IMPULSE TURBINES

By

ELY. C. HUTCHINSON

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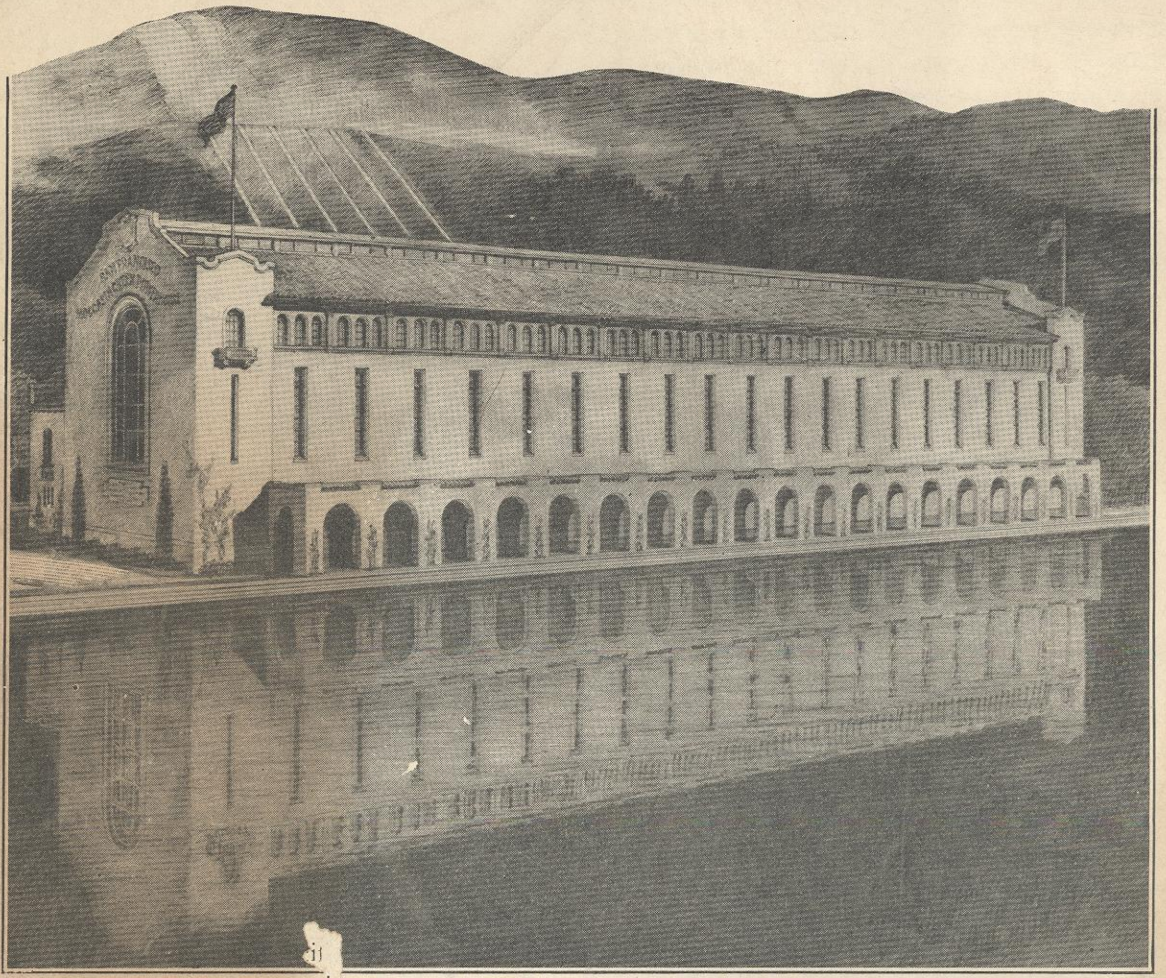

Architect's Drawing of Moccasin Creek Power House, Hetch-Hetchy Water Supply Project, City of San Francisco, under construction and to be completed early in 1924. Four 25,000 H. P. Pelton Impulse Turbines are being installed

THE PELTON WATER WHEEL COMPANY

Hydraulic Engineers

SAN FRANCISCO and NEW YORK

Designers and Builders
of
Hydraulic Turbines, Governors, Valves

Associated Companies:

Wm. Cramp & Sons Ship & Engine Bldg. Co.
I. P. Morris Department
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Montreal

The Tangential Impulse Water Wheel

ELY C. HUTCHINSON
First Vice-President & General Manager
The Pelton Water Wheel Co.

In the field of impulse turbines, the tangential wheel has virtually supplanted all other types. Practically all tangential wheels now manufactured use buckets that, however they may vary in details, make use of the central dividing wedge or splitter characteristic of the original Pelton wheel patent. In fact, although this usage is not theoretically exact, in popular and even technical parlance, the term "Pelton wheel" has come to be considered as applying to all impulse turbines.

IN determining the choice between an impulse wheel and a reaction turbine, use is made of the "Specific Speed" formula. Specific speed is the speed at which a wheel would run if it were reduced in size, without changing the design, so as to develop one horse-power under one foot head. Thus the Specific

$$\text{Speed} = N_s = \frac{R.P.M. \times \sqrt{HP}}{H \times \sqrt[4]{H}}$$

Generally speaking, where H is expressed in feet, values of N_s below 9 call for an impulse wheel, values above 11 for a reaction turbine, while values between 9 and 11 belong to a debatable zone where other conditions usually determine the choice.

For any given development, the value of N_s can be varied between fairly wide limits by varying either the number of revolutions per minute or the size of the units. The former, at least, is sometimes done when some of the other considerations outlined call for a different type of hydraulic prime mover than that at first indicated by a trial solution of the formula.

Variation in r.p.m. is limited, in the case of direct-connected hydro-electric units, by the range in generator speeds permitted by the electrical manufacturers. It is hardly necessary to point out that only in small units is the loss in efficiency resulting from belt connection permissible.

For any project where the specific speed formula permits a choice, the maximum efficiency of a well-designed reaction turbine will be somewhat higher than that of an equally well-designed impulse wheel. On the other hand, the efficiency curve for such an impulse wheel will be flatter than the curve for a corresponding reaction turbine, so that on the low-load side, at least, of the point of maximum efficiency, the curves will usually cross, and the efficiency for the impulse wheel will be higher over a considerable range in load. Therefore, for a project in the debatable zone, but which must operate for a considerable part of the time at fractional loads, the average efficiency is likely to be higher for an impulse wheel than for a reaction turbine, even though the maximum efficiency is higher for the latter. Also, as will be explained more fully, the efficiency of a reaction turbine during the first year or so of operation frequently drops more rapidly than the efficiency of an impulse wheel under similar conditions.

The efficiency of a reaction turbine depends upon the maintenance of very close clearances between the runner and the adjacent stationary parts. A relatively small amount of erosion caused by silty water, or of corrosion, due to chemicals in the water, may lower the efficiency so much as to require replacement of the runner. On the other hand, the efficiency of an impulse wheel does not depend upon close clearances, and even when erosion or corrosion finally calls for the renewal of a bucket, nozzle tip, or needle-tip, the cost of making the renewal, not only in labor and material, but also in loss of power during the shutdown, is much less than when a runner is replaced on a reaction turbine.

Erosion of the runner of a reaction turbine, is much higher when operating at fractional loads than at full load. This is because the angle of entrance to the runner is different at fractional loads than at full load. This increased wear occurs whether the water carries silt or not, but is, of course, greatly aggravated when there is a high silt content. On the other hand, in an impulse wheel, the angle between the jet and the buckets is constant, whatever the load, and there is no difference in the rate of erosion.

This consideration of minimum wear at fractional loads is of importance not only where the low-water flow of the stream is less than the capacity of the plant, but also in a new plant with a capacity greater than the demand for power. It is seldom that a newly completed plant finds an immediate market for its entire capacity. More often a period not merely of months, but of years, follows when the plant is seldom if ever operated at full load. When a reaction turbine plant is installed under such conditions, the runner may become badly worn before full load operation becomes the rule.

The question of loss of power output during shutdowns vitally affects both impulse and reaction plants, and as will be shown later, continually crops up as the determining factor in the design. When a plant is shut down for repairs or replacements, the cost for labor and material, however large it may be in the aggregate, is usually small as compared with the loss of power output and consequent loss of revenue. Again when a shut-down actually involves impaired service to the consumer, the indirect cost to the power company is usually the worst of all. Many contracts for furnishing energy carry a heavy penalty clause for failure of current for more than a few minutes. Even when no such penalties are exacted, the loss of good-will is an important consideration.

In the design of any hydraulic prime-mover, therefore, the vital importance of approximating 100 percent time efficiency in plant operation must be constantly borne in mind. It is not sufficient to hold the number of shutdowns at a minimum. With the most favorable of conditions and the best of design, some shutdown periods will occur, but such periods must be made as brief as possible. Here is where the importance of such features of design as will facilitate repairs and replacements becomes manifest. The value of the time saved because of the provision of such devices is frequently sufficient during a single shutdown to pay for their entire cost.

Considering the specific speed formula alone, there is no upper limit to the head for a reaction turbine, provided the water quantity is sufficient to give a proportional power output. However, a point is finally reached where mechanical factors operate against the choice of a reaction turbine. For instance, the size of the casing becomes so great as to require very thick walls. Not only does this increase the cost materially, but it becomes hard to get sound steel castings of the diameter and thickness required.

Leakage and erosion present special difficulties in the design and operation of high-head reaction turbines. For the same speed, the diameter (and therefore the circumference) of the runner increases as the head increases. In addition, large diameter runners require a greater clearance width than small ones. Consequently, the total clearance (or leakage) space around the periphery increases rapidly with the head. Add to this the fact that spouting velocity through this leakage space also increases with the head, and we have in all a very rapid increase in leakage as the head increases. This is an absolute increase. The relative increase of leakage in proportion to the total amount of water used is even more rapid, since the water required for the same power output decreases as the head increases. Therefore, although leakage and loss of efficiency due to leakage are negligible for low-head turbines, they become important in high-head operation. In addition, increased leakage means increased erosion, particularly if the water carries silt.

At the present time the highest-head reaction turbines are the two 25 000 hp Pelton vertical units at the Kern River No. 3 plant of the Southern California Edison Company, which operate under an effective head of 810 feet. However a higher head unit is now under construction, and will be installed early in 1924 at the Oak Grove, Oregon, plant of the Portland Railway Light & Power Company. This is also a Pelton vertical reaction turbine, developing 35 000 hp under an effective head of 850 feet. It is estimated that under certain conditions of fractional load, the loss from friction in the long pipe line will be so much reduced that the effective head will reach 960 feet.

The highest-head hydraulic prime-movers of any kind are four 3000 hp impulse wheels of the Pelton type, near Fully, Switzerland, operating under an effective head of 5320 feet. Opportunities for economic development at such high heads are few, and there are probably not more than a dozen plants in the world where the heads exceeds 2000 feet. In fact, there are several projects in actual operation where development of the entire head at one plant would have been entirely feasible, but where various considerations, usually economic, determined the decision in favor of two or more plants.

All too frequently first cost is made the determining factor in the design of a given installation. No general rule can be laid down as to comparative first cost of impulse wheels and reaction turbines. For some projects an impulse wheel is the least expensive, for others an equally well designed reaction turbine. However, in hydro-electric operation, as in other activities, a better criterion is unit cost per kilowatt-hour produced, computed over a long period of years, thus considering operation and maintenance as well as first cost. In practically every division under operation and maintenance, where any difference in cost exists, the advantage is with the impulse wheel. Several of these instances have already been discussed. Another important feature is the simplicity of construction of the impulse wheel, which renders it more "foolproof" than the reaction turbine. This is a particularly important consideration for plants too small to justify the cost of trained engineering supervision. In general, there are many instances where, although a reaction turbine installation showed a lower first cost, lower costs of maintenance gave the advantage to the impulse wheel.

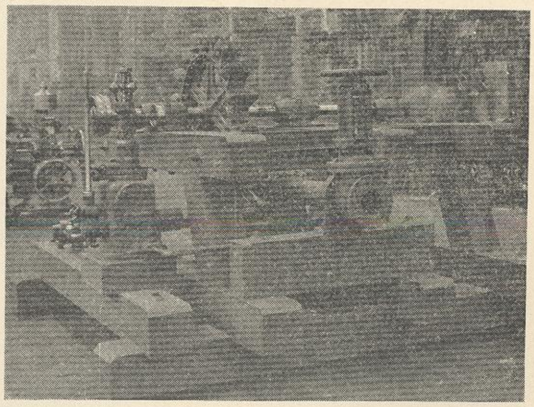

FIG. I—UNIT EQUIPPED WITH PLAIN NOZZLE AND OLD STYLE BUCKETS

Except for the modern governing equipment including the jet deflector, it is substantially the same as the type sold by Lester A. Pelton at the time his original patent was granted in 1880. The housing for a wheel of this type is usually made of wood.

EFFICIENCY AND GENERAL DESIGN

The elementary mathematical formulas governing the design of tangential impulse wheels were deduced as early as 1883. It is evident that for maximum efficiency, after passing through the buckets the water should drop from the wheel under the action of gravity alone, with zero velocity in the direction of the jet. "The principal sources* of loss in Hurdy-Gurdy wheels are in general:—

1—The energy remaining in the water after being discharged from the bucket.

2—The heat developed by impact of the water in striking the bucket.

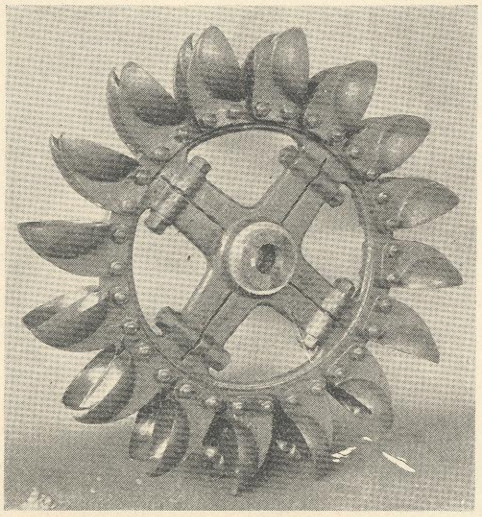

FIG. 2—RUNNER EQUIPPED WITH DOUBLE-LUG BUCKETS

Relatively light stresses permit the use of a skeleton instead of a solid center. This wheel is sectionalized into small units to permit pack-mule transportation.

3—The fluid friction of the water in passing over the surface of the bucket.

4—The loss of head in the nozzle. The loss in the supply pipe is not charged to the wheel.

5—The journal friction.

6—The resistance of the air.

In the following formulas* all of the above sources of loss but the first are neglected; and for the purpose of weighing the importance of curvature in the buckets, it is assumed that all of the water escapes from the bucket with the same velocity: i.e. no water is carried with the wheel. The symbols which will be used are as follows:—

C=Velocity of the bucket in feet per second.
V=Velocity of the jet escaping from the nozzle.
U=Relative velocity of discharge from the bucket.
W=Absolute velocity of discharge from the bucket.
Q=Quantity of water supplied in cu. ft. per sec.
Y=Weight of one cubic foot of water.
L=Useful work in foot pounds per second under above conditions.
E=Efficiency of the wheel under above conditions.
G=Acceleration of gravity.
S=Angle made by the discharge end of the bucket with its line of motion.

$$U = V - C$$

$$W^2 = U^2 + C^2 - 2\,U\,C \cos S = V^2 - (2\,VC - 2\,C^2)\,(1 + \cos S)$$

$$L = \frac{Q\,Y}{2\,G}\,(V^2 - W^2) = \frac{QY}{2\,G}\,(2\,VC - 2\,C^2)\,(1 + \cos S)$$

$$E = \frac{L}{\left(\frac{QY}{2\,G}\right)V^2} = 2\,(1 + \cos S)\left(\frac{C}{V} - \frac{C^2}{V^2}\right)$$

Then for maximum efficiency

$$\frac{d\,E}{d\,C} = 2\,(1 + \cos S)\left(\frac{1}{V} - \frac{2\,C}{V2}\right) = 0;\ and\ C = \frac{V}{2}$$

Also the maximum efficiency $= E_1 = 0.5\ (1 + \cos S)$"

The smaller the angle S, the greater will be the efficiency of the bucket. In other words the design of the bucket should be such that the direction of the jet be reversed as nearly as possible. Also the velocity of the bucket should be one-half the velocity of the jet. In practice, this latter rule is modified by other conditions, although the permissible range is small.

In discussing the design of impulse wheels, the widely different conditions under which they are required to operate must be borne in mind. What is good design for a plant that is to operate on block load as part of the system of a large power company would be entirely inadequate either for the governing plant of that system or for a single plant owned by a small company. Again, not only the style of construction, but the various auxiliary equipment essential to economical operation of a 20 000 kw unit would be absurdly elaborate and expensive for the 50 hp wheel that a miner puts in while he is determining whether or not his prospect is of any value. In a limited space it is possible to mention only a few of the general principles governing design, and as a rule the type of design described is that preferred for installations where the highest efficiency and service is required.

BUCKETS

The bucket described in the original Pelton patent, which was a material improvement over "the prior art", had a central dividing wedge, but its corners were almost square, and its lines, in general, nearly straight. The manufacturing cost of such buckets is relatively low, and they are still frequently used for installations where efficiency is of slight importance, for the reason that the water supply is in excess of power requirements at all times.

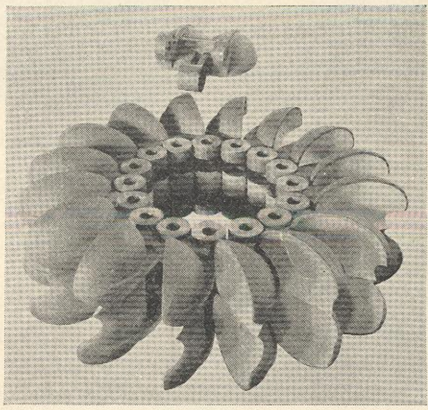

FIG. 3—REAR VIEW OF A CHAIN-TYPE BUCKET AND A SET OF BUCKETS ASSEMBLED WITHOUT DISK

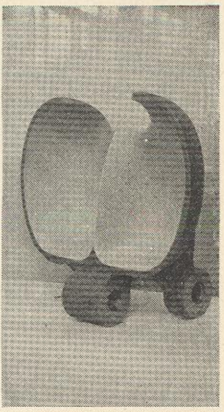

FIG. 4—FRONT VIEW OF A CHAIN-TYPE BUCKET

Many designs were brought forward looking toward improved efficiency, but little progress was made until the present Pelton ellipsoidal bucket was developed. This design ensures that all particles of

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*Quoted from Bulletin No. 1 of the College of Mechanics of the University of California, by Ross E. Browne.

water travel equal distances by smooth curves from the point of entering to the point of leaving the bucket, thus reducing hydraulic losses in the bucket to a minimum. During the past few years, increasing demand for power has caused the rebuilding of a number of old impulse-wheel plants, and the replacement of old style buckets by ellipsoidal buckets has resulted in increases of efficiency as high as 18 percent.

WHEEL CENTERS

Three principal factors determine the diameter of the wheel; namely, the head, the water quantity, and the desired speed. The head determines the spouting velocity of the jet, and, as we have already seen, the spouting velocity determines the peripheral velocity within narrow limits. With spouting velocity computed, the water quantity determines the size of the jet. With peripheral velocity computed and the desired speed in r.p.m. known, the size of the wheel is provisionally fixed. However, this computed size may not give a desirable ratio between pitch diameter and jet diameter. For most wheels, this ratio ranges between ten and sixteen, but by using the chain type of bucket, this may be reduced considerably below ten. Again, the size of individual jets may be reduced by the use of double nozzles, double runners, etc. On the other hand, ratios higher than sixteen are not in themselves objectionable, and in the case of wheels required to run at slow speeds, the ratio may be much higher. For example, for air-compressor drive, a specially-designed impulse wheel is used in place of the regular flywheel, and when such compressors operate at slow speed, the wheel diameter is frequently very large as compared with the jet diameter. With the diameter of the wheel finally determined, and the power to be applied at the periphery known, the computation of stresses and proportioning of members is simply a matter of mechanics.

The details of a design depend mainly upon whether double-lug or chain type buckets are used. In the double-lug type of construction, each bucket is provided with two lugs, designed to mount one on each side of a single-disk runner. Two bolts pressed into accurately reamed holes are used for each bucket, each bolt passing through both lugs. Whichever method of attachment is employed, it is important to have an accurate fit, both of the bolts in the holes and of the lugs to the disk, or, as it is frequently called, the bucket-ring. Even for a 1000 foot head, a relatively low head for a large capacity plant, the peripheral velocity of the wheel is about ninety miles per hour. With such velocities, if there is any play at the points of attachment of the bucket, the resulting wear will soon shear the bolts.

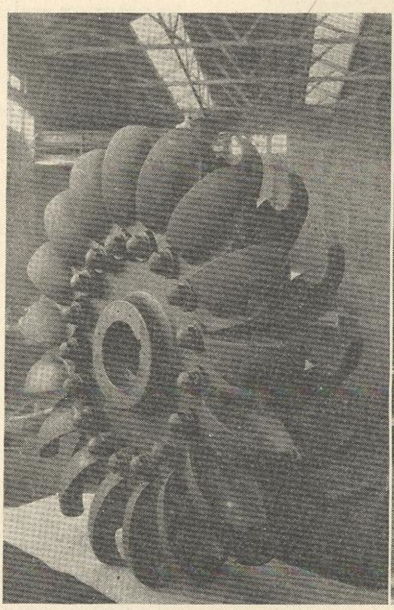

FIG 5—A RUNNER DESIGNED FOR A MEDIUM HEAD AND A RELATIVELY LARGE QUANTITY OF WATER. NOTE THE SMALL WHEEL CENTER AS COMPARED WITH THE DIMENSIONS OF THE CHAIN-TYPE BUCKETS

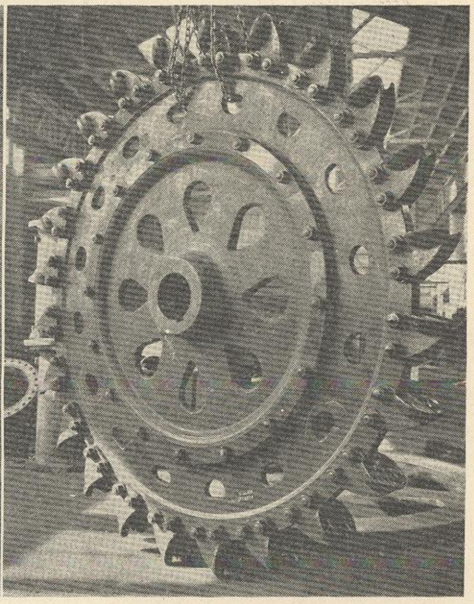

FIG. 6—A RUNNER DESIGNED FOR A HIGH HEAD AND A RELATIVELY SMALL QUANTITY OF WATER. NOTE SMALL SIZE OF THE DOUBLE-LUG BUCKETS AS COMPARED WITH THE WHEEL DIAMETER

As already pointed out, if the speed of the wheel is increased, the diameter of the wheel must be reduced, provided the other operating conditions are unchanged. This crowds both the buckets and the attaching bolts closer together. In the case of large-capacity, high-speed wheels sufficient room is not available for attaching double-lug buckets. For these conditions, the chain type bucket was developed. The wheel center is usually composed of two forged disks and a forged tub to which the disks are attached by bolts in reamed holes. The hub is pressed and keyed to the shaft. For some small wheels the disks and hub are cast integral. Each bucket has three lugs, the middle one fitting into the recess between the two disks and the two outer lugs fitting on the outside of the disks. Each bolt passes through three lugs, namely the two rear, or outer, lugs of one bucket and the middle or forward lug of the bucket immediately preceding it. This construction permits making the most effective use of the periphery of a small wheel center.

An additional advantage of the chain type construction for high-speed wheels lies in the fact that, since all the buckets are bound together in a sort of continuous chain, the entire structure is more capable of withstanding centrifugal stresses than the double-lug type. The fields of the two types overlap somewhat, but in general, each type has a well-defined set of conditions to which it is best suited.

For low heads, a cast-iron is a satisfactory material for wheel centers. For medium heads, cast-steel is preferable, while for large capacity units under high heads, nickel-steel forgings are required. Buckets are usually cast from high carbon steel, but are also occasionally made of bronze.

SPEED REGULATION

The design of nozzles and jet-deflectors is so closely related to speed regulation that a brief discussion of the latter subject is desirable before considering the former. As with other types of hydraulic prime-movers, speed regulation is effected by varying, in accordance with the load, the quantity of water applied to the runner. Devices for doing this may be divided into two general classes, devices varying the size of the jet, such as needle-nozzles, and devices leaving the size of the jet unaffected, but varying the amount of water usefully applied to the wheel, such as deflecting nozzles and jet deflectors. In general, both classes of devices are adapted to either hand or governor control, but accurate regulation practically requires the employment of a governor.

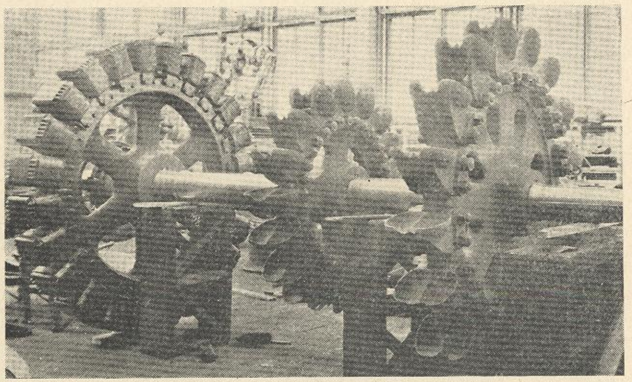

FIG. 9—DOUBLE RUNNER WHEEL AND GENERATOR ROTOR

This wheel takes water from two different heads, the runners being therefore of different sizes.

PLAIN AND NEEDLE NOZZLES

The earlier impulse wheels were furnished with a plain nozzle and some of the simpler installations are so equipped at the present time. To allow for variation in flow, two or more tips can be used, bored for different capacities. Changing tips, however involves shutting down the wheel and a consequent loss in power output and revenue. Various devices were developed at an early date for varying the discharge through the nozzle without shutting down the wheel. Among these only the needle-nozzle has survived, and nearly all wheels are so equipped at the present time. The present designs have completely overcome the old objection to this type of construction because of inefficiency at fractional loads, the nozzle efficiency being above 95 percent for all loads.

When the discharge from the nozzle is reduced suddenly by the governing equipment in accordance with a sudden reduction in the load, a considerable, and in many cases dangerous increase of pipe line pressure will occur. Such pipe surges may even cause bursting of the pipe or else breaking of the water column and collapse of the pipe. In fact, as will be seen below, the function of the needle nozzle, is not so much to regulate speed under momentary variations in load, as it is to get the maximum efficiency from a varying water quantity and, in some cases, to save water by varying the flow through the nozzle in accordance with the general shape of the load-curve.

DEFLECTING NOZZLES

In past years various devices were developed for changing the direction of the jet so that any desired part of it would fail to strike the buckets. In general these depended on swinging the nozzle body on trunnions, the weight of the nozzle being counter balanced by a hydraulic piston.

If the deflecting nozzle was equipped with a needle, this was usually set by hand at frequent intervals so as to discharge an amount of water sufficient to carry the maximum load expected during the interval between adjustments. Speed regulation was accomplished by governor-operation of the deflecting mechanism. In some instances, the needle was actuated by an electric motor controlled from the switchboard by the attendant. In other plants, a further refinement was obtained by mechanism through which, following a load rejection, the governor first deflected the nozzle, and then brought about a gradual resetting of the needle coincident with the return of the nozzle to the original position. This arrangement saved water but was not nearly so efficient in this respect or as satisfactory in general as the auxiliary relief needle nozzle, which was developed at a later period.

Deflecting nozzles have been installed and are still being used in many important plants, but for several years past, their use has been abandoned as far as new work is concerned. There are several reasons for this, among which the most important are as follows:

1—The nozzle body was heavy, sometimes weighing as much as a ton, and the effort required to move it called for a large and expensive governor. In fact, the inertia of the nozzle body was so great that it was not practicable to design a governor powerful enough to give the quick movements essential to accurate regulation.

2—The trunnions and other mechanism required were expensive.

3—At the ball joint between the fixed and the movable part of the nozzle body, a large cup-leather was required to prevent leakage. Wear on this cup-leather under the high pressure involved was rapid, particularly when the water carried grit, and frequent renewals were necessary. On account of the complicated mechanism involved, each renewal meant a long shutdown and a serious loss of power output and revenue.

Jet deflectors have none of the objectionable features of the deflecting nozzle. They are light enough to be operated quickly with relatively small governor effort, they are comparatively inexpensive, and they have no rapid-wearing parts.

JET DEFLECTORS

There are two kinds of jet deflectors. The stirrup type is so balanced that the force of the water against it tends to draw it into the jet, being prevented from doing so by the governing mechanism. If this governing mechanism fails for any reason, instead of a runaway occurring, the deflector quickly shuts off the entire stream, and the wheel is brought to a stop.

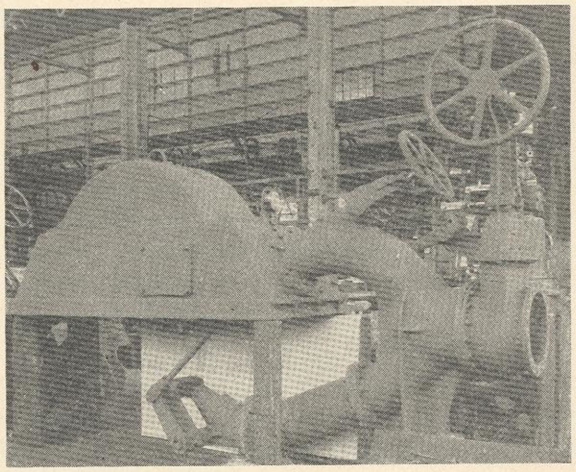

FIG. 8—HOUSING AND NOZZLE ARRANGEMENT FOR A DOUBLE NOZZLE WHEEL

The lower nozzle, which is not provided with a needle is equipped with a stirrup-type jet deflector.

The sleeve type jet deflector has not this advantage, but on the other hand, it requires less space, so that the nozzle may be placed closer to the wheel. This is particularly desirable for low-head wheels. Where no storage is available, or where the flow of the stream is always greater than the capacity of the wheel, a jet deflector operated by a governor is frequently employed in connection with a plain nozzle.

The next refinement is a hand-controlled needle nozzle and a governor-operated jet deflector. The needle is usually set every hour, or even more frequently. The adjustment may be made in accordance with variation in the stream flow, or else the needle may be set to pass enough water to carry the maximum load expected during the interval between adjustments. The jet deflector takes care of the load variations. This arrangement, as well as the one described in the preceding paragraph, gives excellent speed regulation and, since there are no rapid changes in the rate of discharge through the nozzle, pipe line pressures are unaffected and there are no pipe-line surges. It is ordinarily the best possible design where no storage is available or where water right or other requirements prevent interference with the normal flow of the stream. Even where storage is possible, a fair degree of water economy is obtainable, provided the needle is set frequently, and for many relatively small units the additional cost involved in the provision of an auxiliary relief needle-nozzle would not be justified.

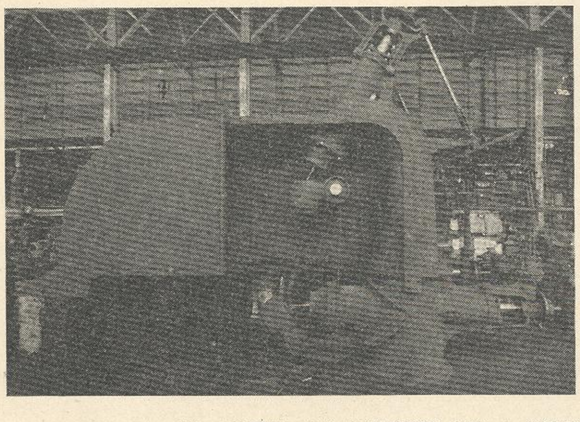

FIG. 9—HOUSING AND NOZZLE ARRANGEMENT FOR A DOUBLE NOZZLE WHEEL

Both nozzles are fitted with needles and with sleeve type jet deflectors.

AUXILIARY RELIEF NEEDLE NOZZLES

The larger plant, however, which is so situated that water economy is of primary importance, requires an auxiliary relief needle nozzle. This device consists of four principal elements as follows:—

1—The main or power nozzle, which is equipped with a needle.

2—The auxiliary relief nozzle, also equipped with a needle and which discharges by-passed water into the tail race.

3—A cumulative differential relay element which controls the action of the relief nozzle, imparting a variable speed of travel, corresponding to the rate of rejection of the load.

4—The mechanical connections between the governor and the needle mechanism.

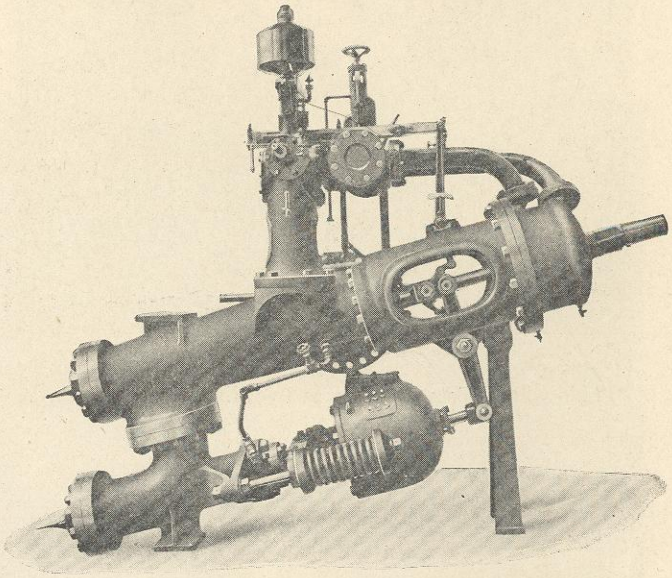

FIG. 10—AUXILIARY RELIEF NEEDLE NOZZLE WITH DIRECT-MOTION GOVERNOR.

The operation of the auxiliary relief nozzle can best be explained by a concrete example. Assume a 1000 hp unit operating under any given pressure, and served by a long pipe line. A load rejection of 500 hp occurs. Immediately there is a movement by the governor to restore the speed of rotation to normal by reducing the opening of the power nozzle accordingly. Coincidentally, but inversely, the relief nozzle opens and for an instant discharges water at a rate corresponding to the load rejection. The relief nozzle then slowly closes automatically. The rate of closing can be adjusted so that the pressure rise in the pipe line is held within any desired limit. The mechanism can be adjusted so that the relief nozzle does not open when the load variation is too small to cause a detrimental change in pipe-line pressure, so that in such cases there is no loss of water.

Even where the load variation requires opening of the relief nozzle, the amount of water that escapes before it closes again is small, and the total amount thus used for regulating purposes is negligible. At the same time accurate speed regulation and limitation of pressure rises within safe limits can be obtained. For best results with the auxiliary relief needle nozzle, a direct-motion governor is required.

Vortex Baffle Plate—Unless the water from the relief nozzle can be discharged in the open, which seldom happens, some provision must be made for "killing the energy" of this water, or damage will be done to whatever part of the structure is exposed to the force of the jet. The best device for accomplishing this end is the Ensign vortex baffle plate, which turns the water through an angle of 270 degrees so that it may be said to expend its energy in discharging against itself.

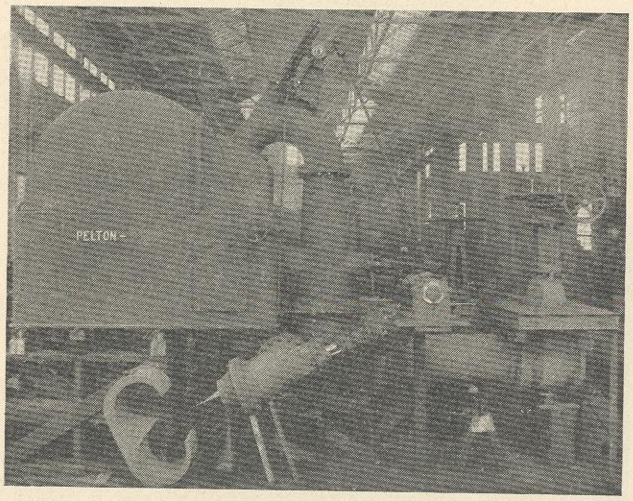

FIG. 11—DOUBLE NOZZLE UNIT EQUIPPED WITH AN AUXILIARY RELIEF NEEDLE NOZZLE AND VORTEX BAFFLE PLATE

MULTIPLE NOZZLE WHEELS

For water wheels of the same design and for a constant head the horse-power output will vary as the square of the diameter, assuming of course, that the water quantity is proportionally increased. Thus for a given head and the same design if it is desired to double the water quantity and horse-power output, the diameter must be multiplied by 1.414. This increases the cost and may also give a size that is objectionably large. Again, and this is frequently more important, the generator speed is correspondingly reduced.

The Double-Nozzle construction is frequently used for this reason where the head is relatively low as compared with the quantity of water, in order to obtain a satisfactory generator speed. This permits twice the horse-power output from the same wheel, using twice the water quantity, the speed remaining the same. The nozzle body has two branches, arranged so that the jets strike the wheel at approximately 60 degrees from each other. In other instances, the double nozzle construction is selected because of the variation in flow of the stream. One nozzle may be of the plain type, without a needle, and the flow through it allowed to remain constant, or in the case of seasonal variation in flow, interchangeable nozzle tips of various capacities may be used. The other nozzle should be equipped with a needle and its discharge regulated in accordance with water quantity available. Where a wheel must be operated on fractional loads for a considerable part of the time, the efficiency, year in and year out, with such an arrangement is likely to be higher than if a single nozzle is used, in spite of the somewhat higher efficiency at full load of the latter type of unit. In other instances both nozzles may be equipped with needles.

Double nozzle units may be equipped, according to the service required, with almost any desired combination of plain or needle nozzles and stirrup or sleeve deflectors. It is even practicable to equip one of the nozzles with an auxiliary relief needle nozzle. The various combinations of equipment possible with double-nozzle units give rise to some interesting problems of governing.

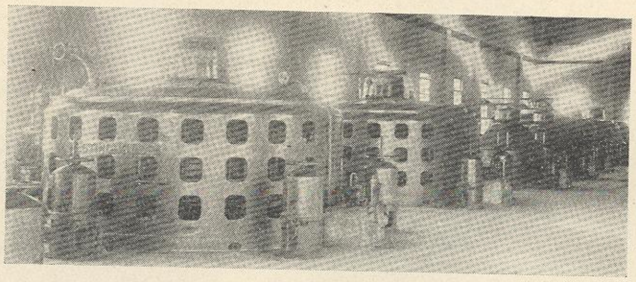

FIG. 12—CROSS CUT POWER PLANT OF THE SALT RIVER WATER USERS ASSOCIATION

Multiple Nozzle Vertical Wheels—The fundamental reason, as already noted, for applying more than one jet to a runner, is the desire to deliver more water to the wheel. Nozzles should be spaced about 60 degrees apart, and the mechanical and constructional disadvantages of using more than two jets with a horizontal-axis runner are so serious as to be prohibitive. Consequently, wheels with three or more nozzles should have a vertical axis. When a project seems to require such a multiple-nozzle wheel, it will usually be possible to design a reaction turbine that will better meet the conditions. The exceptions to this rule comprise those installations where some special condition is adverse to the use of reaction turbines.

An interesting example of this latter class of installation is the Cross-Cut Plant of the Salt River Water Users' Association in Arizona. The relatively low head, 110 feet, and the large quantity of water, which runs as high as 720 second feet, would naturally call for a reaction turbine plant, but the silt content is high during most of the year, and the water also carries corrosive chemicals. In addition, the power output is a by-product of the irrigation system, and the quantity of water varies between wide limits. For these reasons, six specially designed vertical impulse wheels were installed.

Double and Multiple Runner Wheels—Where a single-runner, double-nozzle wheel will not give the power at the desired speed, under the available head, two, three, and sometimes four runners equipped with double nozzles may be mounted on the same shaft to drive the same generator. In other instances the problem is met by using several generators, each driven by a single-runner wheel.

Housings—For the best results each wheel should rotate in a separate housing to prevent interference from discharged water. The lower part of the housing and the floor plates are usually made of cast iron. The upper housing is either cast iron or steel plate riveted to a cast iron frame. A centrifugal water guard is required to prevent leakage where the shaft passes through the side of the housing.

COUPLED AND OVERHUNG WHEELS

The earlier direct-connected units were of the coupled type, the wheel being self contained and connected to the generator by means of either a flexible or a rigid coupling, both wheel and generator being usually mounted on the same sub-base. This type is now used for small units only.

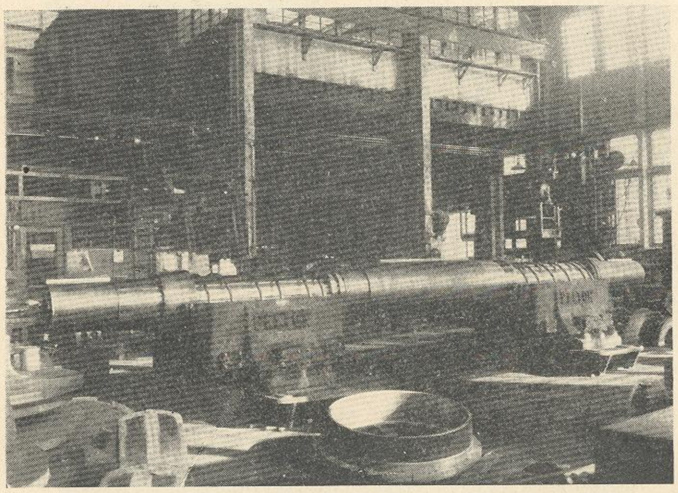

FIG. 13—BEARINGS AND SHAFT FOR A 22,500 HP UNIT
For the Big Creek No. 2 plant of the Southern California Edison Co. The head is 1860 feet.

For practically all large units, and for many small ones, the two-bearing type of construction, with overhung runner is used. The advantages of such self-aligning bearings are self-evident. On the other hand, it is virtually impossible accurately to align four, or even three bearings, and if they are so aligned, they will not stay that way. Unless the alignment is perfect, unequal and heavy wear on one or more bearings is sure to follow.

In the overhung type the generator is mounted between the two main bearings. Where a single runner is used, this is mounted on the shaft extension. The double-overhung type calls for runners on shaft extensions on both sides of the generator. Shafts for small units are forged from 0.30 to 0.40 carbon steel, while for large installations nickle-steel forgings are preferred.

For small single-overhung units, the shaft is usually provided with a solid-forged flange with stub extension, the wheel center being bolted to the flange. Besides being a dependable construction, this arrangement facilitates erection, since the wheel must revolve in a plane perpendicular to the axis of the shaft, provided merely that the bolts are drawn up equally tight. With the double-overhung type, in order that the shaft may be pressed into the hub of the generator, a press fit is required for the runners as well.

BEARINGS

The construction of bearings for large water wheel units, does not differ essentially from that of other high-speed bearings. A babbitted ring-oiling bearing of the pedestal type is used, an oil reservoir being placed in the base of the bearing.

The oil reservoir should be of sufficient dimensions to ensure adequate cooling of the bearing without additional cooling means. However, abnormal operating conditions, such as the accidental introduction of grit in the bearing, sometimes arise, overheating the bearing. Such difficulties are likely to occur when operating requirements make inadvisable an immediate shutdown to determine and to remove the cause. For this reason, for large units, it is desirable to have a water-cooling system, which can be placed in operation to tide over such emergencies. The designer, however, should not consider the provision of such a cooling system as an excuse for inadequately proportioned bearings or oil reservoirs.

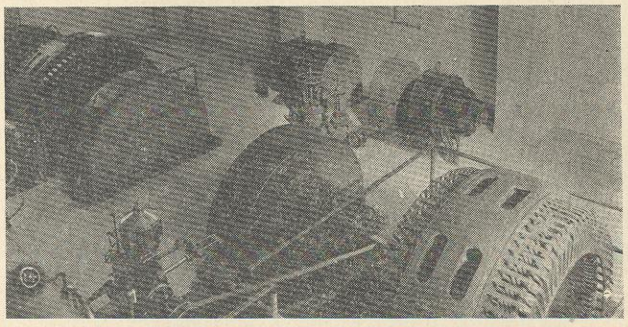

FIG. 14—GENERATING STATION OF THE FONTANA POWER COMPANY, FONTANA, CALIFORNIA
Both main and exciter units are driven by impulse wheels.

GOVERNORS

The general principles underlying the governing of either impulse wheels or reaction turbines are the same, and only such points as apply particularly to impulse-wheel governing will be discussed here. Both mechanical governors and oil-pressure governors of the closed sump type have been tried and found wanting, and all new installations are equipped with oil-pressure governors of the open-sump type. These consist essentially of an actuator element, pilot and relay valves, an operating cylinder or servomotor, and an oil-pumping and storage system. The actuator is provided with the customary fly-balls, which are usually enclosed.

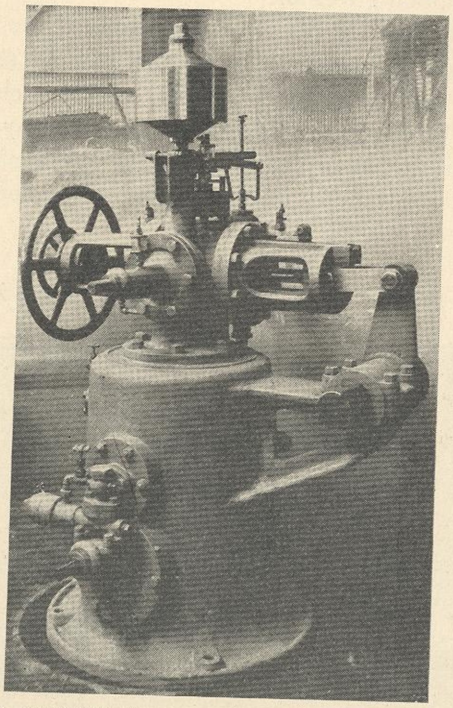

FIG. 15—OIL PRESSURE GOVERNOR FOR MODERATE GOVERNOR EFFORT
The pumping and storage set is contained in the governor base.

The servomotor consists of a cylinder containing a piston connected to the mechanism controlling the supply of water to the wheel, which piston is actuated by oil pressure. The control of large volumes of water requires a large servomotor, while the accurate regulation required in the operation of modern hydro-electric plants (the usual limit of speed variation is one-half percent) calls for rapid movement of the servomotor piston. The servomotor valves must therefore be relatively large in order to permit the rapid passage of sufficient quantities of pressure-oil. Since the actuator must be relatively light in order to be sufficiently sensitive to give accurate regulation, these large valves can not be operated directly by the actuator, and a pilot-valve must be provided as an intermediary.

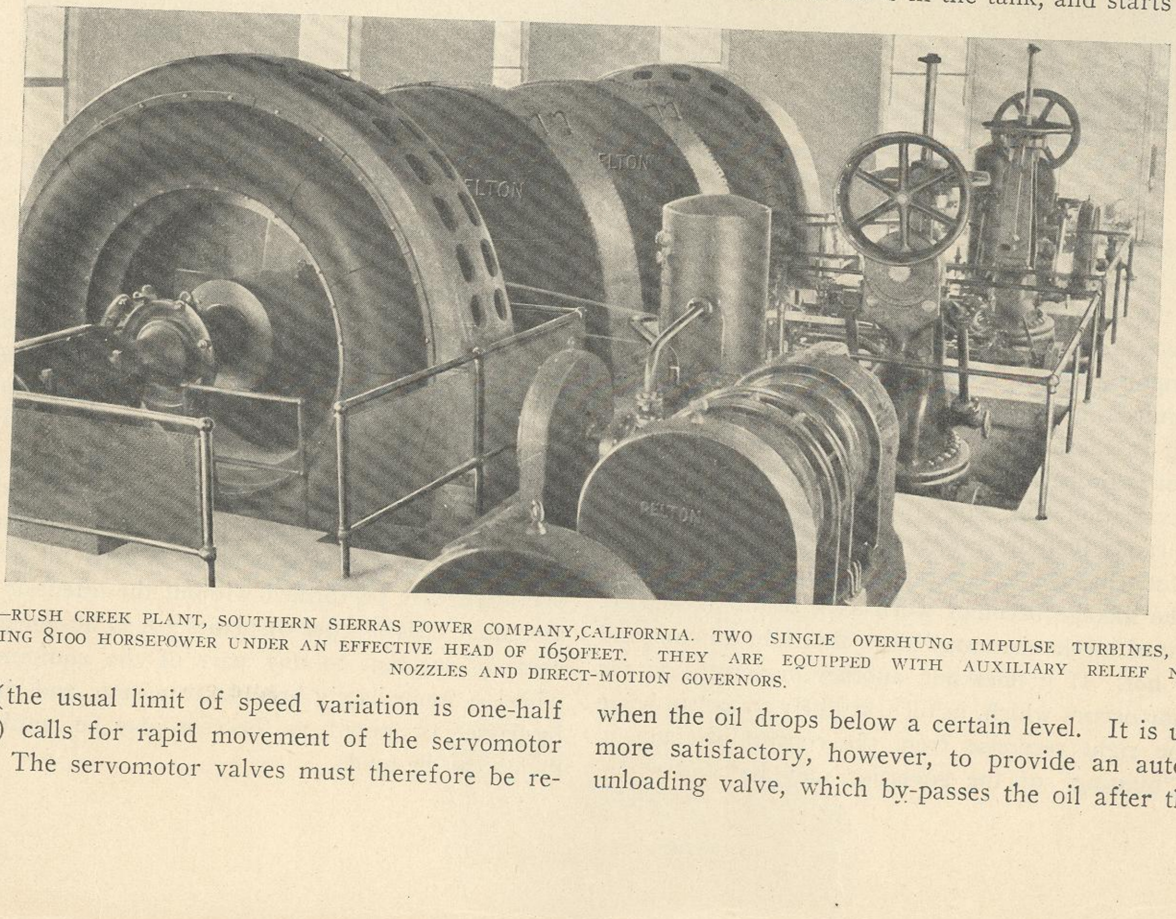

FIG. 16—RUSH CREEK PLANT, SOUTHERN SIERRAS POWER COMPANY,CALIFORNIA. TWO SINGLE OVERHUNG IMPULSE TURBINES, EACH DEVELOPING 8100 HORSEPOWER UNDER AN EFFECTIVE HEAD OF 1650FEET. THEY ARE EQUIPPED WITH AUXILIARY RELIEF NEEDLE NOZZLES AND DIRECT-MOTION GOVERNORS.

The oil-pumping and storage system may be either contained in the governor base, or consist of a separate pump and tank, depending on the service conditions. As a rule the larger governors are equipped with separate systems. The size and general design of a governor depends mainly upon the maximum effort required. The horse-power capacity of the wheel affects the governor effort only indirectly, the principal factor affecting the governor effort being the weight of the water controlling mechanism. A 1000 kw unit operating under a low head and thus requiring a large amount of water and large and heavy controlling mechanism may have as large a governor as a 5000 kw unit operating under a higher head.

The storage or accumulator tank should be cylindrical, with a height five to eight times its diameter. If this tank contained merely oil, a very small withdrawal would in turn cause irregular operation of the servomotor piston. To prevent this, air under pressure is introduced into the tank, thus acting as a cushion above the oil. The space normally occupied by the air is large as compared with the volume of oil, so that a considerable withdrawal of oil has only a slight effect on the pressure.

A rotary pump is the most satisfactory type for furnishing pressure oil. Some systems are provided with an automatic device that stops the pump when the desired amount of oil is in the tank, and starts it again when the oil drops below a certain level. It is usually more satisfactory, however, to provide an automatic unloading valve, which by-passes the oil after the desired maximum level is reached, the pump operating continuously.

Direct Motion Governors—The most common type of governor provides for transmitting the governor effort to the control mechanism by a series of levers, rockshafts, etc. In the direct-motion governor, which is applicable to the control of needle-nozzles provided with auxiliary nozzles, the servomotors operate the needle directly. The direct-motion governor consists essentially of an actuator mounted upon the nozzle body, and a servomotor consisting of a cylinder mounted directly in the rear of, and in line with, the main needle, and supported on a spacer or distance piece forming a part of the main nozzle body. The servomotor encloses a piston mounted on an extension of the needle stem. This type of governor requires a separate pumping and oil-pressure system.

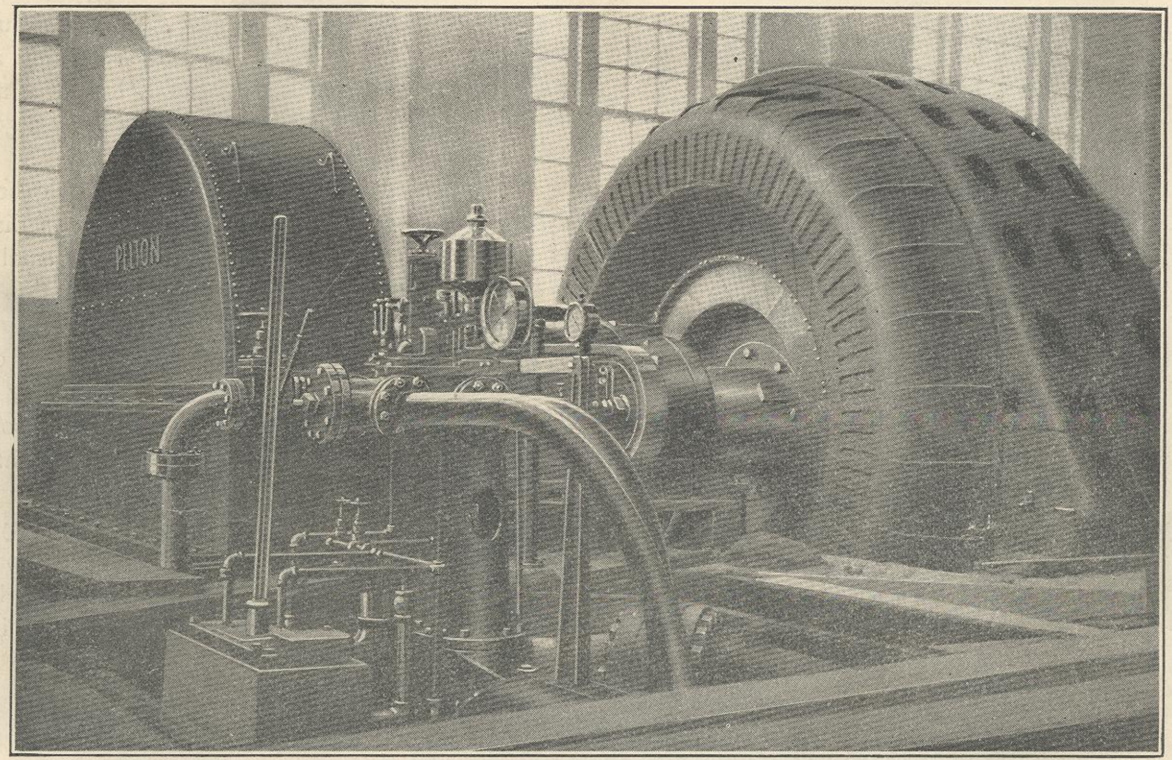

FIG. 17—DOUBLE-OVERHUNG IMPULSE TURBINE 22,500 HORSEPOWER UNDER A HEAD OF 1860 FEET AT THE BIG CREEK NO. 2 PLANT OF THE SOUTHERN CALIFORNIA EDISON COMPANY. ONLY THE RUNNER AT THE LEFT OF THE GENERATOR IS SHOWN. NOTE THE DIRECT-MOTION GOVERNOR MOUNTED ON THE MAIN NOZZLE STEM

In the direct-motion governor, lost motion because of torsion in the rockshaft is eliminated. What is more important, however, is the elimination of the linkage required in other types of governing apparatus. As long as there is no wear on this linkage, and the governor is properly adjusted, a change in speed due to a load variation will, through the actuator and servomotor, cause just the proper movement of the water-control mechanism to correct the speed. When, however, the linkage becomes worn as a result of service, the control mechanism may move the right amount and it may not. If it does not, another movement of the governor occurs which, in turn, is likely to fail to bring just the right response from the control mechanism. Such "hunting" of the governor may be, and sometimes is, continued indefinitely, causing not only poor speed regulation but also loss of efficiency and accelerated wear of all parts of the governing mechanism. In so far as it is caused by linkage wear, and this is usually the case, hunting may be prevented by the use of a direct-motion governor.

Space does not permit a discussion of the various special devices used with governors of both the ordinary and the direct-motion type. These include devices for limiting load, for preventing runaway in case of failure of the ordinary governing mechanism, for shutting down quickly in other emergencies, for change to hand-control, etc.

AUTOMATIC PLANTS

The general scope of this article does not permit extended discussion of remote-control (semi-automatic) and completely automatic plants, nor of the reasons that make impulse-wheel plants particularly adaptable to either remote or automatic control. The various governing devices that have made the operation of such plants possible are the outgrowth of experience in designing governors for the ordinary manually operated plant. Several remote-control plants are now in service which are started, synchronized, stopped, etc., by an operator in a plant miles away, and there are also completely automatic plants where all of these operations are performed without the attention of any attendant. Both types of plants are so designed that in case of accident to any part of the equipment, the wheel is immediately brought to a stop, and the water by-passed or stored, as the case may be, until adjustments can be made.