

RECENT ADVANCES IN UTILIZATION OF WATER-POWER.

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Introduction.—Water-power engineering and development of water-power have, in common with most branches of engineering, made very rapid progress during the last fifteen to twenty years, but the fact that comparatively few opportunities exist in the British Islands for extensive development of water-power, accounts for the relatively small interest devoted to this subject by engineers at home.

The water-power resources of this country, however, are well worth closer attention, and the large amount of water-power existent in Canada, India, New Zealand, Tasmania, and within the Empire as a whole, awaiting development for both domestic and industrial purposes, imposes the necessity of more interest being devoted to this particular branch of engineering than hitherto; the more so since the lesson derived from the War makes it incumbent on ourselves to manufacture within the Gates of the Empire, at any rate, the staple articles necessary for our leading industries, many of which depend to a very great extent on cheap power for their production, in order to compete successfully with material

[THE I.MECH.E.]

produced abroad. This applies notably to the manufacture of calcium carbide, nitrogen, aluminium, wood pulp, and a large number of chemical products, for all of which, with the exception perhaps of aluminium, we have been obliged to rely on foreign resources. Consequently, in view of the important rôle that water-power engineering will play in the coming struggle for industrial supremacy, it is desirable that the general knowledge of this highly specialized branch of engineering should extend over a very much wider circle than hitherto has been the case, and for that purpose the Author proposes to give a synopsis of the most recent achievements, at the same time embodying the developments of water-power engineering from the beginning of the present century, which epoch constitutes one of the most important "milestones" in this development.

It is interesting to note that the progress in the development of hydraulic prime-movers during the last century was comparatively slow, the most common type of turbines employed being the well-known types of "Jonval," "Girard," and various forms of tangential or spoon wheels. With the advent, however, of the application of electricity on a commercial basis and the perfection in system of transmission and distribution, the development of water-power received a tremendous impulse, which marked the beginning of a new era resulting in very rapid progress and enabling the vast water-power resources of the world to be utilized to a degree which now forms such an important factor in our industrial life.

The extended field thus given to water-power development created a demand for a high-speed turbine also under comparatively low heads, and in order to meet this new condition American engineers turned their attention to the Francis turbine, invented in 1849,* and produced a high-speed type of runner known as the "American Type." The Francis turbine, however, was not unknown in Europe, but it was only at the beginning of 1900 that it was generally adopted, and, owing to its great advantages over

* J. B. Francis, *Lowell Hydraulic Experiments*, Boston, 1855.

any other existing type of turbine, it has taken the lead and revolutionized the whole aspect of water-power engineering. Although it was due to the enterprise and ingenuity of American engineers that this type of turbine was developed along experimental lines, so as to make it adaptable to the new conditions brought about by the introduction of electricity, it stands to the credit of European engineers to have laid the theoretical foundations which permitted its development to be accomplished along scientific lines and which has now brought this type of turbine to its present state of perfection.

As an illustration of the rapid extension of the use of the Francis turbine, it is interesting to note the manufacturing records, Table 1, of an eminent European firm of turbine-makers, from which it is clearly shown that the Francis turbine has now superseded all other known types of low-pressure turbines. It is of particular significance to observe the increase in output per turbine, which indicates the modern tendency of installing less units but of larger capacity than hitherto employed.

TABLE 1.

Period.	Jonval No.	Girard No.	Francis No.	Tangen- tial wheels No.	Total B.H.P.	B.H.P. per Tur- bine.
1850-1894	904	883	7	623	179,256	74.2
1895-1899	72	99	98	232	114,818	229.1
1900-1904	8	16	464	300	390,252	495.1
1905-1909	—	—	457	336	886,582	1118.0
1910-1914	—	—	375	219	1,162,380	1956.8

This last-mentioned feature of modern hydro-electric development is also evident from a perusal of Table 2 (pages 58-59), in which the most representative installations built since 1895 have been tabulated; but perhaps an even more striking illustration is furnished

TABLE 2.

No.	Plant.	Country.	Year of Installation.	Working Head in feet.
1	Cataract Construction Co., Niagara	U.S.A.	1895	136
2	A. B. Glommens Traesliberi, Christiania	Norway	1901	64.5
3	Shawinigan Water and Power Co., Montreal	Canada	1902	134
4	Canadian Niagara Co. . . .	Canada	1903	133
5	Svalgfors Power Station, Notodden.	Norway	1904	150
6	Ontario Power Co., Niagara .	Canada	1904	175
7	McCall Ferry Hydro-Electric Power Station	U.S.A.	1905	53
8	Great Western Power Co. . .	U.S.A.	1907	525
9	Trollhattan Hydro-Electric Station	Sweden	1909	106
10	Tokio Electric Light and Power Co.	Japan	1910	396
11	Keokuk Hydro-Electric Power Station, Mississippi. }	U.S.A.	1912	39
12	Aelfkarleby Hydro-Electric Power Station	Sweden	1914	54
13	Cedar Rapids Power Station, Montreal	Canada	1914	30
14	Alabama Power Co.	U.S.A.	1914	68
15	Laurentide Power Station . .	Canada	1915	76
16	The Tallassee Power Co. . . .	U.S.A.	1916	180

TABLE 2.

Output in BHP. per unit.	Number of Units.	Speed in R.P.M.	Output under head = 1 ft.	Output per runner under head = 1 ft.	Type.
5,000	10	250	3.15	1.575	{ Double enclosed vertical.
3,000	4	150	5.8	5.8	{ Single enclosed vertical.
6,000	1	180	3.87	1.94	{ Double enclosed horizontal.
10,250	3	250	6.68	3.34	{ Double enclosed vertical.
11,750	3	250	6.40	3.20	{ Double enclosed horizontal.
12,000	—	187.5	5.18	2.59	{ Double spiral horizontal.
13,500	10	94	35.00	17.5	{ Double open vertical.
18,000	4	400	1.5	1.5	{ Single spiral vertical.
12,500	8	187.5	11.5	5.75	{ Double enclosed horizontal.
12,500	6	—	1.6	0.8	{ Double spiral horizontal.
14,000	15	57.7	57.5	57.5	{ Single open vertical.
14,000	5	150	35.4	8.85	{ Quadruple open horizontal.
10,800	12	55.6	66.0	66.0	{ Single open vertical.
17,500	6	100	31.0	31.0	{ Single open vertical.
20,000	6	120	30.0	30.0	{ Single open vertical.
31,000	—	154	12.85	12.85	{ Single enclosed vertical.

TABLE 3.

No.	Plant.	Country.	Year of Installation.
1	The Mexican Light and Power Co., Necaxa	Mexico	1903
2	Brusio Hydro-Electric Plant . . .	Switzerland	1905
3	Rio de Janeiro Tramway, Light and Power Co.	Brazil	1906
4	British Aluminium Co., Ltd., Kin- lochleven	Great Britain	1907
5	Tysse Hydro-Electric Plant . . .	Norway	1907
6	Rjukanfos Hydro - Electric Plant, Station I	Norway	1908
7	Loentsch Hydro-Electric Plant . .	Switzerland	1908
8	The Mexican Light and Power Co., Extension	Mexico	1909
9	Biashina Hydro-Electric Plant . .	Switzerland	1909
10	South California Edison Co. Kern River, Plant I	U.S.A.	1910
11	Lake Bunzen Hydro-Electric Plant, Station II	Canada	1912
12	Kinugawa Hydro-Electric Plant . .	Japan	1912
13	Rio de Janeiro Tramway, Light and Power Co. Extension	Brazil	1912
14	Loentsch Hydro-Electric Plant Ex- tension	Switzerland	1913
15	Tata Hydro-Electric Plant, Bombay .	India	1914
16	Rjukanfos Hydro - Electric Plant, Station II	Norway	1914
17	Aura Hydro-Electric Plant. . . .	Norway	1916

TABLE 3.

Nett Head in feet.	Output per Unit in B.H.P.	Number of Units.	Speed in R.P.M.	Type.
1,279	8,200	6	300	4-jet vertical.
1,350	3,500	12	375	Single-jet horizontal.
950	9,000	6	300	4-jet vertical.
900	3,300	11	300	{ Double - jet horizontal.
1,260	4,800	7	375	Single-jet horizontal.
930	14,450	10	250	{ 4-jet twin runner horizontal.
1,075	6,000	4	375	{ Double - jet overhanging horiz.
1,279	16,000	2	300	4-jets vertical.
850	11,000	3	300	4-jets vertical.
865	10,750	4	250	{ 2-jet twin runner overhanging horiz.
395	13,500	3	200	{ 8-jets quadruple runner horizontal.
1,050	6,000	6	375	Single-jet horizontal.
950	20,000	2	300	4-jets vertical.
1,150	16,000	1	300	{ Double - jet overhanging horiz.
1,650	13,500	6	300	Single-jet horizontal.
830	16,400	10	250	{ 4-jet twin runner horizontal.
2,350	23,500	6	250	Single-jet horizontal.

by figures recently published by an American manufacturer, who commenced the manufacture of the Francis turbine in 1895, and since that date has completed installations with an aggregate output of 1,683,720 b.h.p. corresponding to an average output of 8,000 b.h.p. per turbine delivered.

The turbines for the Cataract Construction Company, Niagara, built in Europe in 1895, which at that time were the largest units ever installed, in respect of output, have now been placed in the background in comparison with units installed in modern power-plants both in America and Europe. It should be observed, however, that the comparative sizes of turbines can only be indicated by their output under an equal head, and, for the purpose of comparison, the various outputs under the unit head of 1 foot have been tabulated, which shows that the largest turbines in the world in respect of dimension are those erected at the Cedar Rapids in Canada, which installation will be referred to later. By way of comparison Table 3 (pages 60-61) shows the most representative high-pressure turbine installations installed during the last fifteen years.

According to broad principles, the turbines are classified in two categories, namely, Reaction and Impulse turbines.

The Francis turbine belongs to the former, and the high-pressure impulse turbine—or more familiarly known as “Pelton Wheel”—belongs to the latter category, and being the only types of turbines now employed in modern water-power development, it is unnecessary to deal with any other type except as far as historical interest is concerned.

FRANCIS TURBINES.

The Francis turbine, named after its American inventor, has a runner of the radial inflow type, the water entering the runner with a velocity corresponding to only a portion of the head, approximately half, and the remaining pressure-energy is utilized to accelerate the water during its passage through the runner. It is characterized by the varying conditions of head and speed for which it can be adapted, in which is to be found the reason for its

popularity, which has been fully justified by recent developments in its design.

As is well known, the main characteristics of a turbine are:—

- (1) Head in feet (Symbol H).
- (2) Output in B.H.P. (Symbol P).
- (3) Quantity of water in cub. feet per min. (Symbol Q).
- (4) Speed in r.p.m. (Symbol N).

If we assume that under the given head of H feet the characteristics of the turbine are P, Q, and N respectively, the corresponding characteristics for the unit head of one foot would be

$$\frac{P}{H\sqrt{H}}, \quad \frac{Q}{\sqrt{H}}, \quad \frac{N}{\sqrt{H}},$$

which are termed the unit speed, unit quantity of water, and unit output for any turbine.

This turbine under the head of H feet would consequently have the following characteristics:—

$$P_x = \frac{P}{H} \frac{H\sqrt{H}}{\sqrt{H}}, \quad Q_x = \frac{Q}{\sqrt{H}} \frac{\sqrt{H}}{\sqrt{H}}, \quad N_x = \frac{N}{\sqrt{H}} \frac{\sqrt{H}}{\sqrt{H}}.$$

The above conditions apply only to turbines of the same diameter and design, and in order to compare turbines of different diameters and operating under entirely different conditions, the factor known as the "specific speed" has recently been introduced (Symbol N_s), which term indicates the speed any given turbine would run at when operating under the unit head of 1 foot and having an output of 1 B.H.P.*

To arrive at the value of the specific speed N_s which now has been universally adopted in modern classification and design of runners, let it be assumed, as in the previous instance, that a turbine runner has been designed to develop P B.H.P. with a speed of N r.p.m. under a head of H feet, the corresponding quantity of water being Q cubic feet per second. If we let the head remain constant and conceive all the dimensions to be varied in exact proportion to the diameter D, we can obtain any number of geometrically identical runners with a varying diameter D_x . All

* Dr. Camerer.: "Grundriss der Turbinentheorie," 1908.

the areas of the runners would vary in direct proportion to the square of its diameter, and consequently the quantity of water and output would vary in the same proportion, and we can write:—

$$\frac{Q}{Q_x} = \frac{P}{P_x} = \frac{D^2}{D_x^2}$$

where the index X denotes the values of P and Q corresponding to the diameter D_x .

On the other hand the speed would vary inversely with the diameter, and hence

$$\frac{N_x}{N} = \frac{D}{D_x} \quad \text{or} \quad N_x = N \times \frac{D}{D_x}$$

For $P_x = 1$ B.H.P. we write

$$P = \frac{D^2}{D_1^2} \quad \text{or} \quad \frac{D}{D_1} = \sqrt{P}$$

and the corresponding speed

$$N_1 = N \times \frac{D}{D_1} = N\sqrt{P}.$$

If in these formulæ we substitute the values N and P, being the speed and output under head of H feet with the corresponding unit values, we arrive at the expression for the specific speed, thus:—

$$N_s = \frac{N}{\sqrt{H}} \times \sqrt{\frac{P}{H\sqrt{H}}} = \frac{N \times \sqrt{P}}{\sqrt[4]{H^5}}.$$

The value of the specific speed applies only to one runner, and in case of a turbine with two or more runners P in the formulæ represents the output per runner, or if P represents the total output the value of N_s must be divided with the square root of the total number of runners.

The relation between N_s in the metric and foot-lb. system can be expressed through the following formula:

$$N_s (\text{metric}) = 4.447 N_s (\text{foot-lb.}),$$

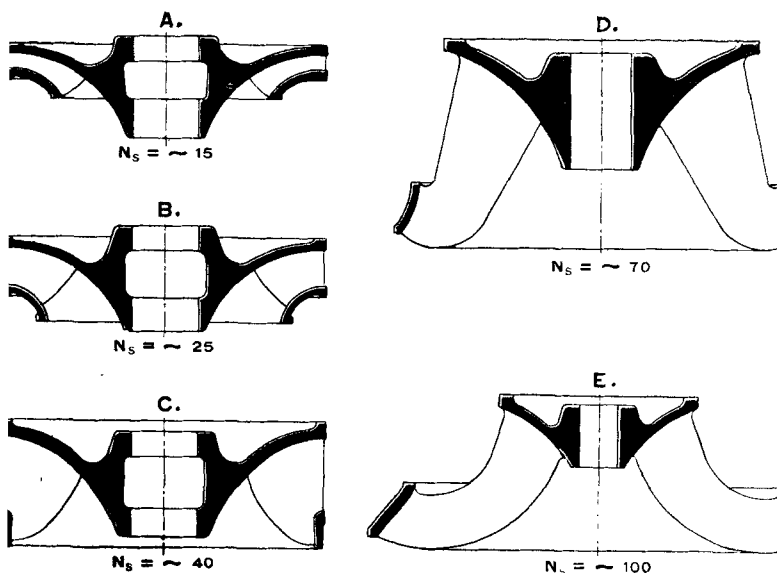
and throughout this Paper the metric equivalent is quoted in brackets.

It is easily recognized that the value of the specific speed owing to the limitation of design consistent with good efficiency has a

minimum and a maximum value, the minimum being approximately 11 (50), and the maximum, only a few years ago, approximately 75 (330), although recent improvements in design of runners have advanced this latter value to approximately 100 (450).*

Fig. 1 shows diagrammatically the various forms of runners with corresponding values of the specific speed, A being a runner of the slow-speed type using a small quantity of water under a high

FIG. 1.—Runners for Francis Turbines.



head, whereas E shows the latest design of high-speed runner using a large quantity of water under a low head.

It has already been mentioned that the high-speed Francis turbine runner was evolved in America by way of experiment, and was made a prototype for standard turbines which were sold under various trade names once so familiar to all engineers. The standard turbine was admirably suited to small water-power installations,

* S. J. Zowski. "Some recent Tests of High-Power, High-Speed Turbines." *Engineering Record*, December, 1914.

and, on account of standardized manufacture, was sold at an exceedingly low cost, but the fact that the method of standardization was not founded on a strictly theoretical basis militated for a long time against improvements in design and manufacture of turbines suitable for conditions of large hydro-electric developments.

In Europe, on the other hand, as soon as the favourable features of the Francis type of turbine had been recognized, its design was developed along scientific lines with a view to utilizing, under the most favourable conditions, the great natural water-power resources existent to meet the growing demand for cheap power in bulk.

The individuality in design and precision in workmanship created by this method, in addition to the established practice of designing each turbine to suit the existing conditions in each particular installation, paved the way for utilizing water-power on a very much larger scale than that at first anticipated. It is significant to note that the first large hydro-electric plant installed at Niagara in 1895 was built in Switzerland, and was followed by several larger plants, which fact, perhaps, brought home to American manufacturers the superiority of the European practice and caused leading manufacturers in the United States to adopt this method.

The many advantages which were undoubtedly offered by the standardization of turbines were, however, fully recognized in Europe, and in the value of "specific speed" was found the basis for a method of standardization which permitted the manufacture under more advantageous commercial conditions, having due regard at the same time to efficiency and high standard of workmanship.

From the foregoing remarks it will no doubt be appreciated what an important link this exchange of ideas between the two continents has been in the development of this type of prime mover, enabling a very much more rapid progress than would otherwise have been the case.

Most of the leading manufacturers have now adopted the manufacture of standard runners, each series corresponding to a certain specific speed and selected to meet the conditions most

frequently met with. It will be realized ~~that~~ owing to the multitude of varying conditions which have to be considered, this system may not always cover the complete field, and special designs have to be resorted to, but usually the modern standard runner covers such a wide range that in most cases where no abnormal conditions are imposed, they can be used with great advantage.

One very important factor in connexion with the modern standard turbine is the exhaustive tests to which each series have been subjected, and consequently a full knowledge of its efficiency and other characteristics is available, making it possible to predict with the greatest accuracy its behaviour under a variety of conditions and enable a selection of a runner which will most efficiently meet a given set of requirements.

It is on these improved methods of systematic tests and correct designs that the standardization of the modern turbine has been based and developed, and is by no means synonymous with the earlier attempt of standardization, where the manufacturer lacked the knowledge of the chief characteristics of the turbine, with the result that the turbines were very often installed under conditions for which they were not suitable; indeed, whereas the modern system has encouraged further developments, the early American practice, due to its empirical nature, tended to bar progress and render abortive every effort of development along rational lines.

Testing plants which have proved so valuable in the development of the design of runners are now installed within the works of most European turbine manufacturers, although in America most tests are carried out at the famous testing plant at Holyoak. Not only are standard runners accurately analysed on these testing plants, but all new special designs are subjected to test, and in the case of turbines whose large capacities do not permit of testing, accurate geometrically similar models of small diameter are made for testing purposes, and the results represent very accurately the performance of the master runner.

The importance of proper tests and rational research work, where the conditions bringing about the best results can be definitely ascertained, has perhaps in few instances manifested itself so

clearly as in the evolution of the Francis turbine, the development of which has only been possible by exhaustive trials and by intelligent application of the results so obtained.

As a point of interest, in view of the importance of this subject to realize fully the limitations and advantages of various types of runners, a brief reference will be made to the tests and the methods employed to analyse the results.

The tests for the purpose of investigating the chief characteristics of runners in order to determine their performance under a varying set of conditions are carried out in specially prepared testing flumes, the turbine being generally placed in a vertical position with the runner suspended from a ball suspension bearing to reduce the mechanical losses to a minimum. A Prony brake is usually employed for recording the output, and the quantity of water measured by means of an accurate weir, by floating vane in a specially prepared channel, or by a large tank of known dimensions; the latter practice is not often adopted but is certainly the most accurate method.

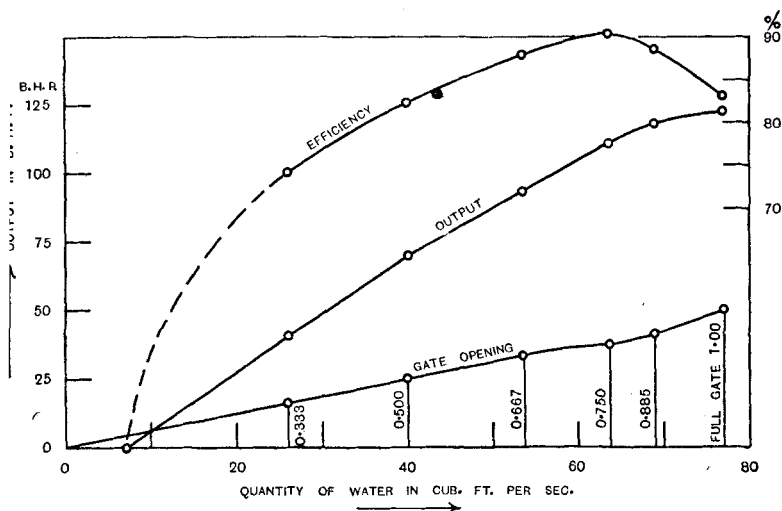
These tests are distinct from, and should not be confused with, the commercial tests carried out *in situ* after the erection of a plant, in which, owing to the entrance losses in the casing and larger mechanical losses due to friction in bearings, the efficiency recorded may fall considerably below the values obtained by the same runner at the testing plant.

The Author considers it necessary to make this observation, as it is often the case that the efficiencies obtained from turbines of different makes are indiscriminately compared without reference to the conditions under which the test has been carried out. It is easily recognized that the efficiency obtained from a particular turbine, for instance at the Holyoak testing flume where efficiencies of over ninety per cent have been obtained, is by no means commensurate with the efficiency obtained from a plant under actual working conditions when a maximum efficiency of eighty-six per cent would be considered exceedingly good; the former, owing to the ideal conditions under which the test has been carried out, representing as nearly as possible the *hydraulic* efficiencies of the runner only,

whereas in the latter case the *total* efficiency of the plant under commercial load is represented.

During the tests in the testing flume the head is maintained as constant as possible, and the output and efficiency obtained at the various speeds and gate openings are plotted in diagrams with the speed as abscissæ and the output and efficiencies as ordinates,

FIG. 2.—Test Results of Francis Turbine designed for Head $H = 17.3$ feet.
Output $P = 124$ B.H.P. Speed $N = 187$ r.p.m. Specific Speed $N_s = 59$.



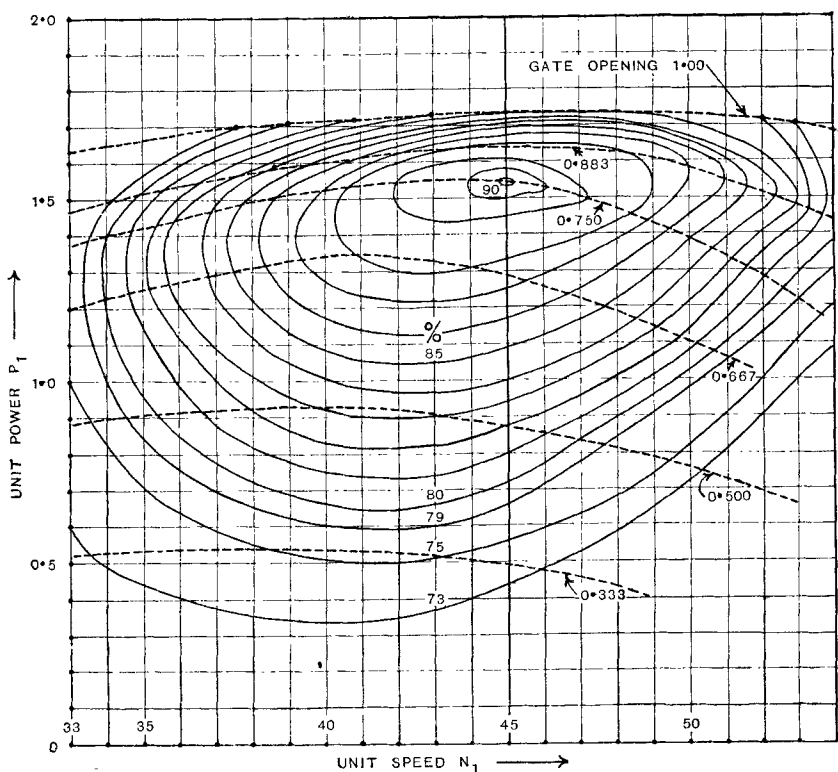
when a “speed-power” and a “speed-efficiency” curve is obtained for a number of different gate-openings.

The power and efficiency curves at normal speed, which is the speed for which the runner has been designed, and if correctly designed the speed at which the maximum efficiency is obtained, can now be plotted in a diagram as shown in Fig. 2. This diagram has been computed from a test at Holyoak with a runner of a specific speed of 59 (260) and gives the values of output and efficiency of the runner under a head of 17.3 feet at a normal speed of 187 r.p.m.* This diagram, however, cannot be used to

* C. W. Larner, Trans. Am. Soc. of C.E., Vol. lxvi., 1910.

determine the behaviour of the runner under other conditions, and a diagram of the "general characteristics" of the turbine must be drawn as shown in Fig. 3, representing one of the several methods devised for this purpose. In this diagram all the values

FIG. 3.—Characteristic Curves for Francis Turbines at Various Gate Openings.



obtained from the tests have been reduced to the values corresponding to the unit head of 1 foot with the unit speed as abscissæ and the power as ordinates, the efficiency being plotted as continuous parabolic curves.

The method of drawing these curves is as follows: The speed-power curves under the unit head and at the various gate openings

are first drawn, as shown in dotted lines on the diagram. From the speed-efficiency curves we find the speeds at which, with the different gate-openings, the same efficiencies are obtained and mark these speeds on the corresponding speed-power curves and draw a continuous curve through the points so obtained. This process is repeated to cover the full range of efficiencies obtained from the test, and the diagram is completed.

The use of the diagram is just as interesting as it is simple. Assume that the turbine as represented by this diagram is selected to work under a head of 25 feet, the power developed at full gate would then be:—

$$P = 1.73 \times 25 \times \sqrt{25} = 216.25 \text{ b.h.p.}$$

and the normal speed:—

$$N = 45 \times \sqrt{25} = 225 \text{ r.p.m.}$$

and the efficiencies the same as those shown in the diagram for the normal unit speed of 45 r.p.m.

Assuming, however, that it is required for some reason that the turbine should run at a speed of 250 r.p.m. instead of 225, the corresponding unit speed would be:—

$$250 \div \sqrt{25} = 50 \text{ r.p.m.}$$

The efficiency corresponding to this new condition of speed can be directly read off from the diagram, which shows that the increase of speed to 250 r.p.m. for this particular turbine would entail a considerable loss of efficiency, the values being:—

					per cent.
1.00 gate	..	..	..	..	82.5
0.883 „	..	..	..	..	87
0.750 „	..	..	..	..	85
0.667 „	..	..	..	..	81.5
0.500 „	..	..	..	..	74

At normal speed the efficiency would have been:—

					per cent.
1.00 gate	..	..	..	..	84
0.883 „	..	..	..	..	88
0.750 „	..	..	..	..	90
0.667 „	..	..	..	..	87.5
0.500 „	..	..	..	..	82

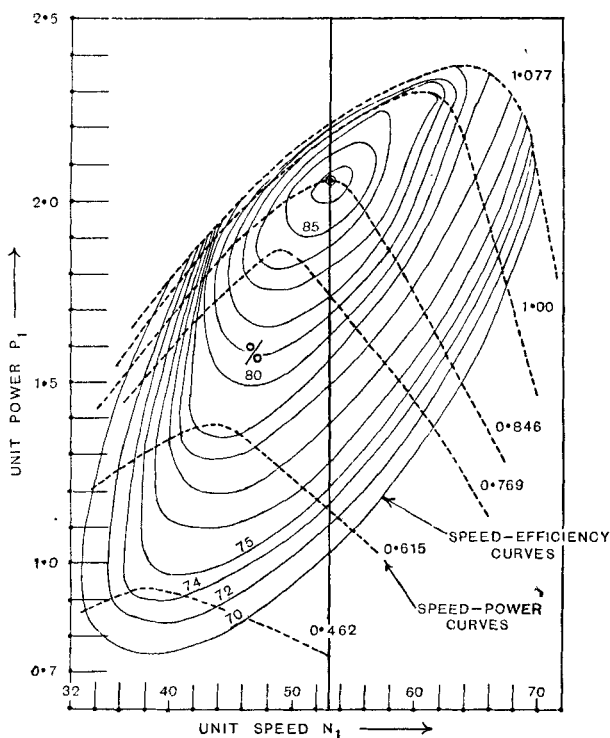
On the other hand, assume that the speed of 225 r.p.m. is kept constant by means of a governor, and that the head is increased to say 36 feet, the unit speed would then be:—

$$225 \div \sqrt{36} = 37.5 \text{ r.p.m.}$$

FIG. 4.—Characteristic Curves for Francis Turbine at Various Gate Openings.

Normal $N_1 = 53 \text{ r.m.p.}$

„ $N_s = 78.5.$



and from the diagram we find that the unit power at full gate is 1.7, corresponding to an output of $1.7 \times 36 \times \sqrt{36} = 367.2 \text{ b.h.p.}$ This particular turbine, represented by the characteristic diagram referred to, would be known by its normal unit speed $N_1 = 45$ and

unit power at full gate $P_1 = 1.73$, corresponding to the specific speed $N_s = 45 \times 1.73 = 59$ (260).

By way of comparison a similar diagram of another type of runner is given in Fig. 4 (page 72).

The selection of the proper type of runner and the determining of the most suitable speed of a plant requires a great deal of consideration and cannot possibly be adequately analysed within these brief pages, but the foregoing résumé of the evolution of the Francis turbine, together with the fundamental principles and essential facts relating to various designs of runners, enables us to appreciate fully the extent and importance of recent advances in the design of "high-capacity" runners and the value of their application in connexion with low head power developments.

Reference has already been made to the effect that early attention was paid to increasing the unit speed of runners, the value of which became more apparent with the introduction of direct turbine-driven generators. Considerable study, both theoretical and experimental, has been devoted to this subject, and all attempts at improvements in design of runners during recent years have been in the direction of increasing the maximum value of the specific speed so as to secure a larger output under a given head and speed, or conversely to obtain the highest possible speed for a given head and capacity.

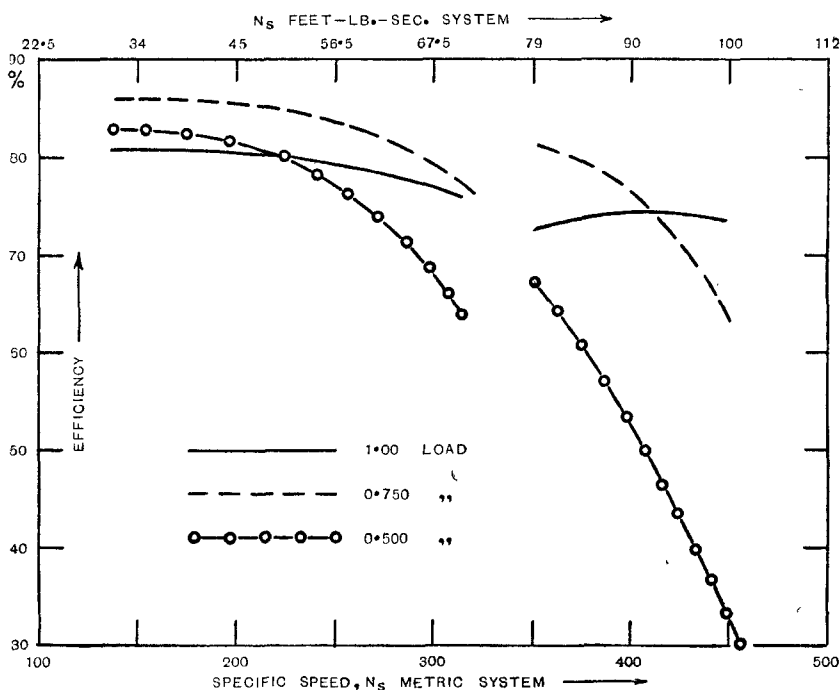
Only nine years ago these conditions could only be obtained at the expense of efficiency which was particularly marked with fractional gate-openings, and a strong current of adverse opinion existed against any attempt to increase the specific speed on account of the unsatisfactory characteristics of this type of turbine which would militate against its commercial utility.

The maximum value of the specific speed obtained at that time was approximately 75 (330 metric system), and Fig. 5 (page 74) represents the maximum efficiencies obtained with runners of various values of specific speed and fairly represents the position at that date.*

* W. Wagenbach: Zeits. für das Gesamte Turbinenwesen, May 1909.

Since this time, however, great strides have been made in the development of the high-capacity runner, made possible by the

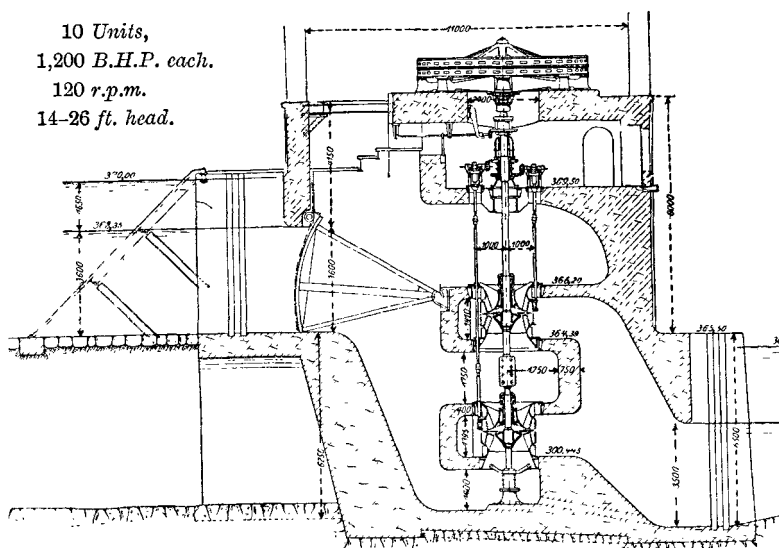
FIG. 5.—Diagram of Efficiencies obtained from Francis Turbines at Various Specific Speeds, 1909.



application of the advanced knowledge of the conditions as the result of systematic tests and theoretical investigations. In this respect much credit is due to American engineers, by whom a number of notable installations have recently been carried out, employing turbines with a specific speed of approximately 95 with most gratifying results as regards efficiency. It is now possible to obtain runners of a specific speed of even 100 together with even higher maximum efficiencies than secured previously with a specific speed of very much lower value and with only comparatively small sacrifice in efficiency at part gate.

The development of the high-capacity runner has had a far-reaching effect on the economical arrangement of units for low-head plants, in addition to obviating many inherent disadvantages in the arrangement of two or more runners on a common shaft, a practice which was adopted to secure a high speed in order to effect a reduction in the initial cost of directly driven generators. To cite an instance to demonstrate this point more vividly,

FIG. 6.—Cross-Section of Power House at Chevres, Geneva.

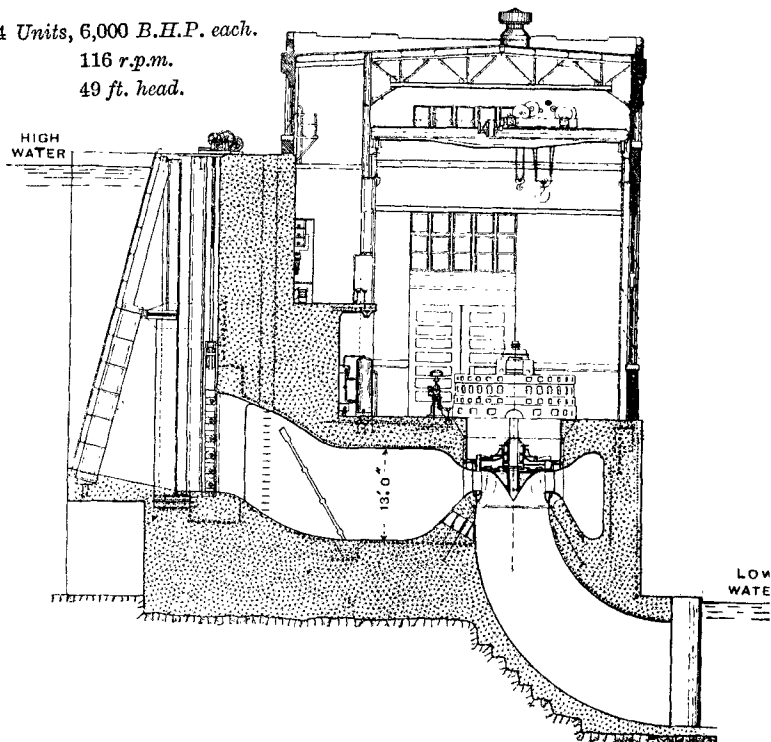


reference is made to Fig. 6, showing the power station at Chevres near Geneva. This plant, erected during 1890-1898, consists of 15 Jonval turbines of the multiple-runner type, each unit having an output of 1,200 h.p. under a maximum head of 26.5 feet and a speed of 120 r.p.m., although the five units first installed had a speed of only 80 r.p.m. If this plant were built to-day and equipped with high-capacity Francis turbines, a *single* runner turbine at 120 r.p.m. would give an output per unit of 2,500 h.p., or conversely with an output of 1,200 b.h.p. the maximum speed

would be approximately 175 r.p.m. With each unit consisting of a double Francis turbine, a maximum output of 5,000 b.h.p. would be secured at a speed of 120 r.p.m., or with the original output of 1,000 b.h.p. a speed of 290 r.p.m. would be obtained.

FIG. 7.—Cross-Section of Power House, Appalachian Power Co.,
New River, U.S.A.

4 Units, 6,000 B.H.P. each.
116 r.p.m.
49 ft. head.



This example indicates sufficiently the great value of this latest development in the enormous saving effected in the total cost of the plant, not only on account of a lesser number of units being necessary, but also due to the reduced size of the buildings and foundations. A striking contrast is offered by Fig. 7, showing a section through the power-house of a modern vertically

arranged turbine plant, which cannot fail to illustrate the compactness in design and less foundation work as compared with the previous plant.

Although European engineers have been far more conservative in the adoption of runners with high specific speed, the maximum being 80 (350) as installed at present, test runners have been constructed up to a specific speed of 160 (750) with fairly good results.*

FIG. 8.
New Type of Turbine.

(Escher Wyss.)

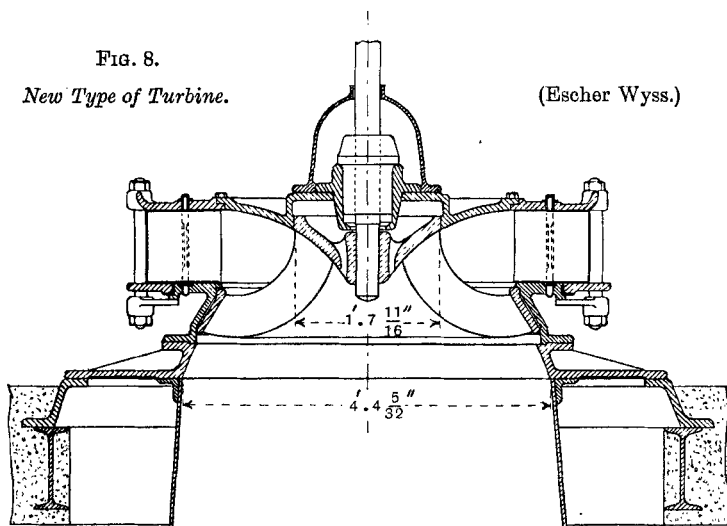


Fig. 8 shows a design of runner recently constructed by Escher Wyss and Co., which under official efficiency tests gave exceptionally good results at varying speeds corresponding to a specific speed of from 85 to 112 (375-500). The arrangement of this new type of turbine is seen from the Fig., the main feature being the large space between the guide-vanes and the entrance edge of the runner. Hitherto the fundamental idea in all designs of turbines has been to allow a minimum of space between the guide-vanes and

* H. Th. Holm, "Moderna Vattenturbiner," Teknisk Tidskrift, Stockholm, July 1914.

TABLE 4.

No.	Plant.	Year.	Maker.	Head in ft.	Normal Output.
1	Svalgfos Hydro-Electric Station, Natodden, Nor- way}	1908	J. M. Voith	150	11,750
2	Reinfelden Hydro-Electric Plant, Switzerland . . }	1908	{ Escher, Wyss and Co. }	15	1,200
3	Hamilton Cataract Co., Ltd., Canada }	1909	J. M. Voith	261	7,000
4	Trollhättan Hydro-Elec- tric Plant, Sweden . . }	1910	{ Nydqvist and Holm }	100	12,500
5	Kanderwerk Hydro-Elec- tric Plant, Switzerland. }	1908	{ Escher, Wyss and Co. }	205	3,200
6	Chippis Hydro-Electric Plant, Rhone, Switzer- land}	1911	{ Piccard, Pictet and Cie }	248	6,500
7	Appalachian Power Co., U.S.A.}	1913	J. P. Morris	49	6,000
8	Pennsylvania Water Power Company. . . }	1914	J. P. Morris	63	16,500
9	Porjus Hydro-Electric Plant, Sweden . . . }	1915	{ Nydqvist and Holm }	162	14,000
10	Massaboden H. E. Plant, Switzerland }	1915	{ Piccard, Pictet and Cie }	142	3,500
11	Great Northern Paper Co., Millinocket, U.S.A.. }	1917	J. P. Morris	108	5,250
12	Forsse Hydro-Electric Plant, Sweden . . . }	1918	Verkstaden	57	3,750

TABLE 4.

Speed in R.P.M.	Specific Speed per runner.		Maximum Efficiency.	Type.	Quantity of water measured by
	foot-lb.	metric.	per cent.		
250	36	160	86.16	{Double enclosed horizontal . . }	Floating vane.
68	40	177	87	{Quadruple open vertical . . }	
286	16	71	86.8	{Double spiral horizontal . . }	
187.5	46.5	206	87	{Double enclosed horizontal . . }	Floating vane.
400	27.5	122	87.4	{Single spiral horizontal . . }	
333	19	85	90	{Double spiral horizontal . . }	
116	69.5	308	93.7	{Single open verti- cal }	Weir.
94	70	312	93	{Single open verti- cal }	Titration method.
250	36	159	92	{Double enclosed horizontal . . }	Current meter.
500	42.6	189	90	{Double spiral horizontal . . }	{Current meter and titration.
240	56	249	92	{Double spiral horizontal . . }	Current meter.
250	80	352	94	{Double enclosed horizontal . . }	

runner, and this new departure in design suggests the possibility of reverting to the axial Jonval type of runner, but retaining the convenient form of wicket-gate for regulation purposes. It is anticipated that further progress will soon be recorded on these lines, but at present no further data are available.

Concomitantly with the development of high-capacity runners is the remarkable increase in the overall efficiencies obtained from plants under working conditions. The increases in the average overall efficiencies have naturally followed in the train of the more careful and correct runner design already referred to, but they are also due to the improvements in the design of casings, guide-apparatus, suction-casings and suction-tubes, based on a better understanding of the conditions of flow in various parts of the turbine, thus eliminating as far as possible impact losses and formation of eddies in the water during its passage through the turbine.

The most notable achievements in maximum efficiencies obtained during recent years are recorded in Table 4 (pages 78-79), and it is to be noted that these figures represent results of test in place under working conditions in the presence of impartial experts, and consequently they can be regarded as highly authentic.

Another significant fact to be recorded is the long range of gate-openings for which an efficiency of over 80 per cent is obtained and which can be seen from the various test-curves, Figs. 9-10 (pages 81-82). In this connexion it is interesting to recall that only a few years ago Professor Dr. Prazil,* in the course of a Paper on Turbine Efficiencies delivered before this Institution, predicted that much further advance in the future could not be expected in regard to efficiencies. The average efficiency of the tests then published was 85 per cent, which value has been greatly exceeded, and a general increase of 10 per cent above efficiencies obtained about 12 years ago can now be recorded. These high values of efficiency fully entitle the water-turbine, when

* Dr. F. Prazil, "Results of Experiments with Francis Turbines," Proc. I.Mech. Eng., 1911.

FIG. 9.—Turbine Efficiency Curves (See Table 4).

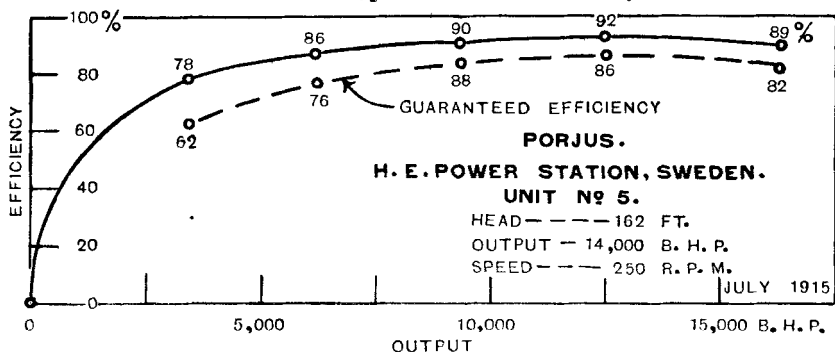
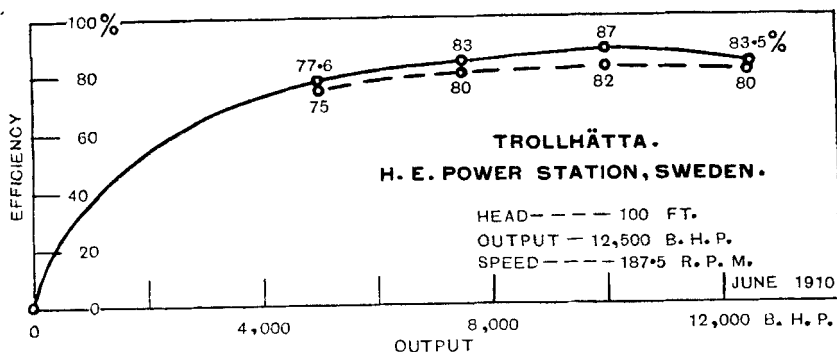
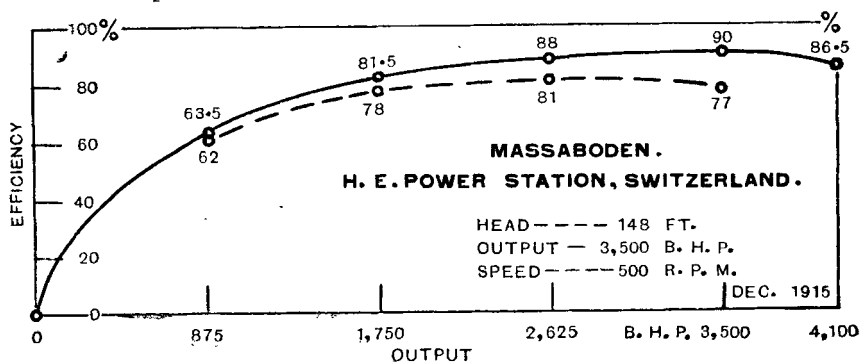
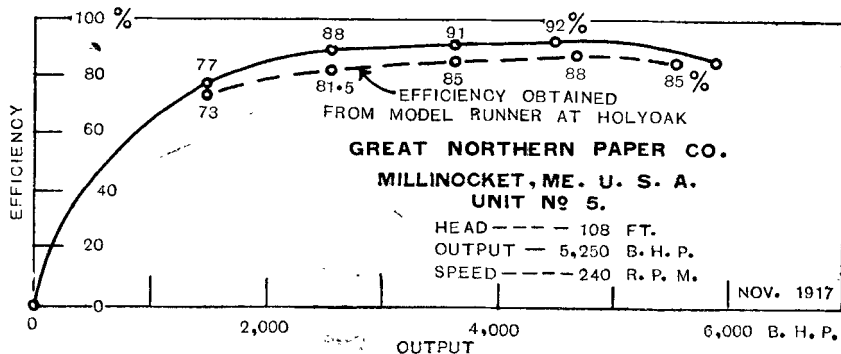
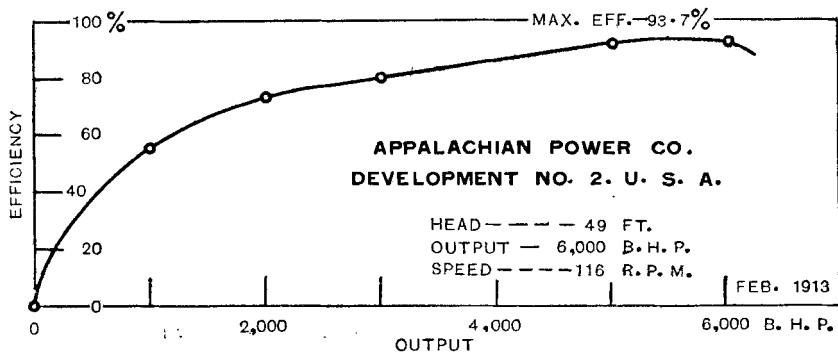
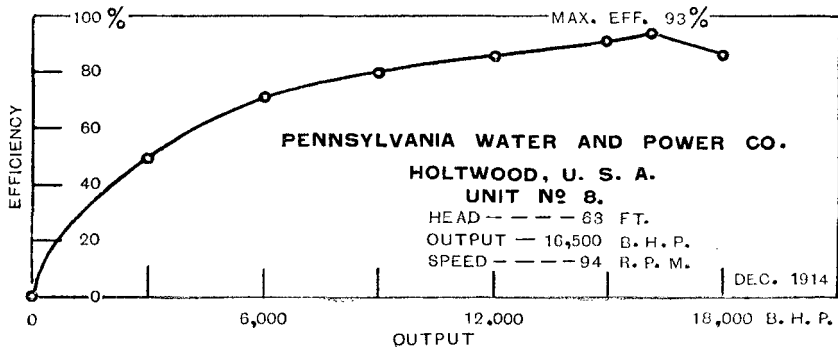
Double Horizontal enclosed. N_s per runner = 36. Tested by Current meter.Double Horizontal enclosed. N_s per runner = 46.5. Tested by Floating vane.Double Spiral Horizontal. N_s per runner = 42.6. Tested by Current meter.

FIG. 10.—Turbine Efficiency Curves (See Table 4).

Double Horizontal Spiral. $N_s = 56$. Tested by Current meter.Single Vertical volute casing in concrete. $N_s = 69.5$. Tested by weir.Single Vertical volute casing in concrete. $N_s = 70$. Titration Method.

properly designed, to be ranked as the most efficient prime mover existent.

While on the subject of efficiency tests of plants, it may be of interest to record the increase in the use of the chemical or titration method for measuring the quantity of water. This method is now considered as giving very accurate readings, and from check tests made with current meter the discrepancy in readings averages only 1 per cent. to 1.3 per cent.* This method of testing is principally used for large low-fall installations where generally other known methods of measuring large quantities of water are either inconvenient or impracticable.

The efficiency, in itself a valuable asset, is, however, not the all-important feature of modern turbine developments; the improvement in mechanical details and construction and simplicity in design, together with higher standard of workmanship, are all important factors which have contributed to the advances in the utilization of water-power, by ensuring freedom from breakdowns, continuity of operation, simplicity in working and accessibility to effect repairs, all of which are of vital importance in connexion with any power development.

Space does not permit, within the limits of this Paper, to consider in detail all the important improvements in this respect, but in the following pages will be given a brief description of some prominent modern hydro-electric power plants, embodying various types of turbines and modes of installation which will serve the purpose of illustrating the advances in construction and general lay-out of hydro-electric power plants.

There is, however, one important detail of construction, namely, the guide-apparatus regulating the quantity of water to be admitted to the turbine, which calls for some preliminary remarks. In the past, three distinct types of construction have been employed, Fig. 11 (page 84), namely:—

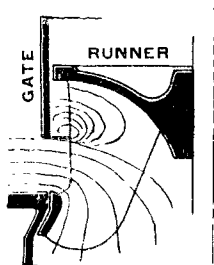
- A. The Cylinder-gate.
- B. The Register-gate.
- C. The Wicket-gate.

* A. Streiff, *Engineering Record*, Sept. 1914, page 276.

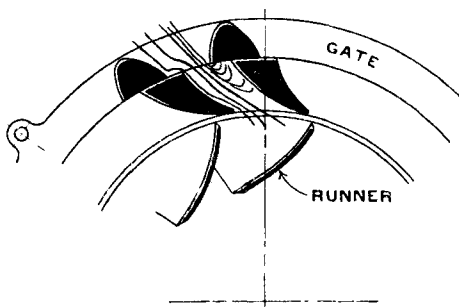
Although both the cylinder-gate and register-gate undoubtedly possessed certain points of merit, they have now been superseded by the modern wicket-gate, on account of the improved efficiency

FIG. 11.—Three Types of Guide-Apparatus for Regulating the Quantity of Water to be admitted to the Turbine.

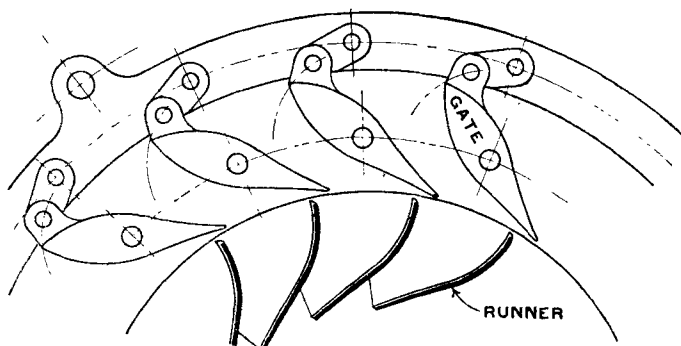
A. Cylinder-Gate.



B. Register-Gate.



C. Wicket-Gate.



obtained by reduced obstruction to the approach of the water to the runner and by eliminating impact losses and formation of eddies, which, particularly at small gate-openings, were a marked disadvantage inherent to the two first mentioned designs. Modern Francis turbines are now, without exception, equipped with wicket-gate regulation, consisting of a number of fin-shaped vanes each pivoted on a gate-spindle and obtaining its movement

from the regulating ring to which each gate is connected by means of a short link.

From the point of view of application to different heights of fall, the Francis turbine is generally classified as follows :—

- (1) Low-pressure turbines up to 75 feet fall.
- (2) Medium-pressure turbines 75 feet to 150 feet fall.
- (3) High-pressure turbines from 150 feet to 550 feet fall.

The low-pressure turbine is installed in open flume, the medium in circular casing, and the high-pressure in spiral casing, although a distinct line cannot be drawn as various local conditions have to be taken into consideration in each case.

Low-pressure Francis Turbines.—This type of turbine is generally placed in open flume, to which the water is conducted through an intake channel, the plant being arranged with vertical or horizontal shaft. The latter arrangement has, where local conditions permitted, been adopted in most low-pressure hydro-electric plants in Europe, being arranged with two or more turbines on a common shaft to secure a high speed.

In America, on the other hand, the vertical arrangement has been exclusively adopted in connexion with modern low-pressure installations, primarily due to the topographical conditions of the rivers from which the power is utilized, inasmuch as the fall of the river is very often distributed along large distances, and dams have to be built to concentrate the fall, which construction lends itself particularly well to the arrangement of vertical shaft units.

It is in this connexion that the most notable developments in hydro-electric power plants have taken place in recent years and which have been stimulated by the development of the "high capacity" runner as already referred to. This latter construction has permitted the adoption of the single vertical turbine, which possesses many economic advantages over the arrangement of the multiple runner, either on vertical or horizontal shaft, and has facilitated the promotion of the large-power low-head hydro-electric undertakings which during the last six years have shown such a remarkable development in the United States of America.

A. *Vertical low-pressure Francis Turbines.*—A typical example of this arrangement is the plant of the Mississippi River Power Co., situated at Keokuk, Iowa, and partly completed in 1913, which apart from its hydraulic features is of unusual interest as being, when completed, the largest power station in the world, with an output of over 300,000 h.p. under one roof. This power plant is situated on the Mississippi River at the foot of the Des Moines Rapids, the fall of the river being 23 feet in the 12 miles above the Rapids, and a total fall of 32 feet has been obtained by the construction of a dam across the river between Keokuk and Hamilton. The power-house forms part of the dam structure, and is built with its entire length parallel with the river, the area between the power-house and the main bank forming the fore-bay. The power-house is constructed entirely in concrete, and its imposing size can be judged from the fact that the total length is 1718 feet by 132 feet 10 inches wide and 177 feet 6 inches high from the lowest point in the tail-race to the highest point of the roof. Accommodation has been provided for 30 vertical single-runner Francis turbines directly connected to vertical generators of which 15 units are now installed and in operation. The turbines are designed for a normal output of 10,000 h.p. under a net head of 32 feet and a speed of 57.5 r.p.m., although each unit is capable of overload up to 14,000 h.p. under a head of 39 feet.

From a hydraulic point of view this installation is of particular interest, as it embodies all the modern practice which has been derived from years of careful study and investigation. This particularly refers to the construction of the intake-chamber and suction-tubes, which have been designed to reduce to a minimum the losses due to impact and formation of eddies. For this purpose the turbine is set in volute casing cast in the concrete which imparts to the water the same entrance velocity at all points round the turbine and removes the possibility of formation of eddies in the intake-chamber, thus ensuring the highest possible efficiency of the turbine. All the sections of the intake and casing have been designed to avoid any sudden changes in velocity and to ensure a gradual and uniform transition in the velocity of the water, which

is of most vital importance to enable a high overall efficiency of the plant to be realized.

What has just been said with regard to the importance of observing hydraulic principles in the construction of the intake and setting of the turbine, applies perhaps in a greater degree to the design of the suction or draught tubes. As in the case of the Mississippi plant, recent practice is, as far as conditions permit, to mould the suction-tube direct in concrete and discharge the water at the bottom end parallel to the flow of the tail-race in preference to using steel tubes, as was formerly the practice.

The suction or draft tube was considered one of the great features of the Francis turbine, permitting the erection of the plant at a convenient height above tail-water level without loss of head. In addition, however, it also performs, if properly designed, the very important function of partly recovering the energy corresponding to the velocity of the water when leaving the runner; hence it becomes necessary to pay particular attention to this part of the construction.

This hydraulic function of the suction-tube may be of less importance in connexion with slow-speed runners operating under a high head, as the discharge velocity from the runner does not exceed a figure corresponding to approximately 5 per cent of the total head, and in most cases less, but in connexion with high-capacity runners the suction-tube becomes one of the most vital parts of the turbine, and, in fact, without this the high-capacity runners would be impracticable owing to the loss of efficiency entailed in not converting the velocity energy of the water when discharging from the runner into useful work. This will be appreciated when it is remembered that the discharge velocity of the water in high-capacity runners may often represent as much as 15 per cent to 20 per cent, and even more, of the total head, which energy without properly designed suction-tubes could not be recovered to the fullest possible extent.

The overall efficiency of modern turbine plants employing high-capacity runners is therefore in a great measure dependent on properly designed suction-tubes, ensuring that the velocity of the

water immediately after its discharge from the runner is gradually and uniformly reduced to the minimum velocity when discharging into the tail-race and thereby increasing the total utilized head. This fact has in many cases not been sufficiently appreciated, with the result that the plant has been working with a permanent loss of efficiency, which could have been avoided if due consideration had been given to this important section of the plant. In this respect the vertically arranged unit has an advantage over the horizontal construction, as in the absence of suction casing or bends a higher overall efficiency is obtained.

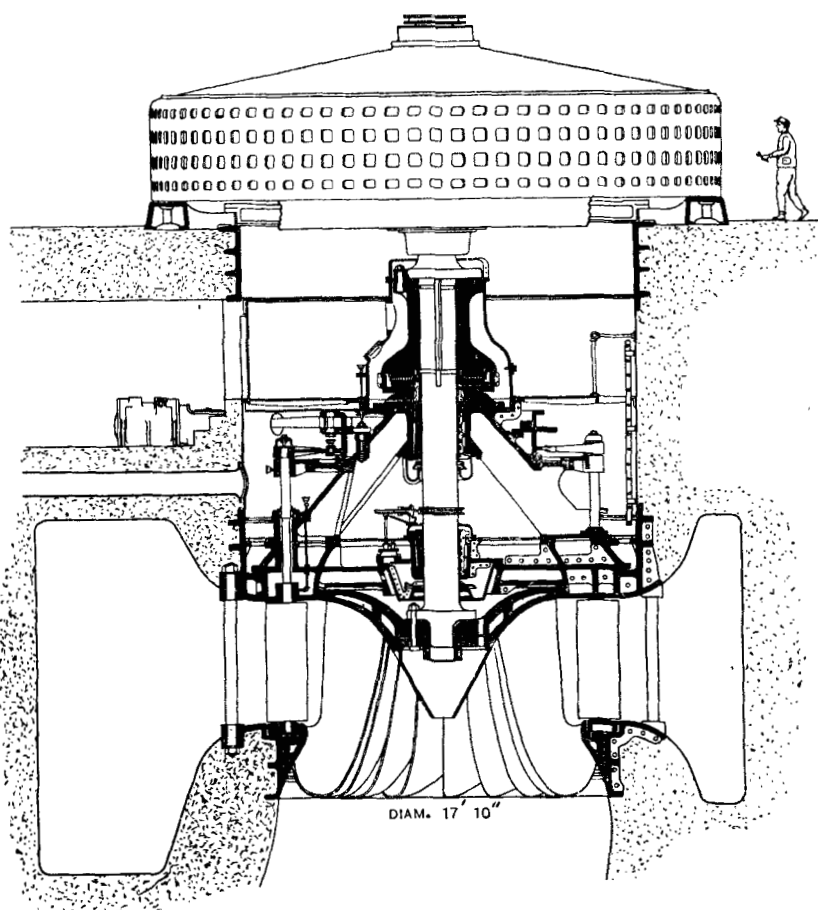
In Fig. 12 (page 89) is seen the mechanical arrangement of the turbine at the Mississippi River Plant. The turbine is placed just below the floor level of the power-house at the bottom of a short shaft lined with a steel casing. One upper and lower heavy foundation-ring is embedded in the concrete conforming to the inner circumference of the volute-casing, and rigidly connected by means of strong stay-bolts which transmit the total weight of the unit to the foundations of the power-house. The runner is of most formidable dimensions, being the largest size runner in the world, with a diameter at the discharge of 17 feet 4 inches and a total weight of 80 tons.

The spindle of each guide-vane passes through a separate stuffing-box and connects with the common regulating ring by means of a lever which in its turn obtains its movement from the servo-motor of the automatic oil-pressure governor. This system of regulation is now the practice adopted in all large vertical units. As all the regulating connexions are above water, it permits inspection when running, access being gained from the power-house floor through a separate inspection shaft.

This plant also illustrates a new departure in the design of guide-bearings just above the runner. Previous practice was to use a *lignum vitæ* under-water bearing, consisting of three blocks fitted in a cast-iron shoe with adjusting screws for taking up the wear. This design of guide-bearing is unsatisfactory in connexion with large units on account of the small bearing-surface and the frequent adjustments necessary. The guide-bearing now adopted consists of

a large number of lignum vitæ strips dovetailed into the bearing-boxes, evenly spaced round the whole circumference of the shaft, the

FIG. 12.—Turbine at the Mississippi River Plant.



small space between each strip allowing the water to circulate round the bearing. It is also an advantage to use this type as an outside guide-bearing when the turbine is not submerged, in preference to babbitt-lined bearings, as the bearing can be placed close up to the

runner and pressure water used as lubricant ; thus the necessity of providing circulating pumps for oil is dispensed with.

The most important mechanical detail in connexion with vertically arranged turbines is the thrust-bearing, on the construction of which perhaps the whole plant depends for satisfactory and continuous operation. It must be admitted that a strong prejudice existed in the minds of many engineers against thrust-bearings, which in many instances militated against the adoption of the vertical arrangement for large units ; and the question of the most reliable type of bearing for such plants, when the load to be supported may exceed 250 tons as in the case of the Mississippi plant, naturally compelled most careful thought and consideration. In America, at any rate, the present practice is to use one thrust-bearing only which, in addition to the weight of and water-pressure on the runner, has to carry the weight of the rotor of the generator, whereas European engineers up to the present have preferred to have a separate bearing for the generator.

The types of bearing which have been used for this purpose are : (1) Oil-pressure thrust-bearing ; (2) Ball- or roller-bearing ; (3) "Kingsbury" bearing.

The oil-pressure thrust-bearing consists of one stationary and one rotating disk between which oil is pumped under pressure. For small loads, oil under pressure is not necessary and the two disks revolve in an oil-bath, although for large plants the load is generally too excessive to permit the use of this latter type of bearing.

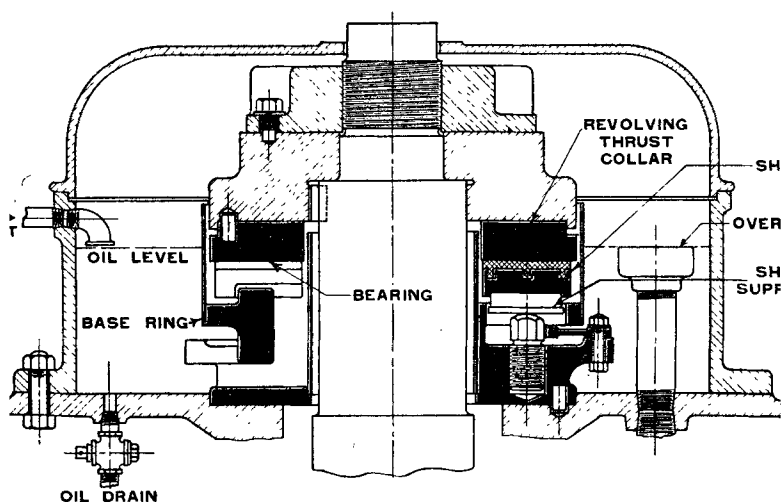
The introduction of ball- and roller-bearings, which are now employed in every possible sphere of engineering, signified a further advance in the construction of thrust-bearings. Ball- or roller-bearings, or both combined, have been used as thrust-bearings in connexion with vertical turbines with unqualified success, and have now more or less substituted the oil-pressure bearing with its intricate system of pumps and pipe-connexions, and thus removed the danger attached to any breakdown of the oil-pressure supply, to which this type of bearing was liable.

The most recent type of thrust-bearing is the "Kingsbury,"

which now severely contests the place of the roller-bearings, and has been adopted in America in connexion with most recent vertical turbine plants. The invention is based on the theory of the wedge-shaped oil film to support the load as put forward by Professor Osborne Reynolds in his standard work on "Theory of Lubrication."*

The construction of such a bearing is seen from Fig. 13, and consists as in the case of the oil-pressure bearing, of one stationary and one revolving disk, the former however being composed of

FIG. 13.—*Kingsbury Thrust-Bearing. Designed for 180,000 lb. thrust load at 100 r.p.m. Outside Diam. of Thrust Collar 31 inches.*



several segments, each of which is mounted on a pivot to permit the slight angular displacement relatively to the rotating disk necessary to allow the film of oil to assume the wedge form. The outstanding feature of the Kingsbury bearing is the very low frictional loss as compared with any other type of thrust-bearing. From tests made with these bearings in connexion with a 10,000 h.p.

* Phil. Trans. 1886.

vertical turbine at 100 r.p.m., the friction loss amounted to from $7\frac{1}{2}$ to 10 kw., or approximately one-tenth per cent of the total power, which fact serves to explain the very high values of total efficiency obtained with modern vertical turbine plants. Not only has the hydraulic efficiency been improved upon, but the mechanical efficiency has, by the adoption of efficient bearings, attained a value closely approaching 100 per cent.

It will be observed that when running there is no metallic contact, the load being supported upon a film of oil and consequently permitting a very much higher specific pressure per square inch of bearing surface than could be allowed in roller-bearings, and hence, with equal load and speed, the Kingsbury bearing would have smaller dimensions than in the case of any other type of bearing. The load to be supported at the Mississippi plant is, as before stated, 255 tons; the diameter of the bearing is 56 inches, with a specific pressure of 350 lb. per square inch. As will be seen from the sectional drawing, the bearing is placed between the turbine and the generator and is accessible from a platform in the inspection shaft. The shaft has a diameter of 25 inches in the bearing and is coupled direct to the generator shaft by means of a solid flanged coupling.

The turbines were tested in place, and the efficiency obtained averaged 90 per cent for all units. The generators are of the "umbrella" type with a capacity of 9,000 kva at 0.8 power factor and rated at 11,000 volts, 3-phase current, 25 cycles and, designed on the principle of a revolving field inside a fixed armature. The extreme outside diameter is 31 feet 5 inches, and the diameter of the revolving field 25 feet 5 inches, the guaranteed efficiency at full load being .96.3 per cent. including all losses from friction and windage. The electrical equipment also includes a step-up transformer, increasing the voltage from 11,000 to 110,000 volts for transmission to St. Louis at a distance of 144 miles from the power-house.

From this short description of the Mississippi power plant, one cannot fail to observe that, in spite of the enormous size and capacity of the plant, the arrangement is the acme of compactness

and simplicity and does not possess the objectionable features inherent to the previous practice of multiple runners. The advantage of the single-runner type is at once evident, if reference is again made to the sectional drawing, Fig. 12 (page 89). The outstanding feature is the absence of any submerged bearings, and the thrust-bearing, guide-bearing, regulating gear, and in fact all auxiliary parts of the runner, are above water level and readily accessible for inspection and necessary repairs.* The cost of maintenance is less, and the arrangement with a single suction-tube secures the highest possible efficiency, together with simpler and cheaper construction of the foundations.

In concluding this brief description of the development of large single-runner Francis turbines for low heads, it may again be emphasized that this development represents the most important advances in hydro-electric practice in recent years, and since its successful inauguration in 1912 it has subsequently been adopted in a number of prominent low-head plants, including the following:—

Alabama Power Company, Loch No. 12, Coosa River :
6 units—17,500 b.h.p. each, 100 r.p.m., 68 feet head.

Cedar Rapids Manufacturing Company, St. Lawrence River, .
Canada: 12 units—10,800 b.h.p., 55.6 r.p.m.; 30 feet
head; ultimate installation 18 units.

Laurentide Company Ltd., Grand Mere, Quebec, Canada :
6 units—20,000 b.h.p., 120 r.p.m., 76 feet head ;
ultimate installation 10 units.

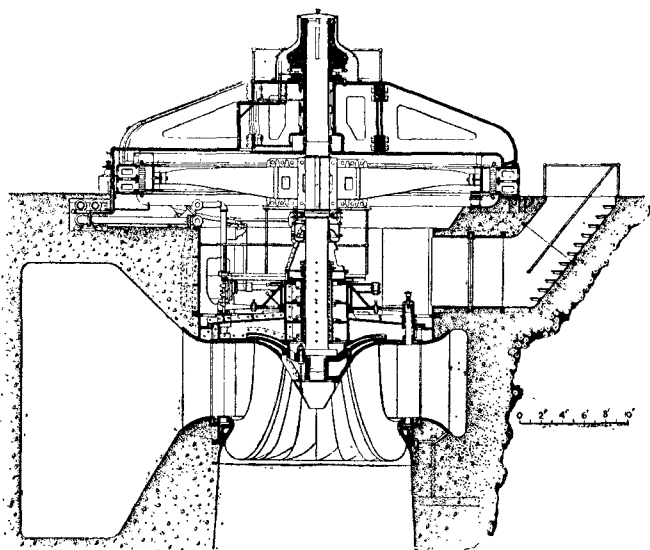
The turbines for the Cedar Rapids are the largest ever contemplated, and show a few interesting improvements over the early Mississippi type. The most notable of these improvements is in the design of the foundation-ring, or the so-called "speed-ring," which instead of being cast in two rings, one upper and one lower, and connected by means of stay-bolts, is now cast with

* H. Birchard Taylor, "Vertical Shaft Single-Runner Turbines as Applied to Low Heads"—*General Electric Review*, June, 1913.

vanes connecting the two rings and given fin-shaped section, which offers less hydraulic resistance and from a mechanical point of view is preferable as being a solid connexion between two rings Fig. 14.

Another point which is worth mentioning, and also seen from the sectional drawing referred to, is the practice of arranging

FIG. 14.—One of the Ten main units of the Cedar Rapids Mfg. and Power Co., Canada.



combined thrust-bearing on the top of the generator instead of below floor level, the advantage being greater accessibility. The Kingsbury bearing has been employed throughout this plant, but a novel feature has been introduced, the bearing being combined with a roller-bearing of reduced dimensions. Normally the roller bearing is not in action, being set with a slight clearance, but in case of weeping action of the Kingsbury bearing taking place, it would support the load for a time, and prevent any serious breakdown of the plant.

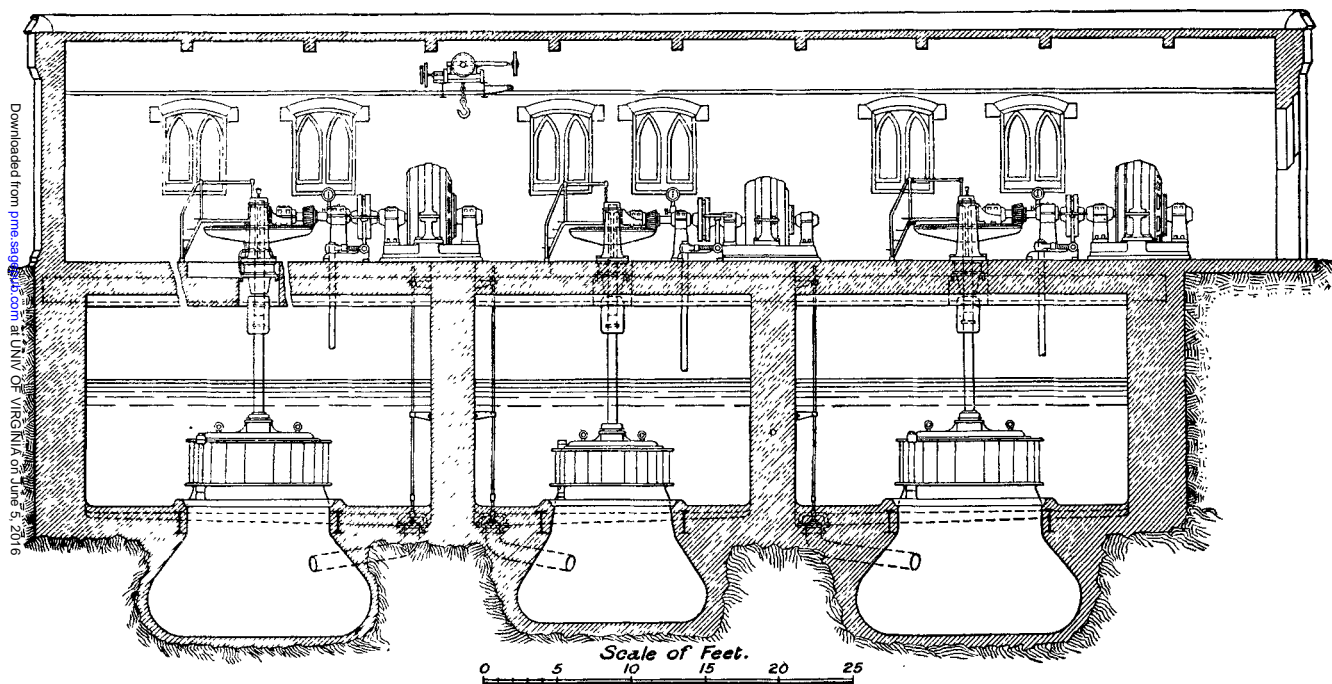
In the adoption of large vertical turbine units has been four

the solution of many undeveloped low-fall hydro-electric schemes, and even larger units than hitherto made have been contemplated, and it is safe to predict that the undoubted economic features of this type of installation will lead to great future progress in the utilization of water-power under low head. Although the vertical arrangement has not been adopted in Europe for such large developments as those described of American construction and operating under heads of from 30 to 70 feet, it has been used extensively for water-power developments under extremely low heads up to about 10 feet or where large fluctuations both in height of fall and quantity of water render this construction necessary, the usual method being to employ two or more runners on the same shaft, of which only one or two are operating under low-fall periods.

The Chester Municipal Hydro-Electric Power Station is a typical extreme low-fall development operating under an average head of 7 feet, although during certain periods of the year the head falls as low as 5 feet and sometimes reaches a maximum of 9 feet. A section and End elevation of the power-house is shown in Figs. 15 and 16 (pages 96-7), the plant comprising two units designed for a quantity of water of 30,000 cubic feet per minute, and one smaller unit to deal with 22,000 cubic feet per minute, all under a maximum head of 9 feet, corresponding to an output of 415 h.p. for the larger and 305 h.p. for the small unit, the speed being 50 and 55 r.p.m. respectively.

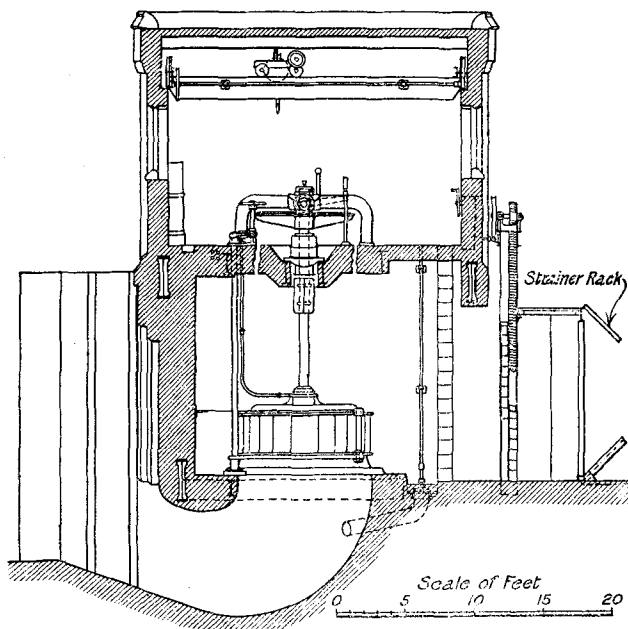
Each turbine is set in a rectangular concrete pit, with concrete-lined suction-tube. The cast-iron regulating ring on the turbine is connected to each guide-vane by means of pins and levers and is operated by hand from the power-house floor, and the submerged guide-bearing on the top of the casing is lined with babbitt-metal and grease-lubricated through pipes from floor level. The vertical shaft is supported by a collar thrust-bearing running in oil bath and combined with guide-bearing to take the side thrust from the helical bevel-wheels, which transmit the power through a flexible coupling to the d.c. generators arranged with horizontal shaft.

The position of the power-house is such that it is affected by tidal

FIG. 15.—*Chester Hydro-Electric Plant.*

water, hence a frequent variation of fall which had to be taken into consideration when designing the turbine plant; and as the load can be kept practically constant, the turbines are not equipped with automatic governors, but are operated entirely by hand and

FIG. 16.—*End Elevation of Large Turbine.*
Chester Hydro-Electric Plant.

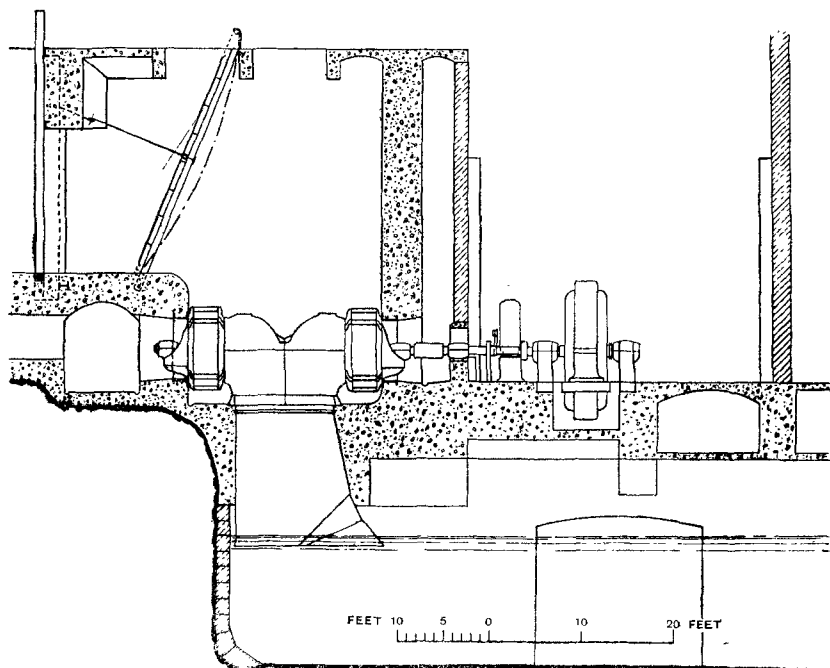


work with full gate-opening as far as permissible, while the speed varies according to the fall available. This arrangement secures the maximum output under the prevailing conditions.

B. Horizontal Low-pressure Turbine Plants.—The Hydro-Electric Power Station at Forshulten, Sweden, represents a typical plant of this arrangement, of which a section is shown in Fig. 17. The units, of which there are six in operation, are arranged with double runners on horizontal shaft with an output of 3000 h.p.,

each running at 187 r.p.m. under a net fall of 42·6 feet and placed in open concrete pits protected by sluice and strainer-racks, the two runners discharging into a common cast-iron suction casing designed with easy curves diverting the water to the suction tube.

FIG. 17.—*Hydro-Electric Power Station at Forshulten, Sweden.*



The shaft is supported at each runner on two outside ring lubricated bearings, in addition to a babbitt-lined automatically grease-lubricated bearing inside the suction-casing. The practice of providing horizontal turbines with lignum vitae under-water bearings has now been discontinued in favour of outside ring oil-lubricated bearings, the bearing on the inlet side being made accessible through an inspection tunnel as in the present case

or through a vertical steel funnel protruding above high-water mark.

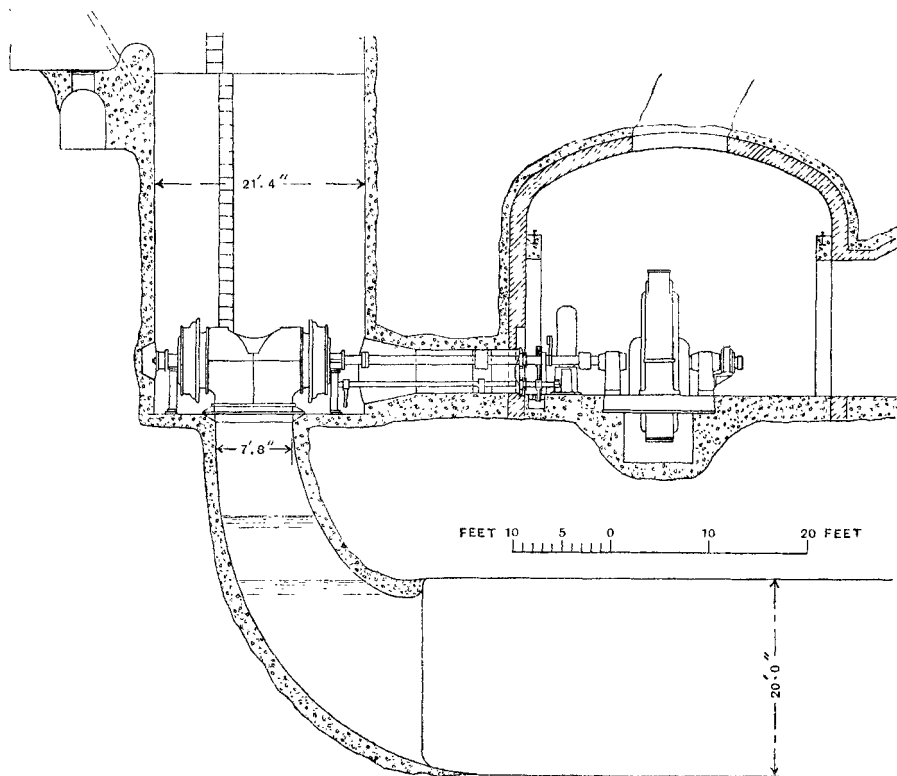
More than usual interest is presented by the arrangement adopted at Mockfjaerden Hydro-Electric Power Station, Sweden, on account of the power-house being situated underground and using open turbines under the relatively high fall of 72 feet. The arrangement of the plant is seen from Fig. 18 (page 100), and comprises four units each having an output of 5,000 b.h.p. at 225 r.p.m. with double runners on horizontal shafts. Each turbine is placed at the bottom of a concrete-lined shaft and discharges into the common tail-race tunnel. The power-house is blasted out of solid rock, the floor level being approximately 70 feet below the surface, whereas the switchboard and transformers are housed in a separate building on ground level and communicate with the power-house below through an inclined shaft. The alternators are directly connected to the turbine-shaft and, due to the underground situation, special arrangements had to be made to ensure sufficient cooling. For this purpose the alternators are totally enclosed and cold air is forced down a separate shaft and distributed through underground ducts to each alternator, the hot air escaping from the top of the housing and expelled through the vertical shaft communicating with the surface.

The foregoing turbine plants will suffice to illustrate the various modes of arrangement of open low-pressure turbines, and no doubt has conveyed that no hard-and-fast rule can be laid down as to the adoption of any particular type, this being entirely dependent on the nature of the available head, the topographical and other local conditions. It is the study of these conditions for each individual case and the adoption of the type of turbine best suited to fulfil these requirements, which has influenced the modern development of water-power installations and contributed to the economical utilization of low falls.

Medium-Pressure Francis Turbines.—The leading features of this type of installation are that the turbines are totally enclosed either in a cylindrical or spiral casing, the former generally adopted

for medium and the latter for high pressure, although the spiral casing, in spite of increased manufacturing cost, is now commonly adopted also for medium pressure plants. As a rule,

FIG. 18.—*Mockfjaerden Hydro-Electric Power Station, Sweden.*

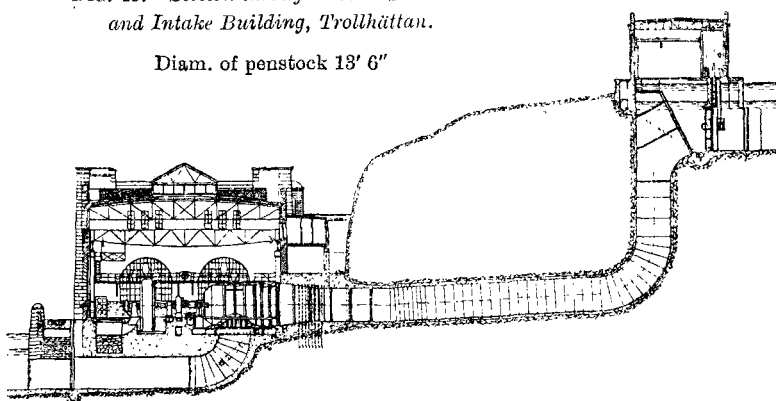


horizontal-shaft turbines are employed, but also in this case American Engineers have lately shown a marked preference for vertical-shaft turbines for medium heads, enclosed in spiral casings.

A typical medium pressure installation with horizontal shaft is the Trollhättan Hydro-Electric Power Station, Sweden, of which Fig. 19 shows a section of the power-house. The fall available is 106 feet, and eight units each having a maximum output of 12,500 h.p. at 187.5 revolutions are installed. Each unit consists of a double Francis turbine enclosed in casing of riveted steel-plate; the water enters the casing axially direct from the penstock and is gradually diverted to all sides of the turbine by the

FIG. 19.—Section through Power-Station
and Intake Building, Trollhättan.

Diam. of penstock 13' 6"



conical end-shield forming part of the inner inspection chamber. The regulating gears for the guide-apparatus are also situated outside, accessible at any time for lubrication and inspection. This feature of turbine design eliminating under-water bearings and regulating gear is of course of great value for large plants in continuous operation for long periods, where interruption of service necessary for inspection of bearings or other parts situated under water cannot be permitted. In addition, the guide-apparatus has in this case been designed in such a manner enabling each separate guide-vane to be renewed without dismantling any other part of the turbine, with a view to reducing to a minimum any interruption of service necessary to affect repairs.

Although the horizontal arrangement of medium-pressure plants

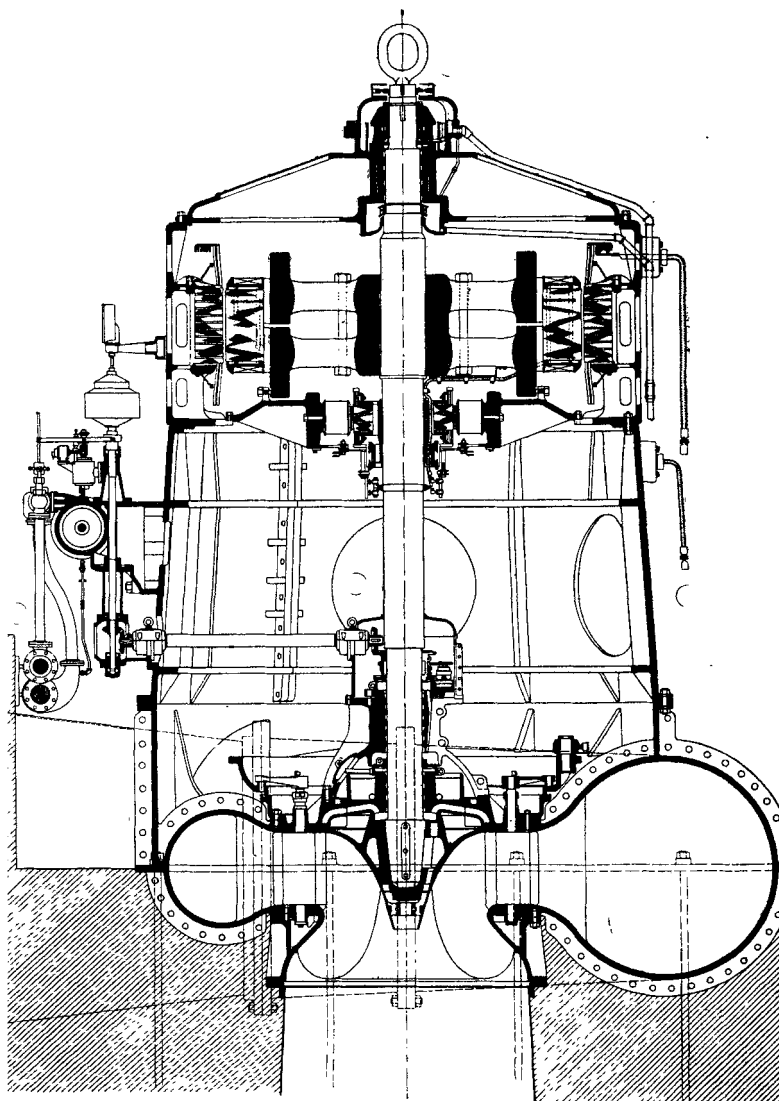
has been adopted in a large number of installations in America, recent designs have, as already stated, again displayed the preference for vertical arrangement entertained in that country and the tendency of using this construction wherever local conditions permit. A typical instance of this construction is shown in Fig. 20 (page 103), representing a section through a unit at the Gatun Lock Hydro-Electric Power-Station, Panama Canal. This station is at present equipped with three units with an output of 3,600 h.p. each when operating under an effective head of 75 feet at a normal speed of 250 r.p.m. The turbines are set vertically in a cast-iron spiral casing connected to the penstock. The runner is cast solid in bronze and designed to eliminate water pressure on the top, so that an upward thrust is exerted relieving the thrust-bearing of one-third of the static load. The generator is placed direct on a cast-iron distance ring 7 feet 6 inches high connected to the spiral casing through which the whole weight of the unit is transmitted to the foundations. The foundation-ring also carries the oil-pressure governor driven from the vertical shaft by means of bevel-wheels. The roller thrust-bearing is placed on the top of the generator, in addition to which there are two automatic oil-lubricated guide-bearings, one immediately below the thrust-bearing and one at the turbine end of the shaft.

Identical design and construction has been adopted for a large number of plants, notably the plant for the Tallassee Power Company, which turbines are designed for the largest output installed up to the present moment, each turbine having an output of 31,000 h.p. with a speed of 154 r.p.m. under a net head of 180 feet and a guaranteed efficiency of 90 per cent.

The Hydro-Electric Power Commission of Ontario contemplates the installing of four vertical single runner turbines at the Chippawa-Queenston plant, having an output of 52,500 h.p. per unit at 187.5 r.p.m. under an effective head of 305 feet.

The vertical arrangement of medium-pressure turbines has been more seldom employed in Europe, having only been adopted where its use has been warranted on account of local conditions in preference to the horizontal construction as, for instance, at the

FIG. 20.—Cross-Section through Waterwheel, Generator, and Exciter, Gatun Lock Installation, Panama Canal.



Seros Power Station of the Barcelona Light and Railway Company, Spain.

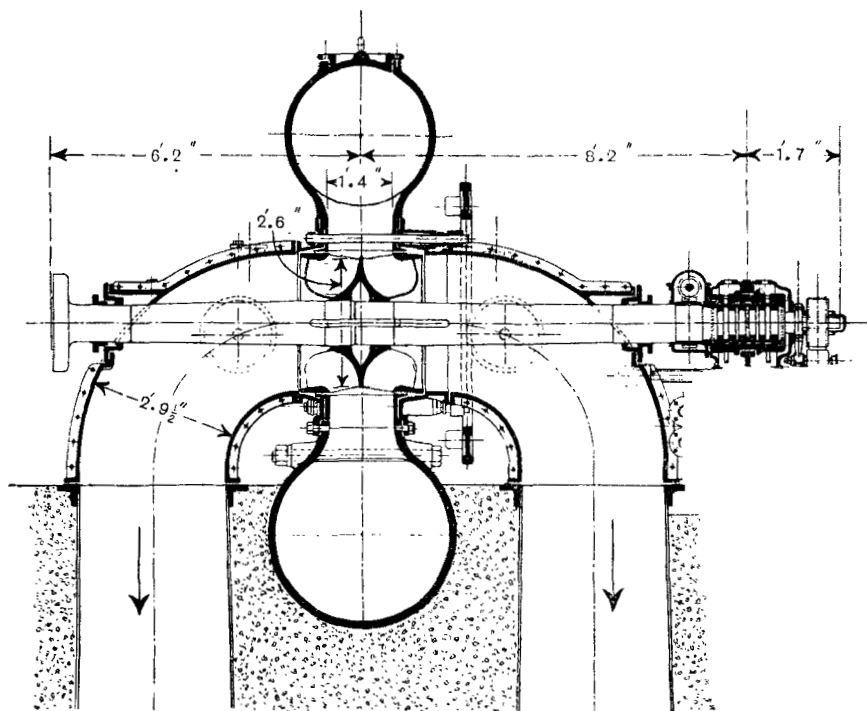
A unique installation of the medium-pressure type turbine is the Porjus Power Station, Sweden. As in the case of the Mockfjaerden Power Station, this plant is also situated underground, but the turbines are enclosed in steel casings and placed at the bottom of the intake-shafts about 160 feet below ground level. The vertical shafts are cut through solid rock and provided with liners of steel pipes with an internal diameter of 11 feet 6 inches and with flanged connexion to the turbine-casing. There are five units with an average capacity of 12,500 h.p. each under a net fall of 163 feet running at 225 r.p.m. The turbines are of the double type with two runners, discharging into the common suction-casing. The power-house is also blasted out of solid rock, and is 36 feet wide and 310 feet long, communicating with the turbine chambers through the short tunnels which accommodate the shaft extension connecting turbines and alternators.

The roof is supported on a strong concrete arch, and by the provision of false walls and roofs leaving a space between the rock and the walls through which warm exhaust air from the generator is allowed to pass, all damp is prevented from penetrating into the power-house. The generators have a normal output of 11,000 kva and 10,000 to 11,000 volts 3-phase current. The necessary switchgear and transformers are also in this case placed in a separate building on ground level, a shaft providing communication between this building and the power-house below, through which the heavy parts of the machinery can be lowered, in addition to which, there is lift accommodation both for passengers and goods. The line voltage is 80,000, the power being utilized for railway traction and for mining purposes.

Finally, as an instructive example of the arrangement of the medium-pressure turbine with horizontal shaft and spiral casing, Fig. 21 (page 105) shows a section through a unit of Massaboden Hydro-Electric plant used in connexion with the Simplon Tunnel in Switzerland. Each unit is capable of developing 3,500 b.h.p.

under a net head of 142 feet at 500 r.p.m. The turbine is equipped with two runners cast back to back in one piece, the outside bearing being arranged with thrust-collars to take up any unbalanced thrust in axial direction.

FIG. 21.—*One of Two Turbines of 3,500 H.P., Massaboden.*



In concluding this brief reference to medium-pressure plants it is a noteworthy fact that, as in the case of low-pressure turbines, recent developments, at any rate in America, seem to favour the single runner units, on account of the higher mechanical overall efficiency obtained and less foundation work coupled with lower initial cost, although each individual case has to be decided on its own merits and considered in conjunction with other factors

depending on local conditions. It is, however, interesting to quote as an instance that the Stave Falls Hydro-Electric Plant, owned by the Western Canadian Power Company, in 1909 installed four horizontal double turbines, each of 13,000 h.p. under a net fall of 110 feet enclosed in casing, similarly arranged as the Trollhättan plant just described. The General Manager of the Company in a Paper read before the Canadian Society of Civil Engineers in October 1915, stated that had this plant been designed three or four years later, the vertical type of single runner would without doubt have been adopted, not only on account of its higher efficiency but because it would have made possible a considerable saving in the cost of the power-house.

High-Pressure Francis Turbines.—Much attention has of late been focussed on the development of low and medium Francis turbines, but nevertheless the high-pressure Francis turbine has shared in the remarkable and rapid development and improvement in design of the hydraulic turbine. The most notable feature of the progress in the case of the high-pressure turbine is its adoption for a very much higher head than ever contemplated until a few years ago, and this has considerably increased the field for the employment of the Francis turbine, in fact, under certain conditions, it even rivals the Pelton Wheel which, until recently, was the only accepted type of turbine to be adopted for high heads.

Whereas only ten years ago Francis turbines working under 300 to 400 feet head were indeed considered high-pressure turbines, to-day Francis turbines utilizing a head of from 500 to 600 feet are not uncommon, the highest fall for which a Francis turbine has been designed being approximately 745 feet.* The reason for the development of the Francis turbine for high pressures is again due to the modern tendency of larger capacity per unit coupled with maximum permissible speed to reduce the cost of the electric generators. This fact is easily appreciated if reference is again made to the conditions of the specific speed which is the governing factor for the type of turbine to be employed.

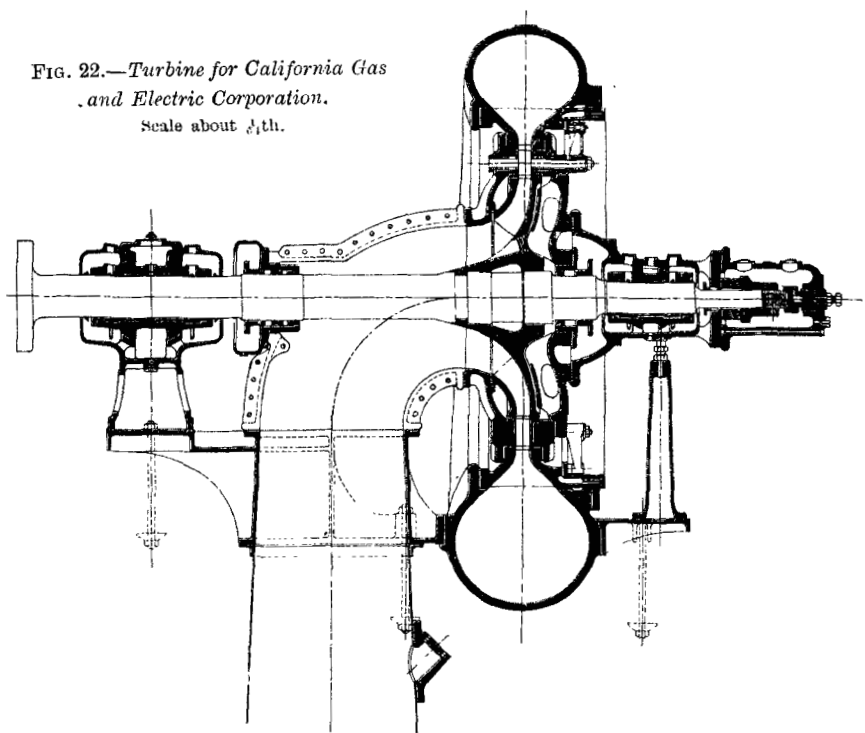
* E. H. da Serra de Estrella, Spain.

As already stated the lowest limit for employment of a Francis turbine with a commercial efficiency corresponds to a specific speed of approximately 11 (49). On the other hand the maximum specific speed for a single-jet Pelton Wheel is approximately 5 (23) which reveals the existence of a "missing link" corresponding to a specific speed of from 5 to 11 (23-49) under which conditions neither a Francis turbine nor a single-jet impulse wheel can be efficiently employed. For a given set of conditions corresponding to a specific speed within these limits, it has been necessary to use Pelton Wheels with two or more jets, or two single-jet Pelton Wheels, one on each end of the generator-shaft. The present tendency, however, of increasing the capacity together with a higher actual speed, would correspondingly increase the specific speed and bring it within the limits of the Francis turbine where previously Pelton Wheels only would be used. This fact, in addition to the introduction of high-speed generators also for large capacities due to the development of the steam-turbine, have equally contributed to this important extension of the field for employing Francis turbines.

As a result, the design of the Francis turbine has been modified and improved to answer the additional requirements of water turbines working under high pressure, and, as already stated, has now been employed under heads h approximately 745 feet. In its early stage, this new departure in the design of Francis turbines was not free from adverse criticism, as it was feared that owing to the high velocities of the water when passing through the runner, excessive wear and erosion would not only reduce the efficiency of the turbine in a short time, but also increase the cost of maintenance as compared with high-pressure impulse-wheels. The improved design, securing proper acceleration of the water through the turbine and eliminating the formation of eddies, together with careful selection of the material for the runners have, however, enabled the high-pressure turbine to answer the requirements fully and successfully to stand the severe test to which it has been subjected, and there exists no reason why this type of turbine, where the conditions permit, should not be employed up to a head of approximately 1,000 feet.

One of the earliest high-pressure plants was the turbine installed by the California Gas and Electric Corporation, of which a section is shown in Fig. 22 and which has been in service since 1907 with most successful results. The plant consists of a single-runner turbine in spiral casing with a capacity of 9,700 h.p. under

FIG. 22.—Turbine for California Gas
and Electric Corporation.
Scale about $\frac{1}{8}$ th.



a net head of 512 feet and a speed of 400 r.p.m., thus corresponding to a specific speed of 14.75 (65.5). Without exception the high-pressure turbine is designed with horizontal shaft for direct connexion to generator and provided with single or double runner enclosed in spiral casing. The guide-vanes are forged solid with a spindle passing through metal-lined packing-boxes, and externally connected to the regulating ring by means of links and levers.

The selection of the most suitable material for the runner to withstand corrosion or pitting due to chemical action, was a factor of great concern in the early development of high-pressure turbines, but recent investigations have established the now generally accepted theory, that the primary cause of pitting is due to faulty design of the runner resulting in the formation of eddies, from which free oxygen is dissociated on account of the high velocity of the water at these points. Corrosion can therefore be entirely eliminated by correct design of the water-passages and the selection of the runner material from this point of view is of less importance. On the other hand the erosive action caused by sand or other foreign matters carried in the water is more difficult to guard against, and where the conditions of the water are such so as to make it liable to produce erosion, the turbine inside the casing is fitted with renewable liners of cast steel, which material, owing to its hard surface skin, probably offers better resistance against erosion than any other material. The runner is also in such cases made of cast-steel, but for smaller diameter runners with narrow inlets phosphor-bronze is used to obtain a cleaner casting. Where sand, however, is carried in any appreciable quantity suitable arrangements are made at the intake so that the sand can settle and not be carried into the turbine. Where the water is comparatively free from grit cast-iron runners are now used to a great extent, even under the highest head, as on account of its smooth surface, as compared with cast steel, it is less susceptible to pitting, and only when the peripheral speed does not permit its use is steel cast resorted to.

For turbines working under high heads, it is at once recognized that the axial thrust must be eliminated by the most reliable method in order to ensure freedom from breakdown and continuous operation. When permissible the double-runner type of turbine is employed as no special thrust-bearing is required, the only precaution necessary is to provide the shaft with a thrust-collar to take up any unbalanced pressure due to unequal wear of the runners. In the case of the single-runner type, the elimination of the axial thrust is one of the most vital considerations of its

design and various methods have been adopted, but in recent practice the aim has been to simplify its design and rely on hydraulic rather than mechanical means for balancing the thrust.

It is evident that the often considerable end-thrust in high-pressure turbines could not be sufficiently eliminated by means of holes cast in the runner communicating with the suction side as used for low and medium pressures, and additional means had to be employed to equalize the end-thrust, principally due to the static pressure behind the runner caused by leakage through the annular space between the runner and guide-casing. Thrust-chambers and thrust-pistons were among the first devices adopted for this purpose. The former device consisted of providing a space between the runner and the casing at the suction side in which pressure-water was admitted so as to balance the pressure at the back of the runner. Where the shape of the runner did not permit this design, the same principle was applied by using a balancing piston, the shaft being enlarged to act as a piston fitted in a gun-metal lined cylinder, the space in front of the piston being connected to the pressure side on the turbine and exerting a pressure opposing the pressure at the back of the runner.

In each case, the pressure was regulated by hand by means of a valve and adjusted to establish equilibrium at the normal output of the turbine and at other gate-openings the collar-bearing would take up the unbalanced thrust. In addition, both the thrust-chamber and piston were connected to the suction-tube through a separate valve, so that in the event of the pressure due to unequal wear of the runner, exceeding the pressure at the back, it could thus be relieved. A balanced runner of modern design is shown in Fig. 23, the area of the runner at A and B being equal and leakage prevented by hydraulic labyrinth joints and any unbalanced thrust is taken up by the combined journal and thrust ball bearing.

Another modern arrangement is illustrated in Fig 24, the space behind the runner being connected with the suction-tube through an amply dimensioned pipe sufficient to reduce the end-thrust on the collar bearing within permissible limits. The clearance between the runner and casing is kept very small and leakage prevented by

FIGS. 23-25.—Various types of Single Spiral Turbines, showing methods of relieving end-thrust.

FIG. 23.

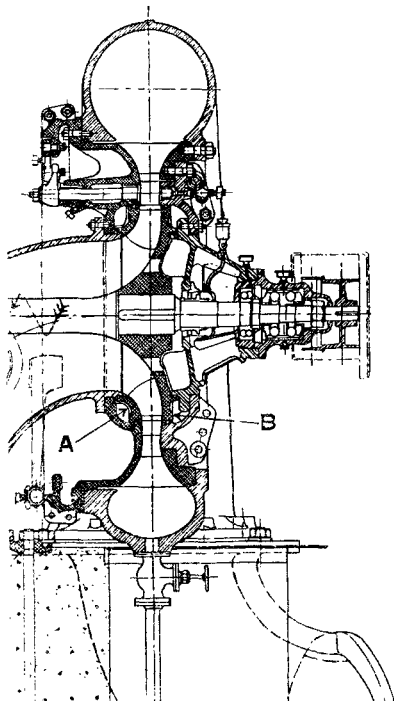


FIG. 24.

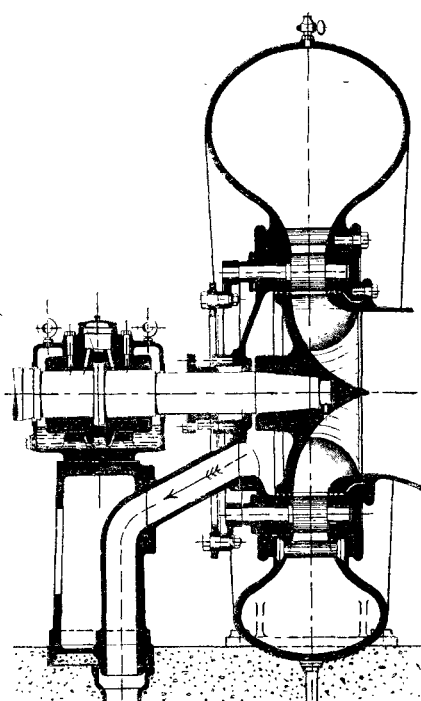
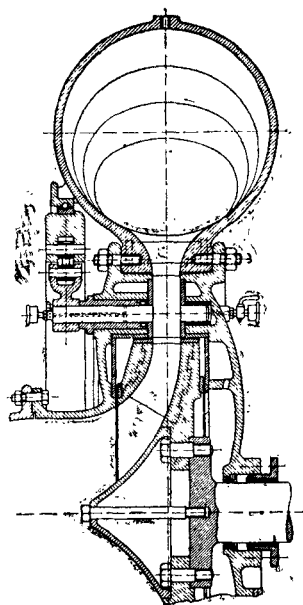


FIG. 25.



labyrinth joints. In special cases, to reduce the wear a steel-ring is shrunk on to the rim of the runner and a corresponding renewable liner fitted to the casing. This figure also affords an illustration of the arrangement with overhanging runner which has the principal advantage of giving a free and unobstructed discharge through the suction bend.

The hydraulic balancing devices have been still further improved by combining automatic action. The first design carried out on this principle consisted of a thrust-plate attached to the shaft, and enclosed in a casing to which the pressure-water was admitted. The shaft with the runner was given a slight clearance permitting the movement in axial direction and the pressure on the thrust-plate was automatically regulated through the leakage between a shoulder on the plate and a facing on the casing, a device which is well-known as being now employed in all modern turbine-pumps.* In applying this automatic device in connexion with recent high-pressure turbines, the runner itself has been designed to substitute the thrust-plate as shown in Fig. 25 (page 111). The clearance on each side of the runner is only 0.02 inch, but from actual practice it has been ascertained that the maximum movement which takes place to reach the ultimate running position with equilibrium established on both sides of the runner, hardly exceeds 0.025 inch. If properly designed this method is entirely automatic in its action, and has been used in turbines of even up to 12,000 h.p. without the addition of any mechanical thrust-bearing.

SPEED REGULATION

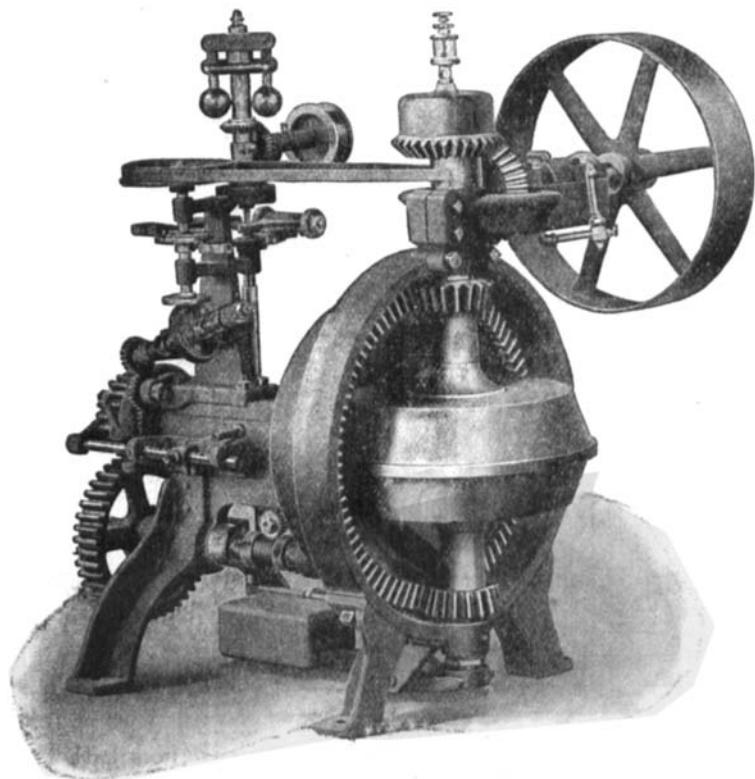
The development of the design and construction of governors has naturally been closely bound up with the general advances in the design of Francis turbines. In fact, it may be stated without exaggeration that the progress in the application of water-turbines is to a great extent due to the satisfactory solution of the governor problem as the provision of a quick acting and reliable speed-

* A. E. L. Chorlton. "Notes on the construction of Turbine Pumps." Proceedings, I.Mech.E., 1917, page 361

controlling device forms one of the most important features of hydro-electric development.

The old type of mechanical governor of which Fig. 26 shows a well-known example, proved totally inadequate for the

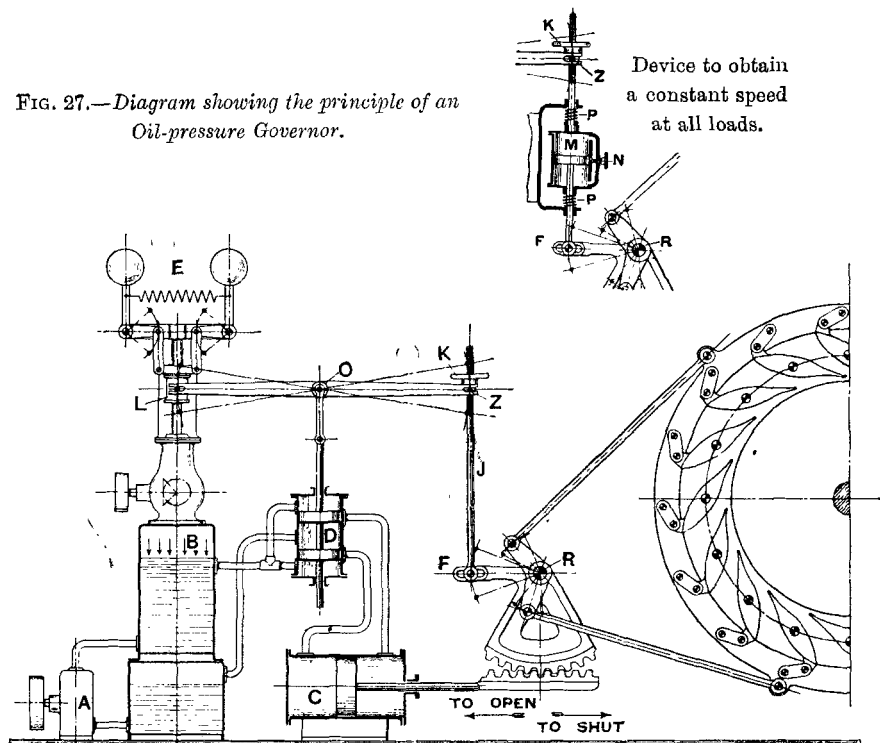
FIG. 26.—*Mechanical Governor.*



needs of efficient speed-control in connexion with hydraulically driven generators. As a consequence the hydraulic type of governor was evolved which in the first place was actuated by the water pressure, but later, however, was substituted by oil pressure in order to eliminate several bad features of the water-pressure governor, that is, sticking due to gritty water, and liability to corrosion of

the various mechanical parts. The automatic oil-pressure type of governor has been steadily improved and has now reached a high state of perfection, possessing all the qualities required by modern practice for effective and reliable speed-control.

FIG. 27.—Diagram showing the principle of an Oil-pressure Governor.



Although a large number of oil-pressure governors have been introduced, all embodying different mechanical construction, the same principle of operation has been retained as is shown diagrammatically in Fig. 27 where A represents oil-pump, B oil-pressure receiver, C Servo-motor or hydraulic cylinder, D Distributing valve, E Centrifugal pendulum, and F Relay motion or anti-racing mechanism. The pump as well as the pendulum is driven from the turbine-shaft, and if the turbine is running at its

normal speed the pendulum is so adjusted that the sleeve L as well as the distributing valve D would be in the central positions as indicated on the diagram. If, however, the load on the turbine should decrease and consequently the speed increase, the sleeve L would rise, in turn lifting the valve D through the lever O with Z as a fulcrum, causing the oil-pressure from the pressure-receiver to be admitted on the left side of the servo-motor piston and moving the guide-vanes in the closing direction through the governor-shaft R. At the moment the shaft R starts to turn, however, the lever F will move, in this instance downwards, and lower the connecting-rod J, consequently bringing the distributing valve back to its central position through the lever O with the point L as a temporary fulcrum. The pressure supply to the servo-motor is thus cut off and prevents the gates on the turbines from closing further than necessary to establish equilibrium between the load and corresponding output of the turbine. By means of the small hand-wheel K on the relay motion, the connecting-rod J can be either shortened or lengthened, thus enabling the speed of the turbine to be slightly decreased or increased during running, independent of the load.

In this arrangement of governor each position of the guide-vanes corresponds to a certain position of the governor-sleeve, the difference in speed between "full" and "no load" depending on the degree of irregularity of the governor, usually 3 to 5 per cent. Under certain conditions it may, however, be necessary to increase the degree of irregularity even up to 10 to 12 per cent. to obtain stable governing conditions, and as this speed variation could not be permitted in connexion with alternators coupled in parallel, such governors are now provided with a device to obtain a constant speed at all loads. This arrangement is shown in diagram Fig. 27 (page 114).

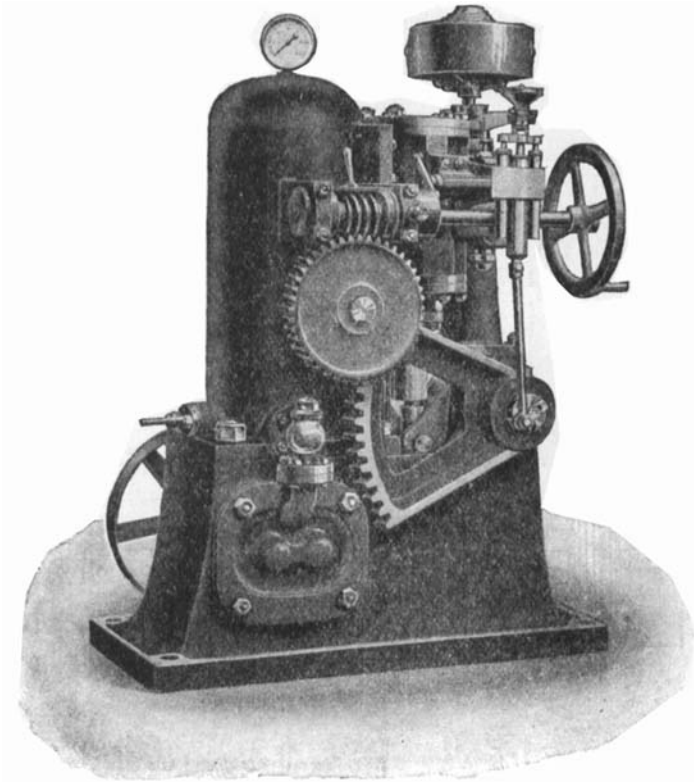
The principle of this device is that instead of the relay motion-gear forming a rigid connexion between the pendulum-lever and governor-shaft as before described, the connecting-rod J is fitted with an oil dashpot with springs, which after each regular movement brings the pendulum-sleeve back to its central position, thus maintaining constant speed corresponding to the speed for which

the governor has been adjusted. The dashpot M consists of a cylinder with a piston and an inter-communicating pipe allowing the oil in the cylinder to flow from one side to the other, the rate of flow being controlled by the adjusting screw N. When a load change occurs in either direction the relay motion will come into operation as before described, but as the oil in the dashpot cannot pass quickly enough from one side of the piston to the other, the connexion between the pendulum lever and governor shafts can be considered as rigid and the dashpot cylinder will follow the movement of the piston and bring the distributing valve back to its central position. The springs P attached to the cylinder, each of which is compressed or under tension according to the direction of the movement of the piston will however bring the cylinder back and thereby the point Z to its previous position, the piston remaining stationary. With the movement of the point Z the distributing valve will again cause the governor either to open or close, thus adjusting the speed until L takes up its central position corresponding to constant speed on the turbine.

Fig. 28 (page 117) shows an outside view of a type of oil-pressure governor built on the principle described. It will be observed that the whole governor is self-contained on its own bed-plate which at the same time serves as an oil supply-tank, the governor-shaft being connected to the guide-apparatus on the turbine by means of levers and connecting-rods. This type of governor is now made in standard series in varying sizes and power ranging from 350 to 40,000 foot-lb. capacity. In addition to the hand-wheel on the relay motion-gear, by means of which the turbine gates can be controlled by hand at any time or used to shut down, a mechanical hand-operating gear is provided for the same purpose, the change-over from automatic to mechanical control being possible during running. The distributing valve on which the quickness and smoothness of the governor action, and the accuracy with which it responds to the speed variation to a great extent depends, generally consists of a relay-valve controlling the ports connecting the pressure receiver with the servo-motor which in turn is controlled by a pilot-valve actuated by the pendulum.

The distributing valve in Fig. 29 shows a typical design, the relay-valve being entirely balanced by oil pressure in its central position. The pilot-valve, however, controls the oil pressure on

FIG. 28.—*Automatic Oil-pressure Governor.*
(Sizes varying from 350 to 40,000 ft.-lb. capacity.)



both sides of the relay-valve, and when lifted or lowered by the governor pendulum, relieves the oil pressure either at the top or bottom of the relay-valve, thus permitting the pressure oil to enter the servo-motor. As the relay-valve is floating in oil, the friction is infinitesimal, and as the valve only overlaps less than 1 mm.

at the ports, the "dead time" is brought to a minimum and consequently the action of the governor is instantaneous. By restricting the stroke of the relay-valve by the screw on the top of

FIG. 29.

*Distributing Valve for
Oil-pressure Governor.*

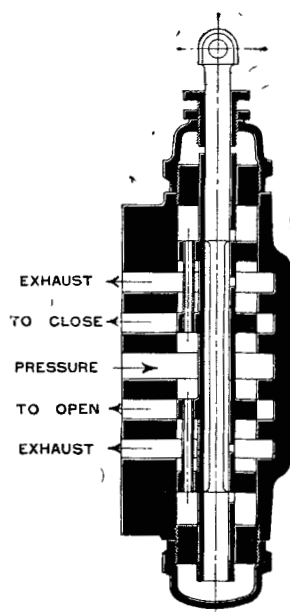
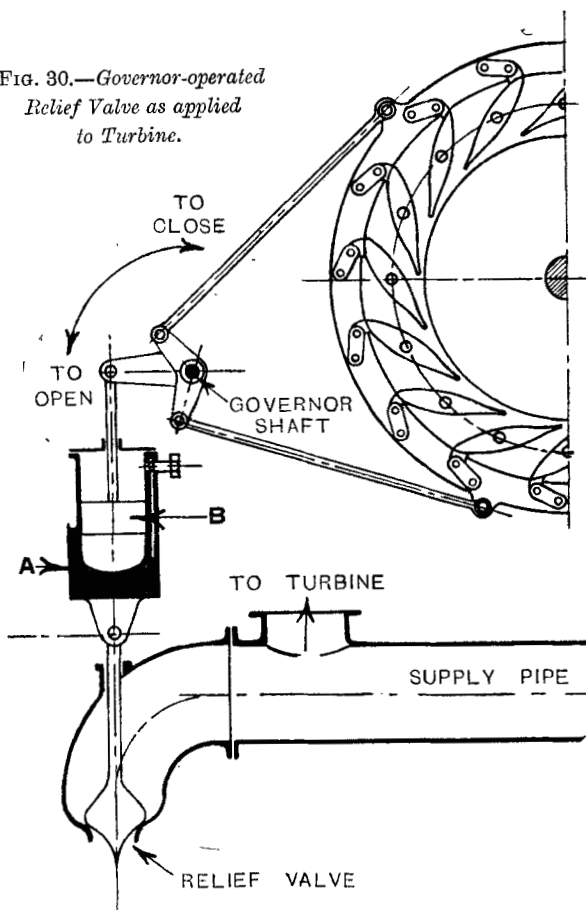


FIG. 30.—*Governor-operated
Relief Valve as applied
to Turbine.*



the valve, the pressure is throttled, and by this means the closing time of the governor adjusted.

In some types of governor the oil-pressure receiver has been dispensed with, the pump being made large enough to supply the necessary oil under pressure required for the servo-motor to make

its full stroke within the closing time for which the governor has been designed. The pressure under which the governor operates is from 150 to 200 lb. per sq. inch, and obtained from a rotary pump driven from the turbine-shaft. In addition to the constant-speed compensation, the modern oil-pressure governor is equipped with an adjustable equalizing device permitting the degree of irregularity to be adjusted within certain limits, which enables the turbine to run in parallel with alternators driven by steam-engines, the governor being adjusted for the same degree of irregularity as the governor-head on the engine-regulator. The governor can also be arranged for distant speed-control from the switchboard, which is of great assistance in the operation of parallel driven alternators.

For large turbine units where a large-capacity governor is required, the servo-motor is built together with the turbine, and in the case of several units, are all supplied from a central oil-supply system. In the case of enclosed turbines supplied through pipe-lines, the closing time of the governor and guide-vanes respectively must be adjusted correspondingly longer than in the case of open-type turbines in order to avoid dangerous pressure rises in the pipe-line, owing to the change of momentum of the flowing mass of water, in addition to providing a heavy fly-wheel to keep the speed variation within permissible limits. This arrangement is only possible where the pipe-line is comparatively short and cannot be adopted for high-pressure turbines where the hydraulic conditions imposed by high head and long pipe-lines render the governing problem far more difficult. In such cases the governor is operated in conjunction with a pressure-regulator or relief-valve, in such a manner that when the governor closes the guide-vanes of the turbine the relief-valve opens, discharging the water into the tail-race, so that the same amount of water is flowing through the pipe-line thus avoiding any change in the momentum, and consequently no pressure rise can occur.

The arrangement of such a pressure-regulator is shown diagrammatically in Fig. 30. Simultaneously as the governor closes the guide-vanes, the piston B in the oil dashpot cylinder A is lifted. The valve is connected to the cylinder which contains a

passage allowing the oil to pass from one side of the piston to the other, the rate of flow being adjusted by a small needle-valve. When the piston B is lifted the cylinder will follow, and consequently the valve will open at the same rate as the governor closes the turbine. The cylinder is however loaded with a heavy weight which exerts a pressure on the oil, which will slowly flow to the lower side of the piston and gradually allow the valve to be closed. By means of the needle-valve the rate of closing is regulated sufficiently slowly to prevent any dangerous shocks in the pipe-line.

In the type of pressure-regulator just described, it will be observed that the governor furnishes the necessary power to operate the valve. This type of valve could not be used with advantage in many plants, as a very large capacity governor would be required to operate the valve. The modern type of pressure-regulator for Francis turbines has therefore been designed in such a manner that the governor only operates a small relay-valve, the water-pressure in the pipe-line being utilized to operate the valve and thus obviate the additional power being imposed on the governor. A section of a valve of this type is shown in Fig. 31, the governor actuating the distributing valve, admitting or releasing the water-pressure behind the piston operating the valve. At the same time, the dashpot device as in the previous illustration, prevents a rapid closing, ensuring a gradual change of the velocities of the water in the pipe-line and obviates any undue pressure increase. This type of pressure-regulator is only suitable for high heads and a comparatively small quantity of water, whereas for medium heads and large volumes of water, its use, for practical reasons, is prohibitive.

A further point which must be subject to particular consideration is the fact that in many medium-pressure plants the pipe-line is often of considerable length as compared with the total head, so that in case of a sudden demand for an increase of flow following a sudden increase of the load on the turbine, the water in the pipe-line cannot accelerate at such rate as required by good governing. It is apparent that the pressure-regulator cannot in

this respect be of any assistance, and under these conditions a standpipe or surge-tank must be provided.

The use of long pipe-lines both in connexion with high and medium pressure Francis turbines, many of which have to work under the most adverse hydraulic conditions, has introduced new factors having important bearing on the problem of speed control and has during recent years been the subject of theoretical investigation and research, notably by Allievi, Prazil, and Johnson *

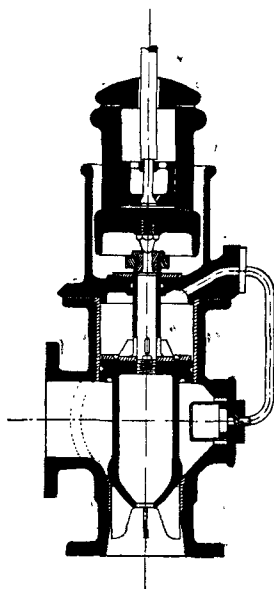


FIG. 31.

Relay-Valve operated by Governor.

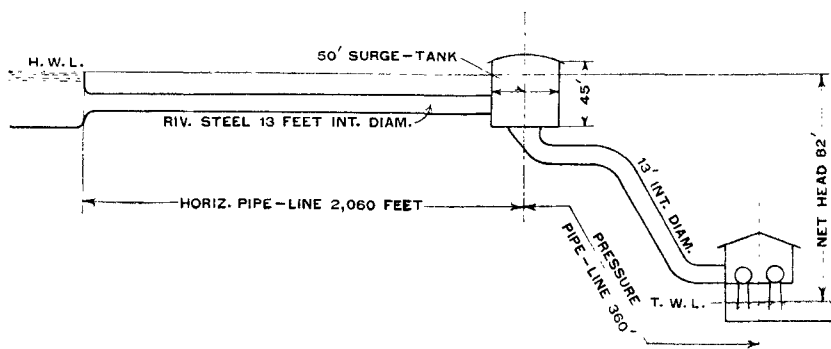
and others, with the result that the laws governing the hydraulic conditions in relation to the speed-control have now been definitely formulated and consequently have enabled a practical solution of this very intricate problem.

The diagram, Fig. 32, illustrates the application of an open surge-tank to a medium-pressure turbine plant, the upper portion

* L. Allievi : *Annali della Societa degli Ingegneri ed Architetti* ; Rome 1903. Dr. F. Prazil : *Schweiz. Bauzeitung*, Zurich, Vol. 52, 1908. R. D. Johnson : *American Soc. Mech. Eng.* 1908.

of the pipe-line being horizontal and the surge-tank situated near the power-house. In the event of a sudden throwing off of the load on the turbine, the water would rise in the tank and absorb the energy given out by the flowing water column when changing its momentum during the retardation of the flow and corresponding to the new load conditions. On the other hand, in the event of a sudden demand for more power, the stored water in the surge-tank would instantaneously supply the additional quantity of water

FIG. 32.—Diagram of Pipe-line and Surge-tank,
Haby Power Plant, Sweden.



required until the water column in the upper portion of the pipe-line has had time to accelerate, and consequently the level in the tank would be lowered. The area of the tank must be so dimensioned that the amplitudes of the water-waves or oscillations are as small as possible and steadily diminish until the quiescent water-level is reached, in order not to influence adversely the conditions for stable governing.

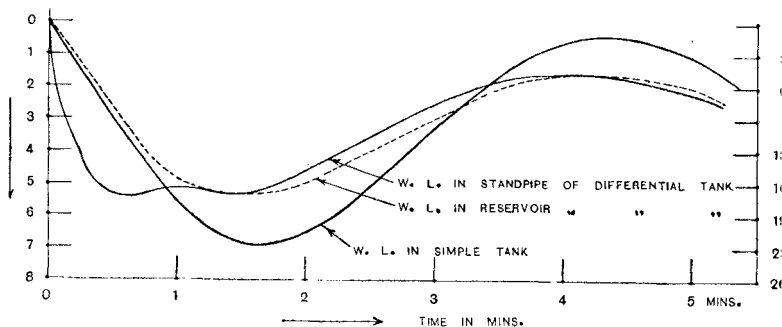
An important improvement in the design of surge-tanks is to be found in the so-called differential surge-tank recently introduced in America.* The object, with this new design, was to obviate the disadvantages of the considerable oscillations obtained in the simple

* R. D. Johnson. "The Surge-Tank." Trans. American Soc. Civil Eng. Vol. 78-79 1915.

tank as often the cost of a larger diameter tank to reduce the oscillation has proved prohibitive. The differential surge-tank consists of a stand-pipe of approximately the same diameter as the pipe-line and communicating with the reservoir through a comparatively small accurately dimensioned opening. When for instance the load is suddenly increased, the water in the stand-pipe will fall very rapidly owing to the throttling effect of the opening to the reservoir, and consequently the water in the pipe-line will

FIG. 33.—*Comparative Curves of Oscillations in Simple and Differential Surge-tanks.*

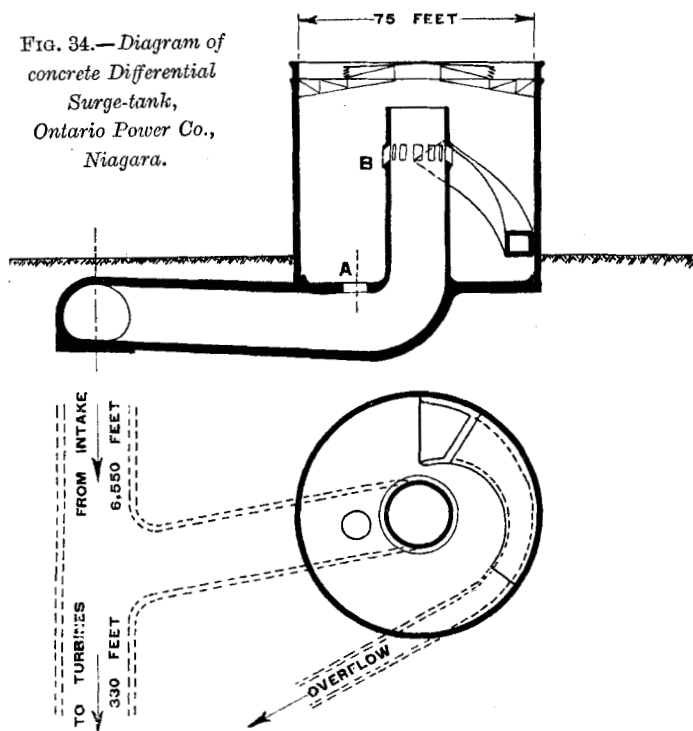
Length of Pipe-line = 11,300 ft. Area of Simple Tank = 680 sq. ft.
Area of Differential Tank = 580 sq. ft. Area of Standpipe = 102 sq. ft. Gross Head = 250 ft.



accelerate at a more rapid rate than in the case of a simple surge-tank where the water column in the upper pipe-line accelerates only at the same rate as the water-level in the reservoir falls. By thus increasing the acceleration from the very beginning of the regulation period, less amount of storage water is necessary which permits a smaller reservoir and consequently less cost than in the case of a simple tank. To illustrate the comparative effect on the oscillations obtained in the two types of surge-tanks, Fig. 33 shows the variation in water-levels in the simple and differential surge-tank respectively during a sudden increase in load, which clearly indicates that the oscillation is of less magnitude in the latter type of tank.

Fig. 34 shows a differential tank constructed in reinforced concrete in connexion with the Ontario Power Company's Hydro-Electric plant at Niagara.* A represents the opening between the stand-pipe and reservoir through which the water flows during normal load variation, but in case of an exceptionally

FIG. 34.—Diagram of
concrete Differential
Surge-tank,
Ontario Power Co.,
Niagara.

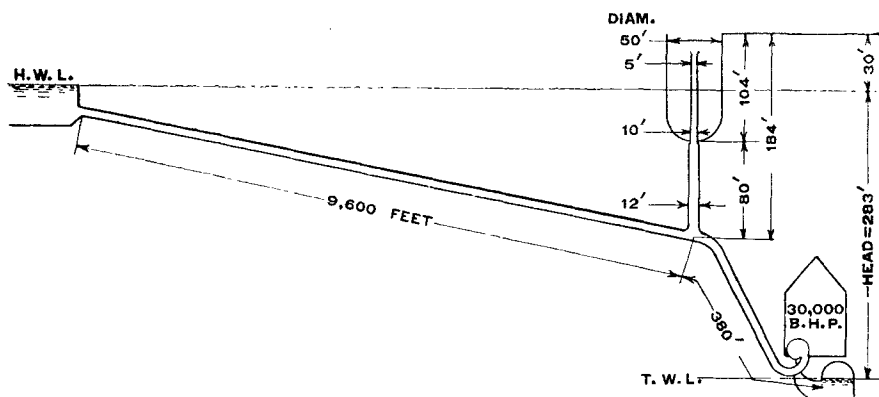


heavy load being thrown off the water would also escape over the top and through the opening B. The internal diameter of this tank is 75 feet, the net-working head on the turbine being only 18 feet 6 inches.

* R. D. Johnson. "Concrete Surge-Tanks." *Engineering Record*. New York, March 1915.

The arrangement of a differential tank as applied to a high-pressure plant is shown in Fig. 35, which is of particular interest on account of its very large dimensions and height. In this case it is obvious that the construction of a simple tank for the existing conditions would be impracticable on account of its great cost. The stand-pipe has a diameter of 12 feet with a height of 80 feet connected to the reservoir having a diameter of 50 feet and a height of 105 feet, the highest point of the roof being 205 feet above ground level, and the total capacity of the reservoir

FIG. 35.—*Diagrammatical Section of Surge-tank,
Salmon River Power Plant.*



being 1,400,000 gallons of water, and is one of the highest surge-tanks yet constructed.

The problem of satisfactory speed-control is necessarily of a theoretical character, but without touching this side of the question the Author has endeavoured to bring out the outstanding fact that the advancement in respect of regulation has played an important rôle in the general development of hydro-electric plants, and without excluding the possibilities of further improvements, it can be said that the speed-regulator of Francis turbines has reached a high standard of perfection, in fact it is second to none compared with any other prime mover.

Long pipe-lines, which from the point of view of speed

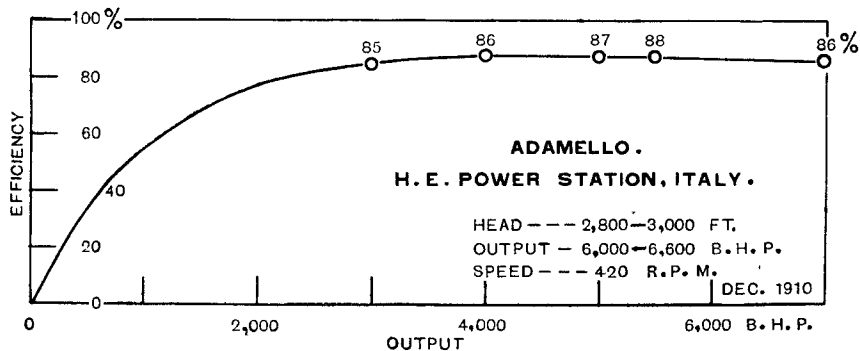
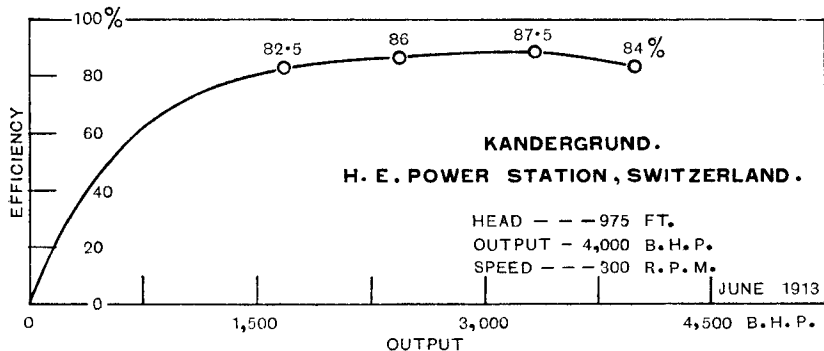
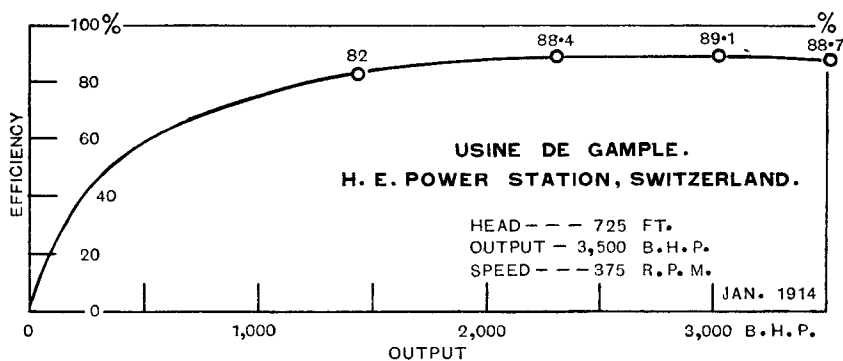
regulation proved to be an obstacle to many power developments, need not now be avoided for that reason, although in addition to the purely technical side the economic aspect requires careful consideration in cases where the topographical conditions necessitate extremely long pipes or conduits. It is imperative, however, that the arrangement of such a plant should be left in the hands of the expert hydraulic engineer, as in the past many plants have proved to be failures for want of consideration of the many complex problems arising in connexion with speed regulations under disadvantageous hydraulic conditions.

PELTON WHEELS.

The second category comprises the high-pressure impulse turbine more familiarly known as the Pelton Wheel, named after its American inventor, and is of the purely impulse type; the water issuing from a nozzle at the full velocity corresponding to the net head and impinging on a set of buckets bolted on to the rim of the wheel centre. The Pelton Wheel is used under heads varying from about 500 to 2,000 feet, although for small powers it can be used under medium heads of down to 100 feet, and on the other hand has been employed under a maximum of 5,400 feet in one stage. In comparison with the great advancement made during recent years in the design and construction of reaction turbines, the improvements in the impulse type of turbine have perhaps not had the same far-reaching effect on account of its design being of a comparatively simpler nature, but great strides have been made in also bringing this type of turbine on the same high level demanded by the present-day practice.

The chief characteristic of the impulse wheel is the long range of load during which the efficiency is nearly constant, as can be seen from the efficiency curves reproduced from official tests, Fig. 36. In each case the efficiency at half load is over 85 per cent, and only falls below 80 per cent, when the load is less than 30 per cent of the normal. To obtain the maximum efficiency the ratio between the pitch diameter of the wheel and diameter of

FIG. 36.—Pelton Wheels. Efficiency Curves.



the jet should not be less than 12, although in certain cases a ratio of 10:1 may be used when a higher speed is secured at the expense of efficiency.

The maximum specific speed obtained for a single runner and jet is therefore limited to 5 (23), corresponding to a ratio between runner and jet of approximately 11. The maximum speed, for instance, obtained with a single jet for say an output of 3,000 h.p.

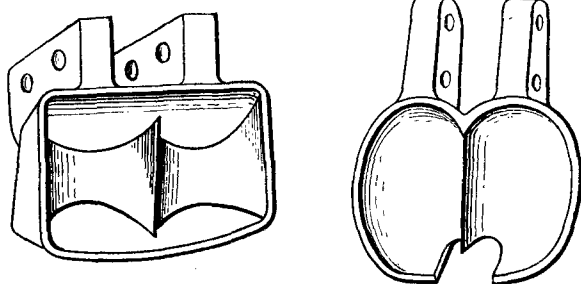
under 900 feet would be $5 = \frac{N \sqrt{3,000}}{900 \sqrt[4]{900}}$. Thus $N = 450$ r.p.m.

To obtain a higher speed under a given head than that

FIG. 37.—*Buckets for Impulse Turbines.*

Pelton.

Doble.

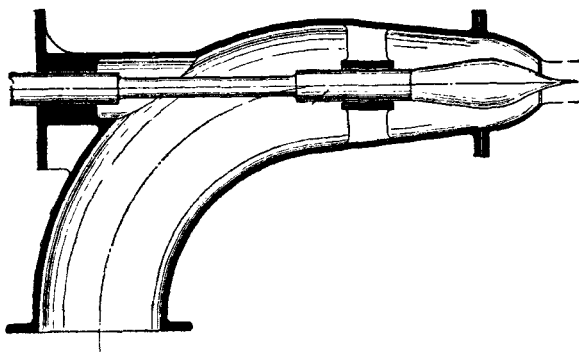


corresponding to the maximum specific speed, it is essential to divide the power over two or more nozzles or wheels. On account of the discharge from the buckets interfering with lower jets, it is now seldom that more than two nozzles are provided for each wheel, and where more nozzles are required the power is divided over two runners each with double nozzles. Double nozzles were also provided where the diameter of a single jet would have exceeded 5 to 6 inches, but in recent years single jets of 8-inch diameter have been used with advantage. The outstanding feature in the improvement has been in respect of the shape of buckets and nozzle and the design of the regulating device.

The original Pelton buckets were rectangular in section, Fig. 37, but have been superseded by the elliptically shaped

bucket which has now been universally adopted by all makers, as the absence of sharp corners and abrupt changes of direction of the stream favours the reduction of the hydraulic losses. The same tendency to adopt a uniform design is also noticeable in respect of the nozzle where the various designs of rectangular nozzle with movable lip have been discarded in favour of the circular nozzle with concentric pear-shaped spear or interceptor movable in axial direction for regulating the quantity of water, Fig. 38, which now without exception is employed in modern Pelton wheel design. The most important improvement, however, is in respect

FIG. 38.—*Pear-shaped Nozzle.*



of the system of regulation which, as in the case of the Francis turbine, had to be adapted for the new conditions of electrical transmission and at the same time conform to the increased demand for accurate and reliable automatic governing.

Three distinct systems of automatic governing are now employed, namely:—

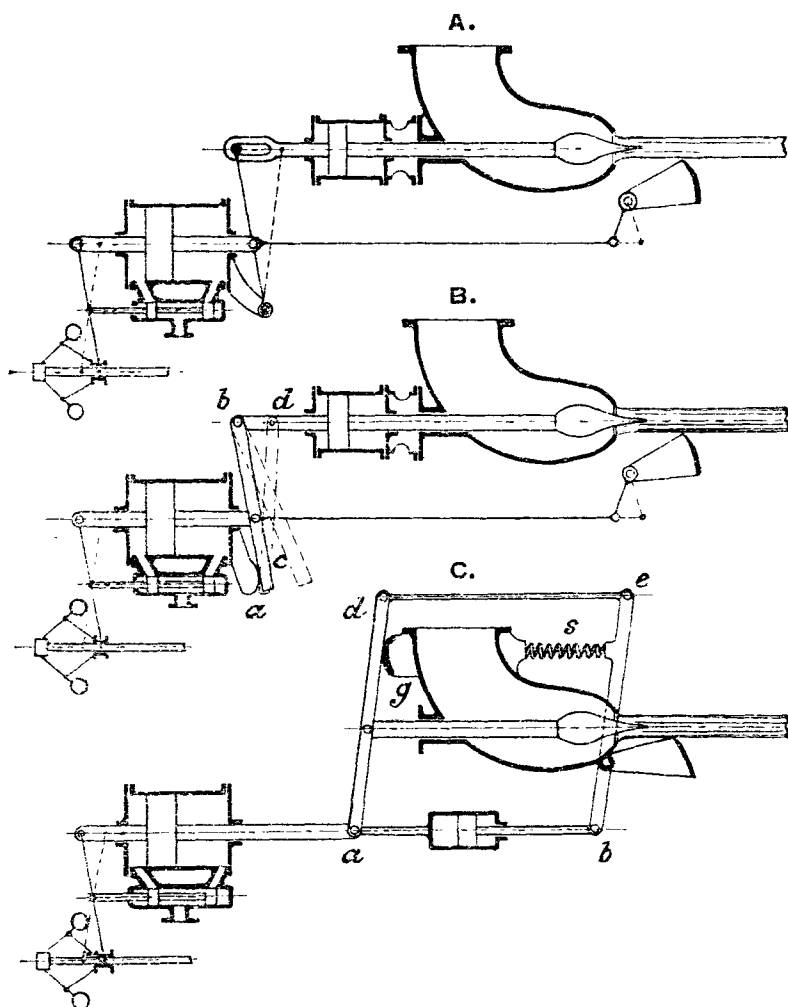
- (A.) By-pass valve regulation.
- (B.) Regulation with deflecting nozzle.
- (C.) Combined spear and deflector regulation.

The object aimed at in each of these methods of automatic control is to obtain an instantaneous regulation of the quantity of

K

water in response to any load changes, at the same time ensuring a slow and gradual retardation of the flow in the pipe-line to obviate any dangerous increase in pressure.

The by-pass regulation is the oldest type used in combination with the automatic governing of Pelton wheels, and as indicated by its name, consists of a by-pass valve, the principle of which has already been referred to in connexion with high-pressure Francis turbines. The regulating shaft on the oil-pressure governor of the standard type acts direct on the movable spear of the nozzle, instantaneously establishing equilibrium between the quantity of water reaching the wheel and the load on the turbine. At the same time, in case of a sudden throwing off of the load, the by-pass valve will open at the same rate as the spear closes, and then close slowly by the pressure of a spring against the dashpot. As the quantity of water is usually small, the by-pass valve consists of a needle-valve directly operated by the governor. For Pelton wheels for large outputs and comparatively low heads, employing two runners with two or more jets, and consequently a large quantity of water, the by-pass valve is generally operated indirectly by the governor in the same manner as the relief-valve in connexion with Francis turbines. Although the by-pass regulation has been employed in a large number of plants, the inherent defect of liability to stick and excessive wear, together with the difficulty of ensuring synchronizing action, called for further improvements in design, resulting in the introduction of the deflecting nozzle; in this construction the complete nozzle is pivoted on its perpendicular axis and deflects the whole or part of the jet from the wheel and discharge direct into the tail-race. A number of plants have been equipped with this particular regulating device, with highly satisfactory results, but in recent years the combined spear and deflector regulation has come to the front, and on account of its simpler design and cheaper construction has now been adopted in the most modern plants. The main feature of this design is the deflecting hood or shoe known as the "deflector" interposed between the nozzle and the wheel and pivoted in such a position that direction of the jet can be altered.

FIG. 39.—*Regulation of Pelton Wheels*

A number of different designs of this method of regulation are now employed, but in each case the principle of operation can be traced to one of the three systems diagrammatically shown in Fig 39. In each case the servo-motor of the oil-pressure

K 2

governor operates the deflector and spear simultaneously when opening, but by sudden closing of the governor the deflector will in the first instance cut into the jet and divert the water from the wheel until the spear by slowly overcoming the dashpot resistance, regulates the water-supply corresponding to the load, when the deflector will be brought back into a position just tangential to the reduced jet. The free movement of the deflector, independent of the spear in the closing direction, is in each case permitted by the "lost motion" existing in the mechanical connexion between the deflector and spear.

In "A" the spear-rod is provided with a slot in which the pin of the lever connecting to the governor-shaft can slide. The opening and closing position of the deflector is shown, the latter in dotted lines, and, by the pressure of the spring against the retarding action of the oil dashpot, the spear will slowly move forward until the slot has regained contact with the sliding pin.

In "B" the operation is identical with "A," although the lost motion between the deflector and spear is obtained through a displacement of the lever system relative to the fixed point *a*. In the closing direction the lever *b c* will follow the deflector movement with *b* as a fulcrum and take up the position as indicated in dotted lines on the diagram. The spring is now free to expand and exerts the necessary pressure to close the spear until the lever *b c* has regained contact with *a*, corresponding to the position *b c* in the diagram. In each of these two methods described it will be observed that, firstly, the governor, irrespective of whether the load is thrown off gradually or instantaneously, always operates directly on the deflector, the spear meanwhile remaining stationary; secondly, that the governor brings the deflector out of the jet after each governing operation.

In diagram "C" a dashpot has been interposed between the governor servo-motor and deflector lever. By sudden discharge of load, points *a* and *b* practically will move the same distance, consequently the deflector will cut into the jet and at the same time lever *a d* is moved away from the stop *g*. The spring, however, is strong enough to overcome the dashpot resistance and slowly brings

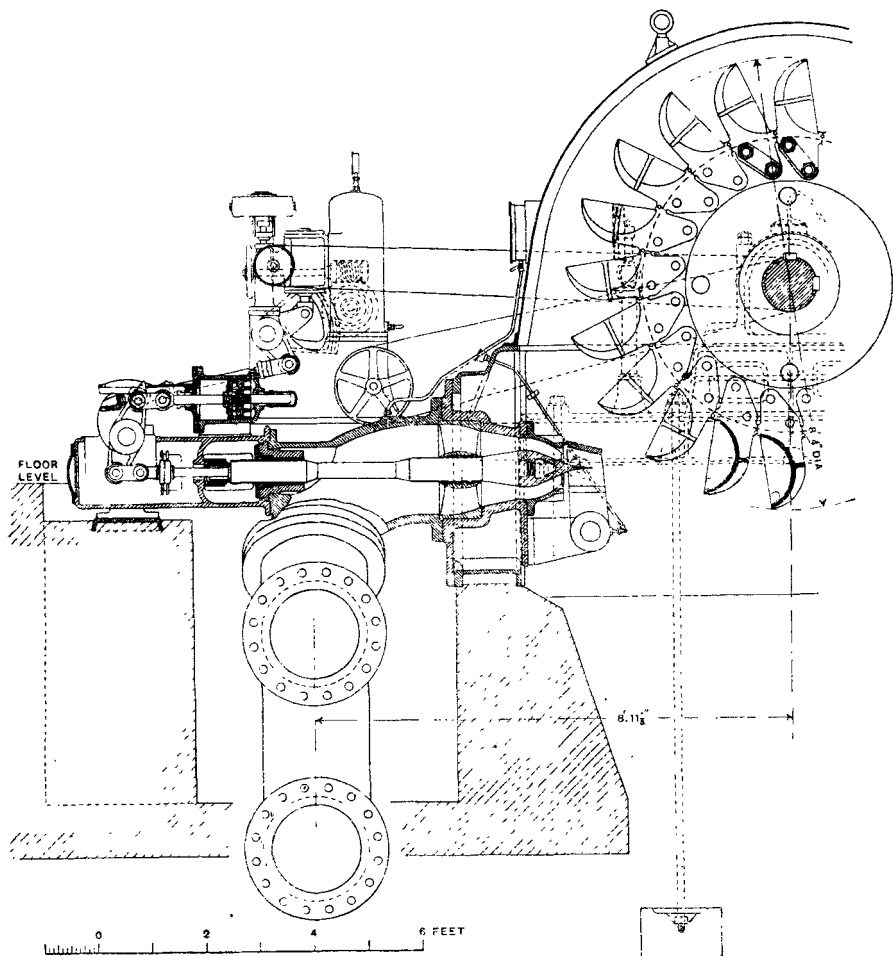
the spear into position, at the same time lifting the deflector into a position tangential to the new jet. If, on the other hand, the load is only gradually discharged, the point *b* would remain stationary and the governor would operate directly on the needle, the deflector being simultaneously moved forward through the lever *d e* to maintain its tangential position corresponding to the reduced jet. This latter design differs from the two foregoing in respect of operation when small and gradual load-changes occur, inasmuch as in that case the governor would operate the needle directly the deflector remains inactive, with which system, it is claimed, more steady speed-regulation for small load changes is obtained.

An illustration of the mechanical design and arrangement of modern Pelton wheels is afforded by the following description of a few representative installations. Fig. 40 (page 134) shows a single-jet Pelton wheel designed for an output of 3,300 b.h.p. under a net head of 875 feet at 300 r.p.m., which plant may be of special interest as being designed and manufactured in the United Kingdom and installed at the British Aluminium Company's works at Kinlochleven. The pitch diameter of the wheel is 82 inches, and both runner and buckets are of cast-steel, the latter sand-blasted and ground on the inside to present as smooth a surface as possible, to reduce the friction losses. The buckets, twenty in number, are secured to the runner by slightly tapered bolts of nickel-steel, and dimensioned to withstand a centrifugal force of 90,000 lb. on each bucket at 100 per cent overspeed. The shaft is carried in two automatic ring oil lubricated water-cooled bearings 11 inches and 8½ inches diameter respectively, each provided with circulating pumps. The nozzle of cast-steel is designed for a jet diameter of 148 mm. and provided with a renewable tip of best gun-metal. The spear end is also made of gun-metal of special alloy to resist the erosive action of the water. The combined spear and deflector regulation is employed, the automatic governor of the oil-pressure type being self-contained on its own foundation and connected to the spear and deflector respectively by means of levers and connecting rods.

The method of operation is in accordance with diagram "A"

FIG. 40.—*Single-jet Pelton Wheel,*
Kinlochleven.

Output 3,200 B.H.P. Head 875 ft. 300 r.p.m.



(page 131), although for the sake of better mechanical arrangement the dashpot is indirectly connected to the spear by means of a system of levers.

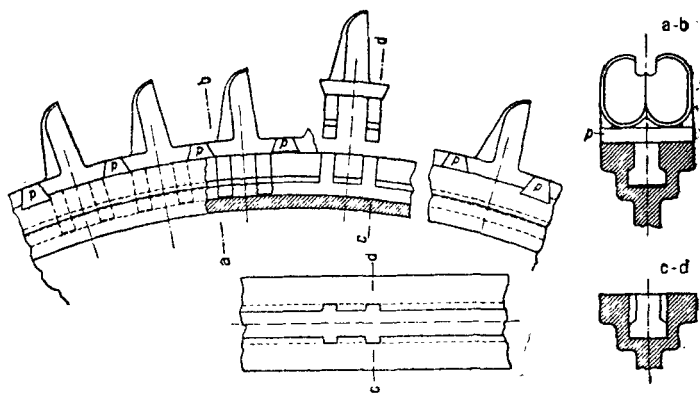
The governor has been designed for a closing time of one second corresponding to a maximum temporary speed variation of approximately 8 per cent when the total load of 3,300 b.h.p. is instantaneously thrown off. By reason of the arrangement of the existing distributing pipe-lines, the Pelton wheel is provided with double inlet, each fitted with a 21-inch hand-operated sluice-valve, which enables, if required, the unit to be supplied through any particular supply pipe. The shaft is provided with a solid flange coupling connecting to the 2,000 k.w. direct-current generator.

*Fully Hydro-Electric Station, Switzerland.**—By reason of the extremely high fall under which this plant operates, it is of singular interest and particularly serves as an illustration of the latest achievements in Pelton wheel design. The output is 3,000 b.h.p. per unit at 500 r.p.m. under a working head of 5,435 feet, being the maximum head for which any turbine has been designed to utilize in one stage. The pitch diameter of the wheel is 11 feet 7 inches, and that of the jet 34 mm., corresponding to a ratio of approximately 105. The velocity of the jet is approximately 35,000 and the peripheral velocity of the wheel-disk 18,200 feet per minute. Under these circumstances the most careful consideration had to be given to the design of the runner and the method to be adopted for fixing the buckets. The runner is a steel forging and designed as a disk of uniform strength. The buckets are also of steel forged on blocks, but on account of the extremely high peripheral velocity the method of fixing by bolts could not be adopted and quite a novel method was resorted to. The runner is provided with a wedge-shaped slot, and each bucket has two lugs of corresponding section, Fig. 41 (page 136), and round the

* R. Neeser. "Les machines hydrauliques à l'Exposition de Bern." *Bulletin Technique de la Suisse-Romande*, 1916.

periphery of the rim openings have been made through which the buckets can be inserted, the required spacing being obtained by means of distance-pieces of triangular section. Of these distance-pieces nine were of special design and spaced evenly round the periphery, after which the disk was heated and the buckets and the intermediate distance-pieces inserted cold. To secure the required pressure fit between the buckets and the distance-pieces a strip of steel plate, the thickness of which had been carefully determined beforehand, was inserted in the nine sections, and

FIG. 41.—*Pelton Wheel, Fully Hydro-Electric Station, Switzerland.*



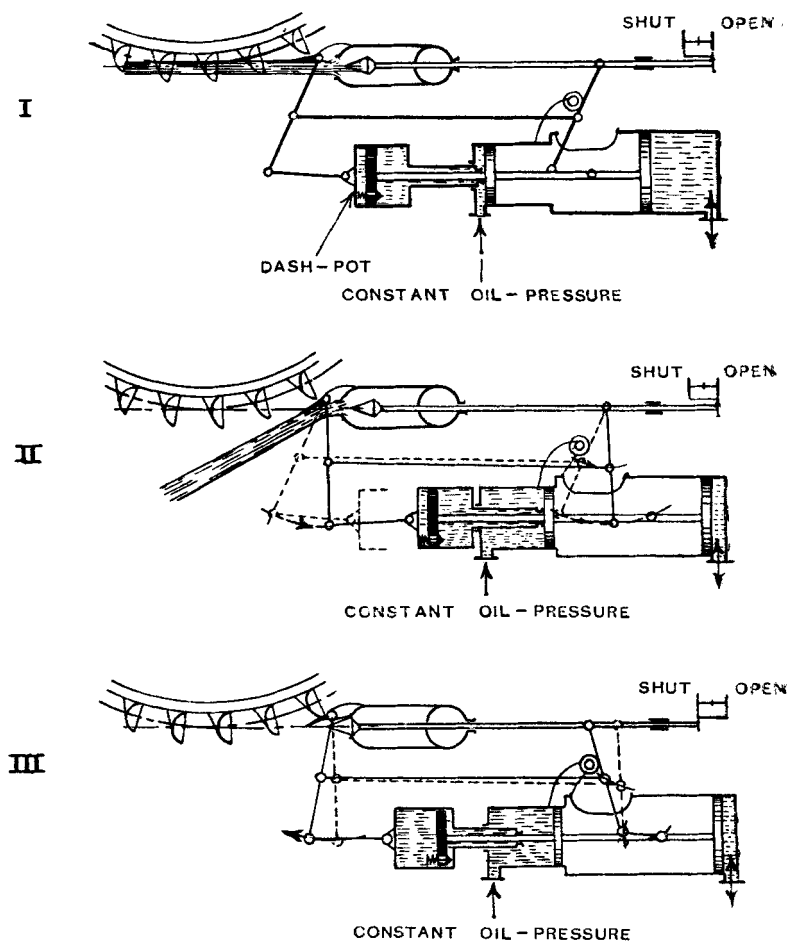
which, after the disk had been allowed to cool, exerted the pressure necessary for a tight fit.

The automatic speed regulation is carried out by means of the combined spear and deflector arrangement (type "C," page 131), and to afford a clearer conception of the various phases of regulation, Fig. 42 shows the relative position of the deflector and spear respectively during closing operation. The spear is in this instance operated by means of an auxiliary oil pressure servo-motor, which, however, has been purposely omitted in the diagram, for the sake of clearer view of the essential parts.

Position I represents the full open position with the deflector tangential to the maximum jet.

Position II represents the moment immediately the load has been discharged, the deflector diverting the jet, but with the

FIG. 42.—Automatic Regulation. *Fully, Switzerland.*



spear still stationary in its opening position, the dashpot having moved from left to right, together with the servo-motor piston.

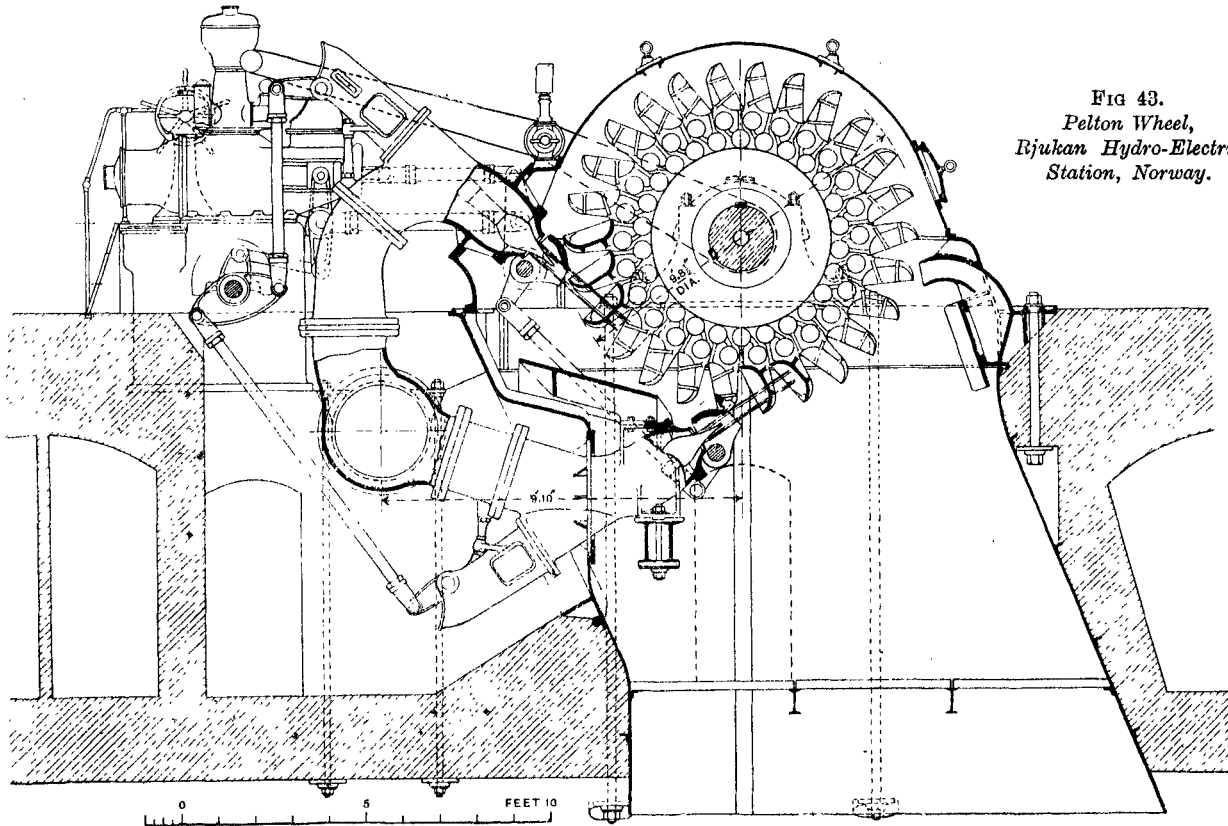
Position III represents the full closed position, the dashpot slowly moving from right to left and permitting the gradual closing of the spear at the same time as the deflector is lifted until it takes up a position tangential to the centre line of the jet.

Rjukan Hydro-Electric Station, Norway.—This plant consists of a Pelton wheel with double runner and four jets, with an output of 16,400 b.h.p. under a net fall of 253 metres and a speed of 250 r.p.m., corresponding to a specific speed of 7.15 (31.7), and consequently illustrates one of those cases where the conditions are such that a multi-jet Pelton wheel is the only type of turbine which can be utilized. The specific speed per jet corresponds to 3.58 (15.9). Each wheel has a pitch diameter of 2,400 mm. and a jet diameter of 164 mm. with both runners and buckets of cast-steel. The buckets are attached to the runners by means of tapered nickel steel bolts. The holes, however, are drilled parallel and loose bush tapered on the inside and provided with a longitudinal slot along its entire length, ensuing a perfect and tight fit when the bolts have been tightened.

The general arrangement of the Pelton wheel is seen from the sections in Fig. 43 (page 139). The two runners being set sufficiently far apart to allow free discharge of the water from each wheel without obstruction and enclosed in a wrought-iron housing. The four nozzles are all operated from one automatic oil-pressure governor, and also in this case the combined spear and deflector regulation has been adopted, of the same design as the Fully plant.

In each of the foregoing plants the wheel has been carried in two bearings and mounted on a separate bed-plate. The arrangement with "overhung" wheel direct mounted on the generator shaft has been greatly in vogue in America, and has lately also been adopted in Europe but to a much smaller extent. This arrangement is characterized by its cheapness and compactness and consequently a great saving of floor space is secured. For double turbines, one wheel is mounted in a similar manner at each end of the generator shaft, which arrangement was adopted at the Southern California

FIG 43.
*Pelton Wheel,
Rjukan Hydro-Electric
Station, Norway.*



Edison Co.'s power plant at Kern River, California,* with a total output of 10,000 b.h.p. per unit and a jet diameter of $7\frac{7}{8}$ inches. The vertical arrangement of Pelton wheels is more seldom adopted, but possesses the advantage of permitting the use of four or even more nozzles with a single wheel. A detailed description of this type of Pelton wheel is contained in the Paper by the late Mr. Zodel on "High-pressure Water-power Works."†

PIPE-LINES.

The design and construction of the pipe-line forms one of the most important sections in connexion with a hydro-electric plant, a fact which becomes more evident when considering the great increase in falls now utilized for power purposes, and where the pipe-line represents the major portion of the initial capital cost. The great stride made in the economical development of water-power under high heads during recent years, and the successful harnessing of falls of over 3,000 feet, have depended to a great extent on the general progress in the design and construction of pipe-lines, and the satisfactory solution of the many problems which have arisen in connexion with the development of high falls. But these developments have also had an important bearing on the economic utilization of falls of comparatively low head, as it has permitted larger diameters to be employed and consequently a smaller number of pipe-lines which, in addition to a great saving in cost, by the reduction in friction losses, has contributed to the higher overall efficiency realized. Pipe-lines in connexion with water-power installations are classified as low, medium, and high-pressure pipe-lines.

* In view of the remarks in reference to the increased employment of Francis Turbines under high heads (page 74) it is of interest to record that for the extension of this plant it has been decided to install Francis Turbines rated at 22,500 B.H.P. per unit and operating under a fall of 800 feet, thus exceeding by more than 50 feet the maximum fall under which Francis Turbines have been installed at present.

† Proceedings, I.Mech.E., 1911, page 617.

Low-pressure Pipe-lines.—The material used in the construction of low-pressure pipe-lines is either concrete, riveted steel, or wood. The concrete pipes are generally built *in situ*, of monolithic concrete with various systems relating to the form of reinforcement. Owing to the liability to leakage and sweating, it is not as a rule used under pressure, being employed in the upper portion of a pipe-line where the gradient is small and the hydraulic gradient varying from zero to about 10 feet. Under these conditions, the concrete pipe-line has certain points of merit as regards initial cost and durability, and has an undoubted field of usefulness. On the other hand, the lack of flexibility and high co-efficient of expansion renders it necessary to make provision to prevent cracks due to uneven settlement where the soil is of a loose nature, and also suitable expansion joints, which is often a difficult matter. In certain places, however, the concrete pipes have been made as a pressure line, when special form of reinforcement and treatment to exclude leakage has been adopted.

Wood stave pipes are utilized to a great extent for pressures up to about 175 feet both in America and Canada where suitable wood, best quality cedar fir, is to be found in abundance. For use in connexion with water-power developments the pipe is made "continuous," the rough lumber being made into staves of correct shape and angles, and joined together on site by means of wooden or metal tongues and breaking joints between adjacent staves so as to form a continuous length. The finished pipe is wound round with iron hoops and secured by adjustable clamps of malleable iron, through which the threaded ends of the rings pass and are tightened by means of washers and nuts. One of the chief characteristics of the wooden stave pipe-line is its durability and low cost, together with a low coefficient of friction, and is therefore of particular advantage for the construction of the upper portion of pipe-lines where suitable wood can be procured.

Steel pipes.—The two types of steel pipes, riveted or welded, are used in connexion with hydro-electric plants, the former for low and medium pressures, and the latter exclusively for high-pressure

plants. For long pipe-lines under low heads, the riveted pipe has been superseded either by concrete or wood, as for large diameter, the riveted pipe must be made sufficiently thick to retain its circular shape, and in addition take all the bending stresses caused by the weight of the water to allow as great a distance as possible between the supports, and consequently the cost is very often prohibitive as compared with a conduit made of either of the first-mentioned materials. For instance, a 12-foot steel pipe-line requires at least $\frac{1}{2}$ -inch plate thickness to fulfil these conditions, whereas, as far as the hydrostatic pressure is concerned, $\frac{1}{4}$ -inch would be ample.

Recent designs of large riveted steel mains under low heads have therefore aimed at a construction which would permit of a minimum

FIGS. 44 and 45.—Types of Water-Gas Welds.



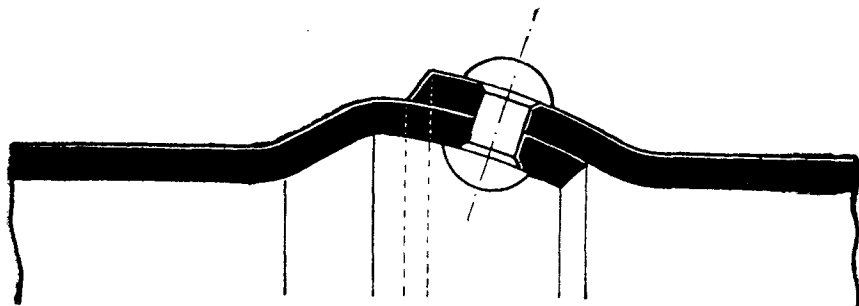
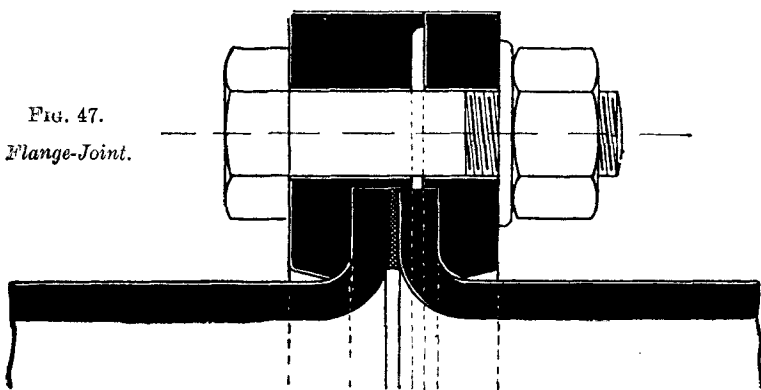
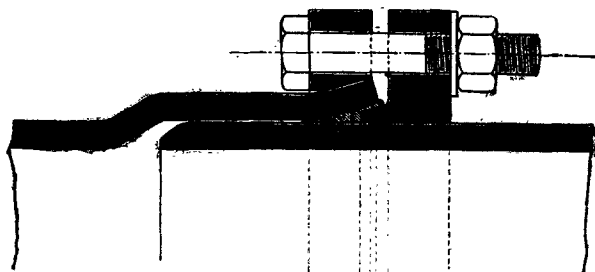
plate thickness and a maximum distance between supports. For this purpose, the pipe is stiffened by means of angle-irons, designed to take up the bending moments, and the shell of the pipe itself is correspondingly reduced in thickness.

The welded steel pipe-lines signify the most important developments in recent years as a result of the progressive utilization of high heads which necessitated a closer study of the pipe-line construction than had hitherto been the case. Moreover, the successful harnessing of falls of 1,000 feet or more could only be accomplished by using pipe-lines where the construction would offer the necessary safeguards and reliability of design required, as a failure under these conditions would have the most disastrous results. Welded pipe-lines are exclusively used for high-pressure installations on account of their superior strength and absence of rivets to obstruct the flow of water and consequently reduced friction losses.

The welded pipes are made by the water-gas process, the plates being bent to shape and the overlapping edges, Fig. 44, heated by means of water-gas and welded together under high speed mechanically-driven hammers, which method produces a weld of a strength of approximately 95-97 per cent of the strength of the full plate. After welding, the pipes are annealed to remove all internal stresses. The foregoing process of welding is only suitable for material up to about $1\frac{1}{4}$ -inch thick, as above this thickness, the heat would not penetrate sufficiently to produce uniform welding heat. For larger plate thickness, the "wedge-welding" method is resorted to, Fig. 45, the edges being brought together and a separate bar inserted forming the weld. With this method, pipes up to a thickness of $1\frac{3}{4}$ inch can be satisfactorily welded. The material used in welded pipe-lines is best Siemens-Martin steel, with a tensile strength of average 28 tons per sq. inch and an elongation of 20-25 per cent in 8-inches test-bar.

On account of the pressure-rises which the pipe-line may be subjected to, the plate thicknesses are calculated with a factor of safety of 4-5 : 1, based on a strength of the weld equal to 100 per cent. The individual pipes are made in lengths of an average of 18 to 20 feet and using riveted joints for medium pressure and flange or expansion joints for high pressures, Figs. 46-48 (page 144) representing the most common type of the three mentioned joints. In the riveted, or so-called "bump" joint, the pipe-ends have been swelled so that the rivet heads do not obstruct the free area of the pipe.

The flange-joint, Fig. 47, represents the most usual type adapted for large pipes, both ends of the pipe being turned up with loose cast-steel flange-rings and rubber insertion joints. In pipe-lines where either of these joints are used, separate expansion joints must be provided. For this reason the high-pressure "muff"-joint, Fig. 48 (page 144), has been extensively used in connexion with turbine pipe-installations, as each individual joint permits of expansion, and separate expansion-pieces are rendered unnecessary. A further advantage which is obtained by this design is, that it permits repacking the joint without displacing the pipe, in addition

FIG. 46.—*Bump-Joint. Single Riveted.*FIG. 47.
Flange-Joint.FIG. 48.—*High-pressure "Muff"-Joint.*

to greater facility in erection. Without exception, turbine pipe-lines are laid above ground to enable frequent inspection, each individual pipe being supported on a concrete support and heavy anchorages provided at all points where the pipe-line changes direction. In many cases, sufficient attention has not been given to this latter requirement, but the present high-pressure work demands careful consideration to this point, in fact, every detail of the pipe-line has to be considered in the light of the very heavy duty imposed under the high falls now employed.

FIG. 49.—*Kinugawa Hydro-Electric Plant, Japan.*



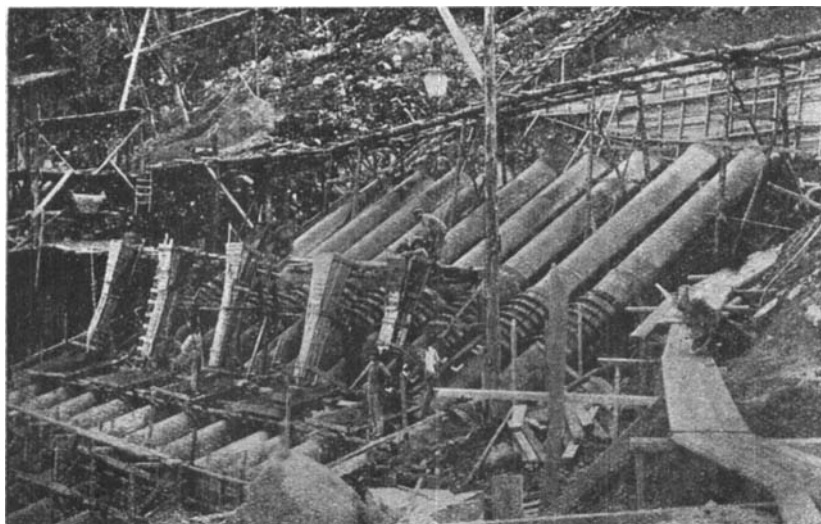
Fig. 49 gives a typical example of pipe-lines for a hydro-electric installation at Kinugawa, Japan. It consists of six main pipe-lines with an internal diameter of 1,520 to 1,100 mm. and a 700 to 500 mm. diameter pipe-line for the separate exciter unit. The total static head is 336 metres (1,100 feet), and the plate thickness varies from 10 mm. at the top to 25 mm. at the bottom of the pipe, the joints used being high-pressure muff-joint throughout.

An anchorage during construction at Rjukanfos, Norway, is

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shown in Fig. 50, consisting of ten parallel pipe-lines with a diameter of 79 inches to 50 inches under a maximum static head of 830 feet, the thrust being transmitted to the foundation by means of a number of cast-iron rings made in halves and bolted together round the pipe. The latest improvement in the art of welding is the reinforced welded pipe, consisting of a number of solid forged rings shrunk on to the outside of the pipe adding further strength to the pipe with a reduction of plate thickness. This innovation in pipe

FIG. 50.—*Anchorage for Steel Pipe-line under construction.*

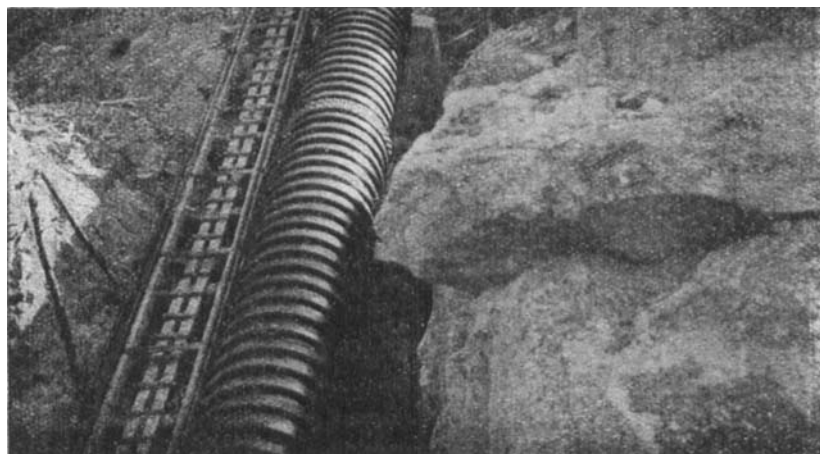


design has been of immense importance as far as turbine installations are concerned, as for high heads it permits a larger diameter pipe being used without exceeding the maximum limit of plate thickness to obtain a reliable weld, and consequently for large installations the number of pipe-lines would be less as compared with the pipes of uniform thickness, thus reducing the initial cost of installation. The first pipe-line where this type of pipe was used was installed at Los Angeles, California, in connexion with the Municipal Hydro-Electric power station. The inside diameter of the pipe was 80

inches with a maximum static head of 930 feet, corresponding to a plate thickness of 32 mm. The pipe was made with a thickness of 16 mm. only, reinforced by steel rings. The rings are rolled solid out of the steel billet, heated and shrunk just tight on to the pipe.

The reinforced pipe has now been adapted for several high-pressure plants, and Fig. 51 illustrates such pipe-line in position, recently installed in Norway. For exceptionally high heads, where smaller diameter pipes only are necessary, solid-drawn pipes are employed. An example is furnished by the pipe-line of the

FIG. 51.—*Reinforced Steel Pipe-line.*



Fully installation, to which reference has been previously made, as being the maximum head yet utilized, namely, 5,435 feet. The diameter varies from 600 mm. at the upper portion to 500 mm. at the bottom, with a plate thickness of from 6 to 43 mm. Water-gas welded pipes are used up to 34 mm. thickness, whereas the lower portion with a thickness of from 35 to 46 mm. consists of solid-drawn or pressed pipes. The present method of manufacture permits only comparatively short lengths of this diameter being made, which, however, are welded together with a circumferential weld in lengths of about 18 feet.

CONCLUSIONS.

It will be appreciated that within the limits of this Paper it has only been possible to direct attention to the main lines along which the development of this highly specialized branch of engineering has taken place, and to indicate briefly its general effect on the utilization of water-power. In considering these developments as described in the foregoing, the outstanding features can be summarized as follows :—

(1) The exclusive use of two types of turbines only, namely, Francis reaction turbines for low and medium heads, and Pelton impulse wheels for high heads.

(2) The extension of the use of Francis turbines under heads approaching 800 feet, and Pelton wheels in single stage up to 5,500 feet.

(3) The exclusive adoption of balanced wicket-gates for regulation of Francis turbines and the circular nozzle with combined deflector and needle regulation for Pelton wheels.

(4) The standardization of turbine runners and increased specific speed permitting the use of single vertical units of large output under low heads.

(5) The general increase of output per unit, the maximum output at present being 31,200 h.p.

(6) The general increase of the overall efficiency of about 6 to 10 per cent.

(7) The exclusive use of oil-pressure governors.

(8) The efficient regulation (by means of differential surge-tanks) of turbines using long pipe-lines.

(9) The employment of large diameter pipe-lines under high heads resulting in an appreciable reduction of the initial cost of development.

These developments, coupled with the improved construction of impounding dams in addition to multifarious improvements in details to ensure effective safeguards and reliability in operation, constitute as such an enormous advance from a purely technical point of view, but of even greater significance has been the

unlimited field thereby opened up for the application of electricity and the extended scope given to the utilization of water-power in the service of civilization; issues of the greatest magnitude have been raised affecting the economic life and future prosperity of nations, and from being a question to be left solely to private enterprise, the control and development of water-power now rank among the vital problems of national interest.

An attempt here even in the most casual manner, to touch upon this aspect of a subject on which much could be written, would be impossible, but it is a gratifying fact to record that the development of the water-power resources has now been recognized as an important factor in the national-economic problem, and in many countries Government departments have been set up to deal with this question to the best national advantage. The active interest thus shown by the respective Governments has proved to be a valuable stimulus to the development as a whole, as by its intervention the laws of water rights and their expropriation have been remodelled and amended in accordance with modern principles, and necessary safeguards provided for the protection of fishing or other vested interests in addition to the valuable services rendered in connexion with hydrographical surveys and the collection of reliable data and records, in fact in all questions affecting the rational and economic utilization of water-power.

State owned and controlled hydro-electric power stations are now in successful operation, notably in Canada and Sweden, and it is anticipated that further important developments in this direction will take place, as the war has caused attention to be concentrated on the development of the valuable water-power resources in connexion with the establishing of new industries necessary to preserve independence of foreign supplies, or with the object of reducing the importation of coal.

According to Professor Gibson's estimate, the total amount of water-power available in the world exceeds 200 million horse-power, and in Table 5 (page 150) is set out the available water-powers capable of economic development in the principal countries in Europe and America, together with the amount already developed,

TABLE 5.

Available Water-Power in the Principal Countries of Europe and America

Country.	B.H.P. Available.	B.H.P. Developed		Area in sq. miles.	Population.	B.H.P. avail- able per sq. mile.	B.H.P. developed per sq. mile.	B.H.P. per head.	
		in B.H.P.	in per cent.					Avail- able.	Developed.
U.S.A.	28,100,000	7,000,000	24.9	2,973,890	98,783,300	9.4	2.35	0.28	0.071
Canada A* . . .	18,803,000	1,735,000	9.2	2,000,000	8,033,500	9.4	0.87	2.34	0.216
Canada B	8,094,000	1,725,000	21.3	927,800	8,000,000	8.7	1.86	1.01	0.216
Austria-Hungary .	6,460,000	566,000	8.8	261,260	51,173,000	24.8	2.17	0.13	0.011
France	5,587,000	1,100,000	11.6	207,500	39,601,500	26.8	3.14	0.14	0.016
Norway	5,500,000	1,120,000	20.4	124,130	2,391,780	44.3	9.62	2.30	0.463
Spain	5,000,000	440,000	8.8	190,401	19,588,700	26.3	2.31	0.26	0.022
Sweden	4,500,000	704,000	15.6	172,960	5,522,400	26.0	4.08	0.81	0.127
Italy	4,000,000	976,000	24.4	91,400	28,601,600	43.8	10.7	0.14	0.034
Switzerland . . .	2,000,000	511,000	25.5	15,976	3,781,500	125.2	32.0	0.53	0.135
Germany	1,425,000	618,100	43.4	208,800	64,926,000	6.8	2.96	0.02	0.010
Great Britain . .	963,000	80,000	8.3	88,729	40,831,400	10.9	0.91	0.02	0.002

ESTIMATE 1915.

* A includes Yukon and Northern Area improbable of immediate development.

as published by the Water-power Branch Ministry of Interior, Ottawa, which cannot fail to reveal the enormous scope for further developments of the world's water-power resources. The harnessing of distant waterfalls with the power arteries conducting the water from the mountains to the power-house in the valley below, the transmission line conveying the potential energy from the remote places to the industrial centres for useful work to the benefit of mankind, has, as already stated, been of the greatest significance to the economic development of nations, and it may be said without exaggeration, is destined to become one of the most important keystones in the industrial structure of this great Empire.

The rapids in Canada, the peaks of the Himalayas, the rugged plateaux of New Zealand and Tasmania, and the Highlands of Scotland and Wales, contain a natural wealth of incalculable value, which, together with the advances in fixation of nitrogen and other electro-chemical processes, the production of pulp, development of mineral resources and other staple industries, will in the near future prove to be a leading factor in the industrial reconstruction of our Empire, and be the means of closely linking together these great independent countries in the coming struggle for industrial supremacy.

May it be the privilege of the present generation, and in particular of the Members of this Institution, to take a leading part in this great work of developing our water-power resources for future prosperity, and to safeguard the glorious traditions of the British Empire.

The Author desires gratefully to acknowledge the assistance rendered by Mr. Lewis Moody of I. P. Morris and Co., Philadelphia, U.S.A., Messrs. Morgan Smith and Co., York, U.S.A., Messrs. Piccard, Pictet and Co., Geneva, Messrs. James Gordon and Co., London, and Messrs. A. B. Finshyttan, Sweden, who have kindly furnished illustrations and particulars of plants described in this Paper.

The Paper is illustrated by 51 Figs. in the letterpress.

Discussion in London Friday, 23rd January 1920.

On the motion of the CHAIRMAN (Mr. Mark H. Robinson, *Vice-President*), a very cordial vote of thanks was passed to the Author for his most interesting Paper.

Professor W. E. DALBY, F.R.S. (Member of Council), said that he was sure all the members would agree with him that the Paper would become a classical one in the records of the Institution. It was so full of information that those interested in hydro-electric stations would turn to it. He thought they were greatly indebted to the Author for collecting and bringing together in available form so much data relating to the subject. He well remembered the great interest which was aroused in the engineering world when the Niagara Power Station was built. He was sorry Dr. Unwin was not present that evening. He was Chairman of the Committee which sat in London to consider and adjudicate on the scheme. But compared with some of the stations described in the Paper, the station at Niagara with its 5,000 h.p. turbine was quite small.

There were three outstanding points of interest which struck him while the Paper was being read. The first point was the simplicity of the mechanical design of the turbines with a vertical shaft and with all the bearings placed above the runner. Obstruction to the free flow of water was therefore removed. He (Professor Dalby) thought this worthy of the closest study by mechanical engineers and designers. The second point was the increase in efficiency obtained by large plants. Not so many years ago it was an article of faith that the best designed turbine would not give a greater efficiency than 80 per cent, but, in the Paper, efficiencies were recorded of over 90 per cent. This was no doubt due to the careful way in which the stream-line flow had been conserved, together with the removal of obstructions and corners likely to form eddies and therefore to use up energy. The turbine illustrated in the Paper showed how the vertical design with the

bearings above the runner lent itself to the establishment of stream-line flow. The third point was the method of governing. Many problems were involved in the successful governing of turbines for large power plants, and the way these problems were solved was well worth close study.

In conclusion, Professor Dalby ventured to suggest that there was an interesting line of comparison between water-turbines and steam-turbines. In the Parsons and other types of steam-turbine an efficiency of 90 per cent was common. A comparison of the methods of design and calculation between the water- and the steam-turbine would prove highly instructive. Both were prime movers. The outstanding difference between the fluids was that the volume of water was practically independent of pressure and temperature, whilst the volume of steam was a function of its pressure and temperature during expansion.

A valuable discussion would no doubt result from the Paper, and he again desired to express his thanks to the Author for the manner in which he had brought together so much information of interest to engineers.

The CHAIRMAN said that other business remained to be done before the conclusion of the present Meeting, and as it was certain that the discussion on the Paper would have to be adjourned, he thought it would be better to adjourn it at once and resume it at the Annual General Meeting.

The Discussion was then adjourned.

Discussion in Manchester, 29th January 1920.

The CHAIRMAN (Mr. J. Phillips Bedson, *Member*) said the Paper was of very great interest. The powers mentioned were so great in comparison with those obtained in this country—hundreds of thousands of horse-power, instead of 250 to 500—that it was difficult to realize the large amount of engineering experience which had been gained on the Continent and in the United States in the development of water-supply for power purposes.

Mr. Joseph Adamson, who was not able to come to the Meeting, had asked him to put this question with regard to Fig. 20 (page 103): "How do you make the joints tight at the bolts?" On referring to Fig. 20, he observed there was an indication of some joints, but whether those were the joints Mr. Adamson referred to, he could not say. The pressure of the water was very great, and it must be a matter of the utmost importance how the joints were made and secured.

His own experience of water-power was limited. In 1874 he became interested in an installation of two 120 h.p. turbines, not of the kind which had been described in the Paper, but what was known as the Fourneron type, which was very much in vogue at that time. Those two turbines ran continuously night and day from 1874 to 1914 with the minimum of expense. They had since been replaced, with much advantage, through the greater economy in the use of the water and the increased power obtained from the new turbines. The latter were of American manufacture and he supposed they would be of the Francis type. These were running now and giving immense satisfaction. He wished he had more water so that he could develop more power. The Fourneron had very small orifices, and one had to keep it free from leaves and similar troubles. These new turbines would pass almost anything in reason; and on the question of expense, he might make the following comparison. He had water, steam, gas, all of about equal powers. He reckoned water as 1, gas as 15, and steam as 50, which was the relative proportion of the cost of running.

Mr. SYDNEY A. SMITH said that he had seen during the last ten years some of the very large electric power plants which had been installed in Sweden. There was very little coal in that country; consequently all coal had to be imported at a high price, and at the present time the cost was somewhere about £8 to £10 per ton. The scarcity of coal had made it essential for that country to utilize other sources of power. There was timber, for one thing, which was used to a great extent, and during the War had been used on locomotives, but better than that were the water-power systems to which the Author had referred. During the past year, and at the present time, many Americans were going to Sweden with the impression that they could teach the people something, but when they had been there a little longer, they would find the Swedes were not as slow as they imagined. Hydro-electric power installations were to be found all over the country. Nearly all the works, and even the refreshment rooms on the railways, were run by electricity, and most of the iron mines had complete electric installations. At one of the large mines, where the workings were carried to a depth of 400 metres, they were winding from two pits about 2,000 tons each in an 8-hour shift. That mine was worked, both on the surface and underground, by electricity as a result of the development of hydro-electric power stations. Those who had not visited the country had no idea of the immense power produced in this way. On an estate, which he knew very well, power was generated and sent out at a pressure of 60,000 volts—a pressure which was practically unknown in this country—and it was conveyed often for long distances up to 30 miles. Wherever a mine was opened, an electric power line would generally be found within a short distance. Power was supplied at the very low price of 50 to 60 kroner (equivalent to £3 6s. 8d.) per h.p. per annum. If 100 h.p. were required, it could be got for a little over £300. As the late Sir William Bailey used to say, the great thing in life was to concentrate. Sweden had concentrated on electric power and could teach the world something about it.

The members had been told about the large power-stations. There were also a great number of small power-stations. On a

(Mr. Sydney A. Smith.)

stream, which in England would not be thought anything of, the Swedes would install a small water-turbine power-station producing 25 or 30 h.p. A short distance further along the stream—half a mile or so—there would be another small power-station established. The great thing in these smaller hydro-electric power-stations was the reliability of working. Even when the ground was covered with snow and everything was frozen, they kept a man breaking the ice to keep the water flowing. Except in the winter, practically all that it required was a man to go there every morning and look round, take his oil-can and spend about a quarter of an hour seeing that the machinery was all right, and it usually required no further attention until the next day.

Mr. J. G. WALTHER asked the Chairman if Mr. Smith would repeat the figure he gave as the price of electricity in bulk in Sweden.

Mr. SMITH replied that it was £3 6s. 8d. per h.p. per annum. In 1912 he made a contract for 500 h.p., and the contract price delivered at the transformer house was £3 6s. 8d. per h.p. per annum, day and night service, although the Power Co. had to put down a special power-line for a length of about 20 miles.

Mr. WALTHER said it occurred to him it was a fairly cheap rate to anyone who could make use of the power day and night, but for ordinary day-load and considered as a pre-War price, he did not think it would be so cheap in comparison with other systems of producing power in this country. He was not complaining there was any overcharging, but was simply trying to make a comparison with pre-War costs in this country. That was the whole point about the introduction of water-power in this country. If ever it came, as they hoped it would (and they had the authority of the Prime Minister who recently said that it ought to come and that it would come), then it would have to come on its merits. In this country, water available for power purposes was not in the place where they wanted it, moreover it was intermittent in flow. It would be interesting if the Author would indicate what he

considered to be the possibilities of water-power in this country, considering the present high cost of coal, also would he state which type of water-turbine he thought should be developed. With low-pressure heads this would probably be the "Francis" type, although the Pelton wheel seemed to offer many advantages.

He could not claim to have had any actual experience with water-turbines, and the few he had seen were in the north of Ireland or the north of Scotland, and in both cases there were periods when they ran short of water, and were compelled to consider some other means of power as a standby. If that were going to happen in this country wherever water-turbines were installed, it would so increase the capital outlay as to be a very serious handicap. Was this not one reason for the lack of development that had taken place? He was interested to note how, to a certain degree, the more recent improvements in the design of water-turbines followed the same lines of the steam-turbines. He referred principally to the very large pipes with easy curves and branches that would only interfere with flow to the least extent, and designed so as to avoid sudden changes in velocity.

He concluded there were serious objections to the vertical type generator, although the Author had referred to American engineers again favouring this type in connexion with water-turbines. One advantage of the Pelton wheel was its horizontal type, as shown in Fig. 40 (page 134). Certainly it was an easier matter to look after the bearings, when they could have the shaft well supported by a number of bearings, than if the entire weight were supported from a foot-step bearing.

Mr. WILLIAM INGHAM said the first thing which struck him about Mr. Bergstrom's Paper was its comprehensive nature. He had been greatly impressed by the remarkable progress shown to have been made in the utilization of water-power, and the development of the turbine, both for water and steam, during the past two decades. The Paper carried him back some twenty or more years to an occasion when he spent a night in the Scottish Highlands at Glenborrodale Castle on Loch Sunart, Argyleshire,

(Mr. William Ingham.)

the Scottish seat of Mr. C. D. Rudd, the South African multimillionaire, for whom he had been carrying out some engineering work. He had a vivid recollection of sailing into Loch Sunart after dark, and seeing the Castle on the hillside overlooking the Loch, one blaze of electric light. On looking into the source of the power the next day he found this was obtained from a small Pelton wheel placed under a steep waterfall, and he remembered thinking at the time what vast reservoirs of power there must be in these waterfalls, and the gain which would accrue if these potential forces could be fully utilized.

The very general recognition and exploitation of the elementary principle that power was the product of speed into resistance had led to the adoption of the amazingly high speeds now attained in the internal-combustion engine, often reaching some thousands of revolutions per minute, and had rendered possible successful navigation of the air. The Author, in this Paper, had shown that by a similar recognition of first principles, man had been enabled to harness the power of falling water to his service, and with even a small head and great volume, it had been demonstrated that a vast amount of mechanical power could be obtained within the British Empire.

The experience in Switzerland and Norway, where they had vast stores of the "white fuel" (as running water had been not inaptly called), appeared to him to bring them appreciably nearer to the time when the energy of the tides could be utilized. The rise and fall, that is, the available head, was certainly small, but the volume of water was almost illimitable. He was led to make these remarks by noting in the Paper the smallness of the head (in many cases as low as 17 feet), by which, owing to the high efficiency of the Francis low-pressure turbine when a sufficient volume of water was available, great power could be obtained.

By the development and perfection of the steam-turbine, he noticed only last week that some makers were able to give a guarantee of 6 lb. of steam consumption per i.h.p. per hour, which was certainly a remarkable advance on the 3 lb. of coal or 24 lb. of steam required per i.h.p. per hour some thirty or forty years ago.

Mr. E. L. LEEMING said it seemed to him that the utilization of the force of the tides was what engineers in this country must look for rather than that of inland sources of water-power. He had recently been doing experimental work with an engineer who had devised an apparatus which would float on a stream. The flow would be confined between two vertical sides, possibly bell-mouthed at the entrance. The apparatus would float with a continuous series of blades—something like an endless series—and possibly the speed would be about one-third of the flow of the water. It seemed to him that was a very cheap method of obtaining power, though to what extent power would be got for the capital involved it was not possible to say just now. But there seemed to be a good chance of getting power out of the tide which was regular. In many cases the velocity of the water was considerable. At Fleetwood, for instance, the velocity was tremendous, and the rise of the tide was about 30 feet. He would like to know whether the Author had any experience of the utilization of the tide; and if he thought that this floating apparatus offered some possibilities of obtaining energy economically.

Mr. A. DUNDERDALE observed that in North Wales two municipalities had under consideration hydro-electric schemes for lighting and power. In one case three tenders were sent in—for steam, gas, and for water. After taking everything into consideration—the capital, the interest, etc.—the water scheme was shown to be by far the cheapest. Whether it would be adopted he did not know at the moment, but it was suitable for the circumstances. The population in the district to be supplied was fairly scattered, and it would be necessary to generate at rather high voltages and transform down, but he thought the saving effected by using water would very greatly compensate for any loss of efficiency due to transformers.

Mr. F. STONE said that in this country they had not the water resources which were available in Tasmania, Norway, and parts of

(Mr. F. Stone.)

America. He agreed that the greatest hope here was the utilization of the tides. Some time ago he visited the Chester hydraulic station and was much impressed with the fact that it worked splendidly with a very small head of water. Where the Chester station was situated the river was tidal. Some years ago he saw the Llanberis Power Station and was also impressed with its simplicity. With a head of 1,200 feet they were distributing current over an area of, he thought, about 200 square miles, at a cost of a penny for 10 units. They were supplying it to the British Aluminium Corporation who also had a hydro-electric station on the River Conway. When the capital cost could be reduced so that current could be supplied at one-tenth of a penny per unit, they could look forward to a time when coal would be abandoned and they would use hydro-electric stations exclusively. But the future of England lay really in the utilization of tidal power. It had not the rivers with the thousands of feet fall that existed in America, and other places, and he therefore looked forward to some device for using, say, up to 10 feet head of water.

He was very interested in the subject of efficiency governing, and he noted that in the Llanberis Station the method of governing was to deflect a constant stream of water from the periphery of the Pelton wheel. If the generator were working at quarter load, it used exactly the same quantity of water as though it were working at full speed. He was informed that that was the best method of governing it, and he would like to know whether there had been subsequent improvements. He could not see the point in regard to the surge-tank, unless it was placed on the Pelton wheel itself; otherwise the inertia of the water came between the surge-tank and the Pelton wheel.

Mr. GILBERT COOK said that the Author referred (page 83) to the measurement of large quantities of water by the chemical method. It was not very long since this method was regarded as at best a very rough approximation, and he would be glad if Mr. Bergstrom would give some details as to the method now used, namely, as to the chemical employed and how it was put into

the water, because this system obviously had an application outside this particular subject.

In Table 5 (page 150) giving the available b.h.p. per head of the population of different countries, he noticed that Germany and Great Britain had the same amount of available b.h.p. per head, but the proportion actually used by the latter country was only one-fifth of the proportion used by Germany. In that connexion he asked whether the available b.h.p. was the actual amount of power that could be used; that is to say, did it take into account water that could not be used for power such as reservoirs for the water supply of towns? Or was it merely water at present unused for any other purpose. The subject was most interesting, and the Author had made a very valuable contribution to the existing knowledge.

Mr. T. ROLAND WOLLASTON asked the Author's opinion as to the possibilities of a combination of the Humphrey pump with the hydraulic turbine as a power unit. He believed that the Humphrey gas-pump had not been an unqualified success—exactly why he did not know—but to some extent it had been a success, and, if he was not mistaken, it had shown something well over 40 per cent thermal efficiency. He noticed on some of the diagrams that they obtained a mechanical efficiency with turbines approximating 90 per cent. If one took them as 40 per cent and 90 per cent respectively, one obtained 36 per cent as the all-round efficiency of the combination, which easily surpassed the steam-turbine or gas-engine. He believed that a good many people were concentrating on that combination, and he thought the Author must have given some consideration to it.

Another matter to which he might allude was the cost per h.p. per annum. He had occasion to go into this problem from almost every point of view. One speaker had mentioned £3 6s. 8d. per h.p. per annum. He remembered Professor Donnen, when speaking at a meeting of the Society of Chemical Industry, held out great prospects for the British chemical industry if and when the cost of the horse-power was reduced to 30s. per annum. He need hardly

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(Mr. T. Roland Wollaston.)

mention that that was before the War. The price of £3 6s. 8d. per h.p. per annum was phenomenally low; there was no possible way in which it could be obtained at the present time. He did not see how any other combination but a hydraulic arrangement such as had been described could possibly give them horse-power under £4 per annum, unless some rebate were obtainable from by-product recovery from the fuel.

There was one other point touching upon that question. The great difficulty in connexion with hydraulic turbines was the enormous capital cost in civil engineering preparation and the standing charges thereby set up. He remembered a young friend, who had been for some years with Escher Wyss and Co. in Switzerland, told him that of the proposals put before that firm a very large number did not culminate in hydraulic installations, but in steam or gas installations, for the simple reason that the capital charges on the hydraulic installation were prohibitive. If they could avoid these capital charges, no other source of power could compete with it.

In Fig. 13 (page 91) the Kingsbury thrust-bearing was illustrated. With regard to this he wished to ask whether the Michell thrust-bearing had yet been used in hydraulic turbines? If not, it ought to be, and it would prove a very substantial improvement.

Mr. E. M. BERGSTROM, in his reply, stated that he wished to record his appreciation of the reception given to his Paper and to thank those who had taken part in the discussion. He understood that the Chairman's question about the joints in Fig. 20 (page 103) referred to the vertical joints on the spiral casing. They were machined joints, and the effective head on the casing was 75 feet, which, after all, was not very high. To make the joints tight there was a recess, and the practice was to use a thin paper gasket for those pressures, but for high pressures rubber gaskets were used.

He was grateful to Mr. Smith for his remarks about Sweden, but his reference to America required some qualification. In the Paper he (Mr. Bergstrom) had particularly emphasized the importance of the interchange of ideas between America and

Europe, as far as the development of the turbine and its manufacture were concerned, and he was certain the same remarks would also apply to other manufactures. America developed the turbine experimentally and then came to a standstill, the reason for which was ascribed by an American authority to the tendency in that country of considering the manufacture of turbines of little above the class of agricultural implements, instead as a high-class machine which should be constructed on most up-to-date lines. In Europe the development on a scientific basis and improved manufacturing methods enabled them to design very much more efficient plants and to become the pioneers even in America for development of hydro-electric power on a large scale, until in this latter country it was realized that it was necessary to adopt improved methods in the manufacture and design of the hydraulic turbines, the development of which had enabled water-power to be developed on the scale it was to-day. During the last fifteen years, America had, however, made tremendous progress, especially in the development of Francis turbines for large units, with improvement of high-speed runners and efficiencies, and it now ranked second to none. The recent development in America had had a most useful effect in the renewed efforts in Europe to extend the possibilities of the Francis turbine both in respect of speed and efficiencies, the result of which he had endeavoured to show in his Paper.

Mr. Smith referred to the cost of water-power, a subject which he had purposely not touched on in his Paper. In itself it was a very large subject. The cost of water-power varied so greatly that it was impossible to lay down any hard and fast rule. In certain districts, where power was very expensive, water-power, if existent, would always pay in spite of its large initial capital cost. On the other hand, there were countries (Norway for instance) where in most cases high falls were available, and the cost of development per unit consequently much less, and hence they were able to develop power at a very much cheaper rate than anywhere else in the world. He knew of a contract which had been recently signed in Norway in connexion with a plant which was now under

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construction, where the contract price was only £1 16s. 0d. per b.h.p. per annum. At the same time, the Hydraulic Department in Tasmania sold power in bulk at approximately £2 to £2 10s. 0d. per e.h.p. per annum.

All through the discussion he noticed that most of the speakers seemed to be under the impression that, as compared with the large water-powers on the Continent and in America, very little could be done in this country. One object of the Paper was to give a review of the improvements and developments of the mechanical equipment of hydro-electric plant, as water-power now formed such a great question in this country, and the resources, however small, were bound to be considered in connexion with the programme of reconstruction, and he understood that a Bill on the subject was to be introduced next Session. The Water-Power Committee recently appointed were carefully investigating and studying the water-power resources of this country, and it was seen from the Committee's Interim Report that as far as Scotland was concerned there were several hundred thousand horse-power which could be immediately and economically developed. These power propositions in Scotland were, of course, far away from industrial areas, and it was necessary, therefore, to develop those powers primarily for such new industries which depended, in the first instance, on cheap power and secondly, employed a continuous process which enabled power to be utilized to its fullest extent at a high load-factor. As an example, he mentioned electrolytic decomposition of zinc as being an industry highly suitable to be developed in connexion with our water-power resources. Its success was entirely dependent on cheap power, and the process had a theoretical load-factor of 100 per cent. Then there was the manufacture of calcium carbide, nitrogen and other important electro-chemical or metallurgical processes, which were of equal importance in connexion with development on a large scale of the available water-powers in Scotland.

On the other hand there were, in this country, a large number of low-pressure installations of medium size well worthy of consideration. The Chester Municipal Hydro-Electric Static was an example of what could be done. The York Municipality

was just considering a similar installation on the River Ouse, and although the capital cost per unit might be considered high, it had been shown, after careful investigation, that it would appreciably reduce the Municipal coal bill and be a boon to the ratepayers. One must also keep in mind the simpler working of the hydro-electric station and the reduced cost of operation. He had been connected with a proposition at a coal mine, where they had on the property a comparatively small water-power, where modern turbines were installed and the power transmitted to the mine, and although they had coal there at a very low figure, the capital expenditure was justified.

Mr. Walthew referred to the vertical type of generators. One reason for their use in America was that they had built that particular type for a number of years in connexion with vertical steam-turbines. The vertical turbine was the only type which suited falls up to 10 feet, and if vertical generators were not used, gears would have to be introduced with corresponding loss in overall efficiency of the plant. Consideration, however, would have to be given to the fact that not only did the flow in the rivers in this country fluctuate to a great extent, but also the available head. Under these conditions it was often impracticable to employ vertical generators on account of the low speed, and the horizontal arrangement with gearing had to be resorted to, but when possible, the direct drive with vertical generators undoubtedly offered the best advantages.

Mr. Ingham, quite rightly, referred to the question of tidal powers. There had been a large amount of thought given to that particular subject. He remembered an excellent article which was published in a French scientific paper two or three years ago, which put together the various suggestions that had been made during, say, the last twenty years for the utilization of tidal powers. In fact, on account of the scarcity and high cost of coal, the question of tidal power had received very great consideration in France, and a Commission had been appointed by the French Government to investigate to what extent tidal power could be economically utilized. He understood the Report of the Commission had been

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already published, but he had not been able to obtain a copy, so that he did not yet know what conclusions the Commission had arrived at.

With regard to tidal powers, the question, of course, was the capital cost. They all knew that tidal powers were intermittent, and to obtain continuous working it was necessary to build two separate storage basins. It was in that connexion that the cost of dams and other civil engineering work was in most cases so enormous that generally it was found not to be an economical proposition. One particular case had been investigated in France where the natural conditions were particularly favourable for utilization of the tidal forces on account of the very short barrages which would need to be constructed, but from the figures obtained, it struck him that even in this particular case, the cost was more than £85 per kw., which, of course, was a large capital on which to pay interest for any power proposition.

Mr. Cook asked a question with reference to the chemical method of measuring quantities of water. The chemical used was in most cases, ordinary salt. On account of the short time at his disposal to reply to the discussion, he was unable to give details, but in his written reply, he would give a short description of the methods of introducing the solution in the water.

Mr. Leeming referred to some arrangement for utilizing the tides by means of a floating apparatus. Some years ago there were suggested several systems of that kind. The difficulty was that one could not store the power; large powers were got intermittently, and it was a question of being able to use intermittent power and, generally, it was not feasible.

Mr. Stone referred to the Llanberis plant governor. Since that time the plant had been modernized, and was now equipped with new governors working on the principle of combined spear and deflector regulation as shown in Fig. 39 (page 131).

Mr. Wollaston referred to a possible combination of the Humphrey pump and turbine as a power unit. This point he would have to deal with in his written reply. Mr. Wollaston also referred to the Michell thrust-bearing. He (Mr. Bergstrom)

had been rather troubled himself as to the proper name of this bearing. He understood it was invented by Mr. Kingsbury in Philadelphia, and was first used with water-turbines on the Mississippi plant. As far as he could gather, the Kingsbury and Michell bearings were absolutely identical, and were now extensively used with horizontal steam-turbines; they were manufactured in this country by Vickers, Limited.

A vote of thanks to the Author was passed.

Discussion in London, Friday, 20th February 1920,

Mr. ALAN E. L. CHORLTON, C.B.E., said that at the last Meeting Professor Dalby (page 152) had raised the question of the efficiency of the turbine as being one of the principal points in the Paper. Unfortunately, the reader of the Paper was not present that evening, and the questions that he (Mr. Chorlton) would have liked to have asked him he supposed could only be dealt with in a written reply. The efficiency of the turbine was shown in the Paper to rise to the extent of probably from 5 to 8 per cent. He desired to ask the Author what was the particular part or parts in the design, the alteration of which had secured that efficiency. He had had the honour some time ago of reading a Paper on some turbine centrifugal pumps. There was always a very close analogy between a pump and a turbine; one was a reverse action of the other. If the Author had actually secured, in his latest designs, that increase of efficiency in turbine wheels of comparatively moderate capacity, it was reasonable to expect that such gains and advantages could be incorporated, at any rate, perhaps, to a modified extent, in the turbine-pump itself. One was a convergent and the other a divergent machine, and that was where the risk lay in applying the

(Mr. Alan E. L. Chorlton, C.B.E.)

gains made in one to the other. The Francis turbine, of which the Author spoke in his Paper, was rarely used as a pump. It had been developed to a certain extent, but not to a great extent. More detail in the exact design of that turbine would be appreciated very much by himself, and probably also by other members.

The Paper was compendious, and did not go into any of the smaller parts of the design; it rather dealt with the main principle throughout. Another point he desired to raise was with reference to the Kingsbury bearing. Was that bearing the same as what was known as the Michel bearing? Was it not on a somewhat similar principle? On page 91 the Author dealt with the question of axial thrust. In turbines working under large heads the axial thrust must be very great, and the description of the automatic arrangement for securing that was not quite as clear, or at any rate appeared to him to be not so necessarily precisely done, as had been found necessary with a pump. Perhaps the Author could give some more details in regard to that point. He could only add his congratulations to those of Professor Dalby on the very excellent form of the Paper throughout.

The Discussion was then adjourned to Friday, 5th March.

Discussion in London, Friday, 5th March 1920.

Mr. LOUGHNAN PENDRED, in opening the discussion, thought that one of the weaknesses of any Paper which endeavoured to cover a very wide field, was that the Author laid himself open to the charge of making omissions. In the present Paper the Author had dealt with hydraulic turbines in many parts of the world, and had endeavoured to cover so wide a field that he had been obliged, simply by lack of space, to omit touching on many points that ought to have been referred to. So far as The Institution was concerned, a very important point indeed was raised by the very fact that the Author had not been able to touch on every problem that ought to have been dealt with. It was very questionable if Papers like the present one were really of the kind that The Institution wanted. Nearly everything that the Author said might be found in other places accessible to the members. It was difficult to find any part of the Paper that was suitable for discussion. The Paper could be reviewed, as a book could be reviewed; but nothing was put forward in such a form that the members could take it up and argue it out. He thought the greatest value to be obtained from the Meetings of the Institution was the discussion of real difficulties or real problems that came before the members as mechanical engineers; and the reading of a mere description of a number of stations was not the most profitable way in which the members could spend their time, especially if those descriptions had already been published in other places.

Turning to the omissions to which he had referred, the members would no doubt have observed that in the Tables which appeared on pages 58-61, power-stations in the United States, Norway, Canada, Sweden, Japan, and Great Britain were mentioned, but there was no mention, either in the Tables or in any other part of the Paper, of the excellent work which had been done in Italy and in France. He thought, in view of the high position that Italy had taken in the development of hydraulic power, that was rather a serious omission, and one, moreover, which the Italian

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(Mr. Loughnan Pendred.)

would feel rather acutely. It must be remembered that there were several very eminent Italian firms which manufactured turbines, among whom might be mentioned Riva-Monneret, Tosi, and Breda; and that Italy possessed many noted stations, for instance, the Vizzola station, which had thirteen turbines of 2,000 h.p. each, and which in 1901 was the largest in Europe; and the Adamello hydro-electric plant, which was referred to in a diagram (page 127)—(that was the only reference in the Paper to an Italian plant)—had five Pelton wheels of 6,500 h.p. each.

In order in some measure to make up for the omissions in the Paper, he desired to place before the members a drawing of a very remarkable turbine made by Riva. (A slide was then shown of an illustration which appeared in a supplement to *The Engineer*, 7th November 1919.) The turbine was of the Pelton type, and had two wheels of different diameters. He would be most interested to hear from the Author if other examples of that arrangement existed. The set was made for the Italian Electric Railways power-station at Bardo-Necchia. The water-power was drawn from two separate sources, one at 2,000 feet head and the other at 670 feet head. A great variation of power occurred, and an automatic device cut out the small wheel when it was not needed. The large wheel developed 3,500 h.p. with one jet, and the small wheel 2,500 h.p. with two jets.

He desired to mention another rather interesting point which also had something to do with internationalism, namely, what was called in the Paper the Kingsbury thrust-bearing, Fig. 13 (page 91). It would be seen that it was practically the same as what was known in this country as the Michell bearing, which, as the members were probably aware, had almost effected a revolution in the arrangement of the engine-rooms of steam-ships. It reduced the thrust-block, which was an enormously long thing and which caused a deal of anxiety, to quite a small space. Michell arrived at his solution of the thrust-bearing problem by a study of Osborne Reynolds's thesis of 1886, which followed Beauchamp Tower's research of 1884, in which this Institution took such a considerable pride. Michell's work was done in 1902-3-4, and

he published an account of it in the German periodical *Zeitschrift für Mathematik und Physik* in 1905. He patented his device in Great Britain and Australia in January 1905, but he had no money to spare, and therefore took out no foreign patents. Kingsbury, who was an American, filed his application two years after Michell, although Kingsbury had been working on the subject; the scientific development of the thrust-block with the tilting pieces was first worked out by Michell, who could be claimed as one of their own people, as he was an Australian. Kingsbury's claim to priority rested on the fact that under the American law a citizen of America was allowed two years priority over any foreigner, provided he could prove that he had been experimenting on his invention, and Kingsbury was able to show that he had done so. Nevertheless the principles were first laid down scientifically by Michell. The mechanical features differed, and it might be necessary to retain the distinguishing names, but in the Proceedings of this Institution, at any rate, attention ought to be called to the fact that the Kingsbury bearing was the same as a British invention, namely, the Michell bearing.

Mr. A. C. ANDERSON said that, speaking as an engineer who was doing nothing else but hydro-electric work, the Paper was rather disappointing to him, because he did not think it was sufficiently up to date, which was unfortunate at the present time when British manufacturers were trying to pull up level with manufacturers abroad in that kind of work. It was very difficult to cover so much ground as was attempted to be covered by the Paper. For instance, he was very sorry to see that the Author had omitted to say anything about costs. The first costs of hydro-electric plant were a very important consideration, and were frequently not sufficiently looked into at first, especially in regard to the development of such things as tidal power. On the top of page 57 the Author gave the Americans credit for the development of the modern Francis turbine. He did not think that was correct. He thought the Americans standardized very much while Europe experimented. Personally he would give the credit for the best

(Mr. A. C. Anderson.)

types of Francis turbine to the Swiss. It was impossible to make a water-turbine as a steam-turbine would be made. For plant of any size the turbine had to be fitted to the hydraulic conditions.

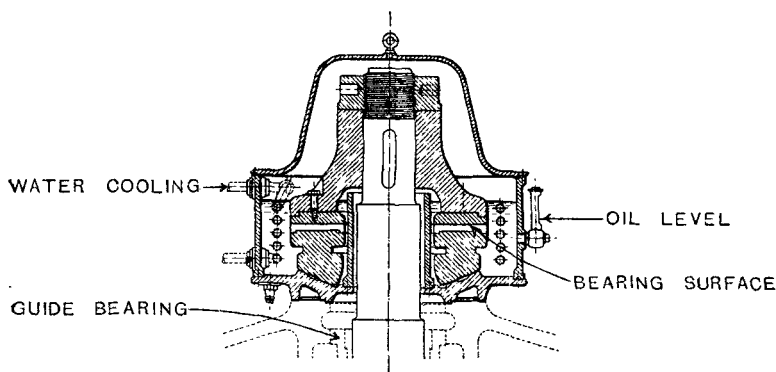
He quite agreed with the remarks Mr. Pendred had made with regard to the thrust-bearing. The Kingsbury bearing contained, however, what some people believed was an improvement on the Michell bearing, while other people regarded it as a complication. The very sweeping statement, "The most recent type of thrust-bearing is the 'Kingsbury,'" was made at the bottom of page 90. That rather led one to think that the Author imagined there were no other thrust-bearings than the Kingsbury bearing, which was not the most recent type of thrust-bearing. In his opinion one of the most recent types in use was the spring thrust-bearing, in which there was a comparatively thin babitted bearing-ring with radial oil-grooves resting on a good many springs, and bearing on that was a ring attached to the shaft. That bearing was only used by one firm, but it might have a very considerable future.

It was interesting to notice that the Author illustrated, on page 94, one of the large vertical generating units of the Cedar Rapids Manufacturing and Power Co., Canada. He believed the last two units which were to be put in there were fitted with that new spring-bearing and not with the Kingsbury bearing. The Author also illustrated on page 103 the generators at the Gatun Lock on the Panama Canal, and he understood that those three units had been converted from using a Michell bearing to the spring thrust-bearing. There were other bearings more simple than the Michell bearing, which simply consisted of rings with alternate flat and inclined sectors so as to keep the wedge principle. They were exceedingly simple and very satisfactory. One of these simple bearings was illustrated in Fig. 52. A robust disk, constituting the revolving member of the bearing, was fixed on the shaft of the turbine; this disk rested on several blocks, separated the one from the other in such a fashion that the oil, after lubricating one block, did not lubricate the next block, but was replaced by fresh oil from the container. The oil was mechanically and automatically entrained from one end of a block to the other by the mere

rotation of the revolving disk. A bearing of this type had been running most satisfactorily for the past six months on a 10,000 h.p. unit at the Hauterive Plant (Fribourg, Switzerland). The load on this bearing was 88 tons, and the speed 375 r.p.m. He was rather surprised to see in the illustration on page 91 of the Michell thrust-bearing, and also in certain other illustrations, that there did not appear to be any cooling coils shown, which, in those large generators, were very necessary in the bearing housings.

The Author went rather fully into the question of the

FIG. 52.—*Simple Bearing.*



modern high-pressure Francis turbine (page 106), in connexion with which he desired to point out that there were certain losses in that type of turbine which might be very serious if they were not carefully watched when the turbines were being designed, for example, the skin-friction loss, which was very serious at low loads because it was constant. Then again there was the question of leakage loss at the sealing rings. If the same type of turbine that was used for low heads were put on for high heads without any difference in design, losses of quite a surprising degree would be obtained. It was necessary to make special arrangements in those cases; the loss of the efficiency must be balanced against the liability to wear.

(Mr. A. C. Anderson.)

There was a slight mistake on page 135 in the description of the Fully station, which he desired to correct, namely, the jet diameter should be 38 mm. and not 34 mm. On page 131 there was given a rather full description with diagrams of the combined needle and deflector method of regulating Pelton Wheels. He was very much surprised, however, that in the Paper, which was supposed to be up-to-date, the Author did not mention at all "Seewers'" method of splaying the jet by means of vanes which could be inclined inside the nozzle itself, which was very substantial. There was less chance of getting an over-pressure in the pipe-line, and very little effort was required to operate the arrangement.

On page 143 the welding of pipes was referred to, but as far as he could see, nothing whatever was said about electrical welding, and he thought that was a most distinct omission. He also desired to refer to the following statement made on page 62 in regard to the Francis turbine, which he did not think was quite correct, namely: "The Francis turbine belongs to the reaction category; and the high-pressure impulse turbine—or more familiarly known as the 'Pelton Wheel'—belongs to the impulse category, and being the only types of turbines now employed in modern water-power development, it is unnecessary to deal with any other type except as far as historical interest is concerned." He did not think that was quite the case; in fact, he would go so far as to say that he thought the Francis turbine was practically doomed for very low falls, and he would predict that in the very near future a more efficient turbine of the axial flow type would be seen, which would be used for quite low falls. It was almost impossible, in a Paper of the kind under discussion, to cover the huge amount of ground that has been attempted under the heading of "Recent Advances in Utilization of Water-Power."

Practically nothing had been said about the civil engineering work which absorbed most of the money, and very little was said about certain modern tendencies and about electrical work. For instance, he would have liked the Author to describe what was considered by certain engineers who were engaged on that type of work, especially for very hot climates, as the most suitable arrangement, namely,

the construction of large generator-frames from reinforced concrete, making the thrust-bearing housings of the same material, water-cooling the machines, and possibly having no power-house building at all. The first cost of machinery had gone up so much that if anything of that nature could be done in far-away places where freight was high and transport difficult, it would help development schemes which might not otherwise be undertaken owing to their high first cost.

The PRESIDENT inquired whether Mr. Anderson would be good enough to supply a sketch for the Proceedings of the method of regulation by vanes to which he had referred.

Mr. ANDERSON replied that particulars and a good description with drawings of the method had already been published in *Revue Générale de L'Electricité*, 27th December 1919.

Dr. H. S. HELE-SHAW (Member of Council) requested that if particulars of the spring-bearing to which Mr. Anderson had referred had also been published, the place of publication should be given by the speaker. It was quite a new method, and he would like to know where particulars of it could be found. It would also be very useful if Mr. Anderson would give a sketch of his most interesting suggestion of a reinforced concrete turbine bearing housing.

Mr. ANDERSON said that a well-illustrated account of the spring thrust-bearing appeared in *Power*, 16th-30th December 1919, while Concrete Parts for Generators were described with sketches in the *General Electric Review* of November 1919, but the consideration of the latter question had not been confined to America.

Mr. E. LANCASTER BURNE said he desired to refer to the statement made on page 84, that:—"Although both the cylinder-gate and register-gate undoubtedly possessed certain points of merit, they have now been superseded by the modern wicket-gate." It seemed to him that that statement required qualification.

(Mr. E. Lancaster Burne.)

His own experience had been with small water-powers up to about 45 h.p., and he knew many small water-powers in this country, employed in driving flour and other mills, where the load was pretty constant and the water-supply ample, and where the lower efficiency due to the cylinder-gate and register-gate did not matter very much. He thought the simplicity and the low first-cost of turbines with the cylinder-gate, or with a gate to the casing, ought to be borne in mind. He referred to a cheap form of turbine, a great many of which had been put down in this country, several by himself, in which the turbine was situated in a scroll casing, and there was just one plain simple gate which controlled the water. The runner was divided in two halves by a partition, and it could be worked at a good efficiency with a full or half gate. That type of turbine, or one with a cylindrical gate, must be a good deal cheaper in first cost and less likely to get out of order than those on the more elaborate wicket-gate system, and there were cases where the former might be useful. For taking thrust, he had found ball-bearings perfectly satisfactory. In one instance the ball-bearings had been running for over ten years, and as far as he knew they had given no trouble whatever.

The PRESIDENT said that it was now impossible to change the name "Kingsbury" to "Michell" in the Paper, because it had already been printed and circulated. He thought, however, it should be definitely stated that the Meeting felt that this type of bearing should not, in this country at any rate, be called the "Kingsbury bearing." When the Paper was first published he asked Dr. Hele-Shaw what the difference was between the Kingsbury bearing and the Michell bearing, and he was told that in the case of the Kingsbury bearing the pivot was in the middle of the bearing, while in the Michell bearing it was one-third from the trailing end. Perhaps Dr. Hele-Shaw would explain the matter.

Dr. H. S. HELE-SHAW, F.R.S. (Member of Council), in reply to the President's question, said one difference between the Kingsbury

and the Michell bearing was that there was a spherical back to the former. Another was that the position of the pivot was different in the two cases. The principle of these bearings was that if a lubricant could by any means be induced to pass underneath, so that the pressure was increased at the back by the wedge-shaped film, unlimited fluid support could be obtained between the surfaces.

The PRESIDENT said he understood that Kingsbury put the lubricant in the middle.

Dr. HELE-SHAW said it had been found that it really did not make any difference after the effect started. The claim in the case of the Michell bearing was that the support was placed behind the centre. The stream-line method of the speaker had been used for the purpose of investigating what was going on. Instead of the metal plate a glass plate was used, so that coloured stream-lines could be observed through it. When that was done, the stream-lines were seen divided to right and left, and thus they naturally broadened. The law of stream-line motion was that the pressure was proportional to the width of the stream-line, and consequently as the lines widened out an optical demonstration was obtained of the fact that the width of the stream-lines and therefore the pressure at the narrow portion (that is, behind the pivot) increased. That was the picture which was presented by the stream-line flow, and at once explained the secret of the bearing.

The PRESIDENT said he desired to add a few words to what Dr. Hele-Shaw had said. As he understood the matter, it was necessary to get a wedge-shaped film of oil between the bearing surfaces, and the angle of the wedge depended on the viscosity of the oil, and in order to obtain uniform pressure, this angle was smaller the smaller the viscosity. At starting the oil was cold, and it had a comparatively high viscosity requiring an angle of a certain size. As the bearing heated, the viscosity of the oil diminished, and the angle ought to be smaller to maintain a

(The President.)

uniform distribution of pressure. Such a change of angle could not be effected in a fixed bearing, but by means of the Michell bearing, supported as described, the angle was automatically adjusted to correspond to the viscosity of the oil. He thought that was the secret of the satisfactory working of the Michell bearing.

Dr. HELE-SHAW said the reason which had been suggested as to why the bearing could be supported in the middle was a curious one. As the oil passed underneath, friction thereby came into play and the viscosity of the oil itself changed, that is, as it passed through the bearing, the oil became thinner and less viscous, owing to the heat which naturally resulted from the friction, and this affected the tilting of the plate. He would like to say that Mr. Michell (an Australian), whose genius had first investigated the subject, and who had advocated for years this solution of the thrust-bearing problem, while he had received comparatively small royalties hitherto from his invention, had been granted, by a Judge of the High Court, an extension of the period of his patent, so that in this country, at any rate, justice had been done to the inventor.

Mr. WILLIAM H. PATCHELL (Member of Council) said that before he discussed the Paper, he desired to remark that an illustration had just been given of the ideal type of discussion at the Institution. The delightful way in which the President and Dr. Hele-Shaw had described the Michell bearing had reminded him most forcibly of an Informal Meeting, and it was at those Meetings that real business was done!

Mr. Anderson had asked for some costs of installations. Personally, he was very sorry indeed that the Author had not said anything at all in his Paper about that part of the subject. Some time ago the Interim Report of the Water-Power Resources Committee was issued by the Board of Trade. One was apt to consider the reports of such committees as authoritative when they were issued by committees with large powers behind them, and when the reports were signed with big names. He thought, however, it was little less than misleading when a committee

based its estimates on pre-war costs, plus 50 per cent, because people were apt to quote the findings of a committee without looking at what the actual basis of the estimate was, and to presume that the Water-Power Resources Committee expected water-power in this country to be developed at a cost which was absurd. The estimate of cost put in by the Committee was £38·5 per effective electrical h.p. for certain stations. That, at pre-war rates, deducting one-third from the total, would be, say, £26. In his opinion, if the figure had been put at two and a half times the pre-war rate it would have been much nearer the mark. That meant £65 per electrical h.p., or £87 per kw., very different figures indeed, but they were the figures which engineers had to face when they were considering the development of water-power in this country. In view of those figures it was very difficult to imagine that water-power could be developed in this country to compete with big steam-turbines. He recently received from America a copy of the *Electrical World* of the 20th December last, in which one of the new Niagara Falls machines was described. It is of 32,500 k.v.a.; the station rating is 242,500 h.p., and the construction and equipment of the new part was to cost 8,000,000 dollars, that is, about 100 dollars per kw. Not reckoning the difference in the present rate of exchange, that came out at about £20 per kw. This included deepening the channels and constructing three new penstocks with the power-house extension, which he presumed was chiefly for mechanical and electrical work. One of the machines was by Allis-Chalmers, one by G. P. Morris—G.E.C., and the other by G. P. Morris—Westinghouse, and 93 per cent efficiency of the water was claimed for them. He thought those figures would be rather useful to keep engineers humble when they were thinking about water-power developments in this country.

The PRESIDENT announced that, as the Author was not present he would be asked to reply to the discussion in writing, and the Meeting then terminated.

Communications.

Mr. J. HAROLD ARMFIELD wrote that the Author had drawn attention to a subject of vital importance to this country at the present time, and a subject hitherto neglected by British engineers. When a substantial Paper of this kind was full of so much interesting and valuable information, it might seem unjust as well as ungrateful to complain of omissions. But there was one aspect of modern water-power development which the Author had passed over, which was, he thought, of extreme importance to this country, namely, the development of small units of 30, 50, or 100 h.p. which could be used either for electric generating or for the direct driving of factories, such as flour, paper, woollen, or cotton mills, small engineering works, saw-mills, etc. It might seem that such small units were not of much account compared with the Kinlochleven units of 3,300 h.p., but he hazarded the guess that in the aggregate there was more water-power in these islands that could be economically developed in units under, say, 250 h.p. than in larger units.

The Author emphasized the advances which had been made in the design of high-capacity turbines, but he omitted to point out that by their use falls as low as 18 inches could be developed with not only hydraulic efficiency, but commercial advantage. He stated that the old "American Standardized" turbines were admirably suited to small water-power installations; but the introduction of high-capacity turbines had opened a whole new field for small installations. In May 1914, *The Engineer* published an account of a high-capacity turbine installation, for which the writer was responsible, which had a specific speed of about 85, and under a fall of only 2 feet 6 inches gave an efficiency under ordinary working conditions of 84 per cent. This turbine was somewhat similar in design to that described in the Paper as made by Escher Wyss. It had the same characteristic of a receding bucket entrance edge. The aim of the design of this turbine was not so much a high specific speed, as what might be termed a high specific capacity, that is, a large amount of water for a rotor of a given size. In this

respect the turbine in question had a slightly higher value than the Mississippi plant described in the Paper. A fairly high specific speed followed more or less automatically. The results of the first installation had been fully maintained in subsequent installations, and with this turbine it was possible to develop 50 h.p. units under 4 feet fall at a lower cost per horse-power than was possible under such circumstances, as for example, the Kinlochleven installation. It was often taken for granted that large installations were more economical than smaller ones, whereas, in the case of water-power, this was not at all necessarily so. Even for the bulk production of electric current he was by no means certain that in this country a number of small automatic water-driven stations might not prove to be the most economical method.

At this point he must join issue with Mr. Bergstrom on the question of turbine-gates. For hydro-electric plants, with which actually the Paper was entirely concerned, where close governing was essential, or where high efficiency at small gate-opening was important, he granted the superiority of the wicket-gate. But where the turbine was worked usually at full gate and where rapid governing against heavy load variations was not necessary—circumstances usually met with in direct factory driving—the cylindrical gate was, in his opinion, decidedly preferable, having the advantages of lower cost, fewer moving parts and therefore less wear, less liability to get jammed or out of order by suspended rubbish, and above all, when the cylindrical gate was closed, it could be made water-tight, which could not be effected with the wicket-gate. This was important in cases where the water was stored and used intermittently.

There was one other point in the Paper to which he would like to call attention. He was not clear whether Table 5 (page 150) was the estimate of the Ottawa Water-Power Branch; but in the figures for Great Britain there was surely something wrong. The Census of Production of 1907 gave the amount of water-power in use in the United Kingdom at 172,000 h.p. Between 1907 and 1915 there were certain developments—he thought he was right in adding the 40,000 h.p. of the British Aluminium Co. There must

(Mr. J. Harold Armfield.)

be well over 200,000 h.p. in use to-day, while the Table gave only 80,000 for Great Britain. But the figures for the potential water-power were probably at least as much underestimated at rather less than a million horse-power. Without pretending to have the data necessary for even an approximate estimate, he would be surprised to find the power capable of economical development in the British Isles, with modern high-capacity turbines, was less than three or four millions of horse-power.

Mr. W. P. DIGBY wrote that he thought the Paper was one of immediate interest to the mechanical branch of the engineering profession, and would, he hoped, be followed by a parallel Paper at the sister Institution of Electrical Engineers on the design of Generators with reference to the conditions ruling on Hydro-Electric Installations. There was room also for further details concerning pipe-line construction and operation, and above all, in the water-turbine or Pelton Wheel itself, they had plenty of ground for further study.

He was by no means certain that they had arrived at a satisfactory selection of materials for the nozzles for Pelton Wheels, and he felt also that sufficient attention had not been given to the serious wear due to corrosion and erosion at this point. Such wear was of a grave character because of the waste of water and loss of efficiency involved. There were, however, very few installations which kept complete records of their water consumption and translated this into cubic feet of water per kilowatt-hour. If this were done more frequently, the demand for replace nozzles and needle-valves would be increased in a good many installations.

Then again, the material for the buckets of Pelton Wheels was by no means standardized. Part of this was due to variations in conditions; a good deal of wear was due to faulty construction and insufficient settling and screening tanks. He knew one case at the moment where some wheels with cast-iron buckets, put down twenty years ago, were still giving excellent service, whereas at the same plant and fed by the same pipe-line, other wheels put down more recently had had to have their cast-iron buckets renewed

twice within three years. This was probably a case of faulty mixture in the foundry.

The Author's reference to the installation at Trollhättan was specially interesting. He did not, however, refer to their method of meeting that serious trouble known as "needle-ice." There, with the whole of Lake Wennern behind them, which lake was frozen in the winter, a good deal of grinding of the ice-floes took place. Needle-ice was melted by warming the water before it entered the Francis type turbine—low tension transformers supplied the necessary current to grid resistances. He was told that as much as 12½ per cent of the maximum rated output at the station was used for this purpose. Yet, without such a device new runner-wheels would be required each summer. Corrosion effects in pipe-lines also needed study, as greater corrosion took place with some forms of welding than with other forms. It was really surprising what good work was done in this country to-day with both longitudinal and circumferential welds. They were not, however, in quite such a happy position as was desirable with regard to internal coating of pipes and the need for securing uniformity of that coating. Sooner or later they would have to agree on something in the way of standardized drastic tests for coatings, as when once a pipe-line was erected and corrosion commenced, any local remedies which could be applied with a paint brush were purely palliative.

They seemed to be on the verge of a great development in hydro-electric work throughout the Empire. To those concerned in this, much could be learned in regard to both large and small scale installations by visiting the French and Italian slopes of the Alps. There, the utilization and conservation of water-power had been undertaken with all the successful frugality which one associated with the wife of a French peasant in culinary matters. Imperial demands would be large and small, and we were apt, perhaps, to be carried away with the magnitude of the 50,000 and 100,000 h.p. schemes. But there was much to be said for the use of small isolated installations of 150 to, say, 400 h.p. There were many promising areas whose development could be helped by small plants,

(Mr. W. P. Digby.)

but in regard to the future, as all our development now seemed to be attached to official "apron-strings," he could only hope that the official wearer of the apron would be far-sighted and intelligent.

Mr. PERCY GRIFFITH wrote that he felt some hesitation in entering into the discussion of this Paper as he was unable to contribute anything relative to the mechanical details of turbines or other plant for utilizing water-power. Nevertheless, the Author had referred to the fact that the utilization of water-power was an important factor in the national economic problem, and to the necessity of providing safeguards for the protection of other interests, so that he (the writer) felt justified in calling attention to the fact that the Author in this connexion mentioned "fishing and other vested interests," but omitted any reference to the prior claim of the community to water for domestic and other uses. It was unnecessary and would be inappropriate to enlarge upon this point, seeing that a Departmental Committee was sitting to consider the question of water-power utilization on a national scale; moreover, this Committee had recently extended its numbers and enlarged the scope of its investigations in order to include the question of water-supplies generally. The Chairman of that Committee (Sir John Snell) had stated before The Institution of Water Engineers that the Committee had realized the necessity of safeguarding the public water-supplies before allocating any sources for power purposes, and it was therefore unnecessary to labour the point on that occasion.

It was desirable in this connexion to consider the possibility of utilizing such power as was available for large works of water supply, because there were certainly cases where, with very slight modification of a water-works scheme, a certain amount of power could be utilized without in any way interfering with the supply of water to the cities and towns concerned. This was even now utilized to a certain extent for temporary use during the construction of the works, but it did seem possible that some permanent sources of power might thus be rendered available which were now wasted.

As regards water-power, this country was not topographically well adapted for providing a large quantity of power under satisfactory economic conditions, and before any appreciable amount of power could be economically utilized, it would be necessary to establish works within the economic range of distribution, which, even in the case of electricity, was limited. This would involve capital outlay in providing a demand as well as a supply, a consideration which might be feasible in a new country, but which was almost out of the question in Great Britain. For this reason the Author's statistics (page 150) giving the available b.h.p. were open to question when considered from the point of view of economics.

The question of economics could be approached from two different points of view: (a) financial advantage; and (b) national advantage.

(a) *Financial Advantage.*—Capital could not be obtained for water-power development unless the cost of power so supplied was less than any alternative source available. While working-costs for water-power were practically negligible, the capital charges were very high, and these were governed by the location of power supply-works relative to the demand. It would therefore be interesting if an estimate could be made of the water-power *economically available* in this country. Sir John Snell, addressing the Water Engineers in June last, expressed regret that there were not more engineers in this country with expert knowledge of water-power problems, but he (Mr. Griffith) ventured to say that such men would soon be available if there were any clear and appreciable demand for them. The reason this demand was not apparent was, he believed, because the amount of water-power *economically available* in this country was very small.

(b) *National Advantage.*—This question arose on the present emergency conditions relative to the supply of coal. Quite apart from the reduced output, and the increased cost of production and carriage, the foreign demand (especially in France and Italy) was very acute, and it was a question of national advantage to release as much coal as possible to meet this demand abroad. It was,

(Mr. Percy Griffith.)

however, impossible to secure the development of water-power (otherwise unremunerative) for this purpose unless the deficit were made good from national resources, that is, by a Government bounty. Such a solution of the difficulty would, however, be very unsatisfactory, partly because present conditions were due to causes which would, in course of time, disappear, and partly because of the difficulty of arriving at any basis for calculating the amount of the bounty.

It seemed to him (Mr. Griffith) that the use of alternative fuels, such as oil or gas, would in most cases prove a more satisfactory solution of the difficulty in regard to coal than any large development of water-power in this country.

Major C. M. NORRIE wrote that it had been the habit to ascribe to American engineers a credit, much too large, for the advances in turbine development in the last 50 years or so. Possibly the greater ease in reading up the results of tests and experiments published in English had given to our insular minds an impression that the American practice was in advance of the continental, because the painstaking and scientific investigations of Swiss, French, Italian, and Swedish engineers were not so familiar to us on account of the language difficulties. Probably in the design of high specific-speed turbines for low heads this ignorance of continental achievements caused Mr. Bergstrom to ascribe to American Engineers the credit for wheels of specific speeds of 95 to 100 (page 74). Continental manufacturers had passed this limit, and with marked success. It was hardly fair of Mr. Bergstrom to publish his Fig. 5, giving results obtained in 1909, without adding a similar figure showing results in 1914. The results given by test runners, as an indication of future practical development, would even be of great interest, and if the Author could add further information on this subject it would be valuable. As an instance of a recent test with a new type of runner, the writer had noted one giving an efficiency of 84 per cent with a specific speed of 119. The same runner, run at the same revolutions per minute, under a 40 per cent reduction in head, gave an efficiency of 68 per cent

with a specific speed of 146. These results were far in advance of the results shown for 1909 and indicated that the consideration of the development of this class of runner was worthy of much more attention than Mr. Bergstrom had thought fit to give in his Paper.

One of the difficulties in the design of high specific-speed runners had been the high runaway speeds obtained. As a matter affecting the electrical plant coupled to the turbines, the question of runaway speeds was important. It would be of some help if the Author would give some information regarding the most recent results in the limitation of the runaway speed to under 200 per cent of the normal speed. Some of the high specific-speed wheels would attain 400 per cent, were not safety-brake arrangements provided. The Author seemed to have ignored this question altogether.

Another point of interest to the generator design was that the point of maximum efficiency of a high specific-speed runner was at a point closer to maximum load than in the case of a low or medium specific-speed runner. There was therefore no necessity to provide overload in the generator, as the turbine maximum load could be used as it was practically at maximum efficiency. Generally, he thought that the Author was right in his remark on the future of high specific-speed runners. The day was not far distant when the Francis turbine would be a thing of the past for low heads. Every recent development in testing pointed to the reversion to the axial runner.

The Author's remarks on the design of the draft-tube were important. In some installations where only a fraction of the total turbine units were erected in the first instance, but where the draft-tube for all the units was constructed, the opportunity to take advantage of the most recent turbine development had been prevented, as the draft-tubes suitable for the initial turbines at the time of first construction of the powerhouse were incapable of utilizing to the fullest efficiency the more modern turbine of later years. The expense of changing a draft-tube already constructed might often be too great, and thus the extensions to the power at the station were not put in to the best advantage.

(Major C. M. Norrie.)

Hydro-electric development had passed through various stages. Unfortunately there existed still in some quarters the idea that the success of the whole development depended upon the electrical engineer. The latter was the first to be consulted, and perhaps rightly, as the market conditions for the sale of electrical power had first to be established, and as the nature of the electrical load must influence the scheme as a whole. Too often, however, the electrical engineer had usurped the place of the hydro-engineer, and the resulting lay-out, based on erroneous hydraulic assumptions and knowledge, had either not utilized the maximum hydraulic possibilities, or had insisted on the establishment of works and plant too large for the existing conditions.

The powers which were available in a river, whether with or without storage, could not be authoritatively stated on general lines for different climates and topographical conditions without careful and extended gaugings and observations, during conditions of flood and drought, made on the particular river to be harnessed. All hydro-engineers were agreed on this, and progressive countries, jealous of the future powers to be developed, had established officers to maintain and collate such observations. Great Britain, although possessing considerable water resources, had not yet undertaken such a duty, and the subsequent power development, which was bound to come, would have to be undertaken without the benefit of the accurate knowledge which such countries as Canada, Switzerland, Norway, the United States, and some of our larger Colonies, were now collecting for future use. When it was realized that the bulk of the capital cost of a hydro-electric scheme lay in the civil engineering works, bringing the water to the turbine plant, the importance of the above remarks would be obvious. A 25 per cent excess expenditure on these works, or a 25 per cent decrease in the water available below the estimated minimum flow might be quite sufficient to turn an otherwise financial success into a failure, whilst similar excess in the cost of the turbine and generator plant would probably affect only very slightly the financial stability. In other words, the high efficiencies and progressive development attained by the turbine and generator manufacturers

might be utterly discounted by the inexperience of the man employed to lay out and execute the civil engineering work.

MR. WILLIAM T. TAYLOR wrote that the development of water-power in this country had not, up to the present, been given very close attention. In fact, the general impression always seemed to be that the location of water-power in relation to a good commercial power-market, and the large number of vested interests in the way, coupled with a relatively poor power-output, did not sufficiently interest engineers and capitalists. Much evidence was available to prove the soundness of these views, particularly so as regards the question of vested interests, but they were much weaker to-day because of the difference in the price and quantity of coal, and danger of interruptions due to railway and miners' strikes.

The subject, as covered by Mr. Bergstrom, was strictly on the utilization of water-power from the standpoint of the turbine and its auxiliaries. In a brief way he treated with the generalities of the subject and illustrated certain proved facts from actual installations, principally from American practice. Several notable examples were mentioned, such as the Keokuk, the Cedar Rapids, the Tallassee, the Appalachian, and the Forsse plant, etc., all of which ought to be carefully studied throughout by hydro-electric engineers in this country, as there were many valuable points to be had from all of them.

As a hydro-electric engineer, the writer was glad of this Paper, which treated in this general way with turbine installations and their speed regulation, because it came more or less as a warning to British engineers, and brought them face to face with figures and facts showing how near they were to being practically out of the field. The position of our turbine manufacturers in relation to the majority of those given in Table 4 (pages 78-9) was not a very satisfactory one. In fact, if our manufacturers were asked to tender to the specifications of the majority of those installations given in Table 2 to Table 4 inclusive, it was questionable whether they would meet with much favour, for the reason that they had not had actual experience in designs and installations of such magnitude.

(Mr. William T. Taylor.)

There was no question as to our ability, in fact the Hydro-Electric Commission of Canada was willing to favour British manufacturers, provided they could give satisfactory guarantees and efficiencies, but it was quite another matter with an independent power company as, for instance, the Tata Hydro-Electric Plant, who might ask for tenders in an open market, and accept only the best guarantees and efficiencies with the maker of widest experience in the field. Unfortunately, some of the promised guarantees and efficiencies had either not been met, or had been short lived, that is, secured only under special conditions for acceptance tests. In view of failures of this kind, specifications and guarantee requirements were now drawn with great care, invariably including provision for final acceptance tests *on site*, the manufacturer being subject to a fine if the guaranteed efficiency were not reached.

The efficiency of a turbine installation might mean the difference between a plant paying a fair dividend, and one losing money or not paying any. That is to say, a turbine installation of, say, 78 per cent efficiency paying a dividend, might not be able to pay if the maximum efficiency remained at 72 per cent, even though the total cost for such a turbine installation was but 6 per cent of the hydro-electric development. In money the output loss would mean a decrease in value of the same percentage for the entire development, including the water rights, reservoirs, dam, conduit-line, turbines, generators, transformers, transmission lines, and, in fact, everything which was covered by the total amount invested. Furthermore, important advantages purely from the standpoint of operation and maintenance were secured by the installation of the best turbines, and there was the advantage of lower generator cost due to an increased speed, and the lower cost of power-house due to the smaller diameter for the same output; there was also the higher generator efficiency due to better design made possible by the higher speed.

The efficiency of the turbine itself was taken as the h.p. output at the turbine-shaft divided by the water-power h.p. supplied to the turbine, as calculated from the actual quantity of water flowing through the turbine and the effective head measured at the unit.

However, the efficiency of the hydro-electric development was an entirely different matter, for it was taken as the electrical output from the generators, transformers, or transmission line, as the case might be, divided by the *total* potential water h.p. as calculated from the *total* flow of water through the turbines and other auxiliaries, together with any leakage and spillway discharge, and the head as measured from the *still water* levels in the head-race and tail-race.

Without doubt the most notable developments in water-power practice (hydro-electric practice) had been in connexion with low-head installations, and more particularly in the perfection of the suction or draft-tube design and in the "high-capacity" vertical single runner. In fact, the writer would like to emphasize that the controlling factors in the design of a hydro-electric plant were the runner, the draft-tubes and wheel-chambers, etc. The vertical runner combined simplicity and accessibility of mechanical parts with superior efficiency due to an unobstructed draft-tube, minimum friction of rotating parts, and convenient application of the casing, whether of metal or concrete, which was the most efficient form of turbine casing thus far devised. In the discussion of this Paper the writer had in mind only the low-head developments common to this country. The world's most powerful hydro-electric turbine was placed in commercial service less than three months ago. The installation was made for the Niagara Falls Power Co. at Niagara Falls; the normal rated capacity of each turbine (vertical single-runner type) is 37,500 h.p., and the speed is 150 r.p.m. The head is 214 feet. This mammoth turbine is coupled to a three-phase, 25 cycle, 12,000 volt, 32,500 k.v.a. generator.

The best practice of to-day adhered to the single vertical turbine, and as a factor in the efficiency of the turbine as a whole the draft-tube played a very important part. The velocity of the water as it left the runner and entered the draft-tube represented a considerable part of the available energy—the function of the draft-tube was to recover this energy and convert it into useful work. The casing, if of spiral or volute form, and for very low heads, was usually moulded in the concrete foundations

(Mr. William T. Taylor.)

of the power-house. For ordinary low heads it was made of cast-steel, or cast-iron or riveted steel plate, as conditions might require, but sometimes the metal casing was embedded in concrete under the floor which supported the generators, and in other cases it was used as a support for the generators. If the casings were large and the head fairly high, it was advisable to embed the metal casing in concrete to avoid damage due to possible dangerously excessive stresses.

In actual practice it was difficult to secure very high characteristic speeds without correspondingly high velocities of the water at the runner discharge, and velocities as high as $0.8 \times \sqrt{2gh}$ would probably incur very great efficiency losses if the draft-tube were not of the very best design. The exit velocity from the draft-tube should preferably be kept under $0.1 \times \sqrt{2gh}$ with an additional limit of 6 feet per second flow. As an example showing a little of the history of turbine design and the advancement of turbine practice, the following would be found interesting:—

A = over-shot turbine.

B = Fourneyron (Tremont) turbine.

C = Nagler Turbine (high-speed low pressure).

D₁ = Francis Turbine (medium speed).

D₂ = Francis Turbine (low-speed double runner).

E = Impulse (Pelton) twin type } (old type)
 } (modern type turbines).

	Old type.		Modern type.			
	A	B	C	D ₁	D ₂	E
Head in feet	14	14	14	200	400	2,000
Total H.P.	50	180	500	40,000	20,000	20,000
H.P. of runner	50	180	500	40,000	10,000	10,000
Speed in r.p.m. . . .	10	53	200	150	360	375
Diameter of runner in						
feet	12	3·5	6	10·83	6	8

In terms of unit values, wherein the characteristic speed of a runner was the speed in r.p.m. which a model of that runner would have if operated under a head of 1 foot, this model to be

reduced proportionally in all dimensions from the original until it would develop 1 h.p. under 1 foot head, we had for the above comparison of old and modern turbines:—

	A	B	C	D ₁	D ₂	E
Unit h.p. . . .	0·95	3·44	9·55	14·14	1·25	0·11
Unit speed in r.p.m.	2·67	14·16	53·5	10·61	18	8·39
Characteristic speed in r.p.m. . . .	2·66	26·3	165	40	20	2·78
Characteristic diameter in inches.	148	21·5	23·3	34·7	64·6	290

To obtain the corresponding characteristic speed in metric system, multiply by 4·45 or

$$\text{r.p.m. by } \frac{\sqrt{P}}{h^{\frac{1}{4}}} \text{ (foot-lb. system)}$$

$$\text{and } 4·45 \times \text{r.p.m. by } \frac{\sqrt{P}}{h^{\frac{1}{4}}} \text{ (metric system)}$$

wherein P = h.p. output of each runner.

h = head.

The formula showed that for a given r.p.m. and head the h.p. output is proportional to the square of the specific speed, also that for a given head and h.p. the r.p.m. is proportional to the specific speed. To facilitate matters, a straight line logarithmic chart, fig. 53 (page 194) is attached from which all desired calculations can be obtained.*

The writer could not agree with the statement of the Author that "it may be stated without exaggeration that the progress in the application of water-turbines is to a great extent due to the satisfactory solution of the governor problem. . . ." Speed regulation and control was of great importance where turbines were employed for running alternators, and this had always been so, long before the perfections described above were known to hydro-electric practice.

Speed regulation was limited by the length of, and velocities in, the penstock and draft-tube, the length of water column in the

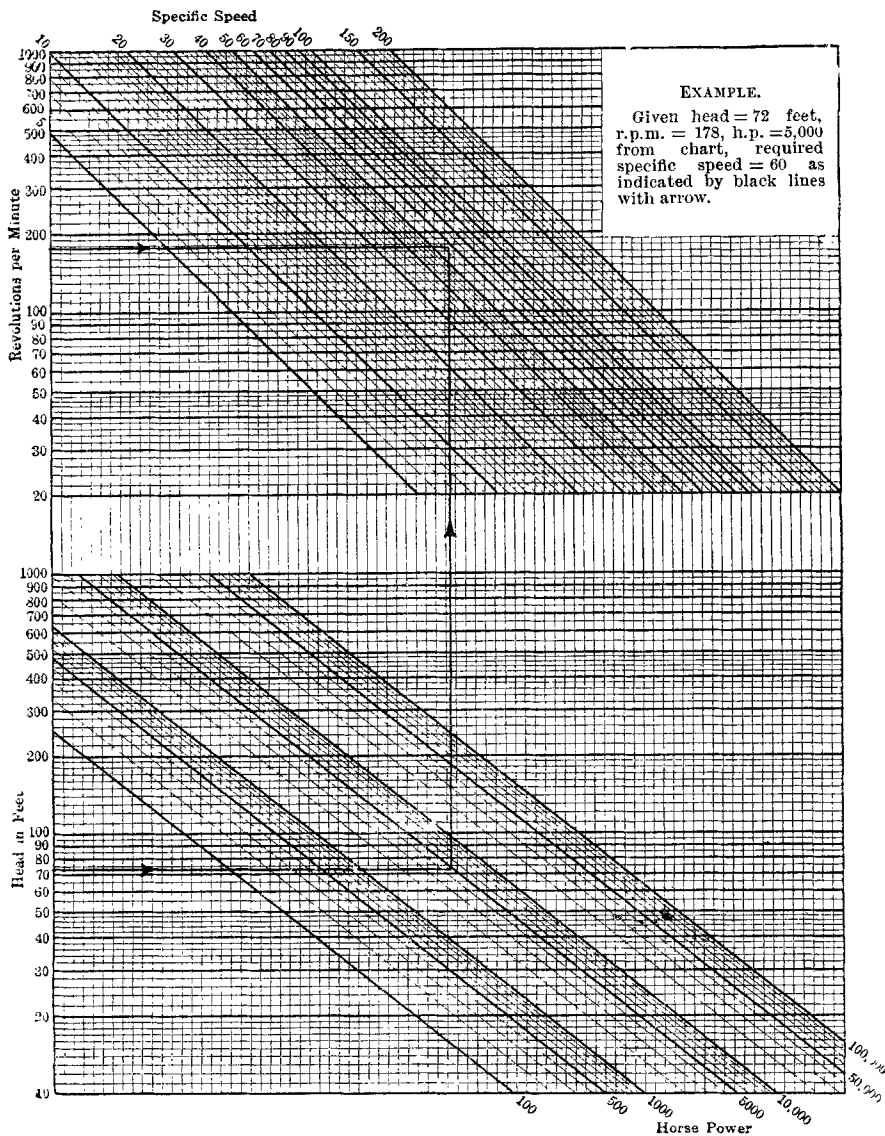
* By the kind permission of the Wellman Smith Owen Engineering Corporation, Ltd., London, W.C.2.

(Mr. William T. Taylor.)

FIG. 53.—*Straight Line Logarithmic Specific Speed Chart.*

DIRECTIONS.

Given head, r.p.m. and h.p. of one runner; project vertically the point of intersection between horizontal head line and diagonal h.p. line in lower diagram to horizontal r.p.m. line in upper diagram, diagonal line passing through this point indicates specific speed of runner.



turbine casing and the fly-wheel effect of the rotating masses, and to some extent it was controlled by the design of the power development as a whole. In low-head plants it was impossible for the governing mechanism to respond instantly to changes in load, for the reason that the heavy gate mechanism required an appreciable time to move, and it might require an appreciable time to accelerate the water column or vice versa. In high-head plants governing with needle-nozzles or other devices for opening or closing the nozzles, appreciable intervals of time were necessary after sudden changes of load before the speed could be brought back to normal.

In hydro-electric plants with a mixed load, it might be that there were not violent fluctuations of load, so that rapid governing was not necessary, but where a heavy fluctuating railway load, hoisting load, or rolling mill load was the dominant feature it might be desirable to install devices to reduce the speed otherwise necessary for the governing mechanism; in these cases fly-wheel capacity was sometimes added to improve speed regulation. This question of water-turbine governing was a subject in itself.

Mr. ERIC M. BERGSTROM wrote that he would now reply in writing to those points which had been raised at the Manchester Meeting and which time had not permitted him then to answer adequately. He wished to refer to Mr. Gilbert Cook's questions (page 160) in regard to the chemical or titration test for measuring the quantity of water. He (Mr. Bergstrom) had already stated in his reply at the discussion that common salt was used for dosing purposes. Salt was used not only on account of being easily obtainable at a low price, but also for the reason that it was chemically indifferent to water; neither was it absorbed by any matters suspended in the water and, what was most important, the degree of concentration of the solution, even if greatly diluted could be readily and accurately determined. The success in obtaining accurate results with this method for testing water turbines depended entirely on obtaining an even and complete mixing or distribution of the dosing solution in the water.

(Mr. Eric M. Bergstrom.)

For enclosed turbines to which the water was brought through a pipe-line, a perfect mixing was obtained without special arrangement, and exceedingly accurate measurements obtained. In such cases the dosing solution was introduced in the upper end of the pipe-line through a short pipe, to which the solution flowed by gravity from a tank with graduated scale. Comparative measurements with current meters had shown that the difference in the results between the two measurements was 0.16 to 0.17 per cent.*

For turbines in open flumes, the method could only be considered as accurate when special arrangements were adopted to obtain a perfect and uniform mixing of the dosing solution. The arrangement generally adopted for that purpose consisted of a number of pipes equally distributed over the section of the intake-flume, which pipe was provided with a number of apertures at various depths and the dosing solution was pumped from a tank to the pipe system, and by this means the dosing solution was uniformly distributed over the full section of the turbine-intake.† The accuracy of measurement by this arrangement as compared with current-meter records was stated to be on an average 1.3 per cent. It might often meet with considerable expense and trouble to make arrangements for dosing in open flumes; and where other methods of measuring were practicable, it would, in the Author's opinion, be preferable to adopt them.

On the other hand, there were cases where this method would be the only feasible one to use, and as long as arrangements, as described, were adopted, the results could be considered as fully reliable. In reply to the further question regarding Table 5 (page 150), the figures given of available power were for water power available for power purposes only.

Mr. T. Roland Wollaston (page 161), raised a most interesting point in regard to the possibilities of a combination of the Humphrey

* Département Suisse de l'Intérieur, Communications du Service des Eaux. "Jaugeages par Titration et Essais comparative," Bern, 1918.

† Salt Solution Test at Holtwood. *Engineering Record*, New York, 1915, page 358.

pump and water-turbines as a power unit. The combination was quite feasible, but for small units the power could be obtained at a lower cost and slightly better thermal efficiency by employing Diesel engines. Its application could, therefore, only be considered in connexion with large units, but the practical difficulties experienced in pumps of this type for large capacities had still to be overcome before the question could be finally considered. There was, however, no doubt as to the future possibilities of this combination, and it was a subject which would be followed with great interest by engineers interested in the question.

With regard to Mr. Chorlton's question (page 167) relating to the efficiency of hydraulic turbines, the increase was due not only to the improved design of the runner in relation to the stream-lines, but perhaps to a greater extent to eliminating obstructions and formations of eddies in the intake-flumes or casings, in suction bends, suction-tubes, etc., in addition to reducing the mechanical friction losses. Without doubt, the same remarks would apply to the design of centrifugal-pump installations, and an improved efficiency would be secured by paying more attention to the arrangements of bends and pipes both at the suction and delivery sides and by adopting ball-bearings to reduce mechanical friction.

The Author regretted that the description of the automatic arrangement for taking up the axial thrust was not so clear as could be desired. Fig. 25 (page 111) showed the arrangement generally adopted, the space on each side of the runner communicating to the suction side through a small clearance between the runner and the casing. The leakage at the entrance edge of the runner admitted the pressure-water on each side, and an unbalanced thrust in either direction would cause the runner and shaft to move axially, as permitted by clearance in the bearings. Consequently, the pressure on one side of the runner would be relieved through the larger clearance to the suction side, and an increased pressure could be thus created in a direction opposite to the thrust, and equilibrium re-established. It was agreed that this arrangement was of a much simpler design than that adopted for

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centrifugal pumps where several impellers on the same shaft necessitated a separate thrust-plate and chamber.

He appreciated the frank criticism put forward by Mr. Pendred, and he agreed that simply from lack of space omissions had been necessary, although he was of the opinion that the most important points had been touched upon in the Paper. He felt, however, constrained to repudiate most emphatically Mr. Pendred's remarks as to the usefulness of the Paper. Mr. Pendred must be fully aware that our Technical Press had, to a great extent, neglected to devote sufficient space to the development of water-power engineering, and from the Author's experience amongst practical engineers in this country, it had always been a source of great inconvenience to those interested in the subject that no information was readily accessible in this quarter.

In view of the interest the question of utilization of water-power now commanded amongst all classes of engineers, it had been suggested that a résumé of the development of water-power engineering would be of interest to those whose time had not permitted them to make a detailed study on the subject, and in the endeavour to meet this desire, the Author had been amply rewarded by the individual appreciation received from the members and the general interest taken in the Paper. He was surprised at the difficulty experienced by Mr. Pendred in finding any part of the Paper suitable for discussion. From the valuable contributions made, it appeared that this view was not shared by those who were directly interested on the practical side in any of the branches of water-power engineering. He regretted that he had unwittingly offended the susceptibilities of the Italians, as mentioned by Mr. Pendred, but he thought that any omission on this score might be excused, seeing that a choice had to be made from a large number of plants, in order to select only those which best illustrated the special features it was desired to bring out in the Paper.

The reference to the Pelton Wheel at Bardo-Necchia was certainly most interesting, but the particular feature of two wheels of different diameter, although exceptional, was not technically

anything so remarkable as attributed to it by Mr. Pendred. Nevertheless, he was grateful to him for drawing attention to this plant and referring to the illustration.

He thanked Mr. Pendred for his explanation regarding the Michell Thrust Bearing. He himself had stated at the discussion in Manchester that he had been puzzled as to the proper name of this type of bearing, and he felt sure that Mr. Pendred's explanation was welcomed by all members as it gave publicity to a fact which was not generally known, and secured to Michell the credit for this invention.

The substance of Mr. A. C. Anderson's criticism (page 171) was that the Paper was not sufficiently up-to-date, which statement in his opinion was not justified. In support of his contention, Mr. Anderson referred in the first place to the spring type thrust-bearing as now being in common use. This statement was not correct, as this bearing had only recently been developed,* and at the time of publishing the Paper very few bearings of this type had been made. The Michell bearing was, at the present moment, in most common use as far as recent plants were concerned, having in the last few years been installed on water-turbine units with an aggregate output of over one million h.p.

Mr. Anderson must further have been misinformed with reference to the statement that the Michell Bearings at the Gatun Power Station had been replaced by spring thrust-bearings; this was obviously incorrect as this plant was originally equipped with roller bearings, and Michell bearings had never been used. Without doubt the spring thrust-bearing had a considerable future, although no special merits, which were not possessed by the Michell, had been claimed for this type of bearing, and the question of cost would probably decide which type of bearing would be adopted for future installations. The other type of bearing referred to by Mr. Anderson, in which the stationary ring was radially divided in alternate flat and inclined sectors was known as the Gibbs type, and was a direct outcome of the introduction of the

* *General Electric Review*, November, 1919.

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Michell type, and obtained perhaps by simpler mechanical design the same effect.

Passing to Mr. Anderson's complaint that the Sewer arrangement for the governing of Pelton Wheels had not been referred to in the Paper, he would point out that this arrangement was tested on a small Pelton Wheel in the Laboratory at the Technical High School, Zurich, in March 1919, and the report published only in June the same year * was too late for inclusion in the Paper. To the Author's knowledge it had not been installed in any plant but would probably, in the near future, be adopted to a certain extent, although it was questionable whether it would supersede the now common form of "deflector," in which the mechanical design was of a far less complicated nature.

In the next place Mr. Anderson pointed to a distinct omission in that nothing had been said about electric welding. It was not clear from his remarks whether he wanted to convey that electric welding was used for manufacturing, in bulk, pipes required in connexion with hydro-electric plants. Electric welding, as well as oxy-acetylene welding, were used for repairs of pipes, and in certain cases for making field-joints, but, on score of cost alone, it could not be used for manufacturing in bulk the large pipes and plate thicknesses required by present-day practice in connexion with hydro-electric work. For this purpose water-gas welding was exclusively adopted, and for that reason no other system of welding was referred to.

As regards Mr. Anderson's reference to page 62 and his subsequent prediction that the axial-flow type turbines would be used for extremely low falls, a careful perusal of the Paper would, he thought, have made his remarks on this point superfluous. On page 80 he made the following statement in connexion with the new type of turbine, illustrated in Fig. 8 (page 77), viz. :—"This new departure in design suggests the possibility of reverting to the axial Jonval type of runner. It is anticipated that further

* *Schweiz. Bauzeitung*, Vol. lxxiii, 1919.

progress will soon be recorded." In making this statement, the Author had in view the development of the axial type of turbine on the lines as suggested by Baudish, Kaplan, and Zuppinger.*

Mr. Anderson's statement that the Author had credited the Americans with the development of the modern Francis turbine must have been made under a misapprehension. It was common knowledge that the Americans developed the high-speed runner then known as the "American type," whereas in Europe the Francis turbine at that time was used exclusively for medium heads (Type A, B, Fig. 1) and developed principally in Switzerland, being known as the "Swiss type." The subsequent development was fully referred to in the Paper, and on pages 56-7 it was clearly stated that whereas the American Engineers introduced the high-speed Francis turbine, the development of the modern type was entirely due to European Engineers.

The point raised by Mr. Anderson in connexion with the high-pressure Francis turbine was very important. Wherever the speed permitted, runners were now preferably made of close-grained cast-iron when very smooth surfaces were obtained, and care was taken to remove any rough places. In this connexion it was not only the skin friction inside the runner which had to be taken into consideration, but also the frictional resistance of the "dead" water on each side of the runner. The "dead" water would rotate at a speed of approximately one-half of the speed of the runner, and friction would occur both between that water and the casing and outside of the runner respectively. The leakage loss would necessarily be serious in high-pressure turbines, as it was proportional to the pressure at the extreme entrance of the runner, and required special attention as compared with low-pressure turbines. By small clearances and labyrinth joints in the renewable sealing rings, the leakage in percentage was not larger than was found in low-pressure turbines.

He was obliged to Mr. Anderson for drawing attention to the use

* "*Electrotechnik u. Maschinenbau*," Vienna, December, 1915. "*Zeits. d. Oesterr. Ing. u. Arch. Vereins*," Vienna, 1917. *Schweiz. Bauzeitung*, Zurich, 1919.

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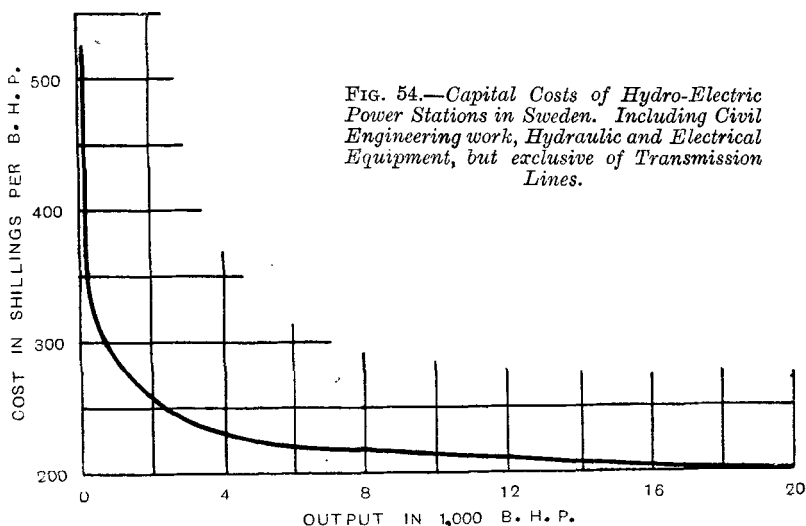
of concrete housings for larger generator statots. This suggestion emanated from Mr. C. M. Hackett, of the General Electric Company, Schenectady, and the last November issue of the *General Electric Review* contained an article descriptive of this arrangement, together with an imaginary illustration of a hydro-electric generator station of the future. As stated by Mr. Anderson, the advantage of this suggested arrangement lay in the saving on the initial cost of installation, and time would show if engineers concerned with building of large hydro-electric stations would readily adopt this radical departure from our old ideas of power-house design.

He could not possibly agree with Mr. Lancaster Burne's statement in regard to the use of cylinder gates (page 176), as it was a well-known fact that this type of gate was now not even manufactured by any of the leading makers. He agreed that assuming constant load and maximum gate-opening, the type of gate was of no consequence, but it must be borne in mind that in most cases the quantity of water fluctuated, which necessitated using the turbine at part gate with reduced power, and with the use of cylinder gate, serious losses would occur at a time when the highest efficiency was desirable.

The Author entirely agreed with the sentiment expressed by the President as to the use of the name of Michell in connexion with bearings based on his invention, and he was particularly indebted to Dr. Hele-Shaw for his valuable contribution on the subject.

In reply to Mr. Patchell (page 178), he regretted that space could not possibly permit a reference to the question of cost of hydro-electric works. The reason was simply that it was a subject in itself, and as cost varied to such an extent in each installation, due to local conditions, height of fall, and numerous other details, it was impossible to generalize, and a most detailed survey would have had to be given. The Author had recently gone into the cost for a hydro-electric scheme in Norway for developing 100,000 h.p., where the total present cost worked out to about £20 10s. per electrical h.p., as against £9 on the basis of pre-war cost. As a further comparison, the diagram, Fig. 54, might be of interest as

giving the mean figures of actual cost taken from 338 installations in Sweden, which figures had recently been furnished by the Census taken in that country under the auspices of the Government. The outlays given necessarily showed pre-war cost, and at the present cost of construction would approximately correspond to at least three times the values given. He quite agreed that at first sight the cost of developing water-power in this country appeared to be very high as compared with large steam-power



installations, but it had to be borne in mind that the running cost was very small in water-power driven stations. It appeared to him to be essential to utilize our large water-powers in connexion with such industries where the cost of power formed a high percentage of the cost of the finished product, and where a continuous process with a high-load factor was employed. In such cases the higher initial cost would be more than balanced by the low running cost, and the utilization of water-powers in connexion with the establishment of electro-chemical or electro-metallurgical industries was bound to be considered.

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The production of atmospheric nitrogen in this country had already been considered by a Government Commission and the electrolytic or electro-thermal refining of zinc and copper, the manufacture of calcium carbide and the electrolytic production of chlorine and caustic soda, to mention only a few examples of important key industries, offered exceptional prospects for utilization of water-power both in this country and in the Dominions.

He was very much interested in Mr. Armfield's contribution, but he was unable to endorse his views regarding the use of the cylinder-gate. In referring Mr. Armfield to the Author's remarks on the same subject already made in reply to Mr. Lancaster Burne, he would add that the cylinder-gate could only be considered in such cases where cheapness was the first consideration without regard to the efficiency of the plant. Contrary to Mr. Armfield's statement, the wicket-gate was, when properly made, practically water-tight.

Mr. W. P. Digby's remarks (page 182) were extremely valuable, and he agreed that erosion demanded more attention than had been given to this matter. There were, however, now many special alloys which had been used with great success, and metal-spraying on the buckets had also been recently introduced to reduce the effect of erosion by maintaining as smooth a surface as possible, but he regretted that the practical results of this method were not yet available. The utilization of the numerous small water-powers must form a decided feature in any scheme of development of our water-power resources, and the question of a linking-up system wherever possible with existing steam-power stations would have to be considered.

He was glad to see that Mr. Percy Griffith (page 184) had contributed to the discussion and drawn attention to the prior claim of water for domestic use. The two branches of engineering dealing with water-power and water-supply had many points in common interest, and he endorsed Mr. Griffith's remark that in many cases water-power could be developed with advantage in connexion with water-supply schemes. Particularly in India, a large number of schemes were under consideration in connexion

with irrigation dams, and there was no reason why such schemes could not be introduced to a certain extent in this country when dealing with the water-supply.

Mr. Griffith appeared to be very pessimistic in regard to development of water-power in this country, and although we were not so fortunately situated as other countries in Europe in respect to our future water-power resources, we possessed a certain amount which could be economically utilized and which were bound to be considered in the near future, apart from the enormous possibilities existing throughout the Empire.

Mr. William T. Taylor's contribution (page 189) was most instructive, coming from a gentleman with extensive experience in hydro-electric works, and he generally endorsed the Author's statements. In the Table given by Mr. Taylor, he introduced a somewhat different nomenclature than that used by the Author. The "characteristic speed" given in the Table corresponded to the "specific speed" as referred to in the Paper, the latter term being now more employed by engineers and in all literature on the subject.

As regards Mr. Taylor's remarks regarding the Author's statement on the important place the speed regulation had in the development of water-power, he did not think any real difference of view existed, as he only desired to convey that the fact that the governing problem was satisfactorily solved opened up a larger field for employing water-power, which in its turn stimulated the efforts of all-round improvements, and resulted in the high standard of perfection reached at the present time.

He desired to say that when Major C. M. Norrie stated (page 186) that it was probably due to ignorance of continental achievements that the Author had ascribed to American Engineers the credit for the development of the high-specific speed turbines, he laid himself open to be criticized for being imperfectly informed on the subject under discussion. It could not be attributed to the Author that he had not sufficiently emphasized the important position in the development of the Francis turbine, which must be accorded to European engineers

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(see pages 57-66). On the other hand, the Author's statement that much credit was due to American engineers in respect of the development of the high-specific speed turbine was based on facts which could not possibly be gainsaid. The diagram in Fig. 5 was given in the way of comparison, to emphasize the important development after that date (1909) in respect of high-specific speed runners. The position in Europe in 1914 was that a specific speed of 79 (350) was the maximum obtained with a commercial efficiency, and no manufacturers had standard series above that value. As early as 1911, a series of tests and investigations were carried out by Professor Zowski of Michigan University on high-speed runners with specific speeds ranging from 87 (387) to 91 (404) which established, for the first time, the characteristics of this new type of runner. In 1913, further tests were made with a design of runner with a specific speed of 102 (453) which showed a test efficiency of 90.7 per cent. This type of runner was adopted as a standard series by Messrs. James Leffel, Springfield, Ohio, at a time when no European makers were in a position to offer any higher specific speed than 79 (350). The Author recalled the fact that in 1915 he was responsible for the equipment of a turbine plant when an American maker offered standard turbines with a specific speed of 95, and on inquiring from several European makers, they were unable to quote on the above stated speed. Apart from being adopted as a standard series, several large plants were built in America where turbines with a specific speed of 95 were adopted. Simultaneously, tests were carried out in Europe on types suggested by Professors Kaplan, Banki and others, and the first complete test was made by Professor Prazil in 1915 on a new type of turbine designed by Messrs. Escher Wyss and Co., and illustrated in Fig. 8 (page 77). He was under the impression that the figures given by Major Norrie referred to the tests on this type, which were given prominence in the Paper as being the type which would lead to the adoption of axial runner for low-fall developments. He felt it necessary to give the above explanation as Major Norrie's statement was based on insufficient knowledge

of the prominent part American engineers had taken in this particular development of the Francis turbine.

He did not know how Major Norrie had arrived at his figure of 400 per cent for runaway speeds. At the test of the high-speed turbine referred to above, specific speed 112 (500), the runaway speed amounted to approximately 180 per cent. of the normal speed. As a comparison, he would quote the following figures from actual tests on different types of turbines:—

No. of Runners.	Head in feet.	Output BHP.	Runaway speed in per cent of N.	Normal N. in r.p.m.	N _s . (Metric.)	N _s . (foot-lb.)
4	35	1,850	159	300	335	73
3	8	400	164	83	320	72
4	35	4,500	165	180	320	72
2	36	1,200	169	250	310	70
2	35	450	155	360	285	64·5
2	66	4,500	176	250	280	63
2	59	1,500	183	300	220	49·5
1	66	225	171	600	213	48
2	100	13,000	178	187	210	47·25

A published record* of runaway speed tests, on various sizes of Francis turbines of American make gave results varying from 152 to 178 per cent of the normal speed. As regards the rest of Major Norrie's Communication, he agreed entirely with the remarks expressed by him.

* D. Mead. *Water Power Engineering*, New York, 1915.