NOTES ON DESIGN OF HYDROELECTRIC POWER STATIONS.

(WITH REFERENCE TO THE INFLUENCE OF LOAD-FACTOR.)

BY DAVID B. RUSHMORE.

Hydroelectric power plants are designed with the ultimate object of being producers of wealth. All factors which have any bearing on fixed charges, cost of operation, or sale of power, must be considered. At the time of designing, operating conditions cannot be known definitely, and such factors as amount and distribution of load can be considered only in a general way. This is one difference between most water-power and steam stations. When the plant is in operation, conditions of load are constantly undergoing change. It is therefore generally impossible to design a system for fixed conditions, and provision must be made for a certain flexibility of operation and for future growth. Also, costs vary widely in different places and are confidential.

The distinguishing feature of hydroelectric installations is the special character of all conditions and apparatus. Hydraulic conditions: amount of rainfall, drainage-area, run-off, stream flow, storage, head of water, speed of wheels and generators—all these are peculiar to the particular location. Generator and transformer capacities and voltages are always more or less special, while the systems for transmission and distribution of power are invariably so.

Definite values can be considered therefore only with regard to a particular application, and a discussion of the subject must be confined to general principles. The selling price of power is also a variable, depending on the particular location and

class of service, and this is the criterion by which the desirability of any development must ultimately be judged.

The two factors of prime importance are reliability of service and commercial considerations. Reliability of service may be obtained from a system all of the separate parts of which do not possess this characteristic; but if the supply of power is unreliable, the sale of power is impossible and no commercial considerations will exist to be considered.

STREAM IN REGION OF FREQUENT RAINS.

FIG. 1.

Duplication of apparatus and isolation of troubles, combined with the best construction and protective devices, are the principles employed to obtain continuous operation. Duplicate ditches, regulating reservoirs, multiple pipe-lines, generator and transformer unit combinations, instantaneous automatic sectionalizing switches, and duplicate bus-bars and transmission lines, together with properly applied relays—are the means used to prevent interruption of service. Additional security

is gained where a number of power stations feed into the same transmission network, as in many western systems. In such instances any power house in trouble can be cut off entirely. Steam auxiliaries at the receiving end, supplying part of the load while floating on the system and possessing large overload capacities, as used at Los Angeles and Schenectady, are insurance against disabilities from line troubles.

The modern tendency is decidedly in favor of transferring the charges for maintenance and repairs to the interest column,

NO 2.

STREAM IN REGION OF CYCLIC RAINFALL.

FIG. 2.

by adopting more expensive construction with greater margins of safety. This is shown by the substitution of tunnels for flumes and ditches, and of steel towers for wooden poles, which is well illustrated in the new Kern River development of the Edison Electric Company of Los Angeles, where the length of tunnels is three-fourths of the distance over which the water is carried; and, in a country particularly adapted for use of wooden poles, the line is to be carried 115 miles on steel towers. The factor of safety in insulators is also wisely being raised.

TYPE OF PLANT.

Hydroelectric installations naturally divide into somewhat clearly defined classes, depending upon conditions. The western high-head plant, with great fluctuations in stream-flow and with long ditches and pipe-lines, containing but few units and feeding into a high-tension network, is under different conditions from a low-head, many-unit, single-plant installation delivering power over short distances or to a single point. Reliability of service is not of such great importance in irrigation pumping as it is in the lighting supply of a large town. This is not always recognized in the discussion of comparative advantages of small complications necessary to obtain reliability of service as compared with extreme simplicity and home-made switching apparatus. Conditions which have proved

FIG. 3.

satisfactory under conditions in the West could not be considered for systems which never allow current off the system.

RELATION OF STATION CAPACITY TO STREAM FLOW.

The majority of plants have a rated generator capacity between maximum and minimum stream-flow. As at Niagara, the plants may be below stream-flow at all times, and some developments, especially when replacing steam plants which are held as a reserve, may have a rated capacity of approximately maximum flow. If coal is high, power is dear; if power is cheap, coal is low, so that a steam auxiliary is always desirable if its use will materially increase the amount of power that can be sold.

The number of plants to the system and the distribution of plants on different watersheds materially affect conditions of

design and operation. A single plant with all the power transmitted to one place represents the most severe conditions; many plants, widely separated, on different watersheds, with steam auxiliaries and widely distributed use of power, the most favorable so far as load conditions are concerned. The type of construction is different for high and low heads and for few and many units. A peculiar feature of high-head building construction is the omission of openings on the hillside to provide for breaks in the pipe-line which sometimes, though very rarely, occurs.

FIG. 4.

The presence or absence of steam or water auxiliaries, and the use of hydraulic or electrical storage, influence distinguishing features in design, such as; 1. rated and overload capacities; 2. number of units; 3. types of wheels; 4. duplication of apparatus; and 5. reserve units.

The class of service has an important bearing on the system of control. Where conditions of contract do not severely penalize trouble, much simpler arrangements can be used than where it is demanded that no expense be spared to insure against interruptions.

LOAD-FACTOR AND LOAD CURVES.

Upon the exact definition of load-factor there is lack of agreement. It will here be called $\frac{\text{average output}}{\text{maximum output}}$. No definition is satisfactory for all classes of load without explanation. A limit on the time of peak-load or the use of rated capacity considerably modifies the figure obtained.

Commercial loads—nearly always mixed in character—can be divided into railway, lighting, general power, pumping,

FIG. 5.

hoisting, and electrolytic. These have seasonal, as well as hourly and daily, variation. Railway and lighting loads are particularly subject to abnormal variations from unusual causes. Both have large peaks over certain hours, and for a part of the day approach zero load. General power-load has an even curve for nine or ten hours with light load at noon, and is then off entirely or very light. A pumping load may be very steady and continuous over the day. During some seasons the pumps, if employed for irrigation work, may be out of use entirely. Fire pumps have a great and unknown

load variation but are seldom used but as part of larger loads. Hoisting loads are extremely variable in themselves, but the effect on the system may be smoothed out by use of a large number of hoists, or by the proper adaptation of fly-wheels and methods of control. Electrolytic loads are ideally constant at all times.

Machinery must be installed to carry the peaks; and the determining of the best methods of meeting large load variations constitutes the problem of prime importance in designing water power installations.

FIG. 6.

HYDRAULIC.

Water supply is extremely variable. The annual rainfall in this country varies from 0 inches to 70 inches. Less than 20 inches gives an arid region, and less than 15 inches requires irrigation. From 0 to 50% of the rainfall may appear as run-off, the remainder going to seepage, evaporation, and vegetation. Run-off may follow rainfall hours or days or months later; in case of snow, depending on the character of country, soil, forests, and vegetation. The percentage of run-off decreases with decrease of rainfall and, under the same conditions, the number of second-feet per square mile per inch of rainfall decreases with increasing area to watershed.

FIG. 7.

Stream-flow varies greatly by the day, season, and year, but over a number of years it averages nearly constant. The curve of stream-flow, especially minimum flow, is of prime importance in water-power development. For considerations of storage, the load-factor of stream-flow has a vital bearing on the amount and cost of development. The great problem of hydraulic development is to transform the daily and annual stream flow to correspond to the respective load curves.

The design of different elements is determined by various limits, some of which are but indirectly connected with the load-factor. Water conductors should primarily be of sufficient capacity for the worst conditions—not always the case. The grade of ditches may vary from 40 feet per mile for small ones, to 10 feet or less per mile for large, the allowable velocity depending on the soil. Velocities should be sufficient to prevent the growth of vegetation in ditches, but not sufficient to cause erosion.

The capacity of water for carrying sand, etc., varies as the sixth power of its velocity, and small decreases of velocity cause deposition of suspended matter—a fact made use of in sand boxes. With large quantities of water, it may be cheaper to replace wheels occasionally rather than to remove sand. In one western plant, after a storm, the diameter of a nozzle was cut from 3.5 inches to 4.5 inches in an hour by sand in the water.

Erosion wears away the ditch, with a possible loss of 20% or more in seepage through a stony bottom. Washes frequently break an embankment, the most annoying and expensive repairs to make. Three feet per second is the average figure in many western ditches; and two feet is necessary in some fine soils. This figure is subject to much variation. The loss of head in water conductors might be, but seldom if ever is, proportioned by Kelvin's law. A change in selling price or operating conditions after construction, then, would be followed by mathematical disaster. Ditches, as actually constructed, are usually in exposed places on the sides of steep mountains; they are costly to build and difficult to repair, and velocity of erosion is a limiting feature. It is estimated that California possesses over 5 000 miles of ditches, most of them constructed originally for hydraulic mining. (The plant at Electra has two ditches of 21 and 19 miles length, respectively.)

Velocities in flumes may range from 8 to 20 feet per second;

one flume about 9 feet wide, falls about 7 feet per mile; another 6 feet wide has a grade of from 8.5 to 17.0 feet per mile, depending on the length of section. Tunnels, when lined with concrete, may have a friction-coefficient of from 0.010 to 0.012. The complete cost may vary from \$5.00 to \$6.00 per cubic yard, or from \$20 to \$30 per lineal foot, for a 9-foot tunnel.* The coefficient of friction with rough rock walls will be from 0.030 to 0.035. For lined tunnels, 12.5 feet per second is given as a conservative velocity. Velocities much higher are in use in short lengths.

Velocities in pipe lines are limited by considerations of cost, efficiency, safety, and regulation. They vary from 3 to 15 feet per second. Wooden pipes with low velocities are often

FIG. 8.

used at the upper ends, but the greatest loss of head should occur at the bottom in the most expensive pipe. The thickness and factor of safety used increase with the head.

For considerations of freight, pipe lines should taper to allow proper packing by nesting. Cast-iron pipe is never now installed, although in use in a number of early plants. For all high-pressure work, riveted sheet-steel pipe is now universally used.

The best type of wheel to be used depends upon the head, quantity of water, speed, and range of load. Turbine wheels are efficient through only a small range of load, and under high heads are not easily regulated. In general, with low heads, large quantities of water and a number of generators to the

* Proceedings Second Conference of Engineers of Reclamation Service.

plant, turbines are used. For small quantities of water, high-head impulse wheels are employed. Improvement in light-load efficiency and some reserve against breakdown may be obtained by mounting impulse wheels on both ends of the generator shaft.

The use of impulse-wheels of the Pelton type is limited by certain features of design. The centre of buckets should run at about 45% of the spouting velocity. The diameter of the wheel should not be less than ten times the diameter of the jet, and this ratio should preferably be 15 or 18. Also, the

FIG. 9.

number of buckets which can be mounted on the rim has an important bearing.

The limiting speed of turbine wheels is not so clearly fixed. Turbine wheels are more flexible in design, and present tendencies toward high speeds and large units, as well as their application to higher heads, are having marked effect upon their development. The best type of wheel for a particular installation is not always self-evident. The use of vertical or horizontal types is still a matter of discussion and, under the same conditions, both types are installed, as at Niagara. Hori-

zontal bearings for large high-speed units become abnormal, and certainly the step-bearing has proved its reliability on the steam turbine. Impulse-wheels may be used with vertical shafts and a number of nozzles applied to one wheel. The Necaxa Plant in Mexico is an example of this construction.

Vertical shafts give a better operating room, requiring less space. Generators and, frequently, wheels also are cheaper; bearings are simple and, with single wheels, have many attractive features. Small units, or units where impulse wheels are used, are generally horizontal.

FIG 10.

The number of water-wheels to use with one generator is often a problem in low-head installations. With horizontal units, one or two impulse-wheels may be used and any even number of turbines. Fluctuating heads are always turbine propositions and, as one design of wheel can at a given speed work efficiently through only a limited range in head, a number of wheels on the same shaft, for use at different times, may be necessary. Overloads can be carried by using the other wheels, though inefficiently. The character of the load needs consideration in this regard.

Water-wheel generators have always been designed for 100% increase in speed, an unnecessarily conservative figure. In certain types of plants, subject to line disturbances, generators not infrequently run away. 63% increase in speed has been recorded in some cases. Of course this value depends upon the characteristics of the particular unit.

RATED AND OVERLOAD CAPACITIES.

In no other place is there opportunity for the display of better judgment in the adaptation of a plant to definite assumed load conditions than in the proper subdivision and rating of the elements of plant design. These principal features are reservoirs, ditches, flumes, pipes, wheels, generators, trans-

FIG. 11.

formers, and lines. The factors especially concerned with the conditions of load are: 1. number of units; 2. the characteristics at different loads; 3. the limiting conditions in the design; 4. commercial considerations of investment; 5. repair and depreciation charges; 6. possibilities for meeting future conditions.

For large developments the selection of reservoir sites and capacities requires special investigation. Often several main reservoirs check the river flow, and a regulating reservoir at the head of the pipe-line gives constant ditch-flow and carries the load temporarily in case of accident to the water supply. The cost of storage increases with the head and often decreases at low heads for increasing capacities. If great fluctuations in stream-flow obtain, it is seldom possible, from a commercial standpoint, to store all the water. Where development ex-

ceeds minimum stream-flow, there are but few high-head propositions where storage is not desirable; conversely, in many low-head installations the cost of storage is prohibitive.

Ditches, flumes, and pipes all come under the head of water conductors. A number of installations have more than one source of water supply. Erosion in ditches and loss of head in pipes are the usual limits of design. For flumes there is a grade for maximum capacity which, if exceeded, decreases the amount of water that can be carried, by causing a wave motion. The load conditions have much to do with allowable velocities

FIG. 12.

in pipes, which are similar in principles of design to electrical conductors. The loss of head at maximum load is important. High velocities and rapidly varying loads make regulation difficult. A subdivision of the pipe-line is desirable. Pipe-lines for high heads are costly and investment for different arrangements are studied before a final decision is reached. Flumes have a definite, and, at times, a troubled life. Ditches need repairs, but no depreciation charges. With pure water, pipes should show no deterioration if properly protected.

Wheels and generators demand careful study to decide the best capacities. The size of the generator is usually indicated

by some conditions in the proposition. The loss of one unit should not cripple the service. The generators and wheels should operate at points of best efficiency. The generator and wheel combinations are limited, and speeds are fixed by number of wheels, type, head, and output. For one-plant systems the number of generators is preferably not less than four nor more than eight. For multiple-plant systems, one unit to the station is not uncommon.

When no strong reasons exist for doing otherwise, water-wheel driven generators should have a rating of 40° cent. rise at full load and 8% regulation. This agrees with a wheel

FIG. 13.

rating for 4/5 gate. A greater approach to standard in this is very desirable. This allows for 25% overload on peaks. There is no reason for a higher generator rating if the capacity does not exist in the wheel. A small margin—about 10% of gate—should be left for governing. The above is for a number of units and a time variation of load not greater than can be cared for by placing in operation additional units. For suddenly-varying loads and peaks over short intervals, it may be desirable to have a wheel rating of 100% in excess of generator. The greater the number of units, the smaller this need be. In some cases it is desirable to take the peaks on a

part of the station and to block the governors on the remaining machines. Transformer ratings are usually the same as generator, and, when possible to do so, it is often desirable to make one unit of the two.

Generators for a given output have a speed for which the cost is a minimum. Unless peripheral velocities are increased, raising the speed does not decrease the active material. So, when this point has been reached, any further increase calls for mechanical requirements which rapidly increase the cost.

NS 14.

FIG. 14.

Water-wheels, within the limit of generator speeds, decrease in cost with increasing speeds.

Most transmission lines are designed from a standpoint of regulation but occasionally a case arises where an application of Kelvin's law is possible. For low-head factors, average losses may be used. A large number of equations have been developed for this work but an equality of interest on investment and value of lost energy is what is required. Unless maximum developments are installed, ample margins in all hydraulic and electrical conductors should be allowed for future

growth. The neglect to do this has adversely influenced many developments.

EFFICIENCIES.

The cost and value of efficiency in power-plant designing is an important but not clearly understood subject. The rough approximation usually made is to compare the selling price of the increased output with the interest charge on the greater cost. Where the saving in energy can be sold, as is usually the case, a higher efficiency in water conductors means a greater output and a greater capacity of installed apparatus with higher total cost, so that the investment charge for the gain in power is greater than usually considered. This is true of all parts of the chain of energy transformation.

Generator efficiency curves are flat beyond half load and are generally slowly increasing at overloads. Above half load, variation in generator efficiency is not of importance. Turbines have, however, a small range of load for best efficiency; while the curve for impulse-wheels is much flatter. Users of electrical apparatus should carefully compare characteristics and costs of different types of machines. Cheapness can nearly always be obtained by the sacrifice of quality.

The cost of efficiency is less susceptible of determination than the value. Water-wheels can be made of the best efficiency by designing them for the special conditions, instead of using standard patterns, and by the employment of a high grade of material with careful finish. The life can be increased by use of expensive metals and by cleaning the water. Wheels probably differ in efficiency much more than electrical apparatus. Doubt simply implies difficulty in hydraulic testing and scarcity of reliable results.

The generator efficiency is improved by using more copper and iron and a higher grade of insulation. Heating or regulation are the limits in design, and efficiency must be good with present types. A cheaper machine can be obtained with greater energy loss, the temperature being controlled by utilizing an increased windage.

Transformer costs may be materially reduced by lowering the efficiency. Low-efficiency transformers are prone to a short life and a hot one, and are, as a rule, much less desirable to operate than to buy. There is a theoretical point in design where the cost increases as the efficiency grows poorer. The efficiency curves of the best transformers are so flat that it is immaterial at what point they are operated.

STORAGE.

With a limited water supply, storage of water determines the possible development. Variations in load occur by the hour, day, season, and year. Auxiliary or regulating reservoirs at the head of the pipe-line take care of daily peaks, keep an even load on the water conductors, and serve to carry the plant over temporary ditch troubles, also serving as sand-boxes. The location of the pipe-line often renders storage at this point impossible. In one case, a flume of large dimensions is used for peak storage. In another, the water supply to a flume several miles in length is cut off entirely and the total stream-flow used for another station.

Main reservoirs are on the river and regulate its flow. If these are of sufficient size, the total run-off can be used. The Reclamation Service is at present doing a great work in water storage, in some cases over a term of years. Snow is a natural form of storage, well illustrated at Puyallup, where with a great variation in rainfall a nearly constant stream-flow is obtained. Forests, vegetation, and the soil fill the function of reservoirs. Dams are built to catch the underground waters.

For suddenly varying loads, as in railway and hoisting work, a fly-wheel is used to provide for instantaneous peaks. Irrigation laws may forbid the storage of water on old ditches. Electrical storage, at the distributing points, bears to the electrical system the same relation that the regulating reservoir does to the hydraulic.

AUXILIARY PLANTS.

The capacity of a water-power installation can usually be largely increased by the use of steam auxiliary plants. A steam plant can supply the deficiencies of stream-flow, can carry peaks in any season. It may act as a regulator with steam turbine floating on the lines, the hydraulic generators running under constant load; it may act as a reserve in case of breakdown on line; and may serve to furnish the wattless current for the system, allowing other machines to carry greater overloads. The turbine unit may be run idle part of the year as a synchronous condenser, or may float on the line as such for part of the day and deliver energy at other times. Contracts for supply of continuous power, with severe penalty clauses, may necessitate the installation of an auxiliary plant at the distributing end of the line. Such a plant is now being installed at San Francisco.

With improvements and reduction in cost and operating expenses of steam generating apparatus, the auxiliary plant becomes of increasing importance and, in some instances, threatens to become the more important.

A form of water-power auxiliary was recently suggested in which the installed generator capacity far exceeds the normal flow of the stream. Water is stored throughout the day and the plant operated for but a few hours on peaks of system.

CURVES.

The curves used to illustrate this paper are intended only to illustrate principles and not to give definite values, and must be so understood. They are considered self-explanatory.