CHAPTER V

DESIGN AND TESTING OF POWER STATIONS

It is impossible to set down any rules or formulæ for the specific design of hydro-electric power stations. With a full knowledge of the apparatus which goes to make up the equipment, and of the river conditions, the selection of sizes of machines and accessories, and the arrangement of the power plant become matters of personal judgment, influenced by the special local conditions. The only thing that can be done here is to set down, in a general way, the character of design which is sanctioned by modern practice and which, in turn, is based on the experience of the many engineers who have been engaged in this work.

Selection of Equipment.—The design of a hydro-electric plant is so intimately related to the design of the turbines and auxiliaries that the general plan is usually the joint conception of the plant designer and the turbine designer. This is particularly true of some of the more recent installations where the wheel casings, draft tubes and wheel chambers are built in concrete as integral parts of the power house. The controlling factors in the design of the power house are the turbines and generators. The power house is built around the generating units, and, hence, the general layout is determined by the design of the turbines and of the generators.

The vertical unit, although unsuitable under some conditions, has manifest advantages over other types. It combines simplicity and accessibility of mechanical parts with the superior efficiency due to an unobstructed draft tube, minimum friction of rotating parts, and convenient application of the spiral casing, which is the most efficient form of turbine casing thus far devised.

Vertical turbines have been built with two or more runners, but experience has shown that the single-runner unit is the more desirable. With multiple-runner wheels, the gate mechanism is almost entirely submerged, and can not be lubricated. The
mechanical design is more complicated, the wheels less efficient, and the entire machine is less accessible for inspection or repairs. The advantage of the multiple-runner vertical unit is higher speed, and that is not sufficient to offset its disadvantages, except under special conditions.

The best practice of today adheres to the single vertical turbine where commercially practicable. The casing is of volute or spiral form, and, for low heads, is usually moulded in the concrete foundations of the power house. For higher heads it is made of cast iron, cast steel or rivetted-steel plate, as conditions may require. Sometimes the metal casing is imbedded in concrete under the floor which supports the generator. The thrust bearing is occasionally located between the generator and the turbine and supported by the latter; but it is usually and preferably placed on top of the generator and supported by a spider mounted on the generator frame. The gate mechanism is exposed, no parts being in the water except the gates themselves, and all bearings and pin connections are accessible for lubrication. The gates are operated by two servo-motors or regulating cylinders connected in balance. No gearing, or gate shaft is required. The governor is located on the generator floor.

Horizontal turbines of the open-flume type have been built with four, six, and even eight runners per unit. These wheels, however, are open to the same objections which apply to the multiple-runner vertical unit. Too much of the vital mechanism is submerged. It can not be inspected or adjusted without shutting down the unit, and the usual result is that it is run until it breaks down or gets into such condition that it will no longer run at all.

Horizontal units may be either single- or double-discharge. Both types admit of exposed gate mechanism. The double-discharge has some advantages over the single in that it is hydraulically balanced against end thrust. On the other hand, if it is central discharge, i.e., both runners discharging into a common draft tube, the draft-tube conditions are not so favorable. If, however, the runners are spaced well apart, this objection is largely overcome. One of the commonest faults in the design of central-discharge turbines, as ordinarily built, is the close spacing of the runners.

Horizontal turbines for very low heads are, necessarily, set in open flumes or wheel pits. For high heads, the volute or spiral
casing is the preferable type, the question of central, double- or single-discharge depending on the conditions to be met. For intermediate heads, the cylindrical-plate steel casing has been commonly used. It is not as efficient, hydraulically, as the spiral casing, but it is considerably cheaper. If the penstock connection is at the top or the side, the gate mechanism may be exposed, which is not the case if the penstock is connected at the end. In the latter case, however, the hydraulic conditions are better.

Whatever the kind of water-wheel case, a drain pipe and valve must be provided by means of which the case, and penstock, back to the headgates, can be completely emptied. This drain pipe must be of ample dimensions, not only to draw off the initial water, but also to take care of the continuous flow from leaky headgates. For small turbines—say up to a pair of 36-in. wheels or a 46-in. single wheel—the diameter of the drain pipe should be not less than 6 in. Larger wheels should have proportionately larger drain pipes.

The number of units in a power plant to produce a given output should be as few as can be reasonably obtained in standard apparatus. At the same time, the whole power should not be concentrated on one unit except in a special case of a water-power plant running in parallel with other power plants, either steam or hydraulic, and these other plants of such capacity that they could carry the entire load temporarily if the single unit were shut down. It must be understood that there are certain periods in the life of every machine, no matter how simple its character, when it must be out of service for inspection, repair, the renewal of parts, or some other reason, and this period of shutdown may sometimes last as long as a month or 6 weeks, this being a reasonable time within which to order a repair part, get it shipped, delivered and installed, if the part required be of any magnitude. Therefore, the capacity of any power station is equal to the maximum continuous output of all the machines operating together, less one of them. There are sporadic occasions of excessive load peak which may occur three or four times a year and for this, the total capacity of equipment may be taken as the maximum continuous output of all the machines working together, but even on these infrequent occasions, one of the units might be unavoidably shut down. For small power plants the best number of units is, usually, three. The maximum overload capacity for continuous operation is, generally, 25 per
cent. more than the normal. Therefore, if each of three units can carry 50 per cent of the load, the three units working together will be loaded at about 80 per cent. of the normal which is around the point of best water-wheel efficiency, while if one machine is out of service, the two remaining ones can carry the entire load. As to whether three or four units should be adopted, depends on the standard machines available in the market. Generator and water-wheel sizes advance by steps with considerable difference in capacity from one size to the next, and in attempting to obtain three machines of the proper capacity it may be found that the available sizes will not permit this selection without provision of an excessive total capacity and a higher cost than by the adoption of four machines. Of course, if four machines are installed, each one should have a maximum capacity of one-third the total load. There have been numerous discussions, some even of a highly mathematical character, on the selection of the most economical generating unit. These discussions are interesting but have no practical bearing on the subject. As has been before stated, no engineer can predict what the load curve of a station will eventually be, and every hydro-electric installation is made in the hope that the demand for current will grow each year and the expectation that the equipment will have to be added to at some future time. This assumes, of course, that the maximum available power is not all capable of being converted into electric energy by the equipment at first installed. Hence, a little excess capacity, even at a small increase in cost, is not objectionable. Hair-splitting in the matter of size of equipment amounts to nothing, even if the load curve is fixed, because a few per cent. more or less in the capacity of a generating unit does not make any appreciable difference in the cost, and even if it did, exact, computed sizes of machines are not available. Generally, the cost of the generating equipment is only 10 or 12 per cent. of the total cost of the development and there is but little gained in reducing the effectiveness of a 100 per cent. investment to save 10 per cent. on 12 per cent. of it. In other words the variation of 10 to 12 per cent. in the size of the generating units will change the total cost of the development less than 1½ per cent.

Frequency.—The present practice is almost universally to adopt 60 cycles per second or 7,200 alternations per minute as the frequency for any plant, no matter what the service.
On long lines, and for low heads, 25 cycles per second has been used because of the generator characteristics, and the inductive line drop, which is proportional to the frequency, is greatly reduced and the regulation is better.

The disadvantages of this lower frequency are:

(a) The higher cost of transformers and motors than the costs for 60-cycle apparatus.

(b) The inability to operate lighting loads from 25-cycle circuit.

These so far outweigh the reduction in the inductive line drop, that 60 cycles is the value now adopted wherever the conditions of head and length of transmission permit (see Chap. I).

Shaft Connections.—Except in special instances, where the generator is built directly on top of the wheel case, and a single continuous shaft is used for both the wheel and the generator rotor, the wheel and rotor have independent shafts, and are usually built by different manufacturers. These shafts are generally connected together by flange-plate couplings, or split-tubular couplings, the coupling, in either case, being keyed to the shaft sections. Various forms of mechanical couplings have been used but the above have been found to be most reliable, satisfactory, and, in addition, cost less than other varieties.

The diameter of the shafting for turbines and generators is usually given by the formula:

\[ d = \sqrt[3]{\frac{100P}{N}} \text{ in.} \]  
\[ (18) \]

\[ d = \text{diameter of shaft in inches.} \]
\[ P = \text{maximum horsepower to be transmitted.} \]
\[ N = \text{number of revolutions per minute.} \]

The size of the shaft actually used should not be much smaller than is given by this formula.

Power House.—The power house is to be regarded as simply a protecting covering for the machine and operators, and the rational method of designing the power house is to lay out the machinery in the most advantageous manner and then plan a house to go over it.

The power station should be located as close to the dam as possible, providing that in this position, little or no tailrace excavation is required. The practice of saving a small amount of money, in reducing the length of penstocks by placing the
power house close to the dam, and then expending great sums in blasting out a tailrace, is not to be approved from the financial standpoint, when by locating the station a comparatively short distance downstream from the dam, most of the tailrace excavation would be avoided. In any instance, the cross-section of the tailrace and the elevation of its bottom must be such that
there is no appreciable loss of head, from the draft-tube pit to the stream.

Where horizontal units are used, they are usually set on concrete or masonry arches, the supporting piers between the arches being midway between adjacent machines. The water is conducted to the turbines through pipes which enter the turbine cases at the top or at one end, as may be best adapted to the conditions, and the discharge is carried down through the crown of the arch, and discharged through the archway. The length of the arch must be equal to the total length of the unit plus any additional distance represented by the width of the power house from the end of the unit to the opposite wall.

The power house itself may be built to include the entire unit, or the turbine may be left outside, the house covering only the generator, the switchboard and accessories.

The water-wheel shaft may pass through the wall of the power house, if the entire water wheel is excluded. In many instances, one end of the water-wheel case projects a few inches into the power house through the wall, the rest of the case being outside, and the wall is built up around the case so that there is no space.
between the periphery of the wheel case and the circular opening through which the case projects.

These two latter methods of construction are used in latitudes south of Virginia, where there is no danger of the water in the turbines freezing when the wheels are shut down so that they may not be easily started again. Figs. 64, 65 and 66 show some small power stations of this general type. Figs. 64 and 65 show two exterior views of a small power station in Tennessee. The first of these is a downstream view and shows the arches through which the water discharges into the tailrace. Fig. 66 shows a sectional elevation of a small power plant in Georgia, in which the water-wheel platform and the discharge tunnel has
Fig. 68—Plan of power house.
at one side of the house, the wheel shaft passing from the water wheel to the generator through the wall.

Where vertical wheels are used, the cost of the foundations is greatly reduced, because the discharge arches are either comparatively short or they are formed into draft tubes so that they fulfill both the function of supporting arch and draft tube. Also, the power house required is usually smaller than that necessary for horizontal units, particularly in cold climates where the water-wheel unit must be housed to prevent freezing.

Fig. 69.—Cross-section of generating station.

Figures 67 and 68 show the general form of a power station with vertical equipment. Vertical units are not adapted for open penstock setting, except under special conditions. The general arrangement for horizontal units in open penstock settings is as shown in Fig. 69, in which the downstream wall of the wheel pit forms the upstream wall of the power house. In this case, the house must be built upon discharge arches for the passage of the water from the draft tubes.
In many installations, the bulkhead of the dam is used as the upstream wall of the power station, and where this is the appropriate location of the power house a considerable saving is effected by this double use of the bulkhead. If, however, this location of the power house necessitates excavation of a tailrace of any considerable length, such design will prove more expensive than it would if the power house were located further downstream. Fig. 70 shows the arrangement of a power house close up against the bulkhead section of a hollow reinforced-concrete dam. The location of the racks, headgate, penstock, generating unit and draft tube are all clearly shown. In this case, the turbine unit comprises two horizontal, scroll-encased wheels, each with a separate intake from the penstock, the two wheels discharging into a common draft tube.

An arrangement of vertical units, each comprising a pair of water-wheels set in a cylindrical case of reinforced concrete, fed by steel penstocks and the water discharged through steel draft tubes without any arches under the power house, is that of the Austin, Tex., plant shown in Figs. 71 and 72 one being the plan, the other the transverse section.

While there are a large number of variations in design of power
houses, they are nearly all classified under some one of the types that are herein shown.

The elevation of the water wheels is always fixed by the fact that they may not be over 22 to 25 ft. above minimum low-water elevation and if the units are horizontal, they must be set high enough to prevent flooding the power-house floor and generators during periods of maximum high water.
Fig. 72.—Transverse section of power station (Austin, Texas).
DESIGN AND TESTING OF POWER STATIONS 135

In the case of vertical units, the elevation of the water wheels can be fixed at any desired level under 22 or 23 ft. above the low tailwater, and the length of draft tube required for gradual increase in cross-section can be obtained by carrying it down to the draft-tube pit at an angle to the horizontal or by making a long sweeping curve and carrying it along horizontally until the required length is attained. The location of the height of the generator floor is dictated solely by convenience, and the topography of the ground on which the power station is placed.

The house may be constructed of brick or concrete, it usually being preferable to use the latter material, due to the fact that the equipment for mixing and pouring the concrete is already on the ground, and the work can be carried on by the same gang of men used in building the dam. Where the machinery rests on reinforced-concrete floors, the design of the floors is fixed, not on the basis of their ability to carry weight, but on the maximum deflection under the loadings imposed. Excessive deflection will result in the alignment of the machinery being disturbed. Final alignment of the machinery should not be made until after the forms have been taken out from underneath the floor, and machinery and floor have assumed their final position.

This also applies to the adjustment of the thrust journals for vertical units. The end play in turbines is extremely small and the wheels should be adjusted exactly to their proper relationship with the surrounding gates.

Where vertical units are installed, the hole through the floor, over which the generator sets, should be as large as it is possible to make it and yet give a sufficient bearing surface for the generator frame to rest on, because it is through this hole that the water wheels will have to be dismantled and the parts removed whenever repairs must be made. It is not necessary for the hoisting chains on the crane to be long enough to reach down to the lowest portion of the water wheel, as anything below the floor level may be lifted with sling chains, which are fastened to the part to be removed and are long enough to reach to the crane hook.

The governors may be placed, either on the main floor of the station or down below where the turbines are, if the latter location makes it easier and cheaper to connect them with the gate shafts or shifting rings. It is better, however, to keep all the operating machinery on one floor, continually under the super-
vision of the attendants, except, of course, the water wheels, themselves. The governors are usually driven from countershafts that are geared to the main turbine shaft in the case of vertical units.

Governor countershafts and gearing are shown in Figs. 71 and 72.

Governors for horizontal units are usually driven directly from the main shaft. In some cases the diameter of the shaft is sufficiently great to act as a pulley to drive the governor belts and where the shafts are not large enough for this purpose, pulleys are placed on them.

![Diagram of a power plant]

**Fig. 73.—Section of power plant. Impulse-wheel driven.**

The power house should be only sufficiently wide and high to give a proper housing for the apparatus. The tendency to construct enormous buildings for this purpose is not to be regarded with approval. The height of the power house must be sufficient to permit the hoisting clear of any part of the equipment with the crane, and when this height is reached, there is nothing gained by making the structure any higher. Sixteen to 18 ft. in small stations, and 18 to 22 ft. for large stations, measured from the power house to the lower chord of the roof truss, is usually ample. The clearance between the machines inside the house, and between machines and wall, need never
exceed 4 ft., except where straight shafts are to be pulled out in some direction which would be obstructed by a wall or machine near to it.

Fig. 74.—Cross-section of power house. Impulse wheel-driven.

In case of horizontal units, it is customary to locate a window in the longitudinal wall opposite each unit, so that the horizontal shaft can be taken out, if desired, together with the generator shaft rotor and the water wheels, these assembled parts coming
clear of the generator frame when the rotor is close against the opposite wall, and that portion of the shaft projecting beyond it, passing through the window.

In case of impulse-wheel driven power stations, the common practice is to locate the wheel inside the house. In many instances the units have only two bearings, one on each side of the generator. The bearing on the side adjacent to the wheel is extended and made considerably longer, and, therefore, has a greater bearing area than is customary for a simple generator bearing. Next to this bearing the water wheel is placed on an extension of the generator shaft. While this practice is not approved by some designers, it has been extensively used. Figs. 73 and 74 show cross-sections through power houses for impulse-wheel driven units.

Figures 75 and 76 show two other forms of turbine-driven power stations and, together with the preceding figures, are
indicative of the different methods and views of designers. They all represent approved practice excepting that in some of them the draft tubes drop vertically into the tailrace instead of being curved to discharge the water horizontally in the direction of flow.

It is recommended that designers refer to the current files of the standard engineering periodicals for descriptions of hydro-electric stations and for the reasons which led the engineers to adopt the apparatus and designs which were used in fixing the type and size of plant, and, in this way, become familiar with the practical application of the principles of design.

A general criticism of most power houses is that they have been built larger and have cost more than was really necessary.

Power-house floors are almost invariably of concrete and the roof covering of slate, tile, or tar-felt and gravel. The flat, tar-and-gravel roof is the cheapest and is a satisfactory roof.

The roof trusses are made of steel, or of a combination of wood members for compression and steel ones for tension. There is a number of types of roof trusses and it is beyond the scope of this work to enter into a discussion of these various forms. The following, however, give some useful data.
Roof trusses must sustain the load due to the roof, covering, sheathing, snow and wind loads.

The weights of the roofing, per square foot, are, approximately, tin, 1 lb.; corrugated iron, 1 to 3 lb.; slate, 7 to 10 lb.; felt, tar and gravel, 8 to 10 lb.; tiles, 8 to 25 lb.

Sheathing 1 in. thick weighs 3 to 4 lb.

Snow loads vary with the latitude and are commonly taken as follows:

New England and Michigan, 30 lb. per square foot.
New York—Chicago, 20 lb. per square foot.
Cincinnati—St. Louis—Baltimore, 10 lb. per square foot.

Wind loads vary with the slope of the roof. The normal component, acts as a roof load. For a wind pressure equal to 40 lb. per square foot against a vertical surface, the following are the values of the roof loads for various inclinations.

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Load (lb. sq. ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5.1</td>
</tr>
<tr>
<td>10</td>
<td>9.6</td>
</tr>
<tr>
<td>15</td>
<td>14.2</td>
</tr>
<tr>
<td>20</td>
<td>18.4</td>
</tr>
<tr>
<td>25</td>
<td>22.6</td>
</tr>
<tr>
<td>30</td>
<td>26.5</td>
</tr>
<tr>
<td>35</td>
<td>30.1</td>
</tr>
<tr>
<td>40</td>
<td>33.3</td>
</tr>
</tbody>
</table>

The approximate weights of steel roof trusses are given by the empirical formula:

\[ W = 0.75 AL (1 + 0.1L) \text{ lb., or} \]

\[ W = \frac{C}{45} AL (1 + \frac{L}{5\sqrt{A}}) \text{ lb.} \quad (19) \]

\[ W \text{ = total weight of one roof truss.} \]
\[ L \text{ = span of truss, in feet.} \]
\[ A \text{ = spacing of trusses, i.e., distance between neighboring trusses, c to c measurement.} \]
\[ C \text{ = total weight per horizontal square foot of roof.} \]

Value of \( C \) is, usually, between 40 and 50.

For \( C = 45 \)

\[ W = AL (1 + \frac{L}{5\sqrt{A}}) \text{ lb.} \quad (20) \]

The switchboard is preferably placed from 6 to 8 ft., from the longitudinal wall of the station on the opposite side of the house from the generating units, the board being parallel with the longitudinal walls. It is fastened to the floor, in any of the several approved methods, and the top is braced by horizontal
rods which connect with each vertical panel supporting member, and are fastened to the wall. These horizontal supporting rods are usually made of 1-in. standard, wrought-iron pipe, that screw into a clamp connector at the end where it fastens to the vertical supporting member of the switchboard, and on the other end, a flat plate is screwed, which rests against the wall and has one or two holes in it through which expansion bolts can pass, and in this manner the ends are fastened to the wall.

The cables leading from the various machines to the switchboard are sometimes carried in special cable tunnels made in the floors. These are simple trenches, which are formed when the concrete floors are cast, ranging from 4 to 12 in. in width, and 4 to 6 in. in depth. The cables are laid in these trenches and then covered with fine dry sand, which is packed hard, after which a thin covering made of light reinforced concrete slabs is laid on top of the sand, their upper surfaces coming flush with the floor, or checkered iron plates are laid over them. It, however, is better and cheaper to run the cables underneath the floor, supported on iron supports, spaced from 4 to 6 ft. apart. Holes are cast in the floor when it is laid, or later drilled through it, and short sections of iron pipe passed through the holes, and grouted in place. The cables pass through these, down under the floor and resting on the iron brackets are exposed so that they can be inspected at any time.

The cables should be heavily insulated with best quality of rubber or varnished cambric insulation, or its equivalent, and triple-braided. A lead sheath outside the insulation gives added protection and its use is recommended.

Care should be taken to cut the sheath away at least 8 in. back from the cable ends, otherwise the system may become grounded. The sheath forms a grounded metallic tube and if its end comes close to a terminal or lug, connection may be established from lug to sheath and in this manner, ground the busbars. These suggestions all apply to conductors carrying less than 15,000 volts. Any interior wires that are subject to greater pressures should be bare, and carried overhead on high-tension insulators. The sizes of wires and cables are usually fixed by the current-carrying capacity instead of the voltage drop, where the length of circuit is under 150 ft. (i.e., 300 ft. of wire).

The following table gives the safe current-carrying capacities of various sizes of insulated wires and cables:
Table 5.—Safe Current-carrying Capacities of Insulated Copper Wires (1913 National Electrical Code)

<table>
<thead>
<tr>
<th>Circular mils</th>
<th>A.W.G.</th>
<th>Table A, rubber insulation (amp.)</th>
<th>Table B, other insulations (amp.)</th>
<th>Circular mils</th>
<th>A.W.G.</th>
<th>Table A, rubber insulation (amp.)</th>
<th>Table B, other insulations (amp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,624</td>
<td>18</td>
<td>3</td>
<td>5</td>
<td>200,000</td>
<td>....</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>2,583</td>
<td>16</td>
<td>6</td>
<td>10</td>
<td>300,000</td>
<td>....</td>
<td>275</td>
<td>400</td>
</tr>
<tr>
<td>4,107</td>
<td>14</td>
<td>15</td>
<td>20</td>
<td>400,000</td>
<td>....</td>
<td>325</td>
<td>500</td>
</tr>
<tr>
<td>6,530</td>
<td>12</td>
<td>20</td>
<td>25</td>
<td>500,000</td>
<td>....</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>10,380</td>
<td>10</td>
<td>25</td>
<td>30</td>
<td>600,000</td>
<td>....</td>
<td>450</td>
<td>680</td>
</tr>
<tr>
<td>16,510</td>
<td>8</td>
<td>35</td>
<td>50</td>
<td>700,000</td>
<td>....</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td>26,230</td>
<td>6</td>
<td>50</td>
<td>70</td>
<td>800,000</td>
<td>....</td>
<td>550</td>
<td>840</td>
</tr>
<tr>
<td>33,100</td>
<td>5</td>
<td>55</td>
<td>80</td>
<td>900,000</td>
<td>....</td>
<td>600</td>
<td>920</td>
</tr>
<tr>
<td>41,740</td>
<td>4</td>
<td>70</td>
<td>90</td>
<td>1,000,000</td>
<td>....</td>
<td>650</td>
<td>1,000</td>
</tr>
<tr>
<td>52,630</td>
<td>3</td>
<td>80</td>
<td>100</td>
<td>1,100,000</td>
<td>....</td>
<td>690</td>
<td>1,080</td>
</tr>
<tr>
<td>66,370</td>
<td>2</td>
<td>90</td>
<td>125</td>
<td>1,200,000</td>
<td>....</td>
<td>730</td>
<td>1,150</td>
</tr>
<tr>
<td>83,090</td>
<td>1</td>
<td>100</td>
<td>150</td>
<td>1,300,000</td>
<td>....</td>
<td>770</td>
<td>1,220</td>
</tr>
<tr>
<td>105,500</td>
<td>0</td>
<td>125</td>
<td>200</td>
<td>1,400,000</td>
<td>....</td>
<td>810</td>
<td>1,290</td>
</tr>
<tr>
<td>133,100</td>
<td>00</td>
<td>150</td>
<td>225</td>
<td>1,500,000</td>
<td>....</td>
<td>850</td>
<td>1,360</td>
</tr>
<tr>
<td>167,800</td>
<td>000</td>
<td>175</td>
<td>275</td>
<td>1,600,000</td>
<td>....</td>
<td>890</td>
<td>1,430</td>
</tr>
<tr>
<td>211,000</td>
<td>0000</td>
<td>225</td>
<td>325</td>
<td>1,700,000</td>
<td>....</td>
<td>930</td>
<td>1,490</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,800,000</td>
<td>....</td>
<td>970</td>
<td>1,550</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,900,000</td>
<td>....</td>
<td>1,010</td>
<td>1,610</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2,000,000</td>
<td>....</td>
<td>1,050</td>
<td>1,670</td>
</tr>
</tbody>
</table>

Note: The current-carrying capacity of bare wires is given in the chapter on "Transmission Lines."

Up to within a comparatively recent time, transformers have been housed, just as the operating machines have been. In most instances they have been placed in extensions of the power house either on the same floor level, or in a story built above the first floor of the power house. Some of the figures showing sections through power stations, show also the location of transformers.

From about 1913, the tendency has been toward using outdoor type transformers, and placing them outside the power house. This practice is more rational than housing them, particularly in the case of high-tension transformers; where the clearances between them and between the connecting wires must be considerable, and this, in turn, requires a great deal of room in any structure built around them. There is no good reason for protecting the transformer from the weather, excepting possibly shielding it from the sun in warm climates. In the southern
part of the United States, where temperatures in the sun reach 135°, the ability of transformers to radiate the heat dissipated in them is greatly diminished, and overheating is apt to result in any except water-cooled units. For such situations some sort of shed should be built over the transformers to shield them from the sun’s rays, and if this is not done, water-cooled transformers

![Cross-section of transformer house.](image)

must be used, the quantity of water required for cooling being considerably greater than that used under normal conditions.

The transformers are usually set on a platform above ground level, so that they are clear of dampness or any surface water. Choke coils and lightning arresters are placed on a framework constructed around the transformers, and made of either wood or
steel. This method of outdoor installation is more fully described in the chapter on "Substations."

The amount of room required by high-tension transformers and connecting wires is shown in the drawings of sections through power plants at various places in this chapter. The relative cubical dimensions of the generating machinery room and the portion of the house occupied by the transformers and connections in impulse-wheel plants should be observed particularly.

Figure 77 shows a transformer house placed adjacent to a power station, to house the step-up transformers, and from which the transmission lines start.

High-tension Wires.—When the high-tension wires and busbars are located inside the power house, ample clearances between wires of opposite polarities are required, varying from 4 ft. for 30,000 volts to 7 or 8 ft. for 110,000 volts. It was the custom for some years to put the wires and busbars in concrete or brick compartments. Present practice, however, favors the placing of the wires in the upper part of the power station or near the ceiling in the case of a single-story house, and without any surrounding compartments.

They are supported on one of the several available types of insulators. Standard line insulators are frequently used either pin or suspension type according to the voltage between the wires. In some cases, special high-tension post insulators are used.

There is no particularly difficult problem involved in the layout and installation of these wires, provided plenty of space to accommodate them be available.

Brass or copper pipe is being used in many installations, for high-tension busbars and connections. Standard fittings cannot be used because of the sharp angles and corners on them. All bends must be of bent pipe, and the radius of bend should be at least six times the diameter of the pipe. End connections are made with interior threaded nipples or plugs, the two pipe ends screwing up together to form a smooth butt joint.

Branches require special fittings of a Y form, the legs of the Y being spread out and rounded in the crotch, so that there is no point at which the radius of curvature, in any direction, is less than that of the pipe.

The transmission line must enter the power station, at some
convenient point, unless the step-up transformers are located outside. A number of different methods of bringing the high-tension wires into the station have been devised. Where the pressure between wires is less than 33,000 volts, the method indicated in Fig. 78 is a good one. As shown, sections of tile drain pipe are set in the power-house wall at the proper elevation, the pipe being placed with its axis making an angle of about 20° with the horizontal so that the entering wire takes an upward direction. This is for the purpose of preventing rain from travelling along the wire into the station. The wire is stretched between two insulators, one inside and one outside the power house, and, generally, there is no strain on these insulators other than that imposed by the short section of cable between them. While this section is a continuation of the transmission wire, the strain, due to the external forces acting on the transmission line, is taken up on a strain frame outside the building and the stress on the cable, from the holding clamp on the strain frame to the outer insulator, is negligible, the wire simply being bent in an easy curve from clamp to insulator.

A framework must be provided inside the power station to carry the interior insulators. In some cases it is expedient to locate the lightning arresters and choke coils on this interior frame, which form of construction is shown in the figure.

Fig. 78.—Line entrance and interior frame, 6600 volts.
Where the voltage exceeds 33,000, the wires should be brought in through special insulated tubes which pass through the wall, or through the roof, as may be the more convenient. A tube of this kind is shown in Fig. 79, and its application is obvious from some of the cross-sections through power stations shown in the several figures. If the voltage exceeds 66,000 volts, the transmission line should end outside the house and a piece of brass or copper pipe attached to it, having a cross-section of metal equal to that of the cable. The ends of the pipe should be curved or tapered down to the diameter of the wire, the wire passing through the reduced opening thus made and sweated or soldered into place. The joints must be filed smooth so that no sharp edge or corner exists, and the increase in diameter from that of the cable to the diameter of the pipe must be smoothly and gradually made. Increasing the diameter reduces the electrostatic gradient and, therefore, the liability of puncture, or flashing over from the lines, where the tubes pass through the wall or the roof. The pipe diameter should range from 2 in. in the case of 88,000 volts, to 4 in. for 150,000 volts. These pipe sections can be carried through specially made wall or roof insulators just as wires are. This method of increasing the diameter of the conductors at critical points is not much used. It, however, has considerable merit and, with the advent of transmission lines operated at 100,000 volts and more, it is probable that it will ultimately become general practice and the manufacturers of electrical porcelain will provide standard insulating tubes of the larger diameters required.

Other forms of line outlets are shown in Figs. 80 and 81.
Windows and Doors.—In accordance with the general policy of making a power station fireproof, the window and door frames should be made of metal, the window sash also of metal, and the doors of wood, covered with sheet iron. Stamped-steel, frames

![Diagram of transmission-line outlet](image)

Fig. 80.—Transmission-line outlet.  Fig. 81.—Transmission-line outlet.

and sash are now available at prices which are but little in excess of those for corresponding wood frames and sash.

One doorway should be large enough to move any piece of

![Power house of reinforced concrete](image)

Fig. 82.—Power house of reinforced concrete.
machinery through it, and in case of a large power station, this
doorway should be of sufficient dimensions to permit the passage
of a railway car over a temporary track laid through it. This
doorway is normally kept closed and is only used for the purposes
for which it is made.

Ventilation is provided through the windows, these usually
being arranged with tilting sections which give a total area
of opening equal to 50 per cent. of the window area. This
will afford ample ventilation if there is sufficient window area.
As a rough approximation, one-half of the wall space should
be occupied by window frames. Fig. 82 shows portion of an
external view of a power station in which the general height and
proportion of the window frames are indicated. There is no
occasion for incurring the expense of monitor roofing for purpose
of ventilation if the window openings are sufficiently large and
numerous.

Lighting.—The power house should be well lighted and pro-
vided with numerous outlets along the wall for the reception of
plugs so that hand lights can be connected with the circuit when-
ever it is necessary to inspect the apparatus. Suspended lights
from the ceiling can not be used as they would interfere with the
movement of the crane. It, therefore, is necessary to use lamps
fastened on brackets which are, in turn, attached to the walls.
The brackets extend between 3 and 4 ft. from the wall, are spaced
from 16 to 20 ft. apart, and an incandescent lamp with reflector
is fastened at the outer end of the bracket. The lamps should
be 100 to 150 watts, and a 16- or 18-in. mill-type reflector is
satisfactory for this service. The reflectors should be set so
that they make a slight angle with the horizontal and tend to
throw the light toward the center line of the room. The best
height of lamps is from 13 to 15 ft. above floor level.

The lighting circuit receives current preferably from the exciter
busbars. The station auxiliaries, such as pump or crane motors,
should be operated from the power busbars.

Plumbing and Fittings.—The stations must be provided with
all necessary comforts and conveniences such as lockers, hand
basins and one or more water-closets. The water supply is
taken from the penstock or forebay. While these are trivial,
they are necessary, and it is easier and cheaper to provide for
them in advance of construction, than to try to work them in
after the station is completed.
Oiling Galleries and Stairs.—Every part of the plant that requires inspection and every journal that is not inside the water-wheel case must be easily accessible. Small oiling platforms, with narrow iron stairways, should be placed wherever necessary for an operator to reach a journal for inspection or oiling. The platforms may be of mesh-reinforced concrete or rolled checkered plate steel. They cost but little, and contribute to insuring the proper attention of the station attendants to their regular duties of inspection and maintenance of ample oil supply.

Auxiliary Steam Plants.—During seasons of low water, if the load exceeds that which the water can supply, it is necessary to have an auxiliary source of power. The water power is sold at a low rate, and steam power costs much more, per kilowatt-hour, for the amount of energy needed to supply the difference between the delivered power and the amount supplied by the water than the income received from it, but, with an auxiliary steam plant, power can be sold for 365 days in the year, which requires steam operation for only 30 or 40 days per annum. In many cases, power is sold to mills and factories that have steam plants already installed and some arrangement can usually be made whereby these consumers will supply themselves with power during periods of low water, paying for electrical energy during the other parts of the year. In this way the existing steam plants become auxiliaries of the water-power plant without the necessity of any investment and its attendant interest and depreciation. In other cases, it is necessary to install a steam plant in connection with the hydro-electric power station, and, in this event, the size and character of the steam equipment must be settled by the specific local conditions. The plant will be operated intermittently only, while its interest and depreciation charges will go on continuously. Therefore, it should be of the cheapest possible character compatible with giving reliable service. Under these conditions, the question of steam economy is of only secondary importance.

Since it will be in service at occasional and widely separated intervals, the question of a staff of operatives is a serious one. They can not be kept continuously on the payroll, and it is equally impossible to assemble an operative force at short notice for a few days service. It is usually the custom to employ regular station attendants who are also good steam-plant operators and it only becomes necessary to obtain common laborers as firemen,
whenever the steam plant is put in service. This arrangement makes it inexpedient to work more than one shift of men, which, in turn, necessitates a larger capacity of steam plant. The size of the plant is fixed to give a base load of some continuous fixed output, the water-power equipment taking the load peaks. Therefore, the number of kilowatt-hours which a small steam plant can produce each day is very great as compared with the output of the usual steam plant operating on a fluctuating load. For these conditions, the steam equipment must have twice as great a capacity if operated on one shift as it would have if operated on two shifts. The impossibility of giving any definite basis for fixing the size of a plant, without a knowledge of all the other conditions, is obvious. Also, the discussion of steam equipment is beyond the scope of this text. A few general suggestions, however, may be given.

In small-size plants, a successful arrangement has been to extend the dynamo shaft on the side opposite to the water wheel and put a pulley, or rope sheave on it. A jaw-clutch coupling between the water wheel and the generator allows the latter to be disconnected from the water wheel and driven by the steam engine, either by belt or rope drive, depending on the size of the unit. In one or two instances, the engine shaft has been direct-connected to the generator shaft through a large clutch coupling, so that the generator would run as a steam-driven, direct-connected unit, or as a water-wheel driven unit, as occasion might require. In large power stations, it is cheaper to install steam-turbine equipment complete, than to use reciprocating engines arranged for connecting with the water-wheel generators. When this is done, the steam-driven units are usually placed in an extension of the power house or in a separate power station near the water-power plant on the river bank. In case of plants feeding very long transmission lines, it is sometimes better to install the steam auxiliary at the substation at the load end of the line. In any case, this auxiliary plant should be so located that it may be supervised by attendants who are regularly and continuously employed.

Tests.—The usual tests which are made on a completed power station are:

1. Test of turbine efficiency.
2. Test of maximum power of the water-wheels.
3. Heat test of generators.
4. Regulation test of governors.

In order to make these tests with any reasonable cost and attain accurate results without waste of time, it is necessary to make proper preparation for them. Makeshift arrangements result only in loss of time and money and produce but uncertain results.

The only practicable methods of loading the water wheels are either by means of the generators themselves, or the Alden brake. While these brakes may be obtained for tests at a reasonable rental, it is expensive to ship them to the point of trial and install them in connection with the water wheel as this requires the removal of the generator. The Alden brake, therefore, is to be regarded as a last resort, to be used only when there is a serious dispute between the engineer and the water-wheel builders as to the efficiency of the wheels which involves a large financial consideration. The universal way of loading the wheels is by means of the generators. These must be tested in the shop and the efficiency at all loads fully known. There are facilities for making the complete electrical tests of generators in every electrical manufactory, and the machine should be tested there before shipment, in the presence of the engineer or his representative, and the water-wheel manufacturer should have a representative present, so that the results of the tests will be agreed on by all parties concerned. There is no way in which the efficiency of the generators can be determined after they leave the factory except by disconnecting from the water wheel and driving them at various loads with an electric motor which itself has been previously tested and the efficiency of which is known. This, while not impossible, is impractical.

The load for the water wheel and generator must be steady, variable at will within the limits of half load to the maximum possible output of the unit, which is usually 125 per cent. load, and, preferably, non-inductive. The best means, and the ones universally used, are water rheostats or submerged iron-wire resistances.

**Rheostat for Test Loading.**—Rheostats for absorbing the full-load energy of a generator, may be of two kinds, one being the well-known "water rheostat," in which the liquid forms the resistance and energy absorbing medium. The other, is the submerged iron-wire rheostat, in which the resistance is made up of iron-wire coils. The wires have a small cross-section and are
prevented from melting under the high-current densities, by being submerged in water.

The water rheostat is usually made up of a number of barrels filled with water up to within 6 in. of the top. The resistance of the water is reduced by the addition of a little salt or sulphuric acid. This must be added to the liquid cautiously as very slight amounts cause comparatively great changes in resistance. The amount required for any test must be determined for the specific conditions. The electrodes are made of wrought-iron pipe of any size between 2 and 6 in. in diameter, there being two pieces of pipe in each barrel. These electrodes are suspended from sash cords passing over the pulleys above the barrel, so that they may be raised or lowered and, thereby, immersed to a greater or less extent in the liquid. A metallic coupling or a piece of heavy wire should be inserted somewhere in the length of the cord so that the latter may not become saturated over its entire length by capillary attraction. By raising or lowering the electrodes the resistance may be increased or diminished and the load on the generator varied. The liquid will heat with passage of the current, and as it heats its resistance diminishes. It, therefore, should be allowed to warm up before beginning the test. The number of barrels and electrodes required depends on the energy which they must absorb. About 50 kw. per barrel or equivalent volume is within the limit of good practice. Fig. 83 shows connections of a rheostat of this kind for loading a three-phase generator. The electrodes in the barrel must be moved until the current is the same in each phase. Where the water is naturally slightly alkaline and the voltage of the generators is high—say 6600 volts—there is no need of adding either salt or acid to the water, and as much as 200 to 300 kw. of energy may be dissipated in each barrel if a small stream of water is fed continuously to the barrels through a rubber hose.

The iron-wire rheostat is simply a series of coils of iron wire
having a resistance such that when in series only about one-half
the normal-load current of the generator can pass through them.
These coils are quickly and cheaply made by winding them in a
lathe around a 2- or 2½-in. iron pipe as a mandrel. The coils
are then placed in barrels or tanks. If placed in barrels, they may
be wound helically, from top to bottom around the inner surface
and held against the side of the barrel by staples. If placed in
tanks, which are shallow wooden boxes, reasonably water-tight,
they are strung back and forth from end to end of the box. Two or
three layers of coils may be placed in each box. If the box is
longer than 3 ft. there should be a middle support, which is
simply a wooden crossbar under each layer of coils at their
middle point, to keep them from sagging. The horizontal
clearance of the coils should be about 2 in. and the vertical
clearance about 4 in. There is one resistance provided for each
phase and, preferably, each resistance unit should be in a sepa-
rate tank or barrel.

The author is aware of the fact that many successful tests have
been conducted with iron-wire resistances strung on frames
and submerged in the forebay or tailrace. While this practice
is satisfactory for streams in which the waters bear no natural
salts in solution, the writer has failed in several instances, to
obtain anything but short-circuits from resistances immersed in
the stream. Wooden boxes which serve as tanks, are inexpens-
ive, allow immediate inspection of the resistances without
removing them, and, generally, will cost no more than the frame-
works and lifting apparatus required for immersing in streams.
As an example, three boxes, each 4 ft. wide, 6 ft. long and 2 ft.
depth made of ordinary, 1½-in. lumber, and supported on 6 by 6 in.
sills laid on the ground, will effectually cool resistances absor-
ing 2000 kw. at 6600 volts. A rubber hose feeding a 1½-in.
stream of water to each box is sufficient to keep the water cool.
The size of the submerged iron wire to carry a given current is
fixed by the following formula:

\[ d = kI^{3/4} \]  \hspace{1cm} (21)
\[ l = \frac{d^2E}{112I} \]  \hspace{1cm} (22)

\( d \) = diameter of wire, in mils.
\( I \) = current in amperes. This, for three-phase currents, is
the number of amperes per phase.
\[ E = \text{voltage. For three-phase currents, } E = \text{Volts between phases} \]

\[ l = \text{length of wire required, in feet} \]

\[ 112 = \text{average resistance per mil-foot of iron wire at 120°F.} \]

\[ k = \text{a constant, varying from 2.75 to 3.25. 3.00 is a good average value.} \]

The size of the coil must be computed for the maximum overload on the generator and the length of the coil must be such as to give it total resistance to limit the current flow to one-half its normal value. Switches must be provided by which proportionate parts of the coils can be cut out, so that loads of 50 per cent., 75 per cent., 100 per cent. and 125 per cent. of normal can be obtained.

**Instruments.**—The switchboard instruments can not be used for a test. The instruments used must be calibrated in connection with their potential and series transformers. Complete testing outfits may be obtained at reasonable rental from several sources. The cost is small, disputes are eliminated and, in addition, the switchboard instruments may be tested incidental to the generator tests. The instruments necessary, comprise: Two wattmeters, one voltmeter, and two amperemeters. A power-factor meter is a convenient instrument to have but not essential. The power measurement is made by the two-wattmeter method. The wattmeter connections are as indicated in Fig. 84. The total generator output is equal to the sum of the two readings of the wattmeters. The current and voltage from the exciter should always be observed as a matter of record.

The efficiency tests of generators include the net energy of excitation but take no account of the efficiency of the exciter itself. Therefore, if the exciter is driven from the water wheel, it should be disconnected and, the generator excited from some other source, unless the efficiency of the exciter is known, in which case, the total load on the wheel is the generator plus the exciter load.
The quantity of water passing through the turbine is measured by a weir constructed in the tailrace, a hook gauge being used to determine the water levels. The weir measurements should be checked by Pitot tubes in the tailrace. A stake should be driven near the edge of the forebay or at some convenient point in the lake and a steel scale fixed to it, about one-half the scale being submerged. The difference in level between the top of the scale and the reference point on the hook gauge in the tailrace, should be established by an accurate survey with a "Y" level. Only occasional readings on the lake-level scale are necessary as this will remain constant over a considerable period of time. Knowing the difference in level between the two reference points, the actual difference can be determined from the readings of the hook gauge and of the lake level on the scale on the stake. The head from the middle point of the water wheel to the reference point on the hook gauge, should also be measured. In the case of a single vertical wheel, the elevation of its middle point will be at approximately the middle point of the gates. If the unit is made of a pair of vertical wheels, the middle point will be located halfway between the two wheels, if the two wheels have a common discharge. If the two wheels have separate draft tubes, each must be treated as a single vertical wheel. In the case of a horizontal unit, the middle point is the elevation of the center of the shaft. This measurement gives the head due to the draft tube.

A pressure gauge should be connected with the wheel casing, the connection being made at any convenient point or height. The elevation of the gauge itself, however, must be at the middle point of the wheel. A vacuum gauge should be connected with the draft chest, the elevation of the gauge being the same as that of the pressure gauge. The gauge pipes on the interior of the turbine case and the draft chest should be set perpendicular to the casing wall, so that the flow of the water is parallel to the end of the pipe. The sum of the readings of these two gauges should give the net head on the wheel, and the net head thus determined should check within 1 per cent. with the net head computed by deducting the loss in head due to entry (exclusive of velocity head) plus the friction loss in the penstock, from the total head.

A reliable tachometer is convenient but not necessary. A good speed counter with a stop-watch is sufficiently accurate. Temporary telephone connections should be made from the
instrument bench to the load rheostat and to the hook gauge unless these points are within 100 yd. of the bench and may be easily seen from it. Light must be provided for the instruments, because tests sometimes run continuously for 18 hr. or more. The staff required usually comprises:

The Chief of Test and such observers as may be present from the manufacturing companies interested.

One assistant to read instruments.
One assistant at the switchboard.
One assistant at hook gauge and Pitot tubes in the tailrace.
One assistant at the headgates who will also take lake-level readings.
One watchman at the load rheostat to report if any unusual steam or flashing appears.

After preparing, a continuous run of 3 or 4 hr. at full load should be made to bring the machinery and water in the load resistances up to a temperature, and to be sure that the plant is working smoothly.

Prior to beginning tests, a number of log blanks should be prepared. These are sheets divided into vertical columns and each column given its proper title under which the records taken are set down. The following is a list of titles and the columns in the log blanks should be arranged in substantially the same order, horizontally. Those which have a star opposite them are not filled in by any records but are the results computed from the readings. They are placed in the order given because it is convenient to so locate them.

Hydraulic Observations

1. Number of run.
2. Time.
3. Lake-level scale.
4. Hook gauge.
5. Total head.
6. Head on weir.
7. Discharge by weir.
9. Discharge by Pitot tubes.
11. Vacuum gauge.
12. Total head by gauges.
13. Entry plus friction head.
Electrical Observations

1. Number of run.
2. Time.
3. Speed of unit.
4. Volts between phases.
5. Current per phase.
7. Wattmeter No. 1.
8. Wattmeter No. 2.
9. Generator output by volts and amperes. (This equals \(1.732EI\phi, I\) being the amperes in one phase, \(E\) volts, \(\phi = \text{power-factor}\))
10. Output of wattmeters.
11. Generator efficiency at load.
12. Horsepower delivered to generator shaft.
13. Temperature of room.
15. Exciter amperes.
16. Volts at field terminals of generator.
17. Exciter kilowatts to generator.

The fixed observations which are made at the beginning of the test are: barometer, and temperature of outside air.

The heat test of the generator is made by running it for 2 hr. at its maximum overload, then for 6 hr. at normal load, after which it is stopped. Immediately after machine stops, thermometers should be fastened against one of the field windings and against one of the armature windings by soft putty and allowed to remain from 3 to 5 min. Where possible, the bulbs of the thermometers should be pushed inside of the armature winding slots.

The following formulae are convenient in computing the results:

\[
\text{Call kw. the total generator output in kilowatts.}
\]

\[
\text{Net hp. of turbine} = hp_n = \frac{\text{kw.} \times 1.34}{E} \quad (23)
\]

\[
E = \text{generator efficiency at given load}
\]

\[
\text{Gross hp. in water} = \frac{h_nQ}{8.8} = hp_o \quad (24)
\]

\[
h_n = \text{net head}
\]

\[
\text{Turbine efficiency} = \frac{hp_n}{hp_o} \quad (25)
\]

\[
\text{Efficiency of unit from water to generator terminals is} \frac{1.34\text{ kw.}}{hp_o} \quad (26)
\]
CHAPTER VI

WIRES AND CABLES

Wires and Cables.—The metals used for transmission conductors are copper and aluminum. Copper has a higher conductivity per unit of cross-section and length than aluminum, but aluminum has the higher conductivity per unit weight of metal for a given length.

The characteristics of these two metals are as follows:

<table>
<thead>
<tr>
<th>Table 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Resistance per cubic centimeter</td>
</tr>
<tr>
<td>Resistance per cubic inch</td>
</tr>
<tr>
<td>Resistance per mil-foot</td>
</tr>
<tr>
<td>Resistance per meter-gram</td>
</tr>
<tr>
<td>Temperature coefficient of</td>
</tr>
<tr>
<td>electrical resistance</td>
</tr>
<tr>
<td>Specific gravity</td>
</tr>
<tr>
<td>Weight per cubic inch</td>
</tr>
<tr>
<td>Weight per mil-foot</td>
</tr>
<tr>
<td>Tensile strength per square inch</td>
</tr>
</tbody>
</table>

All above for metals at 20°C. Commercial copper conductivity about 97.8 per cent. of above values.

Aluminum.—From the preceding table it is seen that the volume of aluminum required to give a conductivity equal to a certain copper conductor, having a fixed length is 1.616 times the volume of the copper, or 61.6 per cent. more of aluminum than copper is required to give the same resistance.

The weight of a given volume of aluminum is 30.2 per cent. of that of an equal volume of copper. Hence, the weight of aluminum for a given conductivity is $1.616 \times 0.302 = 48.8$ per cent. of the weight of the copper, having the same conductivity.

Copper has but few advantages, as compared with aluminum, and these are negligible when the lower cost of aluminum is
considered. For equal costs of transmission material, over twice as much per pound, can be paid for aluminum as for copper. Manufacturers of aluminum, usually, vary the selling price of that metal in accordance with the fluctuations in copper prices, keeping it at such a value as to make it cost about 23 per cent. less than the equivalent copper, which is a compelling factor in the selection of the metal to be used.

During the years 1911 to 1915, the price of aluminum cables has been between 23 and 25 cts. per pound.

The advantages of aluminum over copper, briefly, are:

1. Its lower cost.

2. The greater diameter of the wire for a given resistance, or given cost. This tends to reduce the corona effect on high voltages, as is elsewhere explained, and also, the better radiation gives a lower temperature under load, thereby, slightly, reducing the conductor resistance. Besides, a better mechanical tie can be made at the insulators, than on a smaller copper wire.

3. The surface of aluminum oxide appears to shed sleet better than does copper.

4. Due to its lightness, freight charges and the cost of distributing along the line on reels are lower.

The disadvantages of aluminum as compared with copper are:

1. It can not be soldered.

2. Nearly all electrical fittings being of copper, there must be connection at certain points between the aluminum conductors and the copper fittings. A good joint between them is difficult to make and, unless well made, electrolytic action may, ultimately, cause failure of the joint.

3. It is soft and easily abraded if dragged over stones or hard substances, and, therefore, it has to be carefully handled in the field.

4. The lower cost of aluminum does not appear as an actual saving except for lines having short spans—say 250 ft. or less. The elastic limit of aluminum and its modulus of elasticity are lower than those of copper, while its change in length with temperature is greater. Hence, for a given clearance between the ground and the wire, with maximum sag, the supporting poles or towers must be higher if aluminum cables are used than would be necessary if they were of copper.
Since the cost of the towers or poles increases very rapidly with
increase in height, the total cost of a line, having aluminum
conductors, may equal, or even exceed, that of a line having
copper conductors, though the cost of the aluminum cables may
be considerably less than the cost of copper conductors.

For these same reasons, aluminum is not adapted for lines in
which the spans are great and the cables small, because they sag
so greatly under high temperatures and are stressed so little that
they will “snake” or whip under sudden gusts of wind, which
means that all the cables on a pole do not sway together, preserv-
ing their normal separation, but whip about individually, thus
tending to come near enough together to produce corona or even
actual contact, and consequent short-circuiting.

These objections have been largely overcome by making
aluminum cables with steel cores.

The advantages usually outweigh the objections so that,
aluminum is now being used to a considerable extent for trans-
mission lines.

The Aluminum Co. of America has perfected and is marketing
a number of fittings, connectors and other accessories that make
the construction of an aluminum line as easy and simple as that
of a copper one.

Joints.—For straight line joints the dovetail splice, when
properly made, is satisfactory. This is illustrated in Fig. 85
and is made by opening the ends of the cable to be joined,
fitting the strands of one between those of the other and wrapping
one strand at a time tightly round the others and the cable
which they surround.

Compression joints are generally used on sizes of cable from
2/0 B. & S. up. They are of two forms, namely the three-piece
and the single-piece. The three-piece joint is shown in Fig. 86.
It consists of two cast-aluminum sleeves bored to fit the cable
and provided with bosses which are pressed down to the diameter
of the sleeve by hydraulic pressure, compressing all strands of
the cable to form practically a solid section. The ends are
threaded right and left hand, and united by a similarly threaded
stud. These joints are put on in the factory, the sleeve which is
threaded right hand being invariably put on the end of the cable
that is on the inside of the reel.

Thus, in erecting the cable, the left-hand threaded sleeve,
which is on the outer end of the cable, is pulled off one reel to the
reel that is ahead of it along the line and is connected by the stud to the inside of the cable on the second reel after this cable is pulled out.

The single-piece compression joint is similar in form but of one piece and is put on in the field, a suitable hydraulic press and pump being provided for the purpose. The ends of the cables to be joined are brought together in the middle of the sleeve which is then compressed. A finished joint of this kind is shown in Fig. 87. These joints are very efficient, both mechanically and electrically.

Fig. 85.—Dove-tail joint. Fig. 86.—Three-piece joint.

Fig. 87.—Compression joint. Fig. 88.—McIntyre joint.

Fig. 89.—Wedge joint. Fig. 90.—Tap-off clamp.

Fig. 91.—Parallel groove connector. Fig. 92.—Strain clamp.

The joints are made in the field by means of a portable hydraulic jack and dies. The weight of these tools is about 200 lb., the largest piece weighing about 150 lb.

The McIntyre joint, Fig. 88, is used chiefly on the smaller sizes of cable, though it has been used on sizes as large as 650,000 c.m. Like the compression joint, it is both mechanically and electrically efficient. It is made of seamless drawn aluminum tubing, oval in section, into which the ends of the cables to be joined are pushed side by side from opposite ends of the sleeve, after which, the joint is completed by giving the sleeves three twists, the ends of the sleeves being held in splicing clamps.
The wedge joint, Fig. 89, is designed primarily for use on larger sizes of cable than 2/0, in emergencies, being a form of joint that can be quickly made up. It consists of two cast-aluminum sleeves, bored conically on the inside, the strands of the cable being forced out against the conical surface by driving a cone over the center strand. A right- and left-hand threaded thimble screws over the two sleeves and pulls them together.

This joint depends upon tension for its electrical efficiency and should not be used in places where cable hangs without tension, and its use is not recommended, excepting for emergencies.

Two forms of joints are provided for making tap connections. The tap-off joint, Fig. 90, is made in two pieces to clamp over the main-line cable. The tap wire is sweated into the lug, which is bored to fit the tap wire and tinned ready for solder before leaving the factory. In the field it can be handled like a tinned copper lug, and a wire sweated into it in the usual way.

The parallel groove connector, Fig. 91, is designed for use where a joint is required to transmit the full carrying capacity of the main-line cable, or for connecting jumpers to the main line, or making a connection at the end of a line to a power house or substation. It is of two pieces, grooved to fit the cables to be connected, and bolted together over the two cables. When one cable is of copper, the groove for it is copper bushed, the bushing being sweated into the groove in the factory.

For dead-ending at the end of a line or at points along the line, the dead end or strain clamp, Fig. 92, is furnished. It has been designed to give sufficient bearing on the cable, when clamped over it, to develop the full strength of the cable. Eye-bolts are provided for attaching it through messenger wire and strain insulators to the pole or crossarm.

The bolts used in the above three forms of joints are galvanized and a galvanized lock washer is used under all nuts, so that once set up there is no chance of their becoming loose.

**Bimetallic Wires.**—Both copper and aluminum cables are made with steel cores to give added strength. This arrangement is not so necessary for copper cables, but for high-tension lines on towers with long spans it is almost essential to reinforce aluminum to compensate for its high coefficient of expansion and its low elastic limit. The electrical characteristics of bimetallic wires are:
Resistance, copper and steel wire.

\[ R_1 = R_e + [r_1^2 \times 57,275 \times 10^{-9}] \text{ ohms per foot length.} \tag{27} \]

\( R_e \) = resistance of copper cable having same diameter as compound cable.

\( r_1 \) = radius of inner steel core in inches.

Resistance, aluminum and steel wire.

\[ R_2 = R_a + [r_1^2 \times 51,128 \times 10^{-9}] \text{ ohms per foot length.} \tag{28} \]

\( R_a \) = resistance per foot, of aluminum cable having the same diameter as the compound cable.

The inductance does not differ appreciably, from that of an all-copper or all-aluminum wire having the same diameter and distance of separation from its neighboring wire, provided the distance of separation be 30 in. or more.

Physical Properties of Compound Wires.—The weight of a copper wire having a steel core is

\[ W_1 = W_e - 1.4756 r_1^2 = W_e - 0.369 d^2 \text{ lb. per foot.} \tag{29} \]

\( W_1 \) = weight per foot length.

\( r_1 \) = radius of core in inches.

\( d \) = diam. of core in inches.

\( W_e \) = weight per foot length of an all-copper wire having the same outside diameter as the compound wire.

The general formula for weight of wire is

\[ W = \pi[(r_1^2 S_1 + (r_2^2 - r_1^2) S_2) \text{ lb. per foot.} \tag{30} \]

which for any two metals reduces to

\[ W = W_1 + r_2^2 \pi (S_1 - S_2) \text{ lb. per foot.} \tag{31} \]

\( r_2 \) = radius of outer shell, or tube of wire, in inches.

\( S_1 \) = weight per foot length of metal forming the core having a cross-section of 1 sq. in.

\( S_2 \) = weight per foot length of one square inch of metal forming the shell.

\( W_1 \) = weight per foot of solid wire all of the same metal as the shell and having a diameter equal to that of the shell.

For aluminum and steel this reduces to

\[ W_2 = W_a + 7.057 r_1^2 \text{ lb. per foot.} \tag{31a} \]

\( W_a \) = weight per foot of solid aluminum wire of same diameter as compound wire.
Example. Take a 0000 B. & S. gauge wire of aluminum and steel.

Diameter of core = $d_1 = 0.3$ in.

$r_1 = 0.15$ in.

$W$ from table = 0.195 lb. per foot length.

$7.057r_1^2 = 0.0225 \times 7.057 = 0.15878$

$W_2 = 0.195 + 0.15878 = 0.35378$ lb. per foot.

**Strength of compound wire**

\[ H = H_x + \pi r_1^2 (U_1 - U_z) \]  \hspace{1cm} (32)

$H =$ ultimate strength of wire in pounds.

$H_x =$ ultimate strength of a wire made of same metal as that of shell material and having same diameter.

$U_1 =$ ultimate strength of 1 sq. in. of steel wire.

$U_z =$ ultimate strength of 1 sq. in. of metal, of which shell is composed.

Thus, for the aluminum-steel cable of dimensions given in the preceding example, the ultimate strength would be

$H_x = 0.1662 \times 30,000 = 5000$ in which 0.1662 is the area of a No. 0000 cable in square inches.

$H_e = 5000 + \pi \times 0.0225 (100,000 - 30,000) = 9,950$ lb.

**The elastic modulus of a compound wire is**

\[ M_e = M_2 + \left(\frac{r_1}{r_2}\right)^2 (M_1 - M_2) \]  \hspace{1cm} (33)

$M_2 =$ elastic modulus of shell.

$M_1 =$ elastic modulus of core.

**Reels.**—Wire and cables are usually shipped on wooden reels, which are returnable to the manufacturer. The quantity of different size wire and cables, which are usually wound on a single reel, are given in the following table:
## Wires and Cables

### Cable and Wire Carrying Capacity of Standard Reels

(General Electric Co.)

<table>
<thead>
<tr>
<th>Over-all dia. of cable, in.</th>
<th>Reel No. 6 24×12×12</th>
<th>Reel No. 5 30×21×15</th>
<th>Reel No. 4 48×24×28</th>
<th>Reel No. 3 60×24×34</th>
<th>Reel No. 2 60×41×34</th>
<th>Reel No. 1 66×41×34</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>1,500</td>
<td>5,500</td>
<td>9,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>1,050</td>
<td>3,900</td>
<td>8,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.35</td>
<td>790</td>
<td>2,850</td>
<td>7,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>600</td>
<td>2,075</td>
<td>6,000</td>
<td>9,700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>480</td>
<td>1,675</td>
<td>5,900</td>
<td>7,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>385</td>
<td>1,375</td>
<td>4,000</td>
<td>6,100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.55</td>
<td>290</td>
<td>1,100</td>
<td>3,400</td>
<td>5,100</td>
<td>9,900</td>
<td>12,400</td>
</tr>
<tr>
<td>0.60</td>
<td>240</td>
<td>890</td>
<td>2,930</td>
<td>4,400</td>
<td>8,300</td>
<td>10,400</td>
</tr>
<tr>
<td>0.65</td>
<td>220</td>
<td>785</td>
<td>2,430</td>
<td>3,700</td>
<td>7,150</td>
<td>8,900</td>
</tr>
<tr>
<td>0.70</td>
<td>165</td>
<td>650</td>
<td>2,120</td>
<td>3,180</td>
<td>6,100</td>
<td>7,600</td>
</tr>
<tr>
<td>0.75</td>
<td>145</td>
<td>580</td>
<td>1,760</td>
<td>2,650</td>
<td>5,200</td>
<td>6,500</td>
</tr>
<tr>
<td>0.80</td>
<td>...</td>
<td>550</td>
<td>1,460</td>
<td>2,200</td>
<td>4,400</td>
<td>5,500</td>
</tr>
<tr>
<td>0.90</td>
<td>...</td>
<td>410</td>
<td>1,180</td>
<td>1,780</td>
<td>3,580</td>
<td>4,470</td>
</tr>
<tr>
<td>1.00</td>
<td>...</td>
<td>300</td>
<td>1,000</td>
<td>1,500</td>
<td>3,000</td>
<td>3,750</td>
</tr>
<tr>
<td>1.10</td>
<td>...</td>
<td>...</td>
<td>830</td>
<td>1,250</td>
<td>2,500</td>
<td>3,120</td>
</tr>
<tr>
<td>1.20</td>
<td>...</td>
<td>...</td>
<td>730</td>
<td>1,100</td>
<td>2,200</td>
<td>2,750</td>
</tr>
<tr>
<td>1.30</td>
<td>...</td>
<td>...</td>
<td>600</td>
<td>900</td>
<td>1,750</td>
<td>2,180</td>
</tr>
<tr>
<td>1.40</td>
<td>...</td>
<td>...</td>
<td>530</td>
<td>800</td>
<td>1,600</td>
<td>2,000</td>
</tr>
<tr>
<td>1.50</td>
<td>...</td>
<td>...</td>
<td>430</td>
<td>650</td>
<td>1,300</td>
<td>1,820</td>
</tr>
<tr>
<td>1.60</td>
<td>...</td>
<td>...</td>
<td>550</td>
<td>1,100</td>
<td></td>
<td>1,370</td>
</tr>
<tr>
<td>1.70</td>
<td>...</td>
<td>...</td>
<td>490</td>
<td>1,000</td>
<td></td>
<td>1,250</td>
</tr>
<tr>
<td>1.80</td>
<td>...</td>
<td>...</td>
<td>420</td>
<td>850</td>
<td></td>
<td>1,060</td>
</tr>
<tr>
<td>1.90</td>
<td>...</td>
<td>...</td>
<td>400</td>
<td>800</td>
<td></td>
<td>1,000</td>
</tr>
<tr>
<td>2.00</td>
<td>...</td>
<td>...</td>
<td>375</td>
<td>720</td>
<td></td>
<td>900</td>
</tr>
<tr>
<td>2.25</td>
<td>...</td>
<td>...</td>
<td>270</td>
<td>550</td>
<td></td>
<td>690</td>
</tr>
<tr>
<td>2.50</td>
<td>...</td>
<td>...</td>
<td>220</td>
<td>460</td>
<td></td>
<td>570</td>
</tr>
<tr>
<td>3.00</td>
<td>...</td>
<td>...</td>
<td>165</td>
<td>360</td>
<td></td>
<td>450</td>
</tr>
</tbody>
</table>

### Approximate Maximum Weight of Cable, per Reel, Pounds

| 175 | 500 | 1,500 | 2,500 | 5,000 | 6,250 |

### Approximate Weight of Reel with Slat, Pounds

| 36 | 100 | 240 | 495 | 650 | 760 |