascertain the true resources of its territories.

(4) The development of the Empire's natural resources is inseparably connected with that of its water powers.

To illustrate the importance of the utilization of water power, a diagram is given in Fig. 2, prepared by the Dominion Water Power and Hydrometric Bureau of Canada, showing the growth of hydraulic developments in Canada from 1900 to 1936.

In order to secure a reasonable share of the world's output of hydro-electric machinery, it was necessary for British engineers to create features in design and manufacture affording real advantages, both technical and economic, to the prospective user. It is the purpose of the paper to describe briefly some of the most important of these features which have met with approval, especially amongst water power engineers of considerable experience. The main requirements were simplicity, high specific speeds for both reaction and impulse wheels, exact and automatic regulation for the turbines proper, and reliable control apparatus such as governors, valves, and discharge regulators.

Automatic Aerofoil Flow Recorder. Hydro-electric power plants involve large financial investment and therefore demand accurate knowledge of all operating factors, and continuous supervision by means of records of power input and output. Electrical metering and recording instruments capable of a high degree of accuracy are available. The exact measurement and continuous recording of the rate of flow of large quantities of water in the field, however, is still a most difficult problem. Exact and continuous flow recording is of paramount importance for the maintenance of high efficiencies, and for the control of storage reservoirs and concessional water quantities, including irrigation flow. As the output, head, speed, and other hydraulic conditions are continuously changing in service, it is desirable to install apparatus capable of recording accurately the quantities of water discharged in a permanent manner, and independent of all the other variables.

The well-known methods of water measurement by Pitot tube, Venturi meter, salt velocity (Professor Allen), friction loss calibration, time-pressure (Gibson), differential pressure recording by piezometers on the intake vortex, or by weir calibration, while mostly capable of yielding accurate and consistent records indicating the *momentary* rate of flow, are mostly unsuitable or quite impracticable for *continuous* flow recording. Venturi tubes for plants of medium or low heads having pipes of large diameter extending sometimes to 20 or even 30 feet, are cumbersome and expensive, impose appreciable pressure losses, and influence the regulating conditions detrimentally. In common with Pitot tubes they are subject to clogging by dead leaves, sand, and other detritus carried in considerable quantities by many rivers. Furthermore, none of the orthodox methods of water flow recording afford any appreciable power which can be used reliably for the operation of bypass valves or other control devices.

These considerations led to the development of the aerofoil type of permanent water flow recorder. Aeronautical principles have established that a suitably designed aerofoil in a stream of air sustains forces, notably an uplift, which are direct functions of the shape of the aerofoil and the angle of incidence. Fig. 5 shows a characteristic

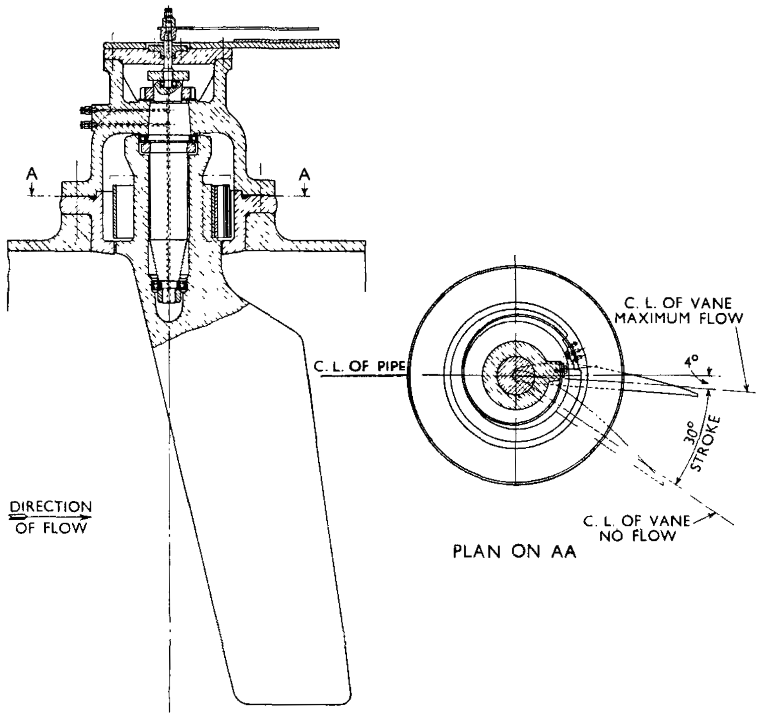


Fig. 3. Sectional Arrangement of Aerofoil Flow Recorder

aerofoil curve, in the form of a polar diagram giving the uplift and resisting forces, the moments established in relation to the front edge, and the angles of incidence. It was also established by theory and experiment that an aerofoil immersed in flowing water, for instance inside a closed pipe, and mounted so as to be capable of rotation, was highly sensitive to changes in the velocity of flow and would take up a definite position for any particular velocity. The torsional moments exerted by the flowing water are balanced by a simple coil spring and

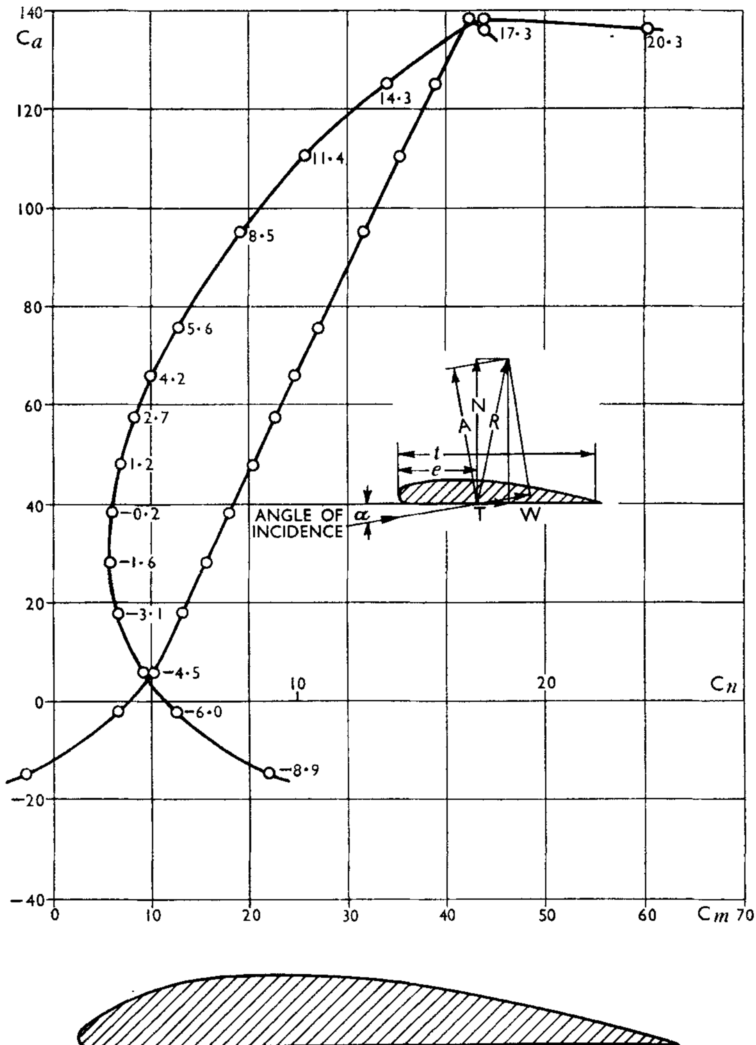


Fig. 5. Polar Diagram of Aerofoil

$$C_a = \frac{A}{qF} \times 100\ ; \quad C_m = \frac{M}{qFt} \times 100\ ; \quad C_n = \frac{W}{qF} \times 100$$

$q = \frac{1}{2}\rho v^2$; $\rho = \gamma/g$ = specific mass of fluid ; g = gravitation constant ; γ = specific weight of fluid ; F = area of aerofoil = width × length ; A = lift perpendicular to flow ; W = drag in direction of flow ; R = resultant of W and A ; M = momentum of resultant R around inlet edge.

the aerofoil is mounted in two rustless steel ball races permanently working in grease, while an extension of the pivoting shaft operates the flow indicator and recording apparatus and any control devices. The aerofoil can be used for the operation and adjustment of relief valves or other discharge apparatus in order to establish a permanent or variable flow according to requirements. This is especially useful

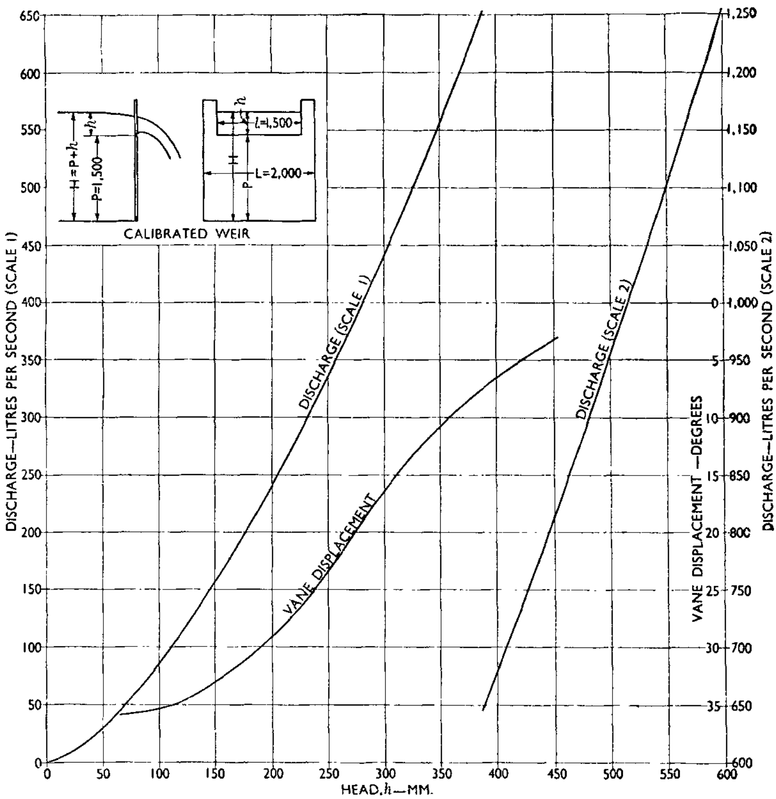


Fig. 6. Quantity Chart of Automatic Aerofoil Flow Recorder

in cases where, as for irrigation purposes or for superimposed plants along a river, an exactly predetermined flow must be kept to and guaranteed, independent of the momentary load, which, however, must be adjustable according to the constantly varying requirements. The aerofoil is a very simple and robust apparatus which is independent of the pressure prevailing in the pipe or duct and is free from disturbing influences due to impurities contained in the water. There is no discrepancy between the flow as measured by a weir and as indicated by the aerofoil meter, except below 10 per cent of maximum flow, where the degree of inaccuracy of the latter is of the order of ½ per cent. Fig. 6 shows the operating characteristics of an aerofoil flow meter in relation to a calibrated weir. For convenience the experimental results were superimposed on a mathematically determined calibration curve for the weir. Fig. 7 gives an example of a recording chart obtained in the field, and Fig. 8 a curve of moments, which shows how powerful the instrument can be. The aerofoil is free from vibration in service

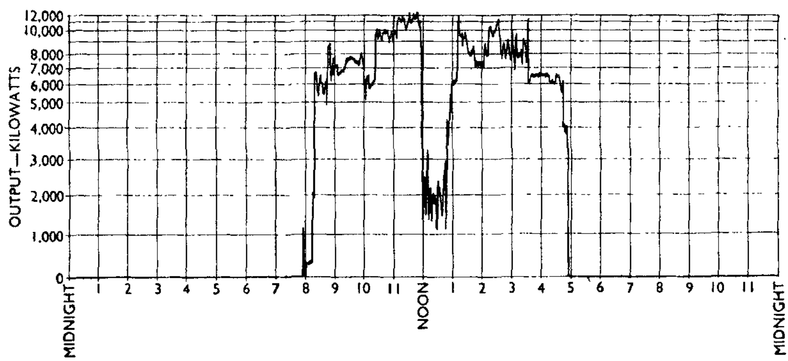


Fig. 7. Glenlee Plant Aerofoil Recorder Quantity Chart

and no measurable detrimental influence whatever on the efficiency of the turbines can be detected.

The Automatic Governor-Actuator and Mechanical Drive. The automatic governor-actuator can aptly be called the brain of the whole plant as it controls the speed, load, and pressure variations. Upon it depends the safety and uninterrupted service of the plant. A governor-actuator must ensure: maximum safety under all conditions of service; high sensitiveness with freedom from vibration and "hunting"; compactness and freedom from wear, that is lost motion, and it must be foolproof; easy accessibility, sturdiness, and simplicity of every part; and standardization so as to be adaptable to every kind of service, and every size of plant. It is made up of three main parts:—

(1) The centrifugal device or governor head.
(2) The actuator gear with which is combined the double-acting return motion gear or compensating device.
(3) The oil pressure relay and main steering valve through which the oil pressure is distributed to the servo-motor.

The governor also comprises a number of accessory parts which permit synchronization through speed adjustment by hand and remote control, several safety devices in case of oil pressure or drive failure,

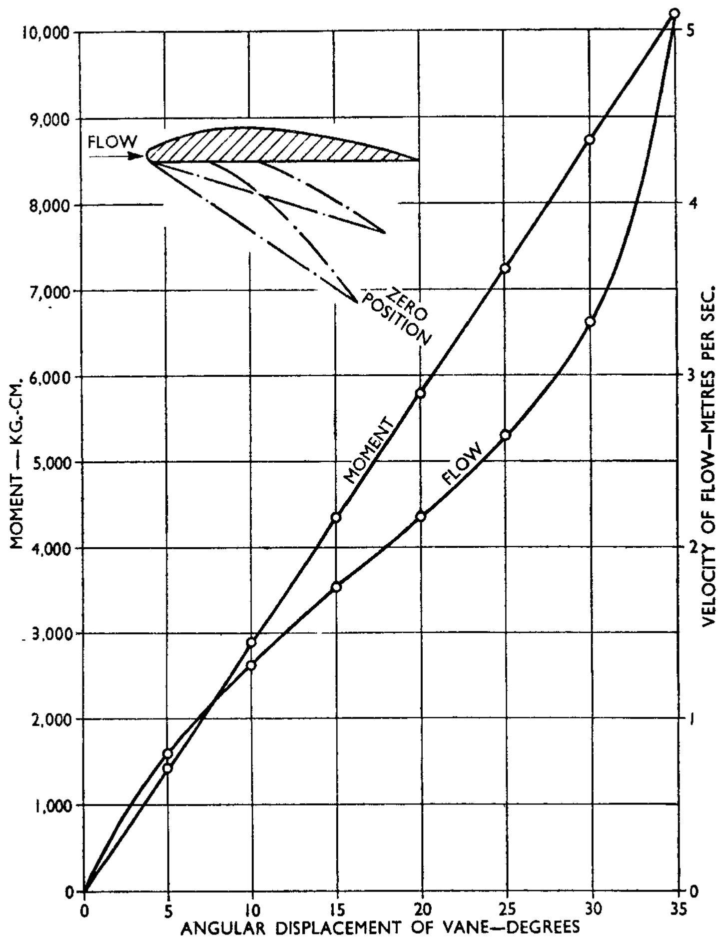


Fig. 8. Operating Characteristics of Aerofoil Pe~manent Flow Recorder

the necessary starting and stopping devices both hand-operated and automatic, and a dial tachometer.

The centrifugal device is of the hydraulic type and comprises two

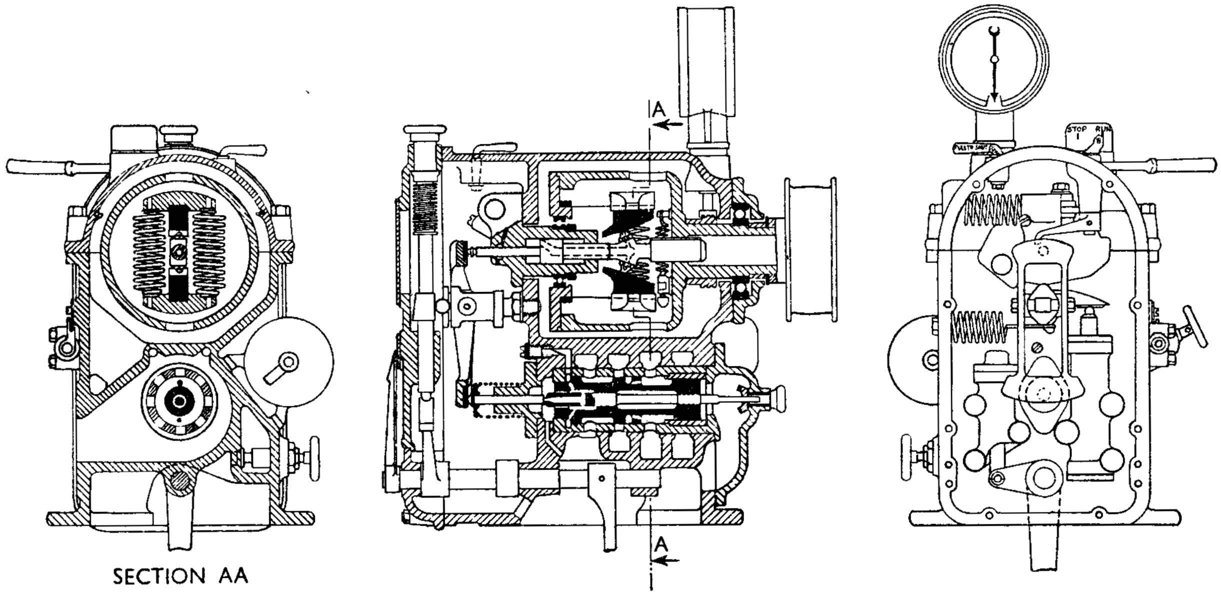


Fig. 9. Automatic Governor-Actuator

compensated flyweights in cam form which control the differential pressure on one side of an oil pressure relay by regulating the oil discharge through two nozzles connected with this differential pressure chamber, the piston of which revolves with the flyweights. The latter are suspended by two springs and linked together by two coil springs by which the centrifugal forces developed in rotation by the flyweights are counterbalanced. The centrifugal device contains neither fulcrum pins nor knife-edges, and its relay piston moves axially while rotating

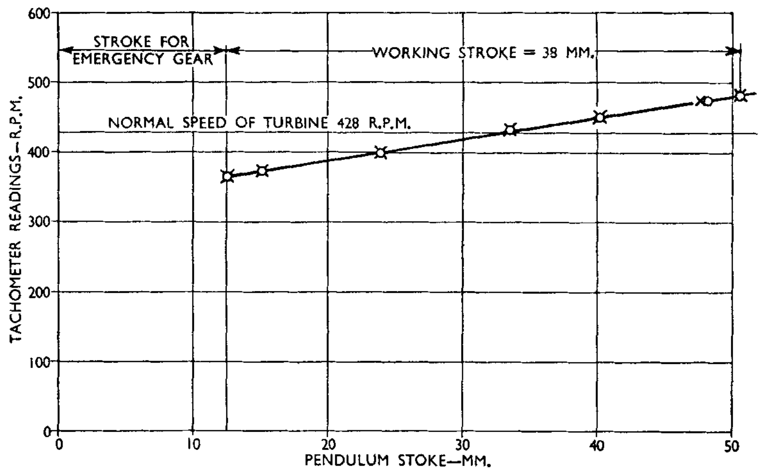
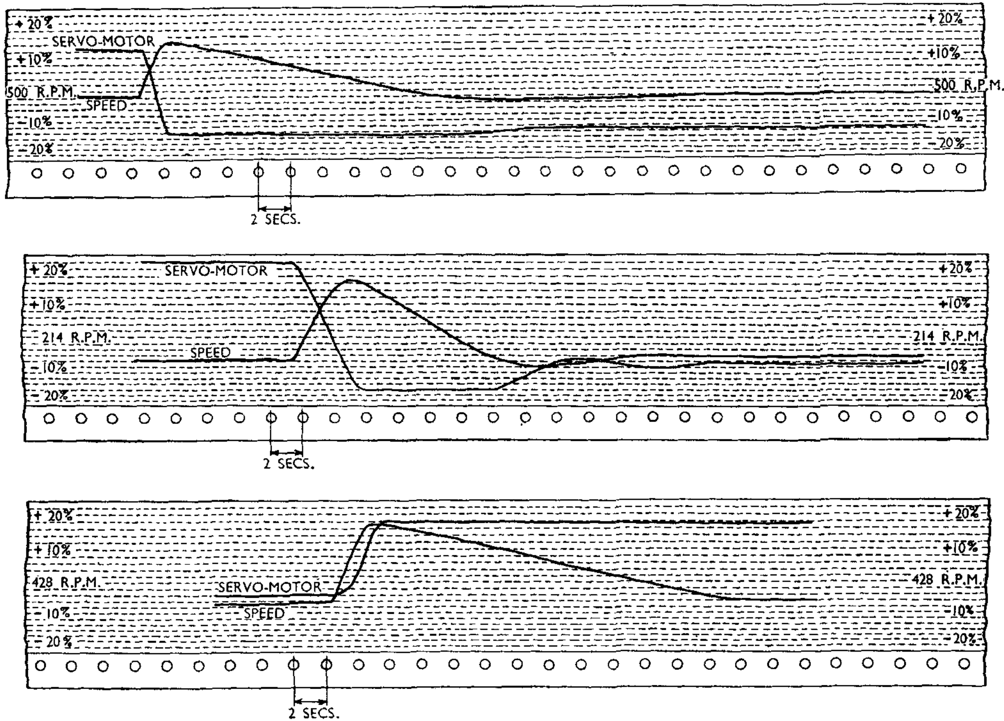


Fig. 12. Pendulum Operating Characteristic obtained by means of Electric Speed Adjustment, Micrometer Measurements, and Dial Tachometer Control

○ Speed up. × Speed down.

and while completely immersed in oil. The flyweight cams regulate the position of the relay piston by controlling a thin oil film at the nozzles. The device contains no parts subject to wear and is extremely sensitive. It rotates in two ball races which have no influence on its sensitiveness.

The actuator gear and compensating device are concentrated on one single pivoting lever which has a treble movement as follows. It transmits the movement of the rotating pendulum pin to the operating valve underneath by pivoting, thus causing the relay of the main operating or steering valve to move in accordance with the speed. A small arm on the sleeve which supports the actuator bridge is in continuous contact with the hydraulic return motion or compensating



Rannoch No. 3 machine
15,060 kW. thrown off.

Tongland No. 1 machine
11,000 kW. thrown off.

Glenlee No. 1 machine
12,000 kW. thrown off.

Fig. 13. Tachogram Curves of Governor

device connected with the servo-motor. The latter neutralizes the steering valve after the initial operating movement by means of inclined compensating rails mounted on the actuator bridge, this being the secondary pivoting movement. The compensating rails are also pivotally adjustable so that the temporary statism or damping can be adjusted to suit any plant conditions. The third and translatory movement is imparted to the actuator bridge by the second and mechanical return motion device by means of a cam and roller which brings about the permanent speed variation or permanent statism of the governor. This is adjustable by hand by a simple cam in continuous contact with a roller on the actuator bridge mounting. It will be remarked that all contacts always bear in the same direction so that no lost motion can develop without immediately being compensated. This is important for the elimination of "hunting".

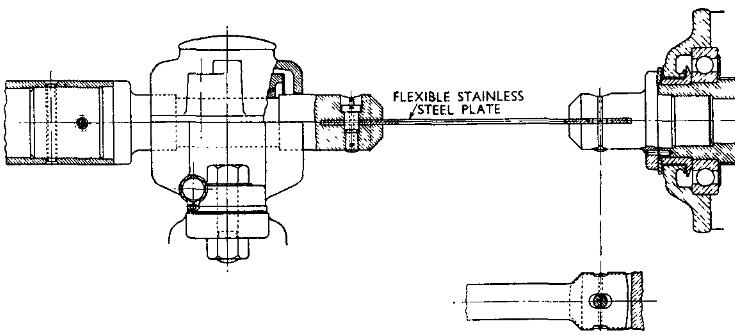


Fig. 14. Flexible Mechanical Governor Drive

The return motion or compensating device is of the hydraulic type and operates by means of a compensated and spring-loaded neutralized dashpot connected by pipes with the servo-motor piston. It cannot develop lost motion and its operation is asymptotic in both the closing and opening directions. It makes it possible to operate the turbine with the same regularity and steadiness for any degree of statism down to zero when there is no difference in speed between full load and no load ("isodrom" regulation).

A flexible mechanical governor drive, Fig. 14, has been adopted by the firm with which the author is associated as standard on all important sets. It permits of direct mechanical drive with its attendant reliability and yet embodies the necessary elasticity to eliminate vibration and the detrimental effect of temperature changes. It consists of a spur- and bevel-gear drive connecting the governor head to the turbine shaft

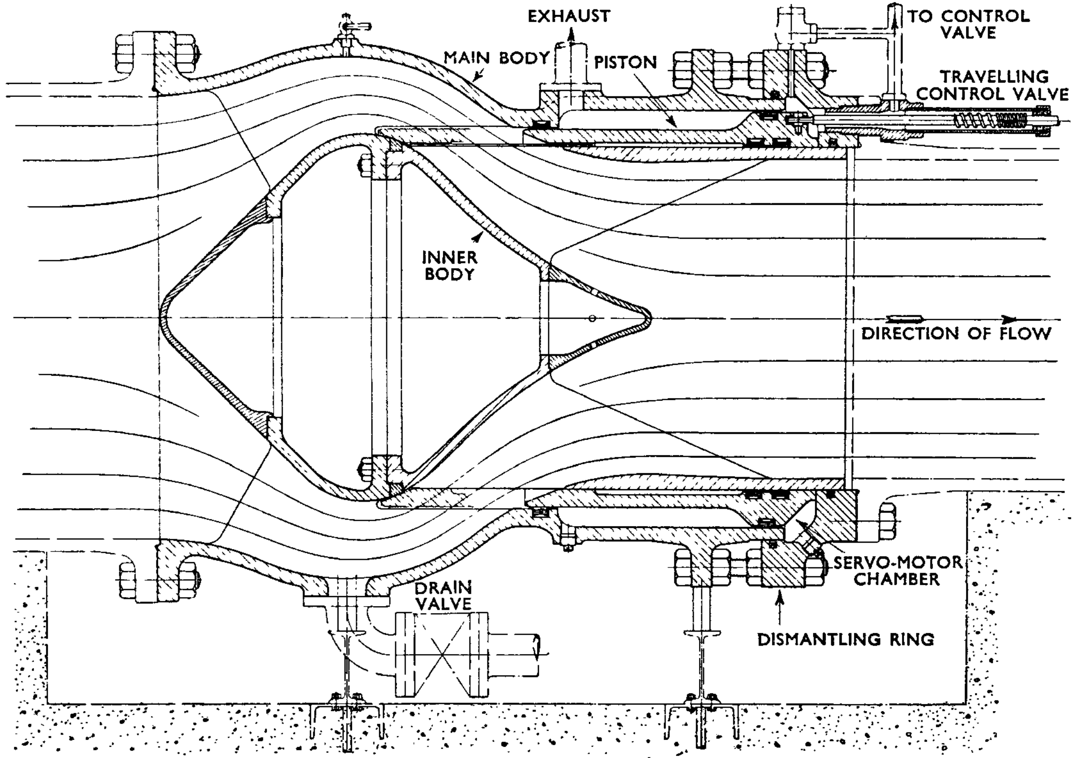


Fig. 15. Section of Cylindrical Balanced Valve

by a shaft into which a flexible and oval-slotted stainless steel plate is inserted. The latter provides the required combination of rigidity and flexibility. The gear drive operates entirely in an oil bath, the oil being constantly renewed by the oiling system of the bearings. Fig. 13 shows some typical tachogram curves, which are very consistent.

Cylindrical Balanced Valve and Discharge Regulator. Stop and relief valves, that is, discharge regulators, must ensure rapid and smooth closing and opening combined with absolute safety and freedom from water hammer. The valve, Fig. 15, consists of a cylindrical hollow piston gliding continuously on stainless steel strips on an inner body

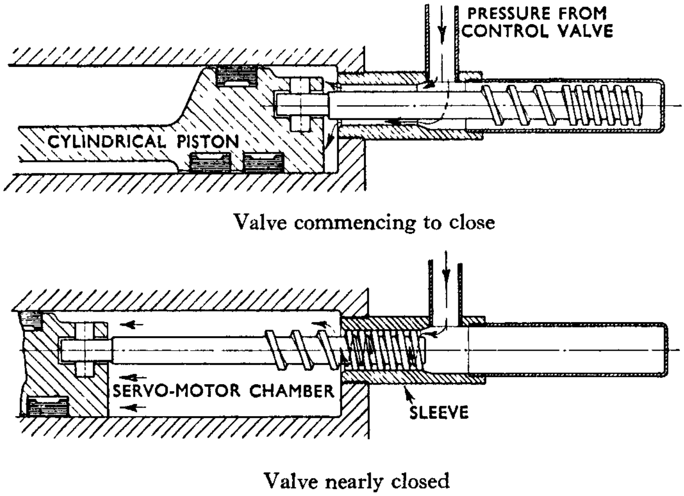


Fig. 16. Travelling Control Diaphragm

provided with ribs.* The valve piston ends in a head which moves axially inside the servo-motor, operated with filtered water under pressure. The radial and axial pressures on the piston are evenly distributed and self-balancing. The valves operate either automatically or by hand and remote control, by admitting the water pressure on either side of the servo-motor. The valve piston closes circularly against a neck ring embodied in the inner stationary body, which forms a streamlined smooth annular water passage with the outer body when the valve is in its open position. The balanced principle in design renders the valve inherently free from slam shutting and

* See *The Engineer*, 1927, vol. 144, p. 418 ; also *Engineering*, 1928, vol. 125, p. 771 ; vol. 126, p. 190 ; and 1934, vol. 138, p. 640.

opening, thus obviating dangerous water hammer. The design so far described would result in opening and closing at constant speed. In order to reduce the operating times and make the latter adjustable, without increasing the pressure rise in the pipe line, a desirable requirement for all cases of emergency, a simple device in the form of a control diaphragm, Fig. 16, is fitted rigidly to the valve piston and travels with it. This travelling diaphragm is in the form of a threaded rod with variable pitch and depth of thread, working within a hollow cylindrical chamber so that the pressure water encounters on its passage into the servo-motor a flowing resistance which increases with the degree of closure. It is thus possible, in a simple manner, to obtain an asymptotic closing and opening movement, Fig. 17, so

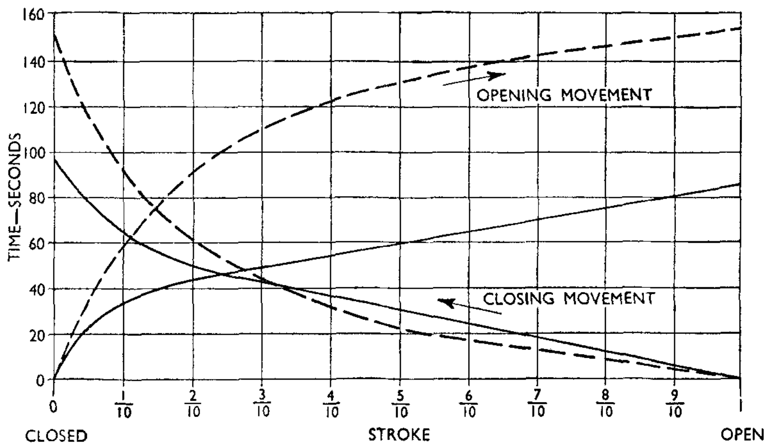


Fig. 17. Asymptotic Opening and Closing Time Characteristics

——— Alouette; 12 feet × 8 feet diameter valve; net head 120 feet; stroke of piston 3 ft. 9 in.

- - - - Lochaber; 3 ft. 6 in. × 3 feet diameter valve; net head 800 feet; stroke of piston 1 ft. 4¾ in.

that the valve can be made to operate rapidly over its full stroke and nevertheless close and open very gently, thus obviating pressure rise. This also completely obviates the necessity of a bypass for priming.

Experience has shown that the valve is drop-tight in service and that due to the streamlined design the friction losses are negligibly small. The valve embodies also a dismantling ring, thus rendering a special telescoping joint for dismantling unnecessary. This circular valve can conveniently be arranged underneath the power station floor, so saving valuable floor space round the machine. It is free from wear and vibration.

Used in the opposite direction of flow the valve becomes a relief valve or discharge regulator, Fig. 18.* It lends itself very conveniently to the purpose of guiding the water in a straight path from the turbine casing to the tailrace. By dispersing the water in a hollow cone which quickly loses its energy no harm is done to the tailrace, its foundations, or other surroundings. The design of the valve lends itself conveniently to automatic operation in connexion with the governor and

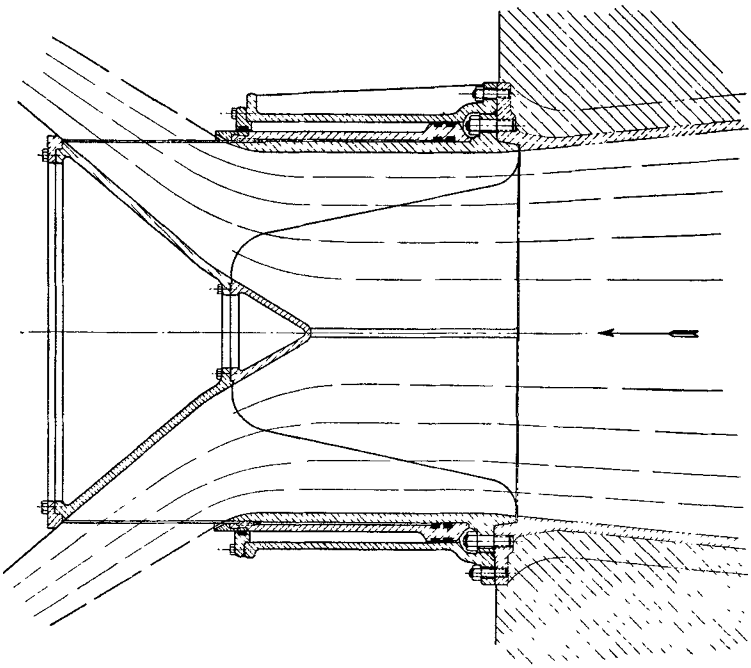


Fig. 18. Section of Cylindrical Balanced Relief Valve

turbine gears. It forms a correct cylindrical nozzle for any degree of opening and thus produces a smooth discharge for both small and large strokes. The synchronism with the turbine and governor, both quantitatively and in time, is very simple and permits of the plant being operated with a minimum pressure rise in the penstock.

Apart from the use of the valve as a relief or bypass on the turbine

* See *The Engineer*, 1931, vol. 152, p. 218 ; also *Engineering*, 1934, vol. 138, p. 640.

proper it is also in use as a discharge regulator on the dams of reservoirs, where it can conveniently be arranged for hand operation or for remote control.* Fig. 20, Plate 2, shows a characteristic example of its use in this case.

The Hydraulic Brake. The desirability of a reliable brake, with which the generating set can be brought to rest rapidly and safely without producing any heat or danger to the machine or operating staff, is fully appreciated. It is by no means necessary solely in a case of emergency, for it is well known that journal and thrust bearings

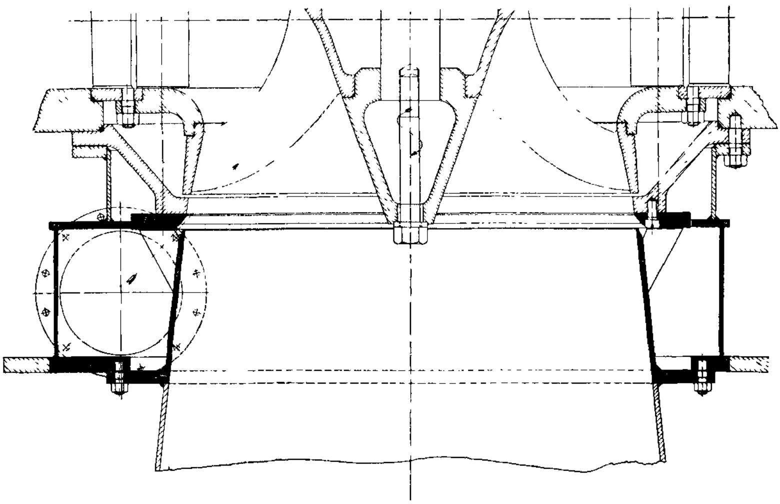


Fig. 21. Vertical Shaft Arrangement of Hydraulic Brake

especially suffer most if subjected to slow running down of the rotating element. Now the deceleration of turbine sets, embodying, as in most cases, very considerable moving masses, is very slow, so that large sets often take from 15 minutes to 1 hour to come to rest. Mechanical brakes can be made, but they are cumbersome and expensive; they always develop considerable heat and sometimes even cause sparks with dangerous consequences. Mechanical brakes are generally not allowed to be thrown into action at any speed because of the danger of causing exaggerated wear and heat. In case of an actual runaway the efficacy of the usual mechanical brake is therefore very problematic. If the mechanical brake is in daily, or almost daily,

* See *Engineering*, 1933, vol. 136, p. 681.

use for the routine stopping of the set as a safeguard for the bearings, the brake lining and drums require relatively frequent renewal, causing interruption of service and increasing maintenance costs. On machines with horizontal shafts the adoption of mechanical brakes is especially undesirable as they lengthen the distance either between bearings or between turbine and bearings, thus adding to the cost by necessitating increased shaft diameters.

These considerations led to the development of the hydraulic brake, by means of which reaction turbine sets up to the largest sizes, both of

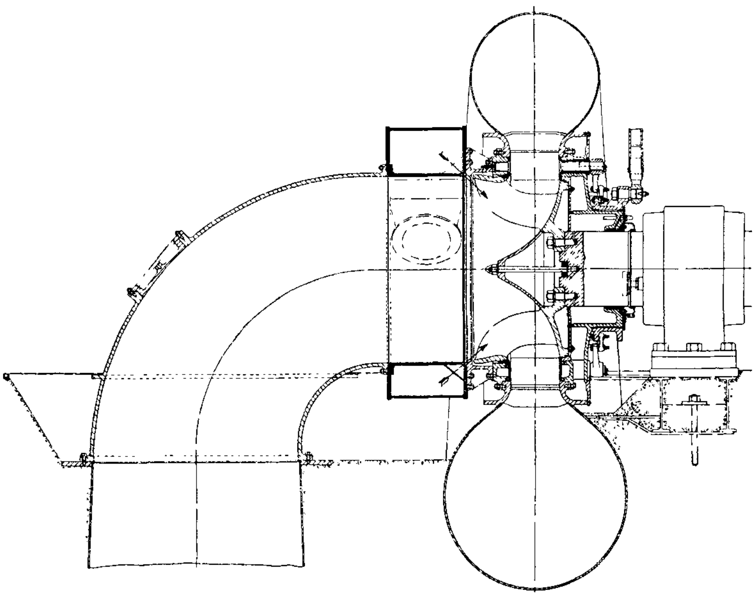


Fig. 22. Horizontal Shaft Arrangement of Hydraulic Brake

the horizontal and vertical shaft types, can be safely brought to rest in record time regardless of the size of the moving masses or the speed, and without production of heat or wear. The principle of hydraulic braking by means of jets impinging on the runner wheels of impulse turbines in the opposite direction to the rotation is well known. The application of hydraulic braking was somewhat more difficult in the case of reaction type turbines. A similar device to the single braking jet impinging on the back of impulse wheel buckets was, of course, of no use, and it was necessary to create a powerful circular braking vortex impinging on the back of the runner wheel blades at a certain angle without interfering with the normal operation or the balance

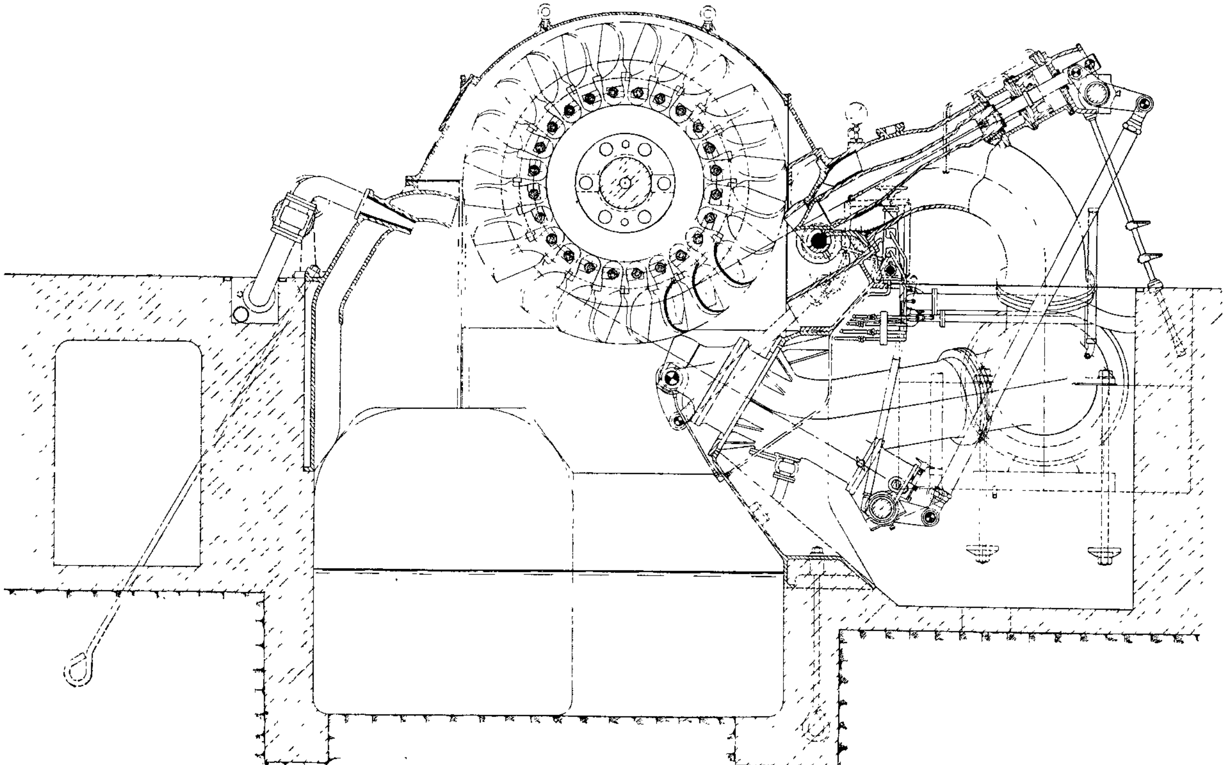


Fig. 25. 9,600 h.p. Double-Nozzle Impulse Turbine for Lochaber

of the runner or the strength. The arrangement is illustrated in Figs. 23 and 24, Plate 3. Reaction turbines of any size can be brought to rest within two or three minutes without any inconvenience, by simply utilizing some pressure water from the penstock. The operation of the hydraulic brake can be made automatic by hand or by remote control. It requires no additional space and simply utilizes the runner wheels as brake drums.

The Impulse Wheel Jet Disperser Governing Device. The usual systems of governing turbines of the impulse or Pelton type are by nozzle and bypass valve, or by nozzle and deflector. In the first system, the nozzle which forms the working jet is rapidly closed and a bypass or discharge regulator simultaneously opened so as to avoid excessive water hammer in the pipes by compensating the water cut off from the turbine. To obtain reasonably close governing considerable operating forces must be set in action, requiring in turn cumbersome mechanisms. The size of the governor must be adapted in each case according to the head and water quantity prevailing in the plant. The rapid handling of large jets is always difficult and risky since the momentum of quantities of moving water is very large. In medium- and low-pressure plants, where combined bypass governing is resorted to, the pipes can generally be designed to withstand an abnormally increased pressure rise in case of failure of the relief or bypass valve. In high-pressure plants, however, the provision of pipes of greater thickness to increase the safety factor is generally fraught with considerable difficulties, both technical and economic. For this reason the bypass system of governing is inadvisable for high-pressure plants, quite apart from the fact that the results, in spite of the large and expensive mechanisms required, are by no means perfect.

The second system, comprising a combined double-acting nozzle and deflector governing device circumvents the necessity of practically slam-shutting the nozzle in case of a drop in load, but for close governing it also requires very considerable forces to deal rapidly with the large quantities and high heads. The size of the governor must in this case also be adapted to the particular plant and, in addition, an automatic and quite intricate relationship must exist between the size of the jet for each load and the position of the deflector. This is vital in order to avoid "hunting", because the primary or deflector system must be made to act on any given size of jet without lost motion. It is the practice of the author's firm to provide combined nozzle and deflector governing systems on plants which do not require particularly close governing, such as the Lochaber turbine shown in Fig. 25.

In most high-pressure plants, however, the governing system must

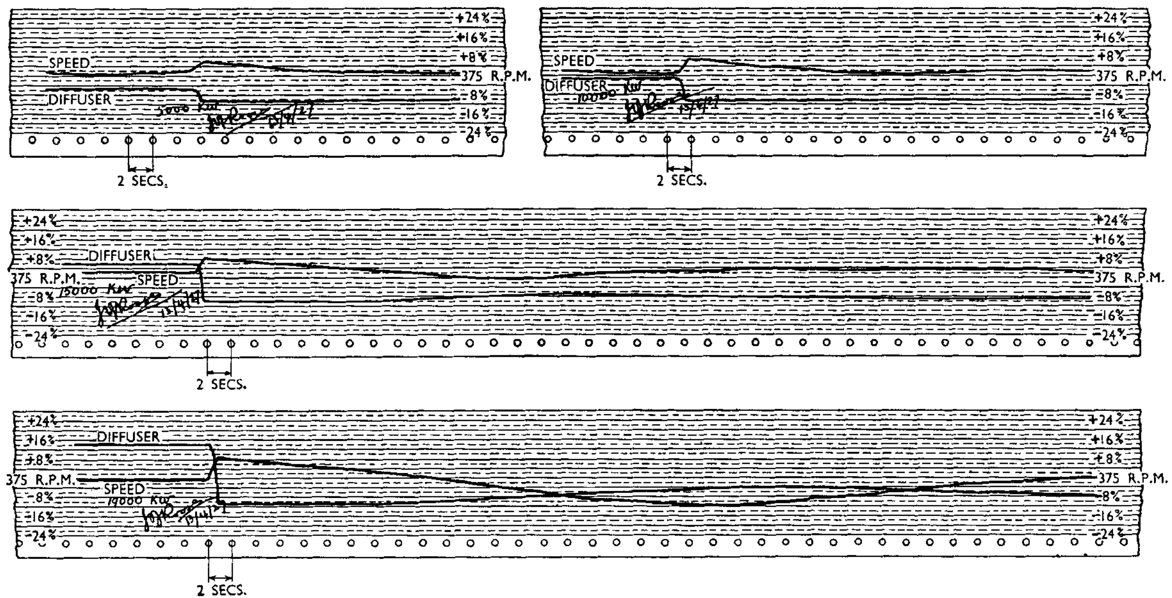


Fig. 27. Tachogram Curves of Governor with Jet Disperser

Fig. 4. Automatic Aerofoil Flow Recorder

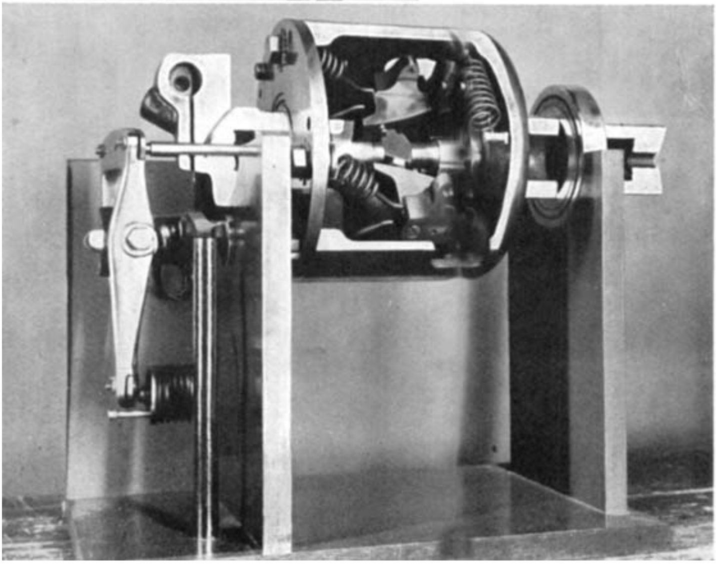


Fig. 10. Model of Automatic Governor-Actuator

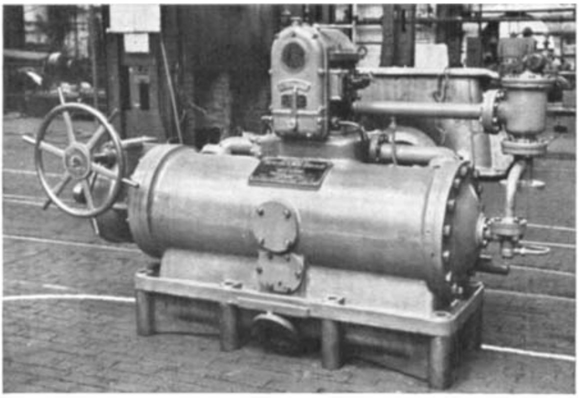


Fig. 11. Governor-Actuator and Servo-Motor

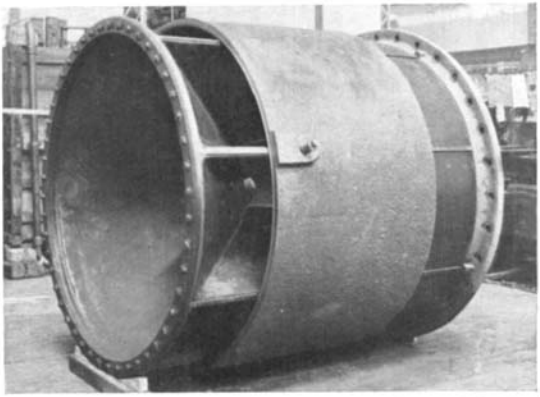


Fig. 19. Shop Assembly of Cylindrical Balanced Relief Valve

Fig. 20. Discharge Regulator in Operation on Mahinerangi Dam, N.Z.

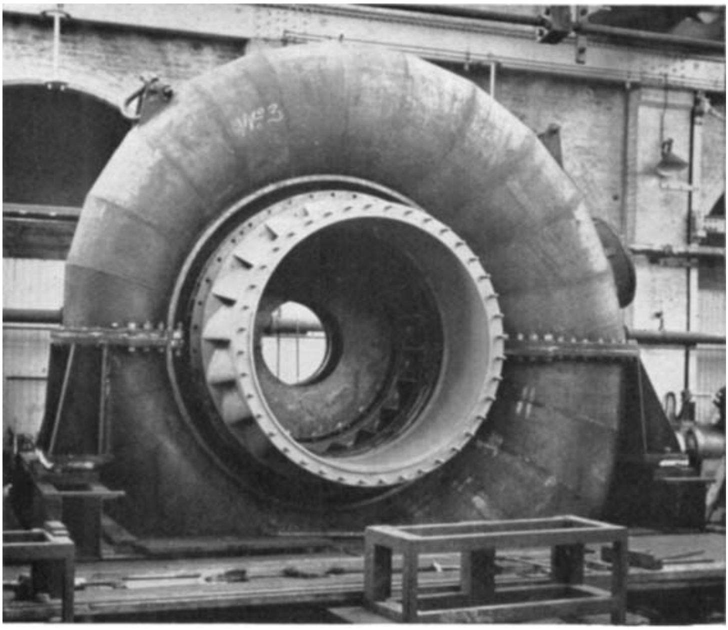


Fig. 23. Brake Nozzle Piece Assembled on Reaction Turbine

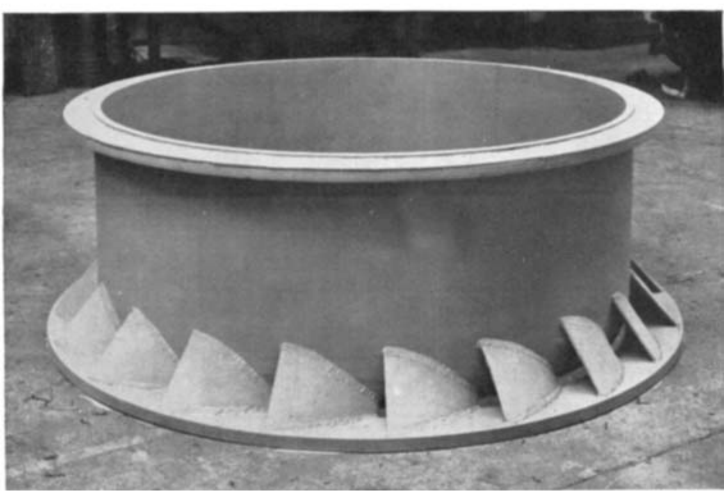
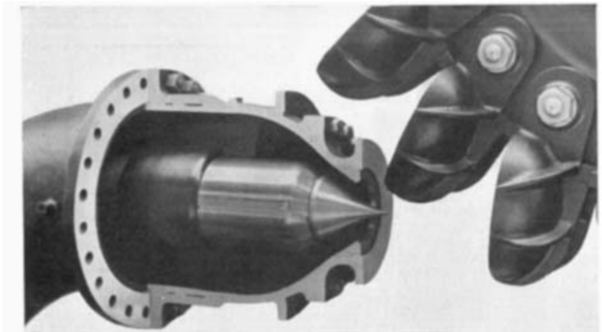
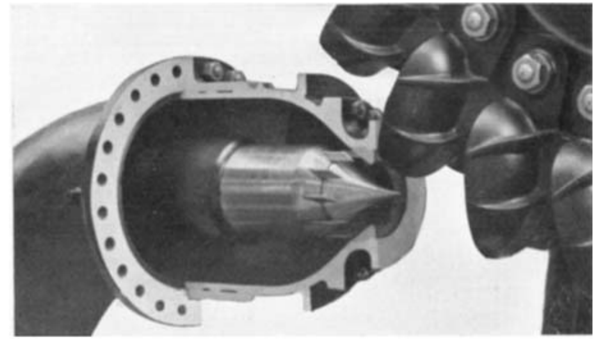


Fig. 24. Nozzle Piece for Hydraulic Brake for Reaction Turbine

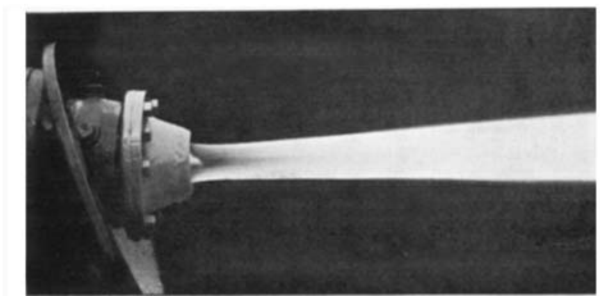
[I.Mech.E., 1936]



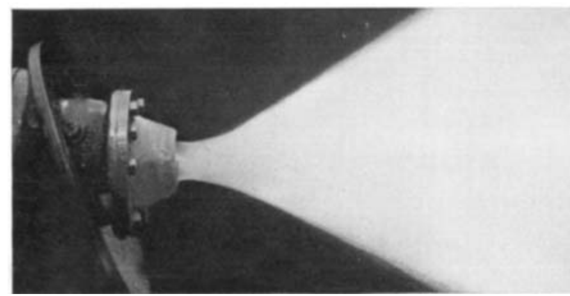
Needle shaft and diffusing blades in normal position under load



Needle shaft with diffuser in acting position



Jet operating under normal conditions



Jet with diffuser in action

Fig. 26. Governor Gear for Impulse Water Turbines

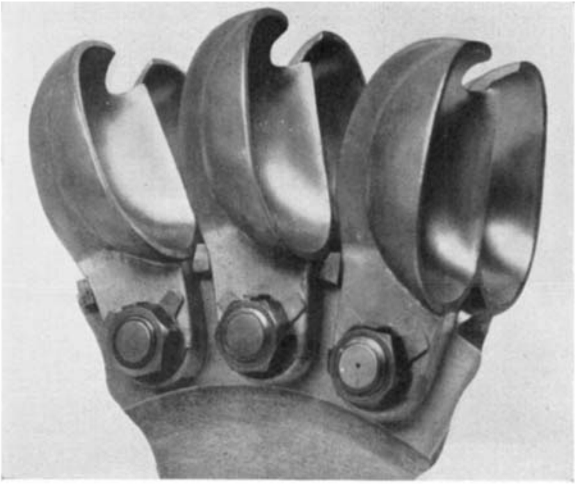


Fig. 31. Attachment of Impulse Wheel Buckets

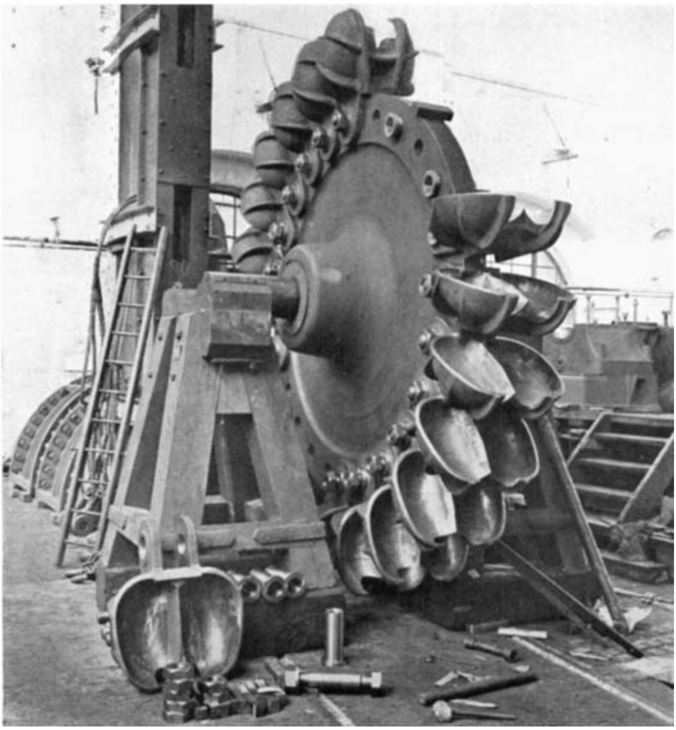


Fig. 32. 15,000 h.p. Impulse Runner in Course of Erection

[I.Mech.E., 1936]

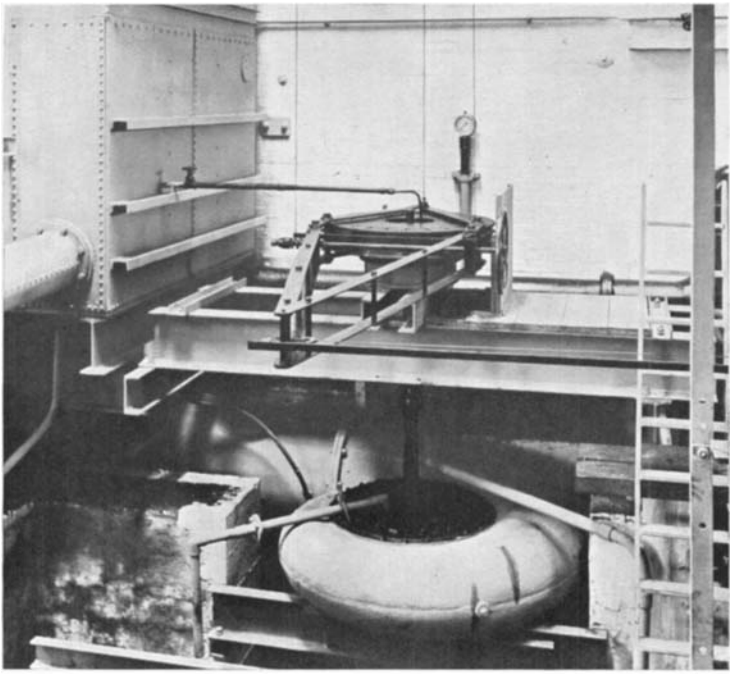


Fig. 34. Spiral-Cased Reaction Turbine and Test Brake

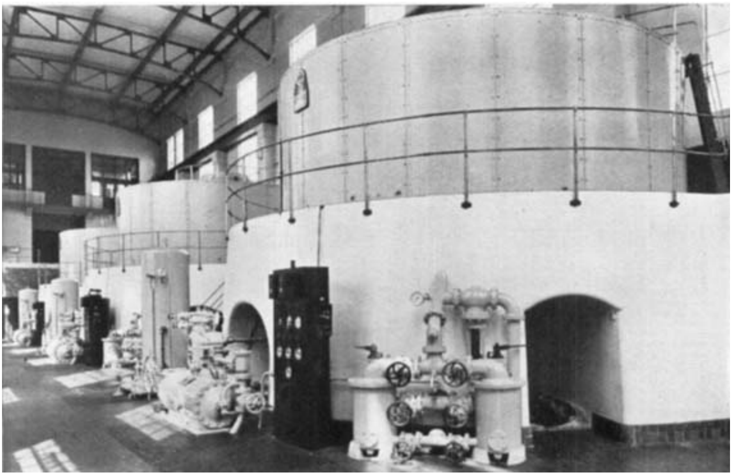


Fig. 37. Block and Step Type of Power Station
15,500 h.p. generating units at Tongland.

[I.Mech.E., 1936]

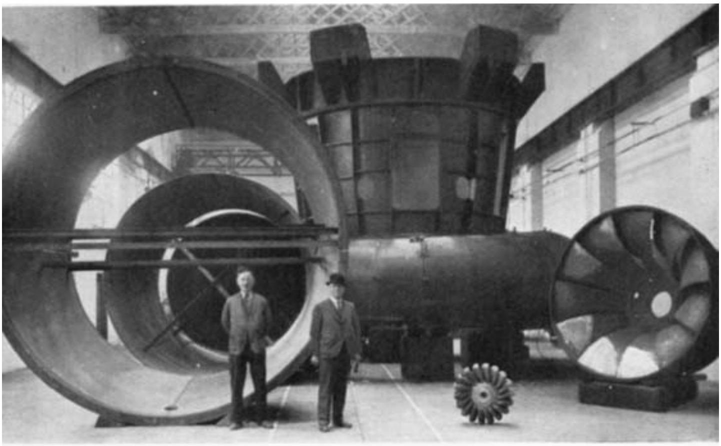


Fig. 38. Shop Assembly of 15,500 h.p. Turbine (Tongland)

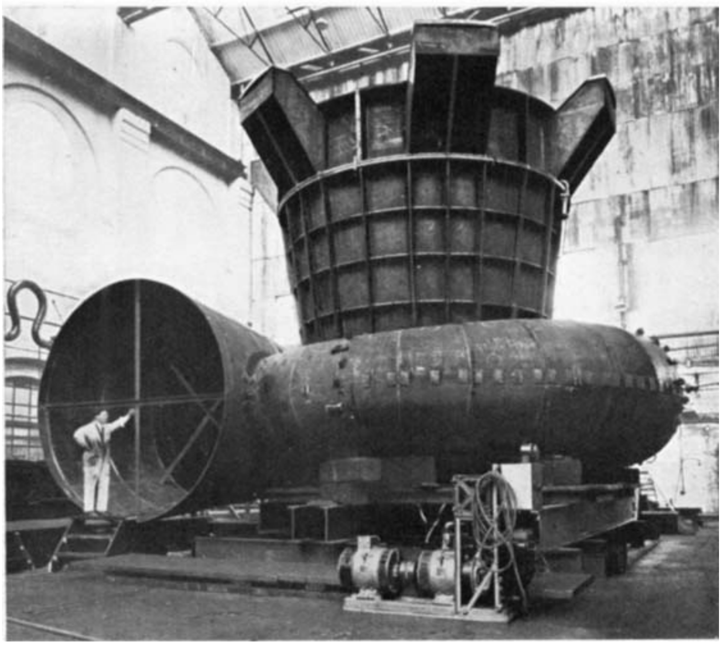


Fig. 40. Spiral Casing and Generator Support Assembly

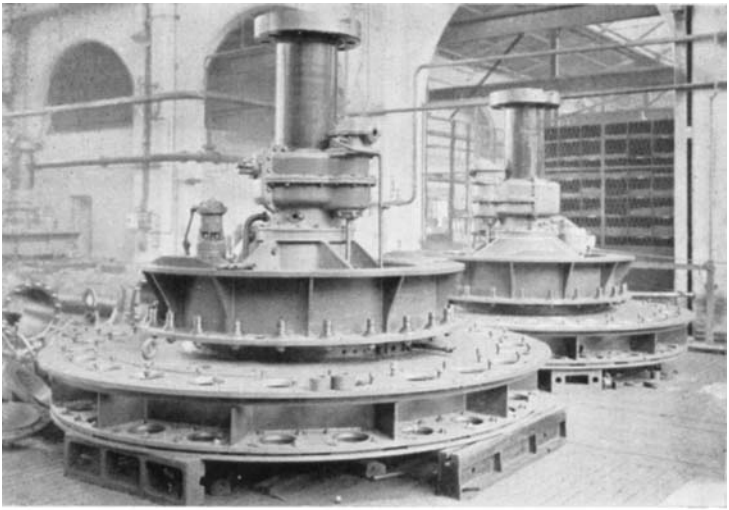


Fig. 41. Turbine Top Cover Assembly

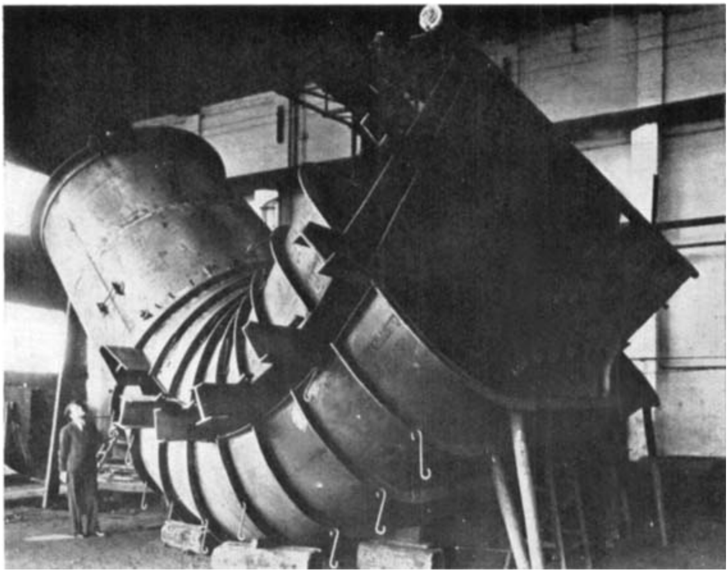


Fig. 42. Draught Tube Assembly

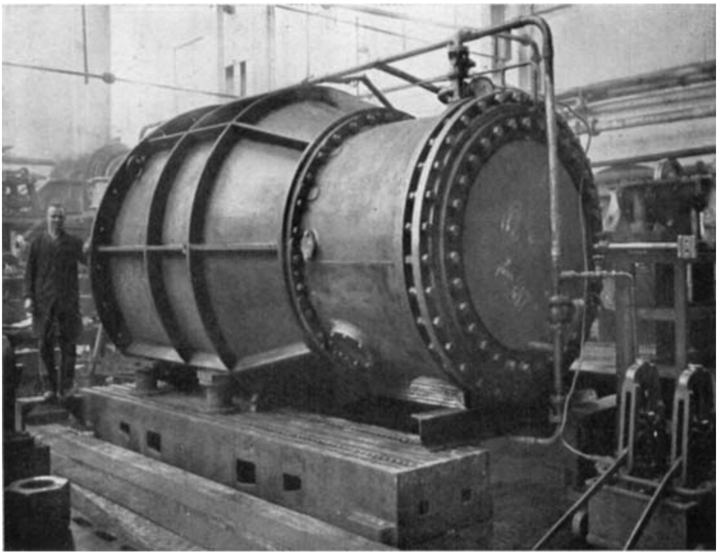


Fig. 43. Relief Valve on Test at Works

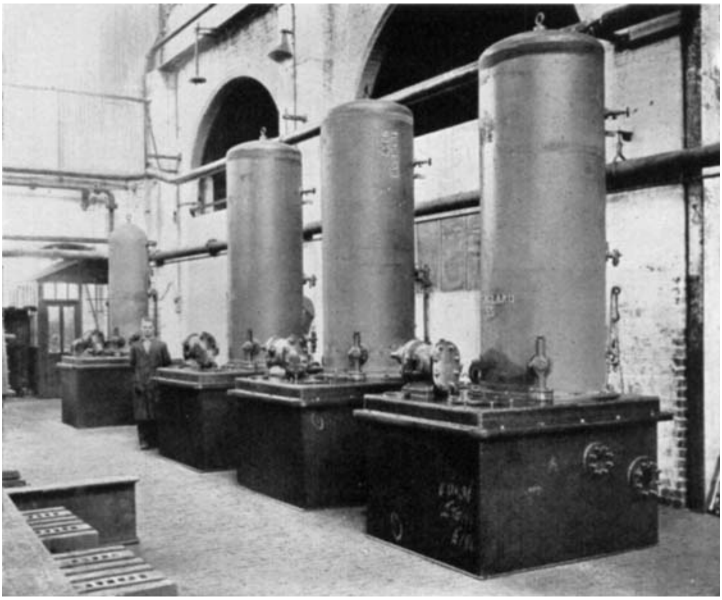


Fig. 44. Governor Oil Pressure Pumping Sets

[I.Mech.E., 1936]

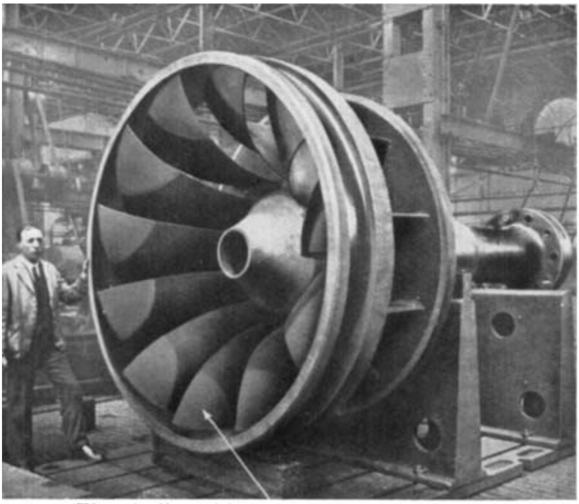


Fig. 45. Turbine Runner showing Stainless Steel Protection

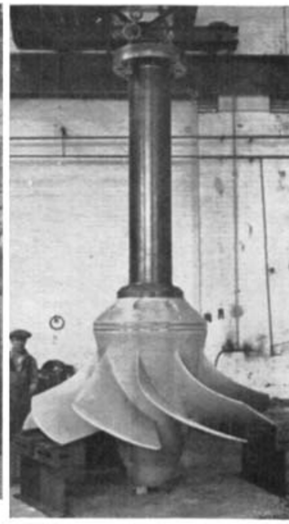


Fig. 47. 8,500 h.p. Propeller Wheel

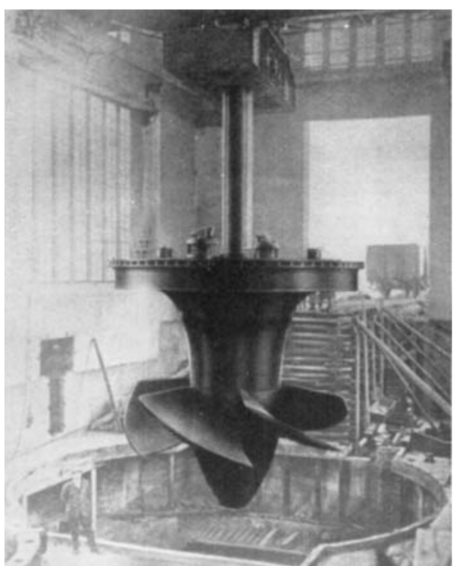


Fig. 49. 36,600 h.p. Propeller Runner and Cover

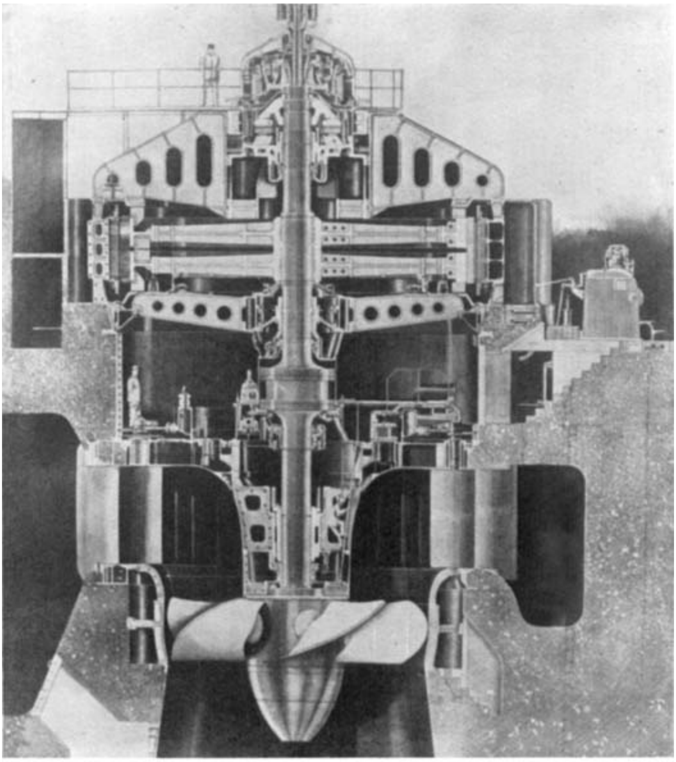


Fig. 50. 42,500 h.p. Vertical-shaft Kaplan Turbine

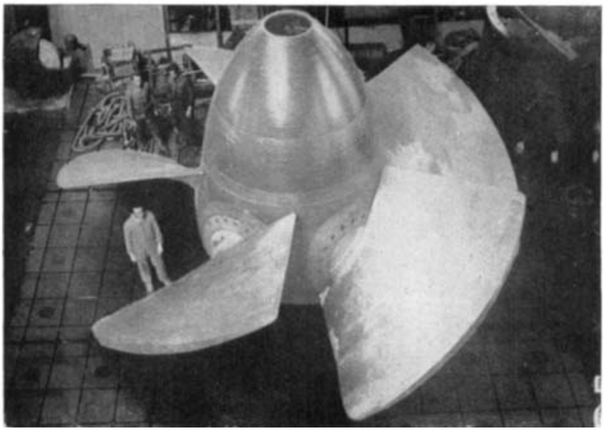


Fig. 51. 42,500 h.p. Kaplan Runner Wheel

[I.Mech.E., 1936]

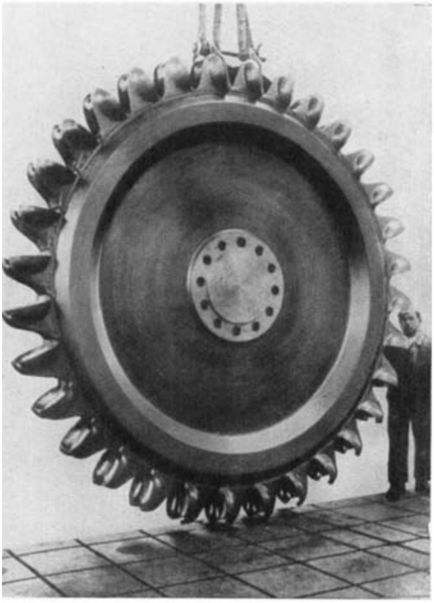


Fig. 52. Runner Wheel

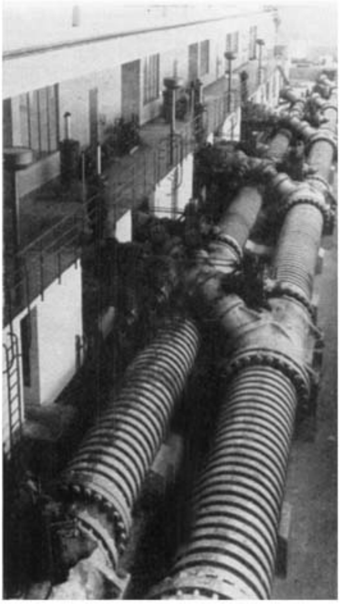


Fig. 53. Distributing Conduits

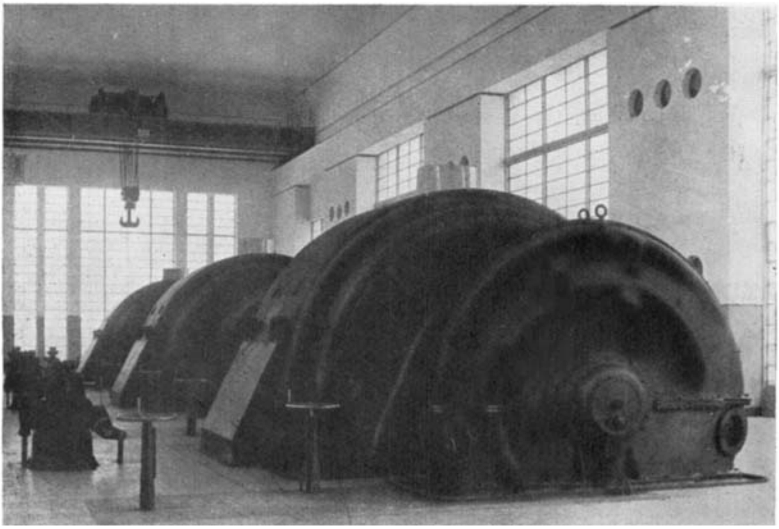


Fig. 54. Two 50,000 h.p. Sets in Power House

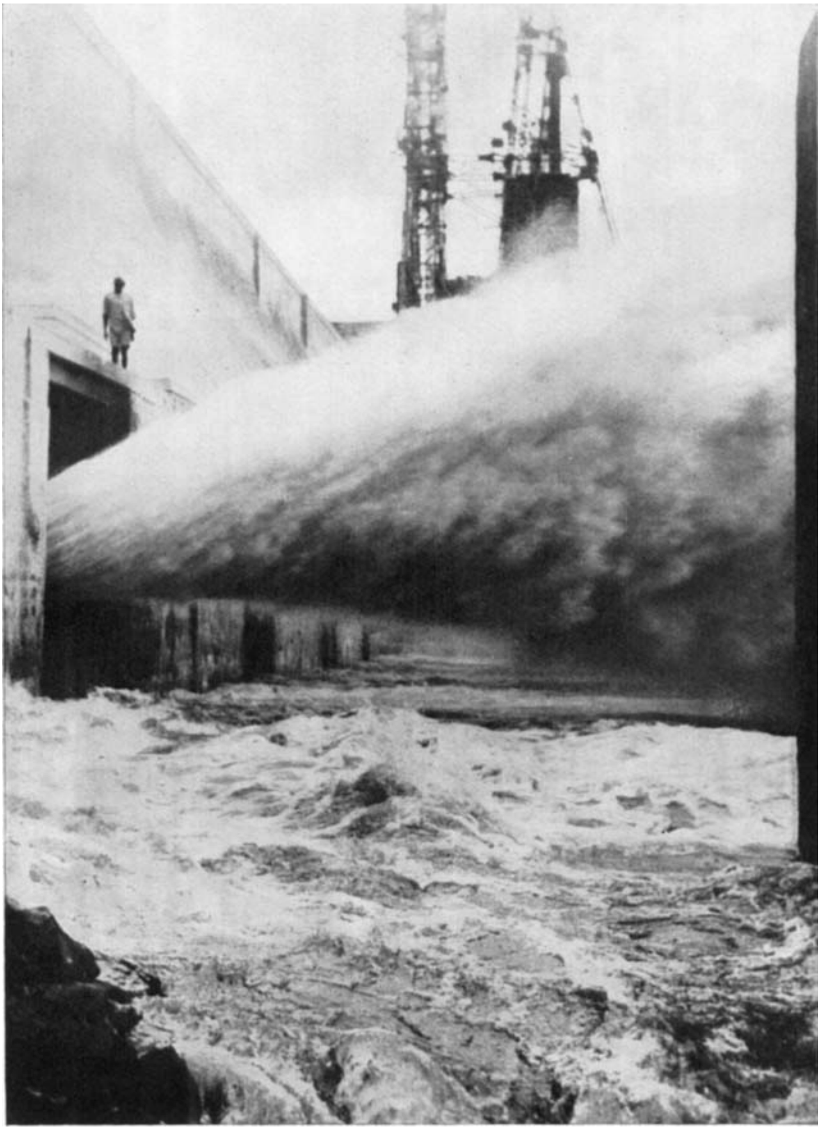


Fig. 56. 72-inch Jet Disperser Discharging under 156 feet Head
Cauvery Mettur Dam, India
(Illustrating Mr. Bruce Ball's remarks, p. 333)

[I.Mech.E., 1936]

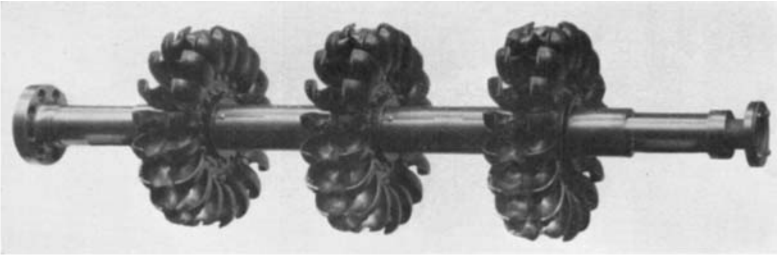


Fig. 57. Assembly of Runners on Experimental Turbine
(Figs. 57–62 illustrate Mr. J. F. Peck's remarks, pp. 349–2)

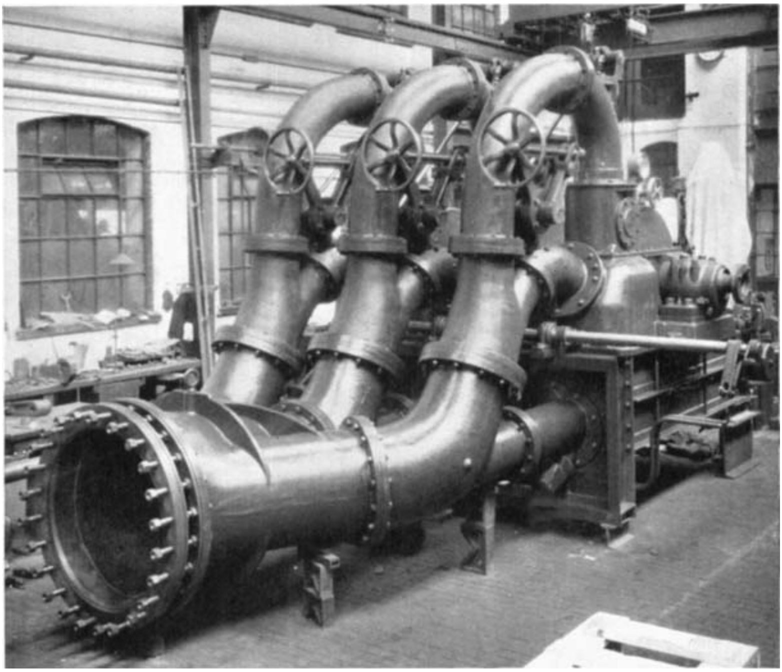


Fig. 58. Partial Front View of Experimental Turbine

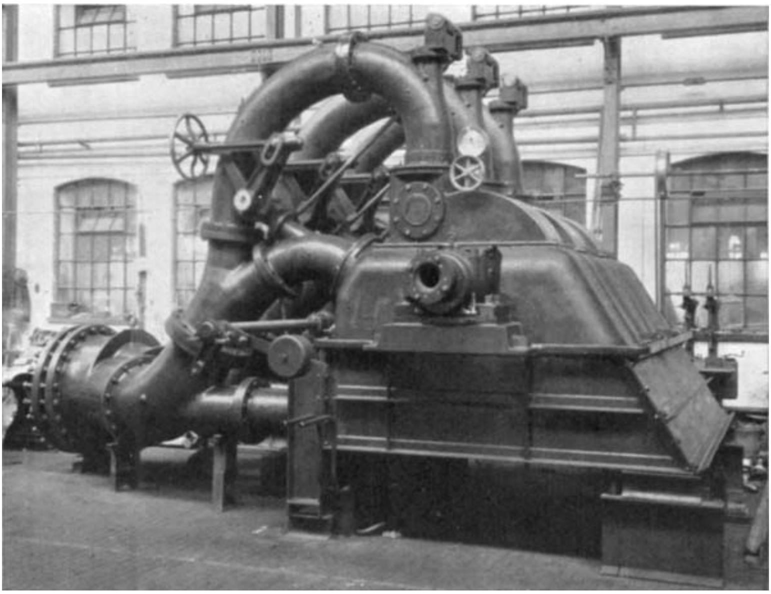


Fig. 59. End View of Experimental Turbine

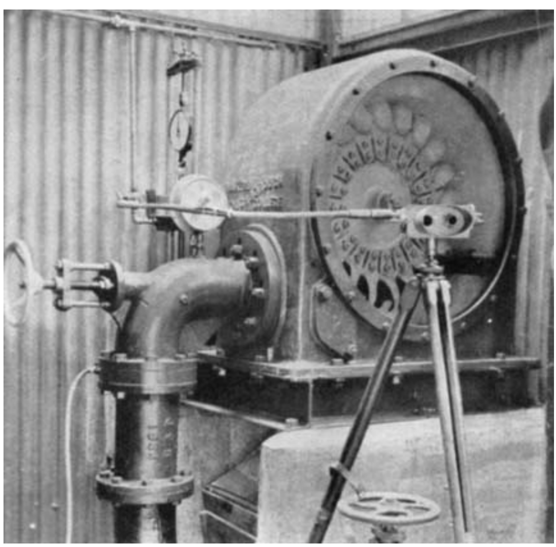


Fig. 60. Experimental Pelton Wheel

[I.Mech.E., 1936]

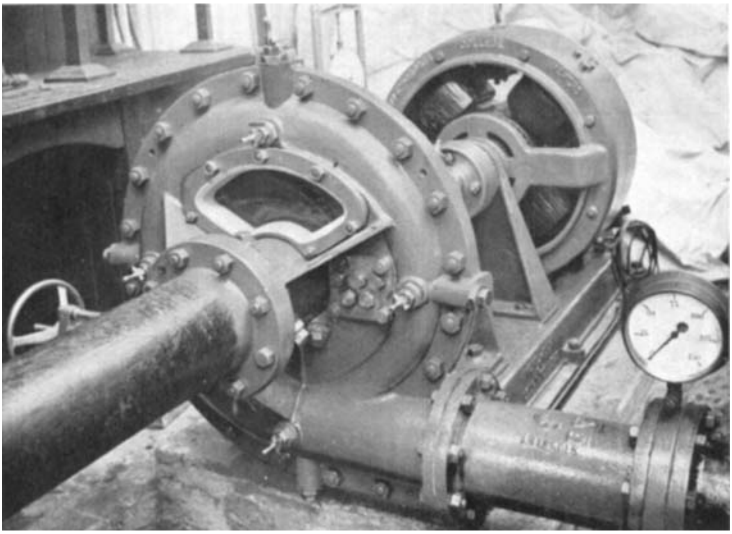


Fig. 61. Experimental Turbo-Pump Driven by Torque Reaction Motor

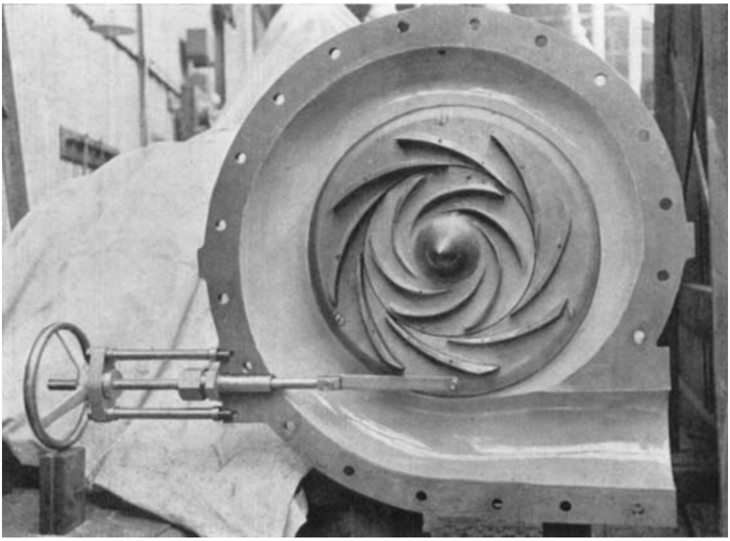


Fig. 62. Experimental Turbo-Pump with Front Half of Casing Removed

provide very close governing in case of a drop in load and yet be simple in operation, whilst ensuring absence of wear and maximum safety under all conditions of service. Efforts were therefore made to devise a governing system requiring very small forces for its operation, thus permitting of a universal governor for all impulse wheels up to the largest sizes. The well-known conical nozzle and needle are carefully designed for the formation of a compact cylindrical jet so as to ensure maximum efficiency. The size of the jet is regulated in the usual way by means of a needle or spear moving axially inside the nozzle. It was observed that even slightly conical or "broomy" jets rapidly diminished the efficiency of the jet and turbine. This phenomenon was used in the invention of the diffuser governing system.* This consists in dispersing or diffusing the jet by means of a number of slightly slanting and streamlined guide vanes surrounding the needle which, when protruding from the needle, as when governing, impart a slight rotary motion to the jet. This initial vortex is enormously enhanced by the transformation of the potential energy into kinetic energy which takes place inside the nozzle, with the result that the jet outside the nozzle is rapidly and completely broken up into a hollow cone whereby the energy imparted to the runner wheel is very rapidly destroyed. In normal operation the diffuser plates are permanently withdrawn inside the needle, thus permitting the formation of an efficient cylindrical jet. The initial vortex can be brought about by comparatively small forces even for turbines of the largest sizes and for very high pressures, and diffusion takes place almost instantaneously, resulting in very close governing.

This system of regulation has now been in continuous commercial operation for many years and is giving consistently good results. No detrimental influence on the pipe line pressure occurs during its operation, and no wear whatever takes place on the diffuser plates. In fact there has never been occasion to renew or replace any diffusers.

Fig. 27 shows some results obtained on an important installation, and Fig. 29 shows the operating characteristics of the governor. No special protection in turbine pits or tailraces is necessary because the energy of the diffused jet is largely destroyed when it reaches these points. Finally, no system of interdependence between the size of the jet and the position of the diffuser is required, because the diffuser, after action, always withdraws to the same position inside the needle flush with the latter, and is thus ready to act instantly on any size of jet without lost motion.

* *Engineering*, 1927, vol. 123, p. 317.

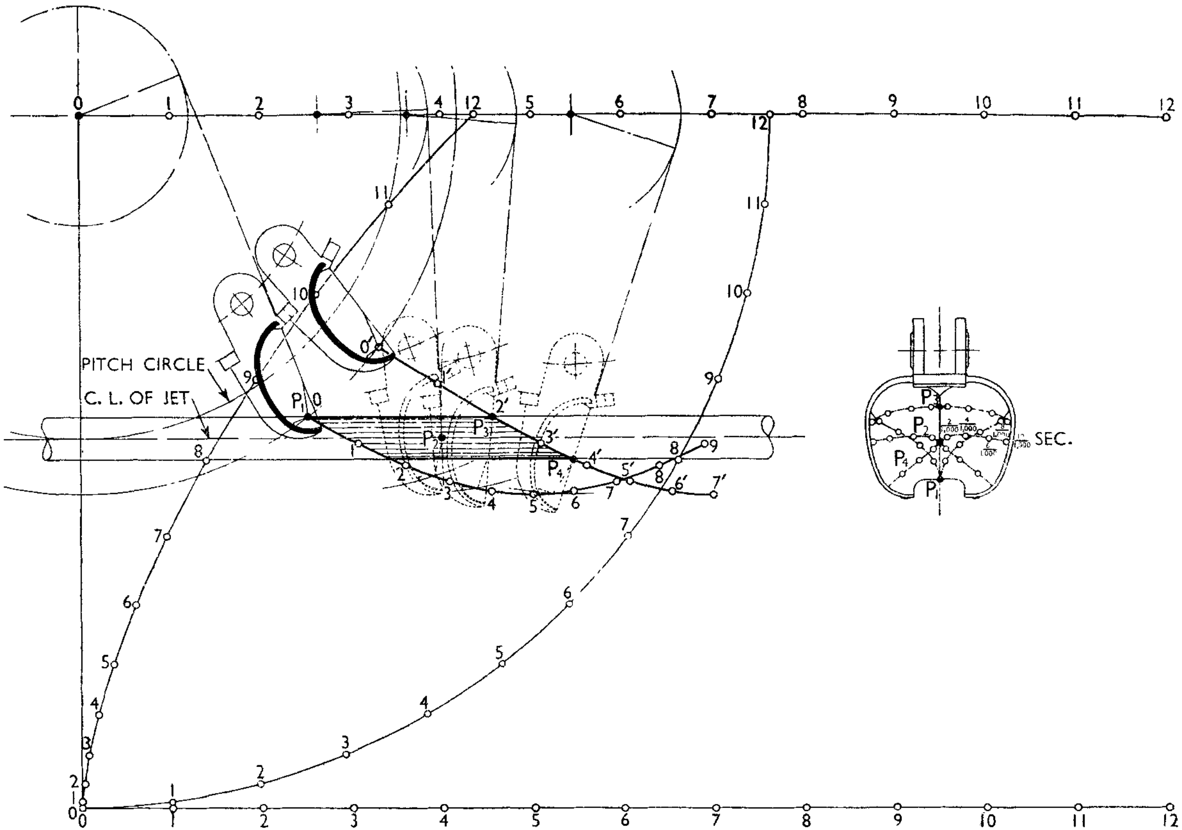


Fig. 28. Determination of Relative Paths in Impulse Wheel Bucket

Impulse Wheel Bucket Fastening. The dynamic forces and stresses prevailing in impulse wheel buckets and their attachments present a problem which, apart from conditions encountered in ordnance work is, the author believes, unique in engineering practice. A satisfactory bucket fastening must afford absolute security under all conditions of service and ensure perfect interchangeability and easy and rapid handling in the field.

For the attainment of high efficiency and freedom from wear it is necessary to design the form of the buckets by determining the relative paths of at least a number of the most important drops inside the rotating buckets. This is done by the judicious application of Coriolis's theorem of relativity, and is corroborated by frequent tests in the field. The size and weight of buckets for important machines are often considerable.

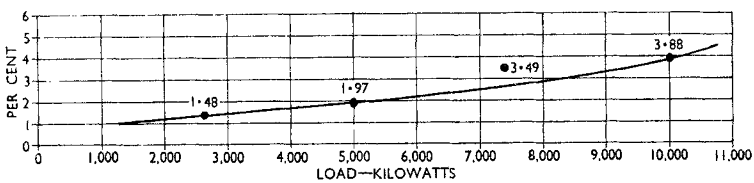


Fig. 29. Operating Characteristic of Jet Disperser Governing Device

Percentage speed rise above no-load speed (in case of sudden drop in load).

The attachment of the buckets to the wheels or disks must be designed and manufactured to withstand:—

(1) The alternating stresses due to the jet impact.
(2) The centrifugal forces at normal and runaway speeds.
(3) The stresses set up by the application of the full jet with the wheel at rest (short-circuit).

An example will best illustrate the method of design. For a wheel developing 15,000 h.p., for instance, and running at 375 r.p.m. under 1,650 feet head, each bucket sustains a thrust from the jet amounting to 27·5 tons 6·25 times per second, or 540,000 times per day. Fig. 28 shows how relative paths are determined and it will be seen that each particle of water traverses the bucket in about $\frac{1}{100}$ second. The thrust of the jet, therefore, is decidedly in the nature of a blow. Each bucket after passing through the jet is completely emptied again so that the resultant forces alternate continuously and very rapidly. In addition there are the centrifugal forces set up concurrently by the rotation. It will thus be realized that the demand on the attachment is very severe and it is not surprising that numerous bucket attachments by several cylindrical and also conical bolts, rivets, or even dovetailed edges, have proved inadequate, resulting in dislocation and rupture with disastrous consequences.

The system of attachment adopted by the author's firm * consists of one bolt only for each bucket, made up of a bush in nickel-chromium steel, cylindrical outside and conical inside, which is split over its whole length. A conical bolt, also of nickel-chromium steel, is introduced into the bush, and is provided on either side with a fine thread, nuts, and locking washers. The holes in the bucket and disk are cylindrical and of identical diameter. This facilitates manufacture and enables the attachments to be completely finished in the shops so that the buckets become strictly interchangeable, chiefly because

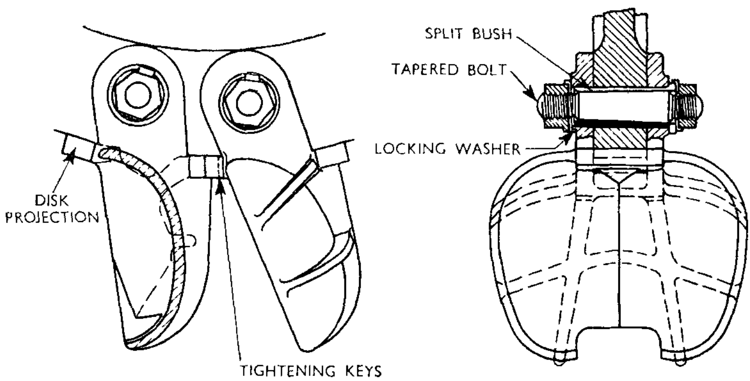


Fig. 30. Method of Attachment of Impulse Wheel Buckets

each has only one hole. On introducing the conical bolt into the split bush after assembling the bucket with the disk the split bush expands, and is caused by the cone to bear against the cylindrical holes in the disk and bucket with a tightening force considerably superior to any force the jet can exert on the bucket. No dislocation or weakening of the attachment can therefore take place and in practice no bucket attachment of this type has ever shown any dislocation or similar trouble. Every alternate bucket is made to bear against a part protruding from the disk and cast integral with the latter by two strong transverse (axial) keys, each of which is separately locked. The conical side or taper is arranged between the two keys so that each bucket presents parallel facings only, thus again ensuring perfect interchangeability.

* See *Engineering*, 1928, vol. 125, p. 747.

Dismantling is easy and expeditious as the keys can be separately withdrawn as for an ordinary wheel and shaft attachment, while the bucket can be slackened by simply withdrawing the conical bolt from the split bush by means of its threaded end and nut. No reamering is necessary on site and thus prolonged stoppage of the plant is obviated in case of replacements.

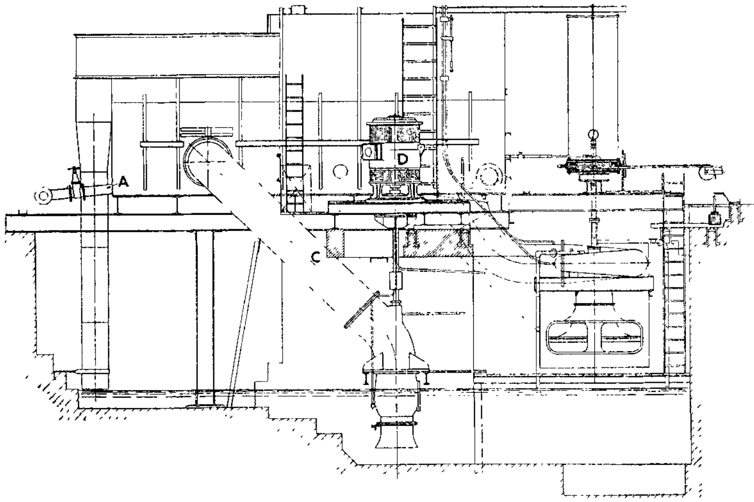
Experimental and Research Plants. In every hydro-electric scheme nature imposes peculiar conditions of pressure, output, quantity, and local setting. Hydro-electric engineering is thus to a large extent pioneer work and it is often necessary to resort to extensive experimental and research work in order to achieve the best results. The firm with which the author is associated has thus been led to establish its own industrial test plant which is, as far as the author knows, the first and only one in the British Isles, apart from the experimental laboratories in technical schools, the purpose of which is chiefly educational.

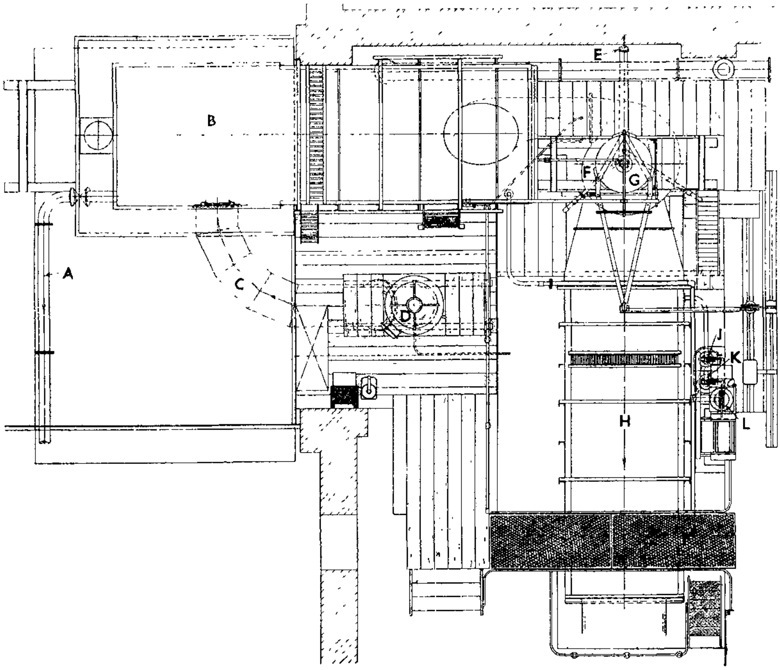
This plant, which is illustrated in Figs. 33, pp. 310–11, and 34, Plate 6, enables extensive tests on model turbines and their accessories to be made. It is established within the factory area so that research can be carried out in constant contact with the design and manufacturing staffs.

By means of a test plant the efficiency of turbine runner wheels covering a wide range of specific speeds can be established without ambiguity. Such a plant enables the correct form of spiral casings, distributing apparatus, and draught tubes to be determined. It can also furnish valuable information on axial thrusts, cavitation, runaway speeds, and other hydrodynamic phenomena which it is very difficult, if not impossible, to establish theoretically with sufficient accuracy. It is possible to establish the deceleration characteristic resulting from the application of hydraulic brakes as compared with the unbraked deceleration, and to determine the quantity of water required for a given braking effect. The characteristic of the aerofoil type of flow recorder can likewise be exactly determined.

The work also includes a thorough testing of all governors and their safety devices, valves, discharge regulators, oil pressure plants, and measuring instruments; the testing of pressure-bearing parts, and the concurrent determination of the properties of the materials employed; runaway tests, and tests of the static and dynamic balance of runner wheels, flywheels, and other important rotating elements.

The original plan to utilize the water level difference of an existing river was dropped in order to enable the tests to be made independently of fluctuations in quantity and head, often considerable in any river. Consistent and reliable tests under steady conditions can only be


A
D
C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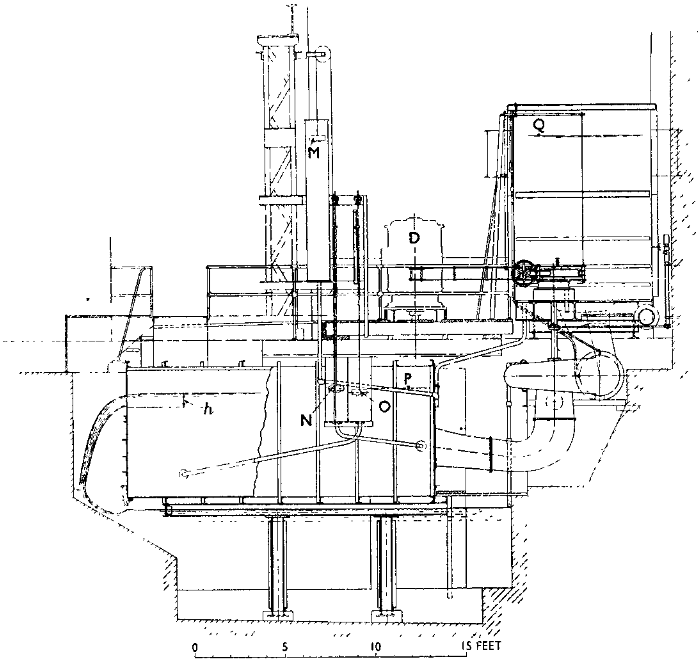

Fig. 33. Experimental Hydraulic Test Station

A Drain
B Headrace tank
C Pump discharge pipe
D Pump motor
E Tachometer
F Test turbine
G Brake
H Measuring weir tank
J Measuring weir chamber
K Tail water level chamber
L Headrace level chamber
M Headrace float
N Tailrace float
O Weir float
P Tailrace level
Q Headrace level

obtained by means of pumped water and tanks which allow of exact adjustment of quantity and pressure. This also made it possible to install the experimental plant within the works. The water circulation plant consists of a vertical-shaft axial-flow pump directly coupled to a vertical-shaft 130 h.p. electric motor permitting variable speed. The pump can deliver a maximum of about 1·2 tons of water per second against a head of 20 feet. The quantity and head utilized by any turbine under test can be adjusted by means of the speed of the pump,

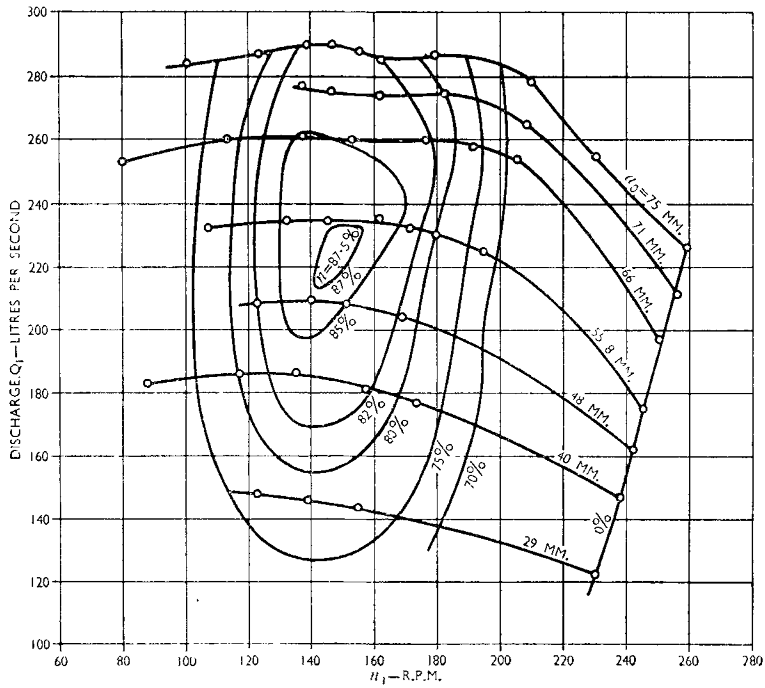

Fig. 35. Test Results on Reaction Turbine

in conjunction with a head tank provided with an overflow weir, into which the water is delivered by the pump. A very steady level of water in the head tank is secured by means of a number of stream-lined flat wooden plates reaching from top to bottom of the tank at intervals of about 1 inch. The water is conducted to the spiral casing and turbine to be tested by means of a pipe and bend and reaches the tailrace through a suction pipe and bend, easily accessible and inter-changeable, to enable various forms of suction bends to be tested. All forms of spiral casings can be tested and the layout can be adapted for testing various forms of guide and distributing apparatus, runner wheels of every form and description, hydraulic brakes, shutters, etc.

The turbine shown in Figs. 33 and 34 is of the vertical-shaft type, but horizontal-shaft turbines can also be adapted and tested. The tail-race is arranged as a gauging tank and is provided with a calibrated rectangular contraction weir by which the water returns to the sump at the bottom of the building where the circulation pump operates. The vertical-turbine shaft rotates in two ball bearings and is suspended in a thrust bearing of the ball race type.

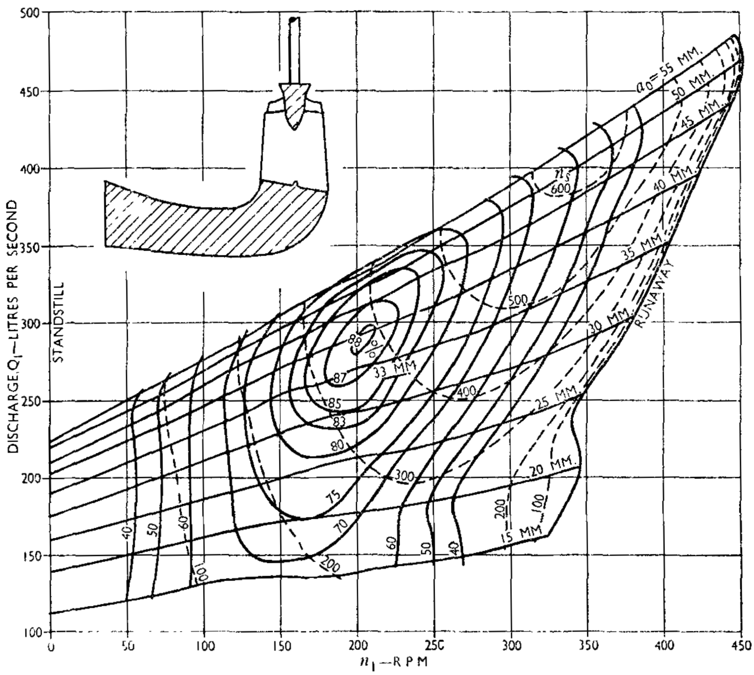

Fig. 36. Test Results on Propeller Turbine

The power developed by the test turbine is absorbed by a mechanical and compensated friction brake of the Prony type provided with three equidistant pivoting brake shoes with Ferodo linings bearing against a fabricated circular drum constantly cooled by water from the inside. The torque is measured by adjustable counterweights attached to a cable connected with the arm of the brake. It is thus possible to determine the power delivered by the turbine under any conditions of load, head, and speed, with considerable precision. The effective head is measured by float indicators in head and tail tanks and the various losses in bends, spirals, and all other vital parts are measured by piezometers. The speed is measured both by a permanent and a belt-driven dial tachometer and is controlled during tests by a hand tachograph.

Sample test results obtained with this plant are shown in Figs. 35 and 36. The tests made in this plant, especially the efficiency tests, have always shown excellent agreement with the results obtained from the full-size machines in the field. It is, however, necessary to apply correcting factors to take into account scale effect. The money invested in the test plants has been amply justified by the invaluable aid it has afforded in devising improved forms and elements of turbines and their accessories.

General Design and Special Mechanical Features in British Practice. One of the most pronounced features of British practice is the comprehensive way in which hydro-electric schemes are being developed. While the turbines, of course, as prime movers, primarily determine the type, speed, local setting, connexion, and operation of the generators, constant contact between the hydraulic and electrical engineers allows the machinery to be treated as a whole "hydro-electric set". From the start careful consideration is given to the adoption of output, type, and speed suitable to both the hydraulic and electrical parts of the plant. Adequate factors of safety are aimed at for all parts of the running machinery under both normal and abnormal operating conditions, including overspeed and short-circuit. At this stage the flywheel effects which it is possible and safe to embody in the sets to ensure satisfactory regulating conditions are determined, taking into account the conditions imposed by the momentum of the moving water both in the pipe line and tunnel. Great care is taken to create permanently rigid settings for the machinery, and to ensure their perfect alignment, connexion, and accessibility. It is then possible to prepare compact designs occupying minimum floor space, and the cost of the power house can be reduced, and control and safety gears can be made simple and reliable.

Comprehensive treatment also includes the other components of the plant. Thus control gears, feeder piping, stop valves, air ducts, discharge canals, cable trenches, auxiliary machinery like exciter and standby sets, interconnecting plant, crane, etc., can be evolved so as to combine economy with ease of supervision, handling, and maintenance. Sufficient dismantling space is carefully considered in relation to access roads, crane height, and capacity. Continuous collaboration with the electrical designers allows the switchboards, transformers, cable trenches, and other electrical gear to be arranged in such a way as to avoid interference with any other service.

The arrangement and size of penstock and distributing pipes and their influence on governing are carefully investigated. The power house foundations, anchor blocks, pipe supports, and expansion joints are designed in the light of all normal and abnormal conditions obtaining in service. Seismic loading, altitude, and climatic conditions and their influence on the aeration and cooling of generators and bearings are also taken into account. Chemical and physical analyses of the water form the basis for the choice of the material for the runners, distributing apparatus, and other vital parts. Such comprehensive treatment, both in design and manufacture, makes possible the adequate design of completely automatic and semi-automatic plants and their controls.

The Block and Step Design of Power House. Except in certain cases where horizontal-shaft machines are preferred for reasons of local setting, existing foundations, or a special type of service, as for example the operation of large direct-current generators, the single-runner vertical-shaft type of reaction turbine and generator has been developed. This type of turbine ensures simplicity, sturdiness, economy of space and superior hydraulic conditions. The casing can be completely embedded in the concrete foundations, thus ensuring great rigidity and freedom from vibration. Hence the vertical-shaft type is given preference practically everywhere for machines of large output and size. The orthodox type of vertical-shaft plant involves, however, the following drawbacks. It is far more inaccessible than the horizontal-shaft plant. The usual design of vertical-shaft power house involves two or more floors, rendering dismantling, supervision, and maintenance awkward. Important parts like pumping plant, governors, and servo-motors must be arranged on different floors, often at a considerable distance from the parts they are destined to control, such as distributing apparatus, relief valves, and stop valves. Substantial interconnecting gears are therefore necessary in order to obviate lost motion and subsequent "hunting", the servo-motors must be embedded in the concrete, where they are inaccessible and difficult to maintain. A further objection is the difficulty of maintaining perfect alignment and rigid connexions between the hydraulic and electrical machinery when they are arranged on separate and independent floors, because of the temperature differences and constantly varying axial loads.

To overcome these drawbacks a permanent and absolutely rigid connexion between the turbine and generator was evolved, consisting of a steel barrel which is in reality nothing else than an extended generator bedplate. This barrel is permanently connected at the bottom to the turbine speed ring and is strongly embedded and anchored into a concrete pedestal surrounding the turbine. It rises

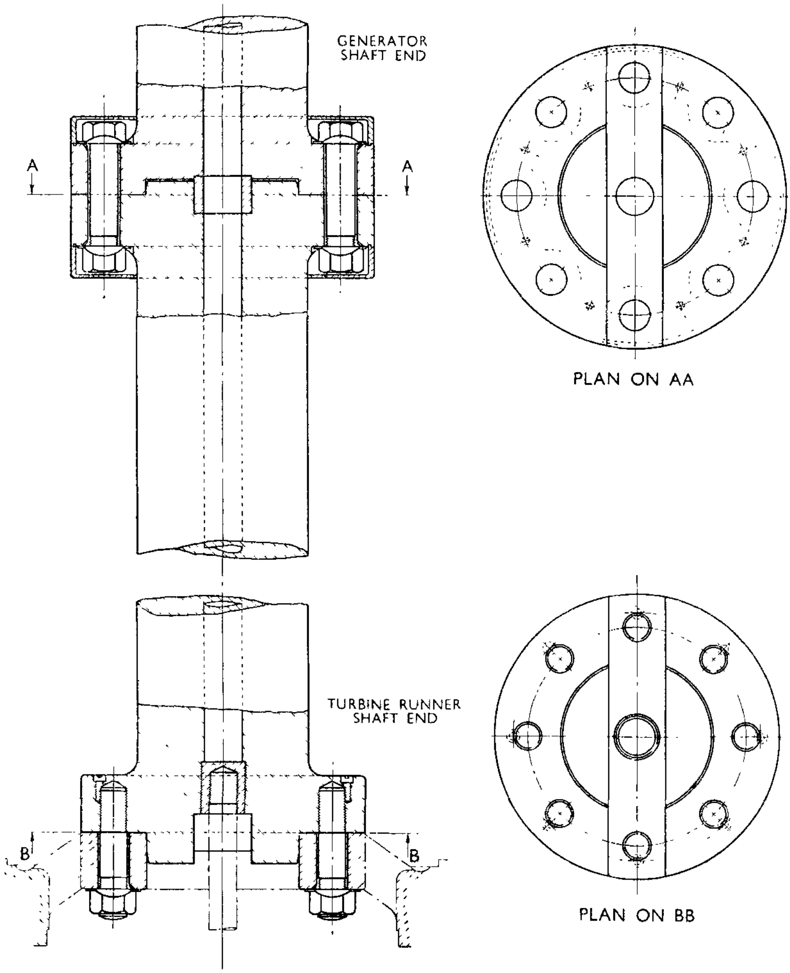

Fig. 39. Turbine and Generator Shaft Couplings

from the power house floor, with which it is strongly interlaced, and is provided with three or more large access ducts traversing both pedestal and barrel. Through these ducts the turbine can be conveniently and rapidly visited for inspection from the single power house floor. In this way it is also possible to arrange the governor, servo-motor, and complete control mechanism in the immediate neighbourhood of the distributing apparatus and relief valve. The barrel transmits the weight of the generator through the cast steel speed ring of the turbine to the foundations underneath, and also takes up the short-circuit torque, which is a multiple of the normal torque. The ducts also allow the governor drive to be arranged in the most direct way. The cylindrical balanced stop and relief valves can conveniently be placed underneath the power house floor and their design greatly simplifies the foundations. All important parts are rendered easily accessible from the single power house floor and by the same crane, and the oil pumping plant is also arranged on the same floor and in the immediate neighbourhood of the governor. The governor actuator can always be combined directly with the servo-motor underneath, that is, it can be of standard type. The inside of the turbine casing and runner is accessible through ducts and manholes from the same single power house floor.

The Coupling. Perfect rigidity, concentricity, and alignment, combined with ease of manufacture, erection, dismantling, and interchangeability in the field, are desiderata in the design of a coupling to serve for the assembly of a turbine runner and shaft and of turbine and generator shafts. The usual multiple-bolt type of coupling involving a number of cylindrical, or even conical, bolts was abandoned because of the considerable difficulty of manufacturing strictly interchangeable spare parts which would permit of expeditious replacement in the field without reamering. It is, indeed, practically impossible to repeat a series of, say, ten or twelve holes, which in respect of both diameter and pitch circle will correspond exactly, the more so as the necessary centring spigot must be made to fit simultaneously with a tolerance of not more than 1/1,000 inch or preferably less. Conical and cylindrical shaft and runner assemblies often render dismantling, after prolonged service, extremely difficult and can lead to prolonged stoppage in case of replacement.

In order to obviate these difficulties a coupling has been designed, as a standard product, made up of a number of studs or bolts separately and jointly locked, which are arranged within holes in the coupling and allow considerable clearance. The torque is no longer transmitted by the bolts, but by one single, amply designed, diametrical key, traversed and kept in position by two of the bolts, and made to jig to fit the coupling halves with a slight interference fit. This jig contains an exact centring fitting each coupling so that the relative positions between centre spigot and keyways are made to correspond exactly. The number of elements which have to be made to fit exactly is thus reduced to two instead of a multiple of this number. This type of coupling, which is illustrated in Fig. 39, is easy to manufacture and handle and obviates reamering in the field.

The Development of Welded Structures. The necessity of reducing both time of delivery and weight has led to the development of composite welded structures on a considerable scale. Not only pipes, but spiral casings, turbine main covers, valves, bearing housings, draught tubes, barrels, rotors, and even runner wheels are now fabricated by electric welding with carefully selected electrodes and welding plant. Experience has shown that most of these fabricated structures are not only lighter and cheaper, but much better than many castings, inasmuch as they are free from blowholes, cracks, and other defects always to be expected, especially in complicated steel castings. The considerable progress made in this field can best be illustrated by examples of the most important pieces, most of which have been in continuous and successful operation for a considerable time.

Spiral Casing. The correct logarithmic form for an intake vortex is made up in lobster-back shape which is obtained by butt-welding the composite parts joining the gradually diminishing sections, and double lap-welding on to the speed ring or centre portion which surrounds the guide apparatus. The longitudinal joints, tail ends, and manhole joints, which are exposed to the greatest stresses, are reinforced by multiple lap- or stitch-welding, which is in reality not absolutely indispensable but is an additional safety factor for these joints and greatly increases their strength. The inside of the spiral casing is smooth and is on that account alone superior to the riveted or lap-welded casing as it presents a minimum of resistance and disturbance to the flowing water forming the intake vortex. There has been no case of failure under pressure or distortion in service with this type of casing.

Immediately above the spiral casing can be seen in Fig. 40, Plate 7, the barrel or generator support. This barrel is also entirely welded and while remarkably light is of considerable strength. It is made in several sections for transport and contains passages or ducts for inspection.

The turbine cover also formerly presented difficulties in manufacture, both of the pattern and of faultless castings. It is made up of top and bottom covers between which twenty-four or more different compartments must be made to correspond exactly with the equal divisions of the guide apparatus of the distributing gear. It can now be made comparatively easily and rapidly by welding. Such a cover (Fig. 41, Plate 8) presents an almost perfect homogeneity apart from being much lighter than a steel casting.

The fabrication by welding of draught tubes is a problem which has much in common with the fabrication of spiral casings. The correct transition from the circular to the parabolic exit form at the bottom is of considerable importance in effecting a smooth and efficient transformation of the kinetic energy contained in the flowing water as it leaves the runner, into negative pressure. Welding enables the draught tube to be made perfectly smooth inside and assists the correct and expeditious building of the foundations (see Fig. 42, Plate 8).

The relief and bypass valves lend themselves admirably to fabrication by welding. The entire outer body, dismantling ring, and discharge hood are welded. The valve piston is of phosphor-bronze and glides on stainless steel strips on the inner body. This relief valve, illustrated in Fig. 43, Plate 9, discharges up to 30 tons of water per second under 150 feet pressure and is much stronger and more homogeneous than a cast valve. The control and operating piping is connected to it by means of adequately reinforced double lap-welded joints.

The success obtained so far with welding is due to careful design, continuous tests of the strength and homogeneity of the welds, and minute supervision and control of the welding material and the welders.

Stainless Steel Protective Welding. Great care is taken to avoid the danger of cavitation by a judicious choice of specific speeds and static and dynamic suction heads. The continuous increase of the specific speed of hydraulic turbines with a view to reducing first costs, however, coupled with the unavoidable deviation from the correct angle of the runner blades at part load, and change of pressure, makes it imperative to provide against the danger of cavitation which is so disastrous to both the life and efficiency of the runner wheels and turbines. The continuous increase of pressure utilized in both reaction and propeller wheels causes the water to traverse and leave the runner canals under far more severe conditions than those prevailing a few years ago. Cavitation is by no means restricted to water turbines running under certain exacting conditions, but is also in evidence in the case of ship propellers.

Protective measures must include the most careful design of the turbine runner blading and the choice of the best possible material. It has been found that "turbadium" bronze, specially created for service in ship propellers, as well as certain brands of stainless steel, show excellent cavitation-resisting properties. Unfortunately the price of these alloys is extremely high and the production of sound castings, both in turbadium bronze and stainless steel, is attended with very considerable difficulties. Runner wheels work under considerable stresses and the risk of casting defects would be a serious consideration. Complete wheels of these alloys would, however, be unnecessarily extravagant because only a small portion of the wheel, the position of which is well known from hydrodynamic consideration and lies at the outer and lower part of the blading, needs protection against cavitation.

The first solution of the problem therefore consists in providing the critical region of the blading with a protective layer of stainless steel applied by welding on to the cast steel basis metal after careful preparation of the latter (Fig. 45, Plate 10). With careful handling no modification of the properties of the stainless steel takes place and wheels treated in this way have shown neither cavitation nor other defect.

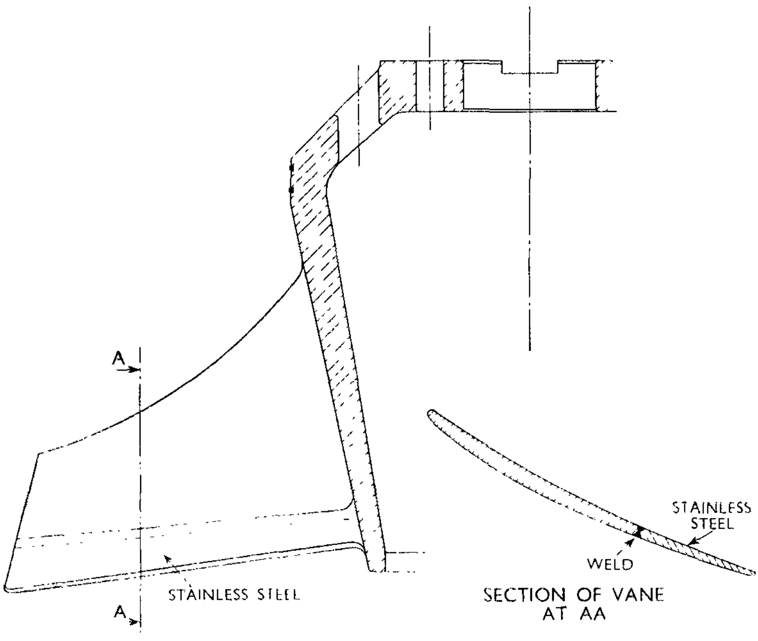

Fig. 46. Method of Stainless Steel Protection of Propeller Wheel

The second solution is to cast the runners with blades of restricted length and to add tail ends of appropriate length and shape in forged stainless steel so that the whole critical region is protected. The junction between the cast and stainless steel portions is electrically welded after preparation and finally ground and polished. Fig. 46 and Fig. 47, Plate 10, illustrate this method of protection. It has the same effect as the stainless steel coating though it is somewhat more expensive, but it avoids the large amount of grinding and polishing necessary with the first method.

Examples of Recent Developments Abroad.

As a supplement to the foregoing account of British practice a short account is given in the following paragraphs of some important developments in hydro-electric engineering which have taken place elsewhere in recent years. They have been chosen as typical examples of the lines on which the utilization of low- and high-pressure water power has developed and of the effective utilization of the combined and reversible hydro-electric and pumping plant for the purpose of accumulation to cover peak loads.

The Kembs Hydro-Electric Plant. This plant, installed on the

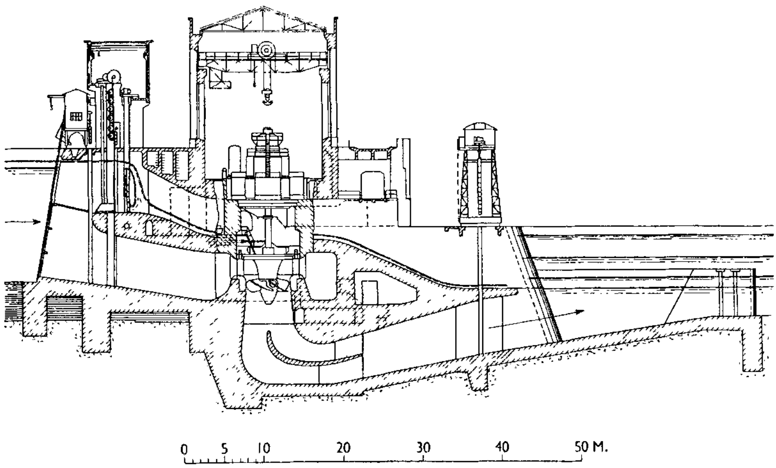

Fig. 48. Kembs Hydro-Electric Power Plant

Rhine in Alsace, operates with an effective head of 48–54 feet and contains five vertical-shaft turbines of the propeller type producing 30,000–36,600 h.p., each running at a speed of 93·7 r.p.m., the turbines being directly coupled to alternating-current generators supplying current at 8,800 volts and 50 cycles per second. Each turbine absorbs 187 tons of water per second. Exhaustive investigation showed clearly that the installation of Kaplan turbines provided with movable runner blades was by no means imperative, as the minimum flow of the Rhine always permits of an adequate number of sets running at, or at least in the neighbourhood of, the maximum efficiency. While the Kaplan or movable-blade type of turbine would have yielded greater output at part loads, the small number of additional units of current

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thus obtained would in no way have justified the considerable extra cost of installation.

The general design of the plant is illustrated in Fig. 48. It comprises a large block of masonry about 430 feet long, 60 feet wide, and 155 feet in height measured from the bottom of the draught tube bends to the roof. A unique feature of this plant is the discharge of the waters of the Rhine through the power house building by way of apertures or canals arranged between the turbines and generators; it is due to the fact that the power house closes the canal over its whole width and it was necessary to provide for the rapid and direct discharge of the total quantity in case of total or partial sudden drop in load on the plant. This design is simple and very ingenious and is protected under patent laws. It obviates a considerable widening of the canal for the discharge weir, which would have been very much more complicated and entirely prohibitive as regards cost.

The discharge ducts or canals through the building are arranged symmetrically about the turbine axis on either side and join above the draught tube exits; in times of flood they have the effect of increasing the suction in the draught tubes. The form of these canals and of the draught tubes was extensively investigated in experimental plants. The discharge canals through the building are provided on the upstream side with two superimposed sluices, the operation of which allows of the discharge of ice formations in winter time and enables the level and discharge quantities to be exactly regulated for the maintenance of shipping and the feeding of hydro-electric plants further down the Rhine. The entrances to the spiral casings proper, which are in concrete, can be closed by large roller train gates operated by mechanisms which are controlled by speed-limiting devices combined with the automatic governors.

The runner wheel (Fig. 49, Plate 10) has a diameter of 18·25 feet and weighs 55 tons. It is made up of a hub in cast steel on to which six separate blades are secured. Each of these six runner blades weighs 4·7 tons and develops in case of runaway speed, which attains 235 r.p.m. or 2·5 times the normal speed of 93·7 r.p.m., a centrifugal force of 625 tons. The automatic oil pressure governors are capable of closing the turbine in 4 seconds by means of two servo-motors of 365,000 ft.-lb. total capacity. The thrust bearing arranged on top of the alternator cross girders supports a maximum thrust of 700 tons and is of the special spherical-seat type combined with movable thrust pads.

The Ryburg-Schwoerstadt Hydro-Electric Plant. This is one of the largest and most modern hydro-electric plants on the Continent and is situated on the River Rhine about three miles from the town of Rheinfelden in Switzerland. It contains four 42,500 h.p. vertical-shaft turbines of the Kaplan type (Fig. 50, Plate 11) provided with movable runner blades capable of absorbing 250 to 300 tons of water per second under 41 feet head and rotating at 75 r.p.m. The runner wheel (Fig. 51, Plate 11) of each turbine contains five rotatable blades in nickel-chromium steel supported in a cast steel hub of 10 feet diameter. The outside diameter of the runner is 23 feet and the total weight of each wheel is 105 tons. Each movable blade or vane weighs 10 tons and develops at the runaway speed of 175 r.p.m., which is 2·33 times the normal speed, a centrifugal force of about 800 tons. The turbine shaft has a diameter of 31·5 inches and is provided with a central hole of 13 inches diameter to enable the operating shaft of the runner blades to pass through to the rotating oil pressure servo-motor arranged between the turbine and alternator shafts. This servo-motor with a piston diameter of 5 feet, which operates simultaneously all five blades of one wheel by means of a closing member and links, has a capacity of about 1,800,000 ft.-lb., leaving sufficient margin of power to move the mobile vanes into their closed position even in case of runaway speed.

The automatic regulation of these large sets is accomplished by two governors, the operation of which can be combined in such a way as to adjust simultaneously the position of the runner blades and that of the distributing apparatus. As a precaution, however, each governor system can operate independently of the other.

As the power plant of Ryburg-Schwoerstadt is not provided with mechanically operated sluices at the entrances to the turbine casings, a third governing system is provided which operates in case of emergency, in the form of a supervisory and independent safety device. It comes into operation when both normal systems of governing would be out of action, at a speed of 30 to 40 per cent above normal speed, by starting a separate emergency oil pump producing 500 lb. per sq. in. pressure which is utilized to move the runner blades from any position of opening into the closed position, thus stopping the set.

The thrust bearing is again of the spherical seating type combined with movable thrust pads. Each supports in normal operation a combined mechanical and hydraulic thrust of 900 tons; it runs of course completely in oil which is separately cooled, and embodies an ingenious device preventing hot oil from issuing from one thrust pad and entering the next.

The efficiency is remarkably high over a wide range of output and attains 80 per cent at 6,000 h.p., while exceeding 90 per cent for all outputs between 12,700 and 34,800 h.p.

Dixence Hydro-Electric Plant. This is one of the largest high-pressure plants in the world and is situated at Sion in Switzerland. It operates under a head of 5,750 feet, the highest pressure ever utilized in one stage. It makes use of the differences of level between an artificial reservoir situated at 7,360 feet O.D. in the Swiss Alps, containing 50 million tons of water, and the River Rhône situated at 1,610 feet O.D. The reservoir is formed by a gravity dam of the arch type about 210 feet high. The water is conducted by a tunnel 7·6 miles long and 7½ feet in diameter to the surge tank, which is provided with upper and lower balancing chambers, the whole being hewn in the rock.

There are two penstocks 18,000 feet in length, each varying in diameter from 56 inches at the top to 39 inches at the power house. The upper part of the penstocks, that is, about one-third of their total length, is made up of ordinary smooth steel pipes varying in thickness from $\frac{3}{8}$ inch to $1\frac{5}{16}$ inches. The lower two-thirds of the pipes or penstocks are made up of banded pipes, their diameter varying from 47 inches at the top to 39 inches at the bottom. These banded pipes are made up of a shell with shrunk-on rings of a size equivalent to $1\frac{1}{8}$ inches up to $3\frac{1}{8}$ inches thickness, all joints being made by electric welding. The complete system of intake tunnel and pipe lines is designed to deal with a discharge of 10·25 tons of water per second, which under the average head available corresponds to an effective output of 133,250 kW., that is, nearly 60 kW. per gallon per second.

The power house is equipped with five sets, one of which is a standby, and an auxiliary set of 7,000 kW. output. Each main set consists of a double turbine directly coupled to alternators arranged in between the turbines, the two runner wheels being rigidly mounted on each generator shaft end. Thus one set contains only two main bearings. The normal output these sets develop is 30,000 kW., the overload is 35,000 kW. and the speed of operation is 500 r.p.m.

Figs. 52–4, Plate 12, show some of the most interesting features of this plant. Fig. 52 shows one of the runner wheels, each of which is composed of 32 buckets in forged nickel-chromium steel attached to the forged hubs or disks by shrinking, with the help of intermediate keys. The wheel disk forms a rigid coupling round its centre by means of which the runners are attached to the rigid flanges of the alternator shaft coupling. Fig. 53 shows the two banded distributing conduits arranged inside the power house, together with their cast steel bends and valves. The whole distributing system is extremely simple in view of the enormous pressure it has to deal with. Fig. 54 shows two of the 50,000 h.p. sets in the power house, a remarkable feature being the housings of the turbines which are arranged very close to the runner wheels so as to cause these wheels to run practically in a vacuum. This results in a gain in output and efficiency because of the considerable reduction of the windage losses of the runners, which turn normally at a circumferential speed of nearly 300 ft. per sec.

Regulation is obtained by a combined double-acting deflector-and-nozzle needle type of governing system controlled by an oil-pressure governor servo-motor, the centrifugal device or controlling member being electrically driven.

The Reversible Hydro-Electric Power Accumulation Plant. The pumping of water by cheap surplus power during low-load periods into either natural or artificial elevated reservoirs, for the purpose of power storage or accumulation to cover peak loads, began on a small scale in 1898 in Switzerland and developed only very slowly during the first twenty or twenty-five years. During the second decade of the twentieth century, however, this method of power storage was developed on a very large scale and at the present time there are in existence and in continuous operation in Germany, Switzerland, France, Italy, Spain, Sweden, and the United States of America hydraulic accumulating plants yielding outputs often in excess of 100,000 kW. per individual station and containing hydraulic turbines, chiefly of the reaction type, of from 40,000 to 50,000 h.p. operating in conjunction with multiple-stage centrifugal pumps of up to 34,000 h.p. and more individual capacity. Synchronous motors are arranged between the turbines and pumps which alternately generate power when driven by the turbines, or operate as motors when driving the pumps. It may be of general interest to mention that nine of the more important stations of this type in Germany alone have at the present time a capacity in excess of 1,000,000 h.p.

Hydraulic accumulation is, therefore, well established and is recognized everywhere as an excellent and economic method of covering peak loads. The reasons for the rapid development and success of this method of power storage can briefly be summarized as follows :—

(1) The demand for power fluctuates during a complete day within very wide limits, often being six or more times greater during the peak loads than at night time ; the machines, either thermal or hydraulic, must constantly be kept in readiness and must be powerful enough to cover the maximum demand, but the plant works of necessity at very low load factor and, except at or near full load, at considerably reduced efficiency. The power production for peak

load thus becomes both onerous and uneconomic and the surplus energy which could be produced cheaply during "off peak" periods cannot be utilized and is, therefore, entirely wasted.

(2) Now hydraulic accumulation enables the cheap "off peak" electrical energy to be utilized by pumping water from a low-level reservoir, lake, or river to a higher level reservoir where it is stored until, during the hours of maximum demand, it is led down again to generate in hydraulic turbines the energy necessary to cover peak loads. This results in a considerable improvement of the load factor and general overall efficiency of existing power plants, both thermal and hydraulic, and it is proved by experience over many years that peak loads can thus be met far more economically than in any other way. The load on the so-called basic plant of a power-producing system can thus be equalized to a great extent with consequent economies in capital and operating costs.

(3) There exist numerous sites in this country and elsewhere where natural lakes, with often a considerable difference of level yet situated very near each other, present excellent opportunities for the installation of peak load plants of this type, where the storage capacity is in fact sufficient to cover not only daily, but weekly, or even seasonal peak loads. The natural precipitation on and around any storage reservoir provides an additional reserve in power which is extremely useful in case of extra heavy demands on the system or temporary stoppage of the basic units.

(4) The overall efficiency of modern reversible hydro-electric accumulating plants is 64–65 per cent. A notable advantage is the fact that power, as generated in any hydraulic plant, is always at disposal at very short notice. In fact it is possible, on demand, to supply up to full output within one or two minutes, according to the size of the unit and plant. The change from pumping to generation and vice versa also takes place with the same rapidity, so that practically no time is lost in the continuous and efficient utilization of both the basic power units and peak load units. All modern hydro-electric accumulating plants can be made entirely automatic, the automatic operation including both generation and pumping, and the change from one to the other takes place without lowering speed or stopping and without taking the machines off the line. During reversal the machines remain synchronized with the basic units with which they run in parallel. The automaticity includes all starting and stopping devices with which the necessary safety and protective gear for turbines, pumps, generators, and pipe lines is combined. In all cases of emergency the machinery and plant are therefore thoroughly protected.

The general design of hydro-electric accumulating plants has greatly changed during the last decade. A first point of paramount importance is to obtain an overall efficiency as high as possible for any site contemplated. Even a cursory computation of the normal losses occurring in turbines, generators, pumps, transformers, pipe lines, valves, tunnels, intake and discharge works will make it clear that in order to obtain a combined overall efficiency of 65 per cent it is necessary to design each of these parts with the greatest possible care. The whole hydraulic system from intake to tailrace must be arranged so as to reduce the losses due to friction, discharge, and turbulence to the minimum. The turbines and pumps must be designed to ensure the highest possible efficiency, not only for any given head and discharge, but within the whole range of variation in pressure of the storage water, the utilization of which often causes both top and bottom reservoir levels to fluctuate within considerable limits. This can only be achieved by systematic and intensive tests on scale models in experimental plants such as that described in an earlier part of the paper.

Hydro-electric accumulation plants are either of the vertical- or horizontal-shaft type. The choice depends on the output, number of sets, head, and its variation, and speed, and must of course be adapted in every case to the local conditions.

Vertical-shaft sets can be housed in comparatively narrow and small buildings, but necessitate foundations of very considerable depth. The position of most of the machines, particularly the hydraulic ones, must be considerably lower than the tailrace water level for reasons of cavitation and priming, and the surrounding foundations and building must be rendered permanently impervious. The superimposition of generator, turbine, and pump leads, in the vertical type, to a multiplicity of bearings, the more so as an elastic and automatic clutch between turbine and pump, either of the hydraulic or friction and claw type, was considered indispensable for most plants for speedy reversal. Whilst it is possible to dispense with this clutch, which is both cumbersome and expensive, provided the necessary precautions for gradual priming and pneumatization, and cooling the momentarily idling machine are taken, the vertical-shaft type is still rather complicated and difficult for reasons of alignment, the considerable vertical thrusts which occur, and access. Nevertheless there exist a number of hydro-electric accumulation plants of the vertical-shaft type, the efficiency of which is of a very high order. The following are some typical examples:—

Schluchsee (*Black Forest*, *Germany*). This plant contains at present four sets, each composed of a synchronous generator, 32,000 kVA., 10·5 kV., coupled to 42,000 h.p. reaction turbines running at 333 r.p.m. and a two-stage centrifugal pump of 28,000 h.p. capacity discharging under normal conditions 7·6 tons of water per second against 655 feet head. The Schluchsee with its dam has a storage capacity of 108,000,000 tons of water and can be utilized for both daily and seasonal storage. Ultimately the Schluchsee will be connected to the River Rhine at Waldshut, about 13 miles distant, and a total level difference of about 2,000 feet will be utilized in about three stages, yielding an output of 390,000 kW. compared with 120,000 kW. at present.

Lac Noir (*Vosges*, *France*). This plant contains four sets, each composed of a synchronous generator coupled to a 40,000 h.p. turbine running at 272 r.p.m., and a two-stage centrifugal pump of 27,000 h.p. capacity discharging 13 tons of water per second against 420 feet head. The Lac Blanc, which forms the top reservoir of the Lac Noir plant, has a storage capacity of 4,669,000 tons and serves to cover chiefly daily, but also weekly, peak loads.

Sillre (*Sweden*). This plant contains at present two main sets, each composed of a synchronous generator coupled to reaction type turbines of 10,080 h.p. maximum output under 650 feet head running at 600 r.p.m. The pump is of the double-stage centrifugal type and can discharge 2·5 tons of water per second against 650 feet head. The storage capacity of three interconnected lakes serving as upper reservoir is 39,100,000 tons of water.

Horizontal-Shaft Hydro-Electric Accumulating Plants. Accumulation plants of the horizontal-shaft type, while requiring larger and wider buildings, present a number of important features which, in the author's opinion, render them distinctly superior to plants of the vertical-shaft type. The foundations need not be located appreciably deeper than for an ordinary hydro-electric plant. This cheapens the foundations to a considerable extent, and the difficulties, mentioned in connexion with vertical-shaft machines, in ensuring impermeability also do not arise. The machines can always be arranged at or near tailrace level so that the power house floor and buildings are only under slight outside pressure. Thus ordinary means for ensuring a dry power house are sufficient and satisfactory. By arranging the pump and turbine on either side of the generator, the number of bearings can be reduced to three, or a maximum of four, according to the type of turbine. This in itself is a considerable simplification as compared with the vertical-shaft type. The horizontal design enables all the machines, inclusive of the governors, oil pressure plant and all accessories, to be arranged on one single floor, which renders every part of the machines easily accessible for maintenance and dismantling by the power house crane. The axial thrust from both turbine and pump is minimized since the weight of the rotating element is borne directly by the journal bearings. Inspection and replacement of spare parts are easier than in the vertical-shaft type of plant. The following are a few examples of modern hydro-electric accumulation plants of the horizontal type:—

Waldeck, Eddertal-Sperre, Germany. This plant contains at present four main sets each composed of a synchronous generator generating 36,000 kVA. at 0·8 power factor, 10,500 volts, and 50 cycles frequency. When operated as a motor to drive the pump the machine has a capacity of 24,000 kW. at unity power factor. The generator is rigidly coupled on one side to a reaction type spiral-cased turbine which develops 40,500 h.p. under 970 feet head and absorbs 12·5 tons of water per second when running at 500 r.p.m. On the other side the generator is coupled to a two-stage centrifugal pump through a hydraulic coupling of the Föttinger type by means of which the pump can be taken in and out of service when the generator is running. The pump absorbs 29,000 h.p. and delivers at normal speed 6·0 tons of water per second against a head of 1,000 feet. The upper storage basin, almost wholly artificial, is relatively small and has a storage capacity of 760,000 tons of water only. It is utilized for daily storage and peak loads.

Herdecke (on the River Ruhr, Germany). This plant contains at present four sets, three of which are in general design very similar to the Waldeck plant mentioned above as far as the general arrangement of the machines is concerned. The fourth set is for generation only. For the pumping units the generator is again arranged between turbine and pump, has a capacity of 40,000 kVA. at 0·8 power factor, and is coupled rigidly on one side to single overhung reaction type spiral-cased turbines which can develop 48,500 h.p. under 542 feet head, running at 300 r.p.m. On the other side the generator, when running as a motor, transmits its power through a Föttinger hydraulic coupling to a two-stage twin pump capable of delivering 12·3 tons of water per second against a head of 542 feet and absorbing a power of 33,000 h.p. The upper storage basin has a capacity of 1,600,000 tons.

The Bleiloch Plant, Saaletal-Sperre, Germany. This plant serves not only for the production of peak loads, but has the further and important object of providing sufficient water in dry years to permit and facilitate navigation on the River Elbe by regulating its level. It is a particularly interesting plant inasmuch as due to the above-mentioned condition, the head varies from 88 up to 190 feet. The problem which had to be solved was, therefore, considerably more complicated than for an ordinary accumulation plant, seeing that the equalization of the level of the River Elbe called for a quantity of water varying from 0 to 70 tons of water per second. The unusually large variation in pressure rendered very special measures necessary to ensure a good efficiency under all conditions. On the electric side two synchronous generators are installed very close to each other, the larger of which runs at 176·5 r.p.m. as a synchronous generator or motor of a capacity of 20,000 kW., while the smaller, also synchronous, has a capacity of 12,500 kW., but runs at 150 r.p.m. only. Each of the two double and synchronous generators of this type is coupled with two turbines which operate together up to a head of 138 feet when they run at a speed of 176·5 r.p.m., producing a maximum capacity of 14,750 h.p. The double centrifugal pump arranged between the generator and the turbine on one side runs at a speed of 150 r.p.m. when pumping against a head varying from 92 feet to 135 feet, and is driven by the smaller part of the double generator running as a motor; when pumping against a head of from 136 feet to 190 feet, it is driven at 176·5 r.p.m. by the larger part of the double motor generator. The turbines absorb a quantity of water varying according to head and output from 32 tons to 61 tons of water per second. The pumps deliver quantities varying from 19 tons per second to 35 tons, according to varying speeds and heads. It is interesting to note that no coupling of the clutch type that can be taken in and out during operation exists between any of the machines. Apart from the pumps, the turbine casings are pneumatized and water-cooled so that no ill effect results from any of the machines running idle.

The top reservoir has the enormous storage capacity of 180,000,000 tons of water, which is utilized both for the generation of a capacity of 40,000 kW. during four hours daily, producing therefore 160,000 kW.-hr. per day, as well as for levelling the River Elbe for navigation purposes.

There exist in Europe about 50 hydro-electric accumulating plants; these particulars relate to a few which the author considers the most important and interesting. Among recent developments in hydro-electric engineering hydraulic storage is one of the most important. There are as yet no plants of this type in this country, but the author is confident that the building of hydraulic storage plants is essential to the utilization of our national power resources in the most advantageous way.

Conclusion. The author has endeavoured to give a brief summary of the extent and importance of hydro-electric engineering and the progress, trend, and lines of development of British practice. The purpose and application of a number of characteristic features for hydro-electric plant which British industry has successfully developed have been described. High efficiencies and marked success have been achieved in numerous plants of considerable importance, so that it may be concluded that hydro-electric engineering in this country is progressive in its own field and alive to progress in other branches of engineering.

Discussion

Mr. E. Bruce Ball (*Member of Council*) observed that the author referred on p. 299 to possible damage to tailraces, dam foundations, and surroundings caused by the discharge jets of the relief valve and reservoir outlets. This touched a matter which had caused concern to engineers, especially when structures were necessarily built on friable rock. The author's method of spreading out the jet into a hollow cone presented advantages over a solid jet, and no doubt many occasions would arise, particularly with relief valves (where the jets were of moderate dimensions) when it could be applied most usefully. So far as he could judge from the illustrations, the conical jet was divided into a number of solid jets by the vanes along the outlet cone. These multiple jets continued to expand as they left the outlet, until the diminishing thickness of the wall of water forming them reached the point of disruption. If the jet were placed sufficiently high above the water surface, the air resistance to the ruptured jet would complete the destruction of its energy; should, however, the released jet be close to the water surface, the lower half of the cone would remain unbroken, owing to its small distance of travel, and its energy would have to be absorbed by a water cushion or by the rock or concrete surface on which it impinged.

The paper dealt with British practice, which the author reviewed most admirably, but it was of interest to recall that the problem of avoiding the destructive effects produced by powerful jets of large diameter had been solved about twelve years ago in this country by a method first described at the summer meeting of the Institution held in Glasgow in 1923.* The term "jet disperser" then applied to the apparatus developed at that date had now become the recognized

* Proceedings, 1923, p. 680.

technical term, and, as a result of the pioneer work which had been carried out, it was now customary for engineers designing large water undertakings to specify that the energy of these powerful escaping jets should be dispersed. The original device disintegrated the jets by the formation of a free vortex at the point of release from a nozzle. The jet was thus broken into millions of drops and the whole of its energy destroyed by air resistance only. Its action could be followed by reference to Fig. 55.

Venturi first discovered that across the surface of a whirl or free vortex the velocity was inversely proportional to the radius, so that

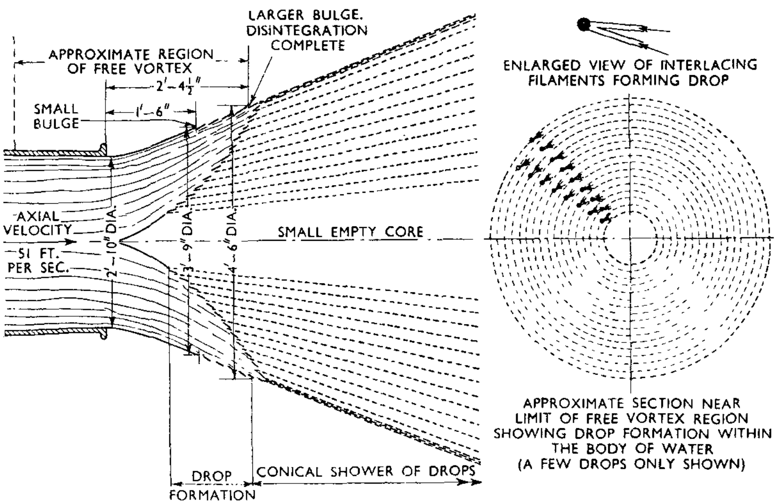


Fig. 55. Analysis of Free Vortex Disintegration from Photograph of 36-inch Disperser

the velocity of the particles increased as the centre was approached. On the release of the jet each filament of water was caused to take a straight-line course determined by its axial velocity together with a tangential twist, the greater tangential velocity of the control filaments causing them to take a more divergent course than those remote from the axis. The result was that the inner filaments tended to pass through the outer ones and the released jet then became an expanding cone of interlacing filaments of fluid and was completely disintegrated at about one diameter of the orifice from the point of release.

So successful had been this application of the law of free vortex that a very large number of these jet dispersers were now in use in various parts of the world, working under heads up to 1,700 feet and dissipating energy up to 38,000 h.p. from a single jet. Fig. 56, Plate 13 (near p. 305), clearly showed the angle of twist at the point of release of the jet and the remarkable absence of mist, an advantage only possessed by this type of disperser. This particular disperser at the time of being photographed was passing 1,000 cu. ft. of water per second and destroying energy equal to 13,000 h.p.

Mr. W. T. HALCROW said that in this country, as was well known, the production of power from the abundant supplies of coal had retarded the development of water power. Whilst individual engineers in the early part of the century had realized the importance of water power, it was not until 1918 that the Government, through the Board of Trade, appointed a committee to investigate the natural water resources of the country. That committee produced a very valuable report in 1921, and stated that the water power resources of Great Britain were of such importance to the nation that their development should be effectively regulated so that they might be utilized to the maximum extent and the best advantage. The information collected by the committee was based to a large extent on preliminary surveys, and their estimate of the available power was some 56,000 kW. for England and Wales, 218,000 kW. for Scotland, and 113,000 kW. for Ireland, making a total of approximately 387,000 kW. of continuous output. Those figures referred to the schemes studied, and did not necessarily represent the total water power resources of the country. Detailed studies of schemes which had since been investigated or carried out showed that the figures were in fact very much on the low side.

The available power in the Highlands had the advantage of low cost, especially when produced on a 100 per cent load factor, and the establishment of the aluminium industry in this country was made possible solely by this cheap water-power supply. Later, the Grampian and Galloway schemes were made possible by the establishment of the Central Electricity Board's grid, which permitted contracts to be entered into for large quantities of power, and so enabled the promoters to overcome the difficulties inherent to the financing of schemes requiring a large capital outlay. Needless to say, the capital required to start a hydro-electric scheme was much in excess of that needed for a steam power station, which could be built up in small units. The promoters of hydro-electric schemes in Great Britain had one great difficulty to face in that, before interfering with the flow of rivers, they had to promote a Parliamentary Bill. It might not be generally realized what that meant. The Lochaber Bill did not get through the first year that it was before Parliament. It came up again for consideration two years later and was passed. The Grampian scheme also was not passed till the second year. About 1928 two important promotions for water power schemes in the West Highlands were rejected by Parliament; a third promoted in the same year—the Galloway scheme—was successful. A well-known industrial company wished to establish a new industry in this country, namely the production of carbide. Their experts went into the matter very thoroughly and decided that it would be commercially possible if the company were allowed to develop water power in the Highlands. In 1935 a bill was deposited, but was rejected on second reading in the House of Commons and therefore was not considered by a select committee. The promoters had removed the features to which Members of Parliament had objected, which were connected with rating and land purchase, and had brought up the bill again this year, but he did not know what its fate would be.

Mr. O. Thott said that he was struck by the comparative levity—if the author would excuse the word—with which the question of cavitation had been dealt with. On p. 320 the author said: "only a small portion of the wheel . . . needs protection against cavitation." That seemed to him a very bold statement indeed, and he asked whether it was based on experience extending over a considerable length of time. He agreed with the author that it was comparatively easy to determine which part of a runner wheel was normally subject to cavitation—the danger area, as it was called—but his experience showed that cavitation often took place outside this danger area. A small indentation on the inlet edge of a blade caused by a stone or other debris would set up whirls in the water which could cause cavitation. A number of cases of that kind had been discovered in Sweden and Finland. He did not agree with the author, therefore, that the adoption of complete runners of stainless steel was extravagant, where conditions were such that cavitation might take place. Only in cases where first cost was the paramount consideration would anything cheaper be justified.

In Figs. 21 and 22, pp. 300 and 301, the author showed a very interesting hydraulic brake. In many Francis turbine plants it had become not uncommon practice to introduce a renewable lining at the beginning of the suction pipe, because that was one of the points where wear occurred. Yet that was exactly the place which the author had selected for his hydraulic brake with all its little holes. It would be extremely interesting to know whether any wear or cavitation had been discovered after such a plant had been running for four or five years.

After giving his most interesting account of foreign accumulator plants, the author said on p. 330: "There are as yet no plants of this type in this country." He was able to say, however, that one such plant had been installed over fifteen years ago in Scotland on the river Tweed, at a place called Walkerburn. There was not enough power in the river for a cotton mill established there, so an accumulator plant had been built by means of which water was pumped to an artificial lake about 1,000 feet high in the mountains. That plant was described, with photographs and drawings, in the technical press in 1922.*

Major E. N. WEBB, D.S.O., M.C. (Messrs. Boving and Company, Ltd.), said that to whatever extent one might agree or disagree with the author's statements, one must admire his fertility of thought and ideas. He trusted that nothing in his subsequent remarks would be interpreted as other than a friendly corrective. From a cursory reading of the paper the impression was conveyed that the author and his associated British engineers had a monopoly of the virtues of hydro-electric practice enumerated, for example, on pp. 286, 295, 297, 309, and 314. He could hardly think this was intended and still less that it would be relished by the many Continental and American engineers who had a long start in many of the ideas the author had brought forward.

At the outset the author stressed simplicity amongst various characteristics of prime importance. Did not some of the author's subsequent matter conflict with this primary desideratum? In view of a paper † recently published under his name, he wished to comment on one point, namely the aerofoil recorder. Doubtless it would be realized that this was really another and rather ingenious form of velocity meter. As such, it had the usual limitations and, possibly, some unexpected ones also. Whilst some clear advantages over the current meter and Pitot tube had been mentioned, the paramount necessity of calibrating each instrument in its individual setting should have been stated. It would be interesting to know the effects on the accuracy of the results due to packing of the spindle under high pressures, to weeds collecting on the blade, and to damage of the blade by stones.

One note might not be inappropriate in relation to the author's experimental laboratory. He remembered the runner designer of a prominent water turbine firm telling him many years ago that he was only then beginning really to feel his feet, notwithstanding many years

* See *Engineering*, 1922, vol. 113, p. 189.
† Jl. Inst. C.E., 1936, vol. 4, p. 259.

as assistant to Professor Pfarr in Germany and some ten years in his own commercial testing station. Apart from the excellence of the laboratory itself, many years of patient and tedious work were essential in accumulating and analysing records before the experimenter could interpret results accurately and readily, and could pursue an investigation confidently without waste of time and effort.

He could not close without thanking the author for introducing poetry into an engineering paper as, for example, on p. 297, where one found "a cylindrical hollow piston gliding continuously on stainless steel strips."

Mr. W. HAWTHORNE (Messrs. Merz and McLellan) thought the paper would be a very valuable addition to the literature of the subject. The fact that the water power resources of this country had not been developed to the same extent as those of some other countries had been attributed to the very good supplies of coal available here. Other countries which had good supplies of coal had, however, developed their water power, and there seemed no reason why there should not be room for both steam and hydraulic stations in Great Britain. There were already in Great Britain important examples of four kinds of installation. There was the station which supplied electro-chemical loads, which had to give an almost constant output throughout the 24 hours, and from week to week; there were the stations which supplied the ordinary industrial and domestic load of a district, with its great variation between maximum and minimum demand; there were the stations which might be called "run of the river" stations, which took what water the river gave them, with very little storage, and fed what power they could, when they could, into a network; and, fourth, there were the pure peak-load stations, intended to run three, four, or five hours a day, except during floods, when they were naturally run continuously in order to utilize to the greatest possible extent the water available.

An example had also been given in the discussion of what the author called a reversible hydro-electric power accumulation plant, but which might be more simply known as a pumped storage plant. That type of installation also dealt with peak loads only, and there might be a field for it in this country if the habits of the people did not change appreciably within the next sixty or seventy years; i.e. if the morning and evening peaks and the demand during the night were to preserve their present ratio. The author said that there were numerous sites in this country suitable for the installation of plants of the pumped storage type, but generally such sites had the disadvantage that they were a long way from centres of population and therefore involved considerable expense for transmission. It was, however, by no means necessary to depend on natural lakes, and it was conceivable that a case might be made for artificial lakes on high ground near large towns, where the pumped storage energy would be close to the load. Such an installation had been in service for seven or eight years near Dresden, where a gully amongst the hills alongside the Elbe had been dammed and a reservoir formed, into which water from the river was pumped during off-peak hours. Similar arrangements might some day be found practicable in this country, and as the reversible efficiency was about 60 per cent, they would stimulate the production of coal instead of reducing it.

One impression which must have been gained from the paper was the care with which the author had worked out the details of his devices in order to ensure ease and accuracy of erection. The author should be judged by the result of his work, and the success which he had attained might be gauged by the fact that in Galloway every one of eleven generating sets, varying in size from 6,000 to 12,000 kW., went into service without a hitch, and had since met all the load requirements without interruptions.

As a designer, the author had dealt mainly with the details of design of the main and auxiliary hydraulic plant and had said little about wear and maintenance. A glance at the Electricity Commissioners' statistics would seem to indicate that the cost of operating and maintaining a water power station did not increase appreciably with the lapse of time. Taking the Lanarkshire stations, for example, the published records showed this cost to be steady at about 0·02*d.* per unit generated over seven years. Seven years was not a sufficiently long period to deduce figures for the cost of maintenance throughout the life of a plant, and he would like to ask the author whether from his experience he could give some idea of how the cost might be expected to vary and how the efficiency might be expected to change as the plant aged.

Major-General A. E. Davidson, D.S.O. (*Past-President*) said that we were, as a nation, very poor at advertising, and very little had been done to show to the world what our engineers had accomplished in these islands and in the Empire in the way of water power schemes. He regretted the omission from the paper of a table detailing the bigger schemes for which British engineers had been responsible, both in this country and elsewhere in the Empire. During his travels abroad, he had found that the foreign engineers in charge of power stations knew nothing of what was being done in this country, although they might be familiar with smaller schemes carried out by some foreign country not far from our shores. In the Irish Free State almost all the power generated was from the Shannon station, which was looked upon by everybody there as something wonderful, although it was only of the same order of size as three schemes in Scotland which had received but little notice. In Finland, which depended so much on its water power, the Imatra Falls were one of the greatest attractions to sightseers, so that what had been done in the development of water power nearby was brought home to everyone in the country, as well as to visitors. He asked what was being done in this country to make known our achievements in this direction.

Mr. N. Brooksbank (Victoria Falls and Transvaal Power Company, Limited) said that the subject was of topical interest to him, because at the present time his company were building a small station and equipping it with hydraulic plant at the Victoria Falls, Rhodesia. It might come as a surprise to some members to learn that his company did not operate hydraulic stations at the present time, but only steam stations, so that its title might seem a misnomer. Some 800 miles of transmission line would, however, be required to transmit power from the Victoria Falls to the Rand, or 300 miles to transmit it to the copper fields. Those who had studied the subject of electrical transmission would therefore appreciate why the Falls had not been used. The hydraulic installation which they had in hand at the present time was quite a small one for supplying Livingstone and other small places in the vicinity.

He was interested to see from Fig. 14, p. 295, that the author had adopted a mechanical drive for the governors. Some years ago he had been interested in a hydro-electric company in Italy, and the machines which he saw had belt-driven governors. This seemed to him, as one connected with steam turbines, to be rather an antiquated method of driving governors ; and more recently he had found a decided inclination to continue driving the governors by means of a belt. He noticed in Fig. 9, p. 292, that a pulley was shown for belt driving ; no doubt that was taken from an old drawing. Fig. 14 showed a direct drive to the governors by means of a flexible stainless steel plate. He asked how long such a drive had been in service, what number of turbines had their governors connected in that manner, and whether there had been any cause of synchronous vibration, lateral or torsional, in the steel plate. If it did occur, it would soon cause a fracture and put the machine out of action.

A good deal was said on p. 300 about the necessity of using brakes to bring the machines quickly to rest. That was not the case with steam turbines, and he could not understand why it should be necessary for water turbines. It seemed to him that it would be better to install an up-to-date system of lubrication. The inference was, he thought, that the bearings were ring-lubricated, which in unattended and fully automatic stations such as his company was building would not be sufficiently reliable. He thought the inference from the remarks in the paper on stainless steel impellers was that they would eliminate all troubles due to cavitation. He did not know whether that was the author's intention, but he himself thought it probable that over a period of time corrosion or erosion would occur. He had been relieved to hear what Mr. Thott had said as to the economic justification of having the impellers entirely of stainless steel, because he had specified it, and he did not want to think that he had been extravagant.

Mr. E. R. Howland (British Pitometer Company, Ltd.) said that the statement in the paper that Venturi tubes imposed an appreciable pressure loss was not always true, as there were many cases where they could be installed without imposing any additional loss. Many pipelines had a reduction close to the power station which could be correctly formed and used as a Venturi tube. There were five examples of that at the Grampian Company's power stations. The Venturi tubes on the intake to the turbine were not subject to the same clogging as the Pitot tube, as the piezometers did not face the flow. He had been very interested in the author's aerofoil recorder and in Major Webb's remarks as to its calibration. In addition to the original calibration the instrument would have to be recalibrated from time to time, because the velocity distribution at the point where the aerofoil was placed would vary with changes in the conditions of the pipe.

Mr. J. F. Peck said he was particularly interested in the subject of Pelton wheels, although he was immediately associated with the educational side of engineering. He noticed in Fig. 26, Plate 4, which showed the jet in the normal position with the diffusing blades withdrawn, that the diameter of the jet was increased to approximately double its initial size in a length of something like twelve diameters. If the jet still remained solid, that meant that the velocity of that section was only a quarter of the initial velocity of the vena contracta, and therefore its velocity was less than the velocity of the buckets with which it had to catch up. There could therefore be very little chance of its ever doing so, so that a fair amount of that water would be lost. He had made some measurements with a funnel collector on an experimental plant, and had found that such losses often amounted to 10 or 12 per cent. It was possible to get very much better jets with the ordinary type of spearhead ; by careful attention to the form and to the nature of the bends before the nozzle it was possible to reduce the spreading in the same length to between 10 and 20 per cent, and hence, he contended, to obtain much higher efficiency. As the last particles of the jet cut off by one bucket had to travel a distance of 8 to 12 diameters from the nozzle mouth before overtaking the previous bucket this was an important point and was referred to by the author on p. 305 as a cause of rapid diminution of the efficiency of the jet and turbine. He appreciated many of the advantages of the author's invention with regard to quickness of operation, but the jet seemed to be inferior to that of the ordinary plain needle.

The author mentioned on p. 286 that one of the main requirements was high specific speed both for reaction and impulse wheels, but he had not referred in the paper to any of the recent developments in this direction so far as Pelton wheels were concerned, and it might therefore be of interest to say a word on this subject. A vertical-shaft Pelton wheel had been built by Messrs. Escher Wyss and Company * for Chile having a ring formation supply pipe which formed a suitable foundation for the generator above it. There were four jets acting on the same runner, and the machine fitted neatly into the power station. The head was 670 feet, the horse-power 18,600, and the speed 250 r.p.m., giving a specific speed of 10, although the specific speed for one jet was only 5.

Another development with the horizontal-shaft arrangement which enabled a high specific speed to be obtained was the Schwarzenbach pumped storage plant,† in which there were three runners on the same shaft and two jets to each, a total of six jets, giving a specific speed of 12 for the unit, or 5 for each jet. The head was 1,170 feet, and the Pelton wheel developed 27,500 h.p. at 500 r.p.m. There were two double-stage pumps geared up to run at 1,000 r.p.m., each of 8,320 h.p. at a head of 755 feet.

A recent development of the horizontal-shaft Pelton wheel was a machine having three runners with three jets per runner, making a total of nine jets. This was for Codorna, Brazil, where the net head was only 200 feet and the water was charged with abrasive silt, so that Pelton wheels were preferred to Francis turbines. It was for an industrial plant where high efficiency at part loads was important and the governing system consisted of hand-operated needles and governor-operated deflectors. The maximum output was 2,220 b.h.p. and the normal speed 375 r.p.m., giving the remarkably high specific speed of 23·3 for the unit and nearly 8 for each jet. Fig. 57, Plate 14

* For illustrations of this machine see Trans. A.S.M.E., 1932, vol. 54, HYD-54-7, p. 129.

† For illustrations of this plant see Z.V.D.I., 1924, vol. 68, pp. 1197-8.

(near p. 305), showed the runners assembled in position on the shaft. Fig. 58, Plate 14, was a partial front view of the turbine and Fig. 59, Plate 15, an end view. The governor, which was of the oil pressure type, was directly connected by a flexible coupling to one end of the turbine shaft. This coupling was shown at the right-hand end of the shaft in Fig. 57, while the coupling at the opposite end provided the connexion between the turbine and the alternator.

Fig. 60, Plate 15, illustrated the experimental plant on which he had worked. It had been made entirely by the students at Loughborough College, and was arranged for both educational and research work. The position of the jet could be altered by a number of distance pieces, the setting of the buckets could be changed from 0 deg. to 24 deg., and the speed could be varied by the brake. He had carried out a number of tests on a single bucket, clamping the brake and measuring the jet force, and had investigated the effect of changing the angle of back tilt of the buckets with various forms of bucket "cut-outs". By using a rotascope of the Ashdown type driven by a flexible shaft so that it synchronized with the machine at any speed, the entry of the buckets into the jet could be examined. With an inclined mirror a view was obtained looking upwards, and with the rotascope the jet could be seen in the process of being split up by the buckets.

For pumped storage plants in this country he considered that a reversible turbine pump unit was required, operating at a moderate head of about 200 to 300 feet, which could be run either as a turbine or as a pump, thereby simplifying the plant and reducing the initial costs. Such a scheme was already in operation at Baldeney hydro-electric power station, Essen,* but in this case the head was only 9 metres, and a reversible Kaplan type runner was used. A single-stage runner could be used for heads up to 300 feet or more and there were probably many sites on the outskirts of London and other towns where such schemes could be carried out. While admitting that the plant would have to be stopped for a short time when changing over from pumping to generating, or vice versa, and the motor-generator would require double windings to give higher running speed when the runner functioned as a pump, he considered that the simplification of the plant would result in considerable economic advantage, which was so important in such schemes. He asked the author's opinion as to the possibility of such a scheme for heads of 200 to 300 feet and suggested that the development of such a reversible turbine pump unit would be a useful field for model investigations in the experimental testing plant referred to in the paper.

* Z.V.D.I., 1934, vol. 78, p. 1183.

Figs. 61 and 62, Plate 16, showed a turbine pump with swivelling guide vanes, driven by a torque-reaction motor, which had also been made by students, and he hoped shortly to be able to reverse it, i.e. to operate it as a Francis turbine driving the motor as a dynamo, and to compare the performance.

Dr. P. W. SEEWER wrote in reply that the method of diffusion or dispersion of the jets by means of a cylindrical and balanced streamlined valve had now been in continuous operation for many years on numerous hydro-electric plants of every description without showing any detrimental influence whatever, like shattering of the foundations of power houses, dams, or river beds.

The dispersion in Mr. Bruce Ball's discharge apparatus was brought about by slanting plates or vanes, arranged some distance behind the nozzle mouth at an appropriate angle, and it was, therefore, misleading to call the dispersion out of this nozzle a *free vortex*, because its formation was due entirely to the slanting vanes, without which there was no vortex. The diffusion or dispersion of the jets was, therefore, brought about in the same way as in the method employed by the author for the primary regulation of impulse wheels. This key invention for the dispersion of the jets was patented by the author on 1st September 1915. The claim that Mr. Bruce Ball's disperser was the only one which was free from the formation of mist was without foundation and was in no way borne out by experience. Mr. Bruce Ball's claim that the filaments of liquid were completely disintegrated at about one diameter of the orifice from the point of release was shown to be erroneous by the far-reaching discharge parabola described by the water which still contained a considerable amount of kinetic energy.

The destruction of energy by the formation of a hollow cone of water, as in the apparatus described by the author, was more complete than by any other method, and the water reached the tailrace in the form of heavy rain which was perfectly harmless to any part of the works.

It was hard to understand why a national asset of such paramount importance as water power was not utilized to a greater extent than had been the case in the past. It was mainly due to the difficulties to which Mr. Halcrow had referred. It was true that the capital required for the building of hydro-electric plant was generally much in excess of that needed for steam plant or the internal combustion engine, but surely it was the cost of the production of energy which must be considered in the first place, and this was in most cases much cheaper in the case of hydro-electric energy. Not only the aluminium industry, mentioned by Mr. Halcrow, but most of the important branches of the electro-chemical industry were dependent on the production of cheap power by utilizing the energy of flowing water.

The effect of stones and indentations, about which Mr. Thott was concerned, could not be tested in any form of laboratory. Only experience with the actual plants could show what provision must be made against stones and debris. Experience over many years had shown that in most cases stainless steel protection of a particular region, amounting to about 10 per cent of the whole surface of the blade, was satisfactory and sufficient. Mr. Thott expressed various warnings against what he called the comparative levity with which the author had treated the problem of cavitation, as well as the method and arrangement of his hydraulic brake. It was perhaps as well to remember that had engineers in this country heeded the grave and oft-repeated warnings against the dangers and pitfalls of hydraulic engineering expressed by their distinguished competitors abroad, they would never have dared to do anything with water except perhaps drink some of it, with appropriate caution. The method of welded stainless steel protection against cavitation had been entirely successful for many years on numerous plants, ranging in size up to the 25,000 h.p. units of Arapuni, where runner wheels of foreign design had been replaced by wheels protected by this method, which continued to give every satisfaction in service.

He was well aware that certain designs of turbine made the introduction of a renewable lining at the beginning of the suction bend indispensable. Appropriate measures in the design stage, so that the maximum permissible suction should not be exceeded under any conditions of operation, would eliminate any detrimental effect and render special protection at this point unnecessary. The oldest hydraulic brake embodying the principle described in the paper was the one built in 1928 for the 8,000 h.p. turbine of the Lanarkshire scheme. In this, as in all other cases, no wear whatever resulted at any point in the turbine.

Major Webb gave the assurance that his comments were to be interpreted solely as a friendly corrective. But surely he was unjustified in accusing the author of endeavouring to give the impression that British engineers had a monopoly of hydro-electric practice. The introduction to the paper made it clear that the new features in design described in the paper were created in order to secure a *reasonable share* of the world's output in hydro-electric industry. He felt, moreover, that Major Webb's opinion that the desideratum of simplicity conflicted with these features could only be explained by his not having taken the necessary trouble to study them thoroughly.

Compared with other constructions, these features justified the claim of outstanding simplicity.

The reproach that he should have mentioned the necessity of calibrating the aerofoil instrument was beside the point because nowhere was it claimed that it was anything else but a recorder and not a calibrating instrument. Apprehension regarding the accuracy of the aerofoil recorder due to the presence of a packing was unfounded in practice because the momentum exerted on the aerofoil was so powerful that the force absorbed by the packing was negligible in comparison.

Doubt as to the efficacy of the hydraulic experimental laboratory was answered in the text of the paper, where it was made clear that tests had always shown excellent agreement with the results obtained with the full-size machines in service. If Major Webb distrusted the reliability of laboratory tests of this character, what did he propose doing instead ? The results obtained in the test plant had been, and would continue to be, the basis for any sound new development. That Major Webb obviously relished his discovery of a passage which he deemed amounted to poetry, showed the extreme modesty of his literary pretensions, but he was gratified to note that he enjoyed at least this passage of the paper, if nothing else.

As consulting engineers to the Central Electricity Board, Mr. Hawthorne and the firm with which he was connected, were in the best position to judge the design of the machinery described in the paper. It was, therefore, very gratifying to learn that everything went to their satisfaction.

It might not be generally known that it was due to the initiative of General Davidson that the paper was written. A brief summary of the hydro-electric plants designed and manufactured in this country was given in Table 2. The total output approached 1,000,000 h.p., distributed as follows:—

British Isles	428,000 h.p.
British Empire	502,000 ,,
Other parts of the world . .	52,000 ,,
	982,000 h.p.

The mechanical drive referred to by Mr. Brooksbank was adopted as a standard for all important hydro-electric sets because it was found to be far more reliable for continuous and uninterrupted service than belt drive. Belt drive was only employed for small auxiliary sets and the governor illustrated in Fig. 9, p. 292, was for such a set. He had had excellent results with the mechanical drive, and not one case of failure had occurred, though such drives had been in continuous service for about twelve years. Neither had there been any necessity for changing of parts or adjustments. This was chiefly due to the fact that the gear drive was designed very generously. The transverse moment of inertia of the flexible stainless steel plate was such as to render it free from synchronous vibrations. The blade was flexible, but nevertheless ensured the necessary mechanical stiffness.

TABLE 2. A SHORT LIST OF THE MORE IMPORTANT HYDRO-ELECTRIC PLANTS IN EXCESS OF 10,000 H.P. DESIGNED AND MANUFACTURED IN GREAT BRITAIN

Total output, h.p.	Type of turbine	Destination	Country
24,000	Reaction	Lanarkshire	Scotland
33,000	Impulse	Kinlochleven Reconstruction	,,
48,000	,,	Lochaber	,,
52,500	,,	Lochaber Extension	,,
72,000	Reaction	Grampians	,,
52,000	,,	Tongland	,,
40,000	,,	Glenlee	,,
33,000	,,	Kendoon	,,
38,000	Propeller	Carsfad and Earlstoun	,,
15,000	Impulse	Khopoli	India
152,100	,,	Bhira	,,
55,000	Reaction	Mettur	,,
14,250	,,	Malakand	,,
14,200	,,	Alouette	British Columbia
18,000	Impulse	Jordan River	Canada
12,650	Reaction	Lake Coleridge	New Zealand
18,000	Impulse	Cobb River	,,
50,000	Reaction	Arapuni Reconstruction	,,
14,500	,,	Shannon River	Tasmania
18,000	Impulse	Mulungushi	Northern Rhodesia
26,500	Reaction	Sorocaba	Brazil

The hydraulic brake was intended for large and heavy sets with rotating masses many times greater than the rotating masses of the small sets which they had manufactured for the Victoria Falls and Transvaal Power Company. The absence of the brake on these small sets would have no ill effect on the bearings because they were designed very amply and the automatic standby set would ensure lubrication during deceleration. For large machines the bearings often could not be designed with anything like the margin which it was possible to embody in bearings for small sets.

The statement that complete wheels in stainless steel or turbadium bronze were really unnecessarily extravagant referred to wheels of from about 4 to 15 tons individual weight. The wheels for the Victoria Falls and Transvaal Power Company's turbines were in quite a different category and could be cast in one piece in stainless steel. To resort to welded stainless steel protection would be more onerous in this case. The use of stainless steel was at present the best that could be done to avoid the effects of cavitation.

The aerofoil type of recorder, referred to by Mr. Howland, was invented at a time when all the other usual methods of recording for an important new plant to be developed were found either objectionable or totally impracticable on account of the danger of clogging, bulkiness, or lack of accuracy. As he had already explained, it was not claimed that the aerofoil was anything else than a recorder. It stood to reason that in a case where the velocity distribution in a pipe changed due to altered conditions of the pipe, the need for recalibration would apply to any method of recording.

Mr. Peck was under a misapprehension with regard to the relationship between the size of the jet and its velocity. The fact that the jet appeared to be double the initial size at a distance of approximately twelve times the vena contracta by no means implied that its velocity was diminished to one-quarter of the initial velocity, because if such were the case the jet at normal speed would have a braking, instead of a driving, effect on the runner. The jet, on account of the subdivision brought about by the succession of buckets, was utilized on a length, according to specific speed, of only about seven times its initial diameter. It was quite correct to say that " broomy " jets were detrimental to the efficiency, but the diffuser gear was by no means particularly conducive to the formation of inefficient jets. The efficiencies obtained in the field with large machines provided with diffuser gear were, according to specific speed, as high as 86 to 90 per cent and were not inferior to those obtained with the ordinary nozzle and spear. Mr. Peck referred to impulse turbines of high specific speed with a multiplicity of nozzles and wheels, but in his opinion in most of these extreme cases reaction turbines would have proved more efficient than impulse turbines, as well as being much cheaper and less bulky, since they could run at a higher speed. With adequate precautions in design, material, and workmanship the detrimental effect of abrasive silt in reaction turbines could be diminished to at least the same degree as in impulse turbines. Reaction turbines had been built and were in regular and satisfactory operation with heads up to 1,100 feet and more.

Mr. Peck had executed some interesting tests in his laboratory with a reversible turbine pump. The utilization of this idea would certainly have to be carefully considered in the case of pump storage plants.

That this could be done was proved in the Baldeney hydro-electric plant at Essen, but the chief consideration for a pump storage plant was, and must remain, the possibility of obtaining high efficiencies for both the turbine and pump, otherwise this type of plant would be ruled out on economic grounds. For storage plants working with heads of from 200 to 300 feet the form of the runner vanes would present far greater difficulties than at the Baldeney plant, which worked with only 9 metres head. The fact that the reversible turbine pump would have to come to rest before being set to work in the reverse direction appeared to be an important drawback because of the unavoidable interruption and complication of the service. In the existing pump storage schemes units up to the largest sizes could be reversed automatically and in rather less than 1 minute ; no resynchronization was necessary, and surplus power could thus be utilized to meet peak loads to the best possible advantage.

Communications

Mr. V. L. BATAILLARD (Messrs. Merz and McLellan) wrote that the turbine-testing plant which had been installed at the Rugby works of the author's firm had already proved its usefulness in a striking manner in connexion with model tests which were carried out to check the design of the turbine runners of the Earlstoun and Carsfad stations of the Galloway Water Power Company, which had a fairly high specific speed. Fig. 36, p. 313, referred to this machine. The test results afforded valuable guidance which led to a radical modification of the type of runner which had been originally considered.

The automatic governors installed by the author's firm in connexion with the five plants of the Galloway Water Power Company had to meet difficult conditions, reflected by the fact that it was necessary at all the plants to allow for a speed rise of 25 per cent when the full load was thrown off, on account of the scanty flywheel effect which could be provided in the alternator rotors. It was pleasing to record that the governors' performance was entirely satisfactory from the start and at more than one of the stations the machines were ready to go into service on the national grid with perfect speed regulation within two or three hours of the first governor trial.

The author had referred in his paper to the two huge power stations on the Rhine at Ryburg-Schwoerstadt and Kembs. It might be wondered why, in view of the great similarity in the conditions of head, output, and number of sets, Kaplan turbines were installed in one case and the much less expensive plain propeller wheels in the other. This was to a large extent due to the fact that Kembs was built as part of a unit, the other part of which was the Lac Noir storage pumping and generating station only a few miles away. The provision of pumped storage had therefore brought about a reduction in the capital cost of the primary power station. This reduction was not important as the cost of the turbines was only a small fraction of the total investment, but what was more important was the great simplification in the turbine construction, which must result in cheaper maintenance cost.

The Walkerburn plant of which mention had been made in the discussion, although on a very modest scale, compared with the Continental pumping storage stations referred to in the paper, was of interest on account of its great simplicity. The primary power plant consisted of a 100 h.p. water turbine utilizing a very low fall on the River Tweed which offered no direct storage facilities. The turbine drove electrically for 44 hours a week the machinery of a woollen mill ; during the night hours and the week end it drove a centrifugal pump which lifted water from the Tweed through a pipe line into an artificial reservoir built on a 900-foot hill in the immediate neighbourhood. The energy thus stored was used during the working hours of the mill by a Pelton wheel and the primary power was practically doubled. As compared with the usual type of pumping storage, the losses in primary alternator, pump motor, transformer, and transmission were in this case eliminated.

The attempt had been made in conjunction with one of the pumped storage stations in Germany to use the same machine as turbine and as pump, but this could only be done at the cost of a loss of efficiency. Further, the arrangement involved a reversal of the direction of rotation which was an obvious drawback. Where the primary power for a storage scheme was water power the units used for pumping cost nothing beyond the night shift wages ; but where steam power came into consideration, as was the case in a number of the German plants, the economy of pumped storage was still very favourable, even if artificial storage reservoirs had to be created. It would be recalled that such reservoirs with pumping plant were a feature of the tidal power schemes of which much was heard a few years ago. There was no doubt that pumped storage in connexion with a steam power station was a much more promising proposal.

Dr. F. V. A. E. ENGEL (Electroflo Meters) wrote that he fully agreed with Dr. Seewer's remarks regarding the importance of continuous flow recorders. A large number of existing hydro-electric power stations were already equipped with Venturi meters ranging up to pipe sizes of 10 feet in diameter and more. The cost of this type of meter was not too high, especially when installed in a concrete conduit. In the latter case, the pressure tappings were situated in specially made piezometer rings which were embedded in the concrete, whilst the inlet and outlet cones were made of reinforced concrete. The tapping holes for a 10-foot Venturi tube were about 2 to 3 inches wide and it therefore seemed unlikely that any clogging by dead leaves, sand, etc., would occur. There were several cases in practice where clogging could be more reasonably expected, particularly in sewage works. Then it was usual to provide the Venturi meter with a flushing system of fresh water and also special cleaning plugs which were occasionally inserted into the tapping points and then withdrawn. The preference for the Venturi tube as a device for measuring large quantities of water flow was easy to understand as it combined the highest degree of accuracy with small head losses. These losses might be of the order of 5 to 12 inches water gauge according to the design and the maximum differential head to be measured. The accuracy of the Venturi tube was generally recognized, and preliminary work was now in hand which should soon lead to a standardization of this type of meter. Hence it would seem that some of the author's remarks were not sufficiently well founded.

There were several other devices which might be successfully employed for flow measurement. In places where the pipe lines had to be reduced, the reducing piece might be designed to form a nozzle across which the differential pressure was a reliable means of determining the rate of flow. Also the contraction of the water stream in the intake of the power plant might be used in connexion with a differential head meter. Weir meters were quite commonly used for determining the efficiency of hydro-electric power stations, but another device should be mentioned which might soon replace the weir meter because of its high degree of accuracy and very small head loss, namely the Venturi flume.* One of its advantages in comparison with the weir meter was that the main section of the water stream was unobstructed, as the meter consisted essentially of side contractions of the channel walls.

Dr. Seewer had added a new design of meter which belonged to the class of vane meter. Different types of this were known, mainly for use in connexion with air-flow measurement. The size of the gate

* C. C. Inglis. "Notes on Standing Wave Flumes and Flume Meter Falls", Government of Bombay Public Works Dept., Technical Paper No. 15, Bombay, 1928. A. H. Jameson. "The Development of the Venturi Flume", *Water and Water Engineering*, 1930, vol. 32, p. 105. F. V. A. E. Engel. "The Venturi Flume", *The Engineer*, 1934, vol. 158, p. 104.

or vane might be as large as that of the total area of the conduit.* At zero flow, the vane would close the pipe line and was deflected with increasing rates of flow. In another meter of this class the fluid impinged on a plate and tended to deflect it, resulting in a change of the control force to restore the plate to its normal position. The velocity distribution in the latter type and also in the design as shown by Dr. Seewer must have an influence on the accuracy of the meter.† Also cross currents must introduce considerable error in the aerofoil flow meter. The scale shape, which closed up for high rates of flow, as indicated in Figs. 7 and 8, pp. 290 and 291, would prove detrimental to a high degree of accuracy. The Venturi meter, of course, had the opposite tendency and opened its scale for the higher rates of flow.

It did not seem to him to be in line with the general practice in hydro-electric plants to operate valves, etc., directly from the meter, as remote control systems employing either electrically operated relays or pilot valves and servo-motors operated with oil under pressure, had been developed to a high degree of perfection. It was not essential for these devices that the available working force of the meter should be of any great magnitude. Considering the elaborate precautions taken in obtaining reliable results for the measurement of water flow in connexion with acceptance tests on hydro-electric plants,‡ he would like to know the actual field of application of the author's automatic aerofoil recorder. Was this new meter meant to replace the current meter or weir meter for this purpose ?

Mr. J. R. FINNIECOME wrote that for many years he had followed the rapid developments of various types of water turbines and so found the paper extremely interesting. The paper described three outstanding developments, the aerofoil flow indicator, the cylindrical balanced valve with the cylindrical sleeve automatically moved to give a variable speed of movement, and the diffuser governing system fitted to the needle valve control.

No particulars were given of hydro-electric power stations installed in this country. He felt sure that such information would add to the value of the paper. He had therefore prepared Table 3, which gave

* E. J. LASCHINGER. "A New Form of Compressed Air Meter", *The Engineer*, 1927, vol. 144, p. 747.

† Even weir meters were subject to the approach conditions and the velocity distribution, as the investigations of W. Dietrich had shown. See W. DIETRICH. "Wassermessung mit Überfall in der Zentrale Handeck des Kraftwerkes Oberhasli", *Schweizerische Bauzeitung*, 1932, vol. 99, p. 1.

‡ Reference should be made to the acceptance tests conducted at the Kembs hydro-electric power station (illustrated in Fig. 48, p. 321 of the paper). L. ALAMARTINE. "Les essais de réception des turbines de l'Usine de Kembs", *Bulletin technique de la Suisse romande*, 1936, vol. 62, p. 1.

TABLE 3. UNITS GENERATED BY WATER POWER IN GREAT BRITAIN IN THE YEAR 1935 BY STATIONS WITH AN ANNUAL OUTPUT ABOVE 1,000,000 KW.-HR.

	Owner	Power station	Units generated per annum, kW.-hr.	Maximum load on generators during the year, kW.	Annual station load factor
Scotland	Lochaber Power Company	Lochaber	202,676,710	24,620	94·0
	Grampian Electrical Supply Company	Tummel	76,801,300	28,900	30·3
	Ditto	Rannoch	71,840,600	29,800	27·4
	Lanarkshire Hydro-Elecric Power Company	Bonnington	52,736,500	10,500	57·3
	Ditto	Stonebyres	27,860,900	5,800	54·8
	Galloway Water Power Company	Tongland *	43,843,410	34,000	—
	Ditto	Glenlee †	39,150,890	26,000	—
	Ross-shire Electrical Supply Company	Lochluichart	3,221,156	2,324	15·8
Wales	North Wales Power Company	Maentwrog	37,294,000	19,900	21·4
	Ditto	Dolgarog No. 2	36,330,100	12,400	33·4
	Ditto	Dolgarog No. 1	9,104,850	4,350	23·9
	Ditto	Cwm Dyli	10,471,000	5,700	21·0
	Yale Electric Power Company	Blaenau-Ffestiniog	1,192,568	440	30·9
England	York Corporation	Linton Hydro	2,362,400	827	32·6
	West Devon Electrical Supply Company	Morwellham	1,764,210	640	31·5
	Ditto	Mary Tavy	1,292,022	850	20·2

* Supply commenced on 14th May 1935.
† ,, ,, ,, 6th March 1935.

for those hydro-electric power stations in Great Britain with an annual output above 1,000,000 kW.-hr., the units generated, the maximum load, and the annual load factor, based on the statistics published by the Electricity Commissioners for the year 1935. During that year the total units generated in hydro-electric power stations in Great

Britain amounted to 625,181,262 kW.-hr. This corresponded to 3·29 per cent of the total units generated by all steam, hydraulic, oil, and other power tations in Great Britain. There were in all 56 hydro-electric power stations, of which nine produced 95 per cent of the total units generated by water power. The total units generated corresponded very closely to the annual output of Barton Power Station with 632,490,500 kW.-hr. The total units generated by hydro-electric power stations in Great Britain in 1935 were 35 per cent above those for the year 1934. The annual load factor at Lochaber was 94 per cent. This was higher than the highest value of 77 per cent obtained with steam stations in 1935.

The author had given, except for a few illustrations and descriptions of two power stations, very little information regarding the progress, performance, and size of runners of propeller type turbines. During the last decade considerable attention had been devoted to the rapid development of high specific-speed propeller type turbines with adjustable runner blades, originally proposed by the late Professor Kaplan in 1912, and first commercially installed in Europe in 1925 and in America in 1928. Sufficient data and experience were now available to predict very closely the performance of a full-scale runner from tests on models. The advantages of the movable runner blades were very soon realized and had it not been for the initial mechanical complications of moving the runner blade manually or automatically the Kaplan turbine would have made a more rapid advance. The fixed-blade propeller type turbine gave a very steep power-efficiency characteristic with a sudden peak at the most economical loads. This particular characteristic applied also to propeller type pumps and fans. With the movable blades it was possible to obtain a very flat efficiency curve over a range of load of from 40 to 150 per cent of the economic load, for the turbine efficiency was only about 5 per cent lower than the maximum efficiency for the 40 per cent and 150 per cent load. It was possible to obtain efficiencies above 85 per cent from 40 to 150 per cent, and above 90 per cent from 60 to 140 per cent of the economic load. The Kaplan turbine was universally adopted in Europe and in America for heads up to 106 feet and outputs up to 50,000 b.h.p. The fixed-blade propeller type was generally installed in Canada, although manually operated blades had been used in turbines of up to 10,000 b.h.p.

The author stated that he had carried out extensive tests on model turbines and found that the values obtained when corrected to the full scale agreed very closely with the test data obtained on actual turbines on site. He asked if the author employed the Moody or the Camerer formula, at present in general use, or had he derived a similar formula from his comparative tests ?

Mr. A. A. FULTON wrote that anyone perusing the paper would be at once struck by the great amount of ingenuity displayed in the design of the apparatus and equipment described. What, perhaps, was not so evident was the part which the author himself had played in their production and perfection. In every instance the design represented an almost complete departure from orthodox ideas. The success that had been achieved was a tribute to his genius and to the soundness of his design.

The aerofoil flow recorder was a most interesting development, and it would be helpful if the author could give some further details with regard to it. For example, must calibration tests be carried out for each individual application, whether for the same size of pipe or not, or were the slight differences in form as between two aerofoil sections so small as to leave the accuracy unaffected? Was it necessary to have a non-corrodible lining in the pipe at the point of insertion of the aerofoil section to prevent alteration in the regime of flow due to incrustation, etc.? Also, what restriction, if any, applied to the length of straight pipe immediately upstream of the measuring section? The author mentioned a degree of inaccuracy of $\frac{1}{2}$ per cent below 10 per cent of maximum flow. Could this be taken to mean that the error at any point between 0–90 per cent of maximum flow did not exceed $\frac{1}{2}$ per cent?

In the description of the cylindrical balanced valve, the question of friction loss was not mentioned. Could the author give an approximate figure for this, either in relation to the head, or in comparison with a smooth-bore valve such as the "spectacle eye" sluice valve or the rotary valve? In the matter of cost, was the cylindrical valve not at a disadvantage compared with these two types of valves?

The main criticism which had been levelled against the jet disperser governing device was the housing of an intricate mechanism in such an inaccessible spot as the nozzle of a turbine. It was reassuring to learn that there had been so little trouble with diffuser blades. There was always the feeling, however, that if for any reason the blades did not return home, the jet was bound to be affected, with consequent spreading and loss of power. Minor objections included the heavy weight which had to be carried by the nozzle bearing and the larger displacement caused by the greater room taken up by this method of control.

Mr. O. THOTT wrote that on p. 286 the author stated that "it was necessary for British engineers to create features in design . . .", and on the following pages he described some of the designs adopted by the firm to which he was attached. Some of these appeared to him as being old and well-known Continental designs, and he asked which were really claimed as inventions "created" by British engineers. Did the author claim, on p. 314, that the "comprehensive" treatment of hydro-electric schemes was peculiar to British practice ? Surely such a fundamental principle of water power engineering could hardly be an innovation nor yet a monopoly of British engineers.

The automatic aerofoil flow recorder was certainly an interesting development, although it would seem that any debris which might stick to the blade would affect the result, as would also any indentation on the front edge of the blade to which flow of water was so sensitive as to make re-calibration necessary. It would be interesting to learn the number and particulars of these recorders actually installed and how long they had been in practical operation.

The automatic oil pressure speed governor was neither particularly new nor particularly British, since many types of very good automatic governors had been built for many decades past by Continental and American firms. The idea of using a flexible mechanical drive to the governor could hardly be described as a recent development. The firm with which he was associated installed a Pelton turbine with an automatic oil pressure governor directly driven from the turbine shaft by means of a mechanical flexible coupling as long ago as 1920 at the Simla municipality's power station in India, and the arrangement had been adopted on various occasions since then. There were other cases, however, where drive by belt or electric motor was preferable. The latter was a comparatively recent development, but the flexible coupling was not.

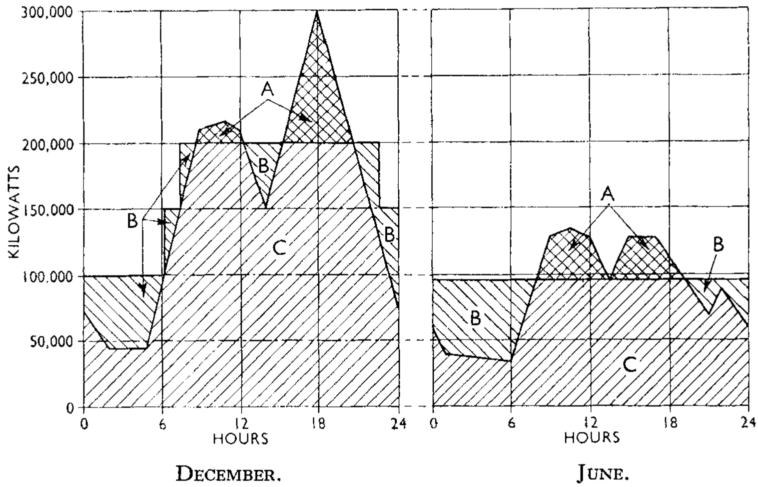
The hydraulic balanced valve, he believed, was known in Switzerland some twenty years ago. It appeared to have the same disadvantage which had been stated against the once so popular Larner-Johnson valve, namely, repeated alteration of direction of flow of the water, with resulting friction losses, especially at high-head plants with high water velocity. Other British firms (Messrs. Glenfield and Kennedy, Blakeborough, etc.) were building valves which had eliminated this disadvantage, e.g. the "spectacle eye" valve, and various designs of rotary valves. He felt that the rotary valve with rubber hose sealing, recently invented by a British engineer, Mr. W. Darling, and covered by Patent No. 444,841, might well have been mentioned amongst "recent developments". One such valve, of 52 inches diameter, designed by his firm, was at present being manufactured at the works of Messrs. Glenfield and Kennedy for the 28,000 h.p. water turbines recently ordered for the Waikaremoana power station, New Zealand.

Fig. 18, p. 299, showed a relief valve which could hardly be claimed as an improvement upon earlier, well-tried types. It would seem that the operation depended upon a sliding cylinder hydraulically operated, where leaking packing rings, or stoppage of operating pressure water, might cause the valve to remain in the closed position. For an inlet valve, such a design could be adopted without serious risk, but it was easy to visualize the grave consequences to power plant and pipe line which might result if the pressure relief valve failed to open when load was suddenly thrown off the turbine. In his opinion it was, therefore, advisable to adopt valves which under no combination of fault or misfortune could be accidentally "locked" in the closed position. Many such relief valves had been built in British works, the largest probably being the two valves with an outlet diameter of 8 feet supplied with two 30,000 h.p. turbines for Arapuni, N.Z. These turbines and the relief valves were built at Chesterfield.

The Pelton bucket fastening by means of a conical bolt and split bush was certainly used by Piccard Pictet well over twenty years ago, but had not been adopted by many other firms, presumably because of certain practical difficulties. It was hardly a "recent" creation. The block and step design of power house had been known abroad, particularly in the U.S.A., for a great many years. His firm put forward this arrangement as an alternative proposal when quoting for the first Arapuni turbines some thirteen years ago, but it was not presented as anything "new" or exceptional. He agreed with the author that the arrangement had certain advantages over the vertical-shaft arrangement with many floors.

Mr. Julian S. Tritton wrote that the paper was a valuable contribution to the records of recent advances in hydro-electric engineering. He was particularly impressed by the reference in the latter part of the paper to hydro-accumulator plants. The term "hydro-accumulator plant", in addition to being somewhat clumsy, was apt to be confused in the minds of mechanical engineers with hydraulic accumulator plant. The term "pump storage plant" seemed more descriptive and convenient. The advantages of this type of plant extended beyond those given in the paper, and it might be pointed out that the combined running costs of a steam station working in conjunction with an efficient hydro-accumulator plant were less than the running costs of the equivalent all-steam station, since the saving in labour and stores and increased efficiency effected by the improved load factor of the base load station more than covered the cost of the labour and financial charges of the pump storage plant. If suitably located the synchronous machines could be used for improving the power factor of the system when running both as generators and as motors.

As there were many sites in England which were ideal for the installation of such plant, it was surprising that, although this type of plant had been developed so rapidly of late years on the Continent and in America, advantage had not been taken of it in this country, except in the small plant mentioned by Mr. Thott. The possibilities of this type of plant for development in this country had been closely investigated, and as far back as 1933 his firm submitted proposals to the



	kW.-hr.	kW.	Load factor	kW.-hr.	kW.	Load factor
A and C	3,810,000	300,000	53·0	1,110,000	135,000	34·2
A	310,000	100,000	12·9	295,000	39,000	31·5
B	520,000	75,000	—	490,000	62,000	—
C	3,500,000	200,000	73·0	1,815,000	96,000	78·8
B and C	4,020,000	200,000	84·0	2,305,000	96,000	100·0

Fig. 63. Load Diagrams for Ordinary Weekdays

responsible authorities for schemes in localities where suitable sites were available.

Fig. 63 showed, for ordinary weekdays in winter and summer, load diagrams which were based on the supplementary particulars of the South East England Electricity Scheme, 1927. For a total load of 300,000 kW. a 200,000 kW. base load plant run in conjunction with a pump storage plant of 100,000 kW. capacity would have a daily load factor of practically 100 per cent, except on some days in winter. It was estimated that this station, with an installed capacity of 120,000 kW., costing about £1,875,000, would show a saving when supplying peak power into an existing transmission network of about £100,000 per annum, quite apart from an annual saving of about £48,000 in the coal costs of the 200,000 kW. base load station, due to improved load factor. Further, it could be shown that provided the site selected was such that the hydro-accumulator plant could be built for £20 per kilowatt, a saving could be effected even over a specially designed peak load steam station. For an ordinary steam station supplying peak loads as much as £35 per kilowatt could be spent on the hydro-accumulator plant.

So far as developments in this country were concerned, however, nothing was done at the time, as the authorities had to plan their extensions some ten years in advance. In view of the many advantages of this type of plant it was to be hoped that proposals for schemes in the near future in this country would include at least one pump storage plant.

Dr. P. W. Seewer wrote in reply that Mr. Bataillard's reference to the hydraulic test plant at Rugby bore witness to its usefulness in one particular case and was of all the more value as coming from one with many years' experience in this branch of engineering. The case of the Earlstoun and Carsfad runners was but one instance amongst many where the test plant had yielded results which were invaluable in new developments.

The governors and all their accessories were subjected to the most stringent tests before they left the works, and the satisfactory performance obtained on the Galloway plants after but a few hours' test would have been impossible otherwise.

He regretted having omitted to mention the existence of a pump storage plant in this country built several years ago at Walkerburn to the designs of Mr. Bataillard. Whilst this plant was of comparatively small dimensions, the information given by Mr. Bataillard would be of interest because it proved that the pump storage plant could supplement peak loads under favourable economic conditions and practically double the primary power. The existence of this plant was a good illustration of the possibility of development on a large scale of this new and interesting type of hydro-electric plant which was long overdue in this country.

Whilst it should be perfectly clear from the text of the paper, he felt obliged to point out once more in reply to Dr. Engel that the aerofoil was always meant to be a permanent recording, and not a calibrating, instrument. Dr. Engel considered that the price of the Venturi meter was not too high, especially if installed in a concrete conduit. This, however, was the exception rather than the rule; in the great majority of cases, the Venturi meter had to be installed in steel pipes, where the price, as well as the detrimental influence on the regulating performance of the governor and the danger of clogging, were more serious. Many rivers utilized for the production of hydro-electric power carried large quantities of sand and leaves so that the clogging of the piezometer holes was an ever-recurring trouble, especially in cases where the water discharge quantities had to be guaranteed continuously for irrigation, navigation, or for concessional waters. There were cases, and by no means isolated ones, where efficient flushing was either impossible or was accompanied by undesirable interruptions in recording, thus upsetting the continuity of the performance of discharge regulators on which the guaranteed quantities of water depended.

Whilst weir meters on large hydro-electric plants were in most cases out of the question because the necessary difference in level either did not exist or had to be created at considerable cost, on account both of building and deficiency in output due to loss of head, the installation of Venturi flumes for recording large water quantities, often amounting to hundreds of tons of water per second, would be altogether prohibitive, especially if compared with the price of the aerofoil permanent flow recorder. He was not aware of the existence of streamlined vane meters used in quantitative aeroflow measurement that could be employed with any chance of success in conduits feeding hydraulic plants. To extend a vane meter over the whole area of the conduit would be unnecessary and altogether dangerous because of the influence on the governor performance and consequent water hammer in the penstock.

He had already pointed out that the degree of precision of the aerofoil recorder was such that there was no discrepancy between it and a weir or volumetric measurement. Fig. 6, p. 289, which showed the calibration curve of the aerofoil witnessed by Lloyd's Register of Shipping, should make that abundantly clear. Obviously the aerofoil recorder, in common with other recording or measuring instruments, would preferably be arranged in a region of the penstock free from eddies and cross currents, so that Dr. Engel's apprehension of the detrimental influence of cross currents on the degree of precision need not arise. Dr. Engel was, furthermore, under a misapprehension inasmuch as it was never intended or claimed that the aerofoil recorder could, or should, be utilized for the *direct* operation of valves and discharge regulators, as the latter required forces often amounting to many tons. But the mere steering of their operating cylinders required a certain amount of power which no standard method of recording instrument, including the Venturi, yielded. There was no doubt that the very small force furnished by the ordinary type of recorder represented by a water pressure of a few inches only might be multiplied mechanically or electrically to furnish the necessary steering power, but not without considerable complications and consequent uncertainty in performance.

The scale shape of Fig. 7 which Dr. Engel found objectionable was due to an existing recorder and could be altered according to requirements in any given case. The answer to Dr. Engel's last question was already given in the text of the paper. The aerofoil recorder would be employed in hydraulic plants where it was desirable to install, at very little cost, apparatus capable of recording permanently and accurately large quantities of water independently of all the other variables.

He regretted the omission from his paper of statistical data relating to hydro-electric plants made and installed in this country. This omission had now been rectified in the answer to General Davidson (p. 345), but the information given by Mr. Finniecome was a valuable contribution.

The reason for the absence of more abundant information relating to propeller and Kaplan type turbines was, that while they could, and had, successfully developed this type of turbine, the field of application in this country and the British Empire was as yet very restricted. Their application was limited, as Mr. Finniecome stated, to low heads. In such cases the initial costs for the machines, buildings, and conduits would be considerably higher per installed kilowatt than was at present considered economic in view of the abundant and cheap supply of coal. Low-head schemes of this description would always have to be carefully judged from this point of view, and as there existed, at present at least, a considerable number of schemes both at home and in the British Empire which could be developed with very much less capital outlay per unit installed, the development of low-head schemes was unavoidably retarded. Heads of 64 and 100 feet had, however, been developed successfully in the Galloway scheme by installing propeller and high-speed reaction wheels. The Kaplan type, while far more complicated and costly, would have yielded very little more power because these stations were run as peak load or block load stations, running mostly at, or in the neighbourhood of, full load, in which conditions the efficiencies were equal or very close to those obtainable with Kaplan turbines.

There was no doubt, however, that if the opportunity presented itself, this type of machine could, with the help of the test station, be developed in this country as well as anywhere else. A good start had already been made on the experimental scale.

The results obtained for the full-size machines in service agreed excellently with the test results obtained on the scale-model turbine in the laboratory; in some cases this agreement was closer than was given by the correcting factors obtained by the application of the Camerer formula for propeller and reaction wheels. The majorating or correcting factors to be applied to impulse wheels were in a separate category, dependent upon the specific speed, and had to be developed specially.

In reply to Mr. Fulton's question as to whether the aerofoil permanent flow recorder would have to be calibrated for each individual application, it could be stated that this was, indeed, the original intention, as this could be effected in conjunction with the initial efficiency tests which always preceded the taking-over of any hydro-electric plant. A good deal, however, depended on the conditions of the pipes in front of the aerofoil recorder. In common with other recording devices, the aerofoil should preferably be arranged in a region of the pipe free from disturbances. It was found that for similar conditions in diameters and general arrangement of pipes, the discharge quantities recorded were remarkably consistent so that, subject to these conditions being fulfilled, calibration in each individual case was not absolutely essential. With a similar distribution of velocities there existed a very simple relation between the area of the aerofoil and the momentum exerted on it, so that the quantities recorded could be predetermined with considerable accuracy.

It was not intended, at present, to provide non-corrodible lining in the pipe at the point of insertion of the aerofoil because the condition of the inside of all pipes would in any case have to be inspected and protected periodically against both corrosion and incrustation, for reasons of security. In cases where conditions were particularly severe, however, for example with water carrying considerable quantities of chloride gases or other deleterious matter, or when the water showed a pronounced tendency towards incrustation, Mr. Fulton's suggestion that a non-corrodible lining should be inserted would be very useful. At present, however, no such case had been encountered in practice.

No discrepancy in measurement existed, between the aerofoil and the calibrated weir between 10 and 100 per cent of the maximum flow registered, greater than of the order of $\frac{1}{2}$ per cent between 0 and 10 per cent of full discharge. The answer to the question as to whether the error in measurement by the aerofoil between 0 and 90 per cent would not exceed ½ per cent was, therefore, in the affirmative, and furthermore, this degree of precision extended to 100 per cent, that is to maximum flow.

The friction losses observed in cylindrical and streamlined valves were generally higher than for the spectacle eye or rotary valve and lay, according to the water velocities, between 0·1 and 0·3 per cent of the head. One of the purposes of the cylindrical balanced valve was to enhance the security of the plant, because it was known to close safely under the most exacting conditions obtaining in service. The increased friction losses, which were small in any case, were therefore well worth facing.

The question of comparative costs of spectacle eye and rotary valves on the one hand, and cylindrical balanced valves on the other, could best be answered by stating that the latter were generally more expensive for small diameters and heads, about equal for diameters between 6 and 8 feet, and medium heads, and cheaper for large diameters and higher heads. Apart from the enhanced security afforded by the cylindrical balanced valve as a protective device, the consideration of costs should in every particular case be extended to the other features afforded by the cylindrical balanced valve, which combined the possibility of reduction in pipe diameters with easy dismantling, saving of space, and freedom from water hammer and vibration without necessitating any bypass.

The danger of the diffuser blades, employed for the primary regulation of impulse wheels, not returning to their flush position after action did not arise because their operating rods were actually the piloting or steering members by which the pressure oil was distributed to the needle servo-motors. Consequently no steady condition could be reached after action unless the diffusers were again exactly flush with the spear corresponding to the new load.

The spear shaft bearing had no doubt to support an enhanced weight but, apart from being lubricated, it could in every case be designed with a very ample factor of safety so that no ill effect had ever been observed. Even a cursory examination would show that the specific loading of this bearing was very modest.

The numerous expressions of appreciation received from people of unquestionable authority were, he trusted, sufficient comment on Mr. Thott's communication, which in his opinion was lacking in technical discrimination.

He fully endorsed the remarks of Mr. Tritton. It was to be hoped that the improved power factors, increased efficiency, and, last but not least, the considerable economies obtainable by the incorporation of the pump storage type of plant into a power system, would soon be more generally recognized, to the ultimate benefit of industry and all power consumers. The pump storage plant was an important factor in enabling the country to utilize its national power resources to the best possible advantage.

The example given by Mr. Tritton was but one instance of the numerous sites existing in this country where pump storage plants could be installed with advantage and peak loads covered at prices which were very considerably cheaper per unit than were obtainable at present. The prices per installed kilowatt given by Mr. Tritton were by no means a record, and it was possible at a number of sites which had been investigated and worked out in detail, to install pump storage plants even more cheaply, in some cases appreciably so.