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LARGE ELECTRIC POWER STATIONS

THEIR DESIGN AND CONSTRUCTION

With Examples of Existing Stations

BY

Dr G. KLINGENBERG

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TRANSLATOR'S PREFACE

In recent years the installation and extension of power stations for the supply of electrical energy has progressed very rapidly, and has left little time to those engaged in this class of work to study in detail problems presented by questions of economy in capital outlay and production. It has, on the other hand, become more and more essential to scrutinise very closely the process of transformation of energy from coal to electricity, with the object of reducing fuel consumption and lowering the price at which the electrical energy can be supplied to consumers.

Dr Klingenberg's book, entitled "Bau grosser Elektrizitätswerke," contains so many important and new points on the above problems in economy that its English version, as presented herewith without additions or curtailment, will not fail to reach the wider circle of engineers for whom it was prepared. The original was the outcome of a lecture and several of the author's publications. Two important works are fully described; this was done in order to illustrate how the principles evolved in the first chapter are carried out in practice.

The comparison of coal transport as against transmission of electrical energy given in the second chapter will be of special interest to the many who are now confronted with questions of locality. The following chapter, on the other hand, illustrates the effect of the utility factor on the economy, and shows how the power station losses may be separated in order to obtain proper balances for heat and running costs.

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INTRODUCTION

I. Policy in Electricity Supply.—The growth in the public importance of electricity supply has brought about a considerable change in opinion as to the basis on which electricity should be produced and distributed. Whilst only in some countries there is an increasing demand for agricultural purposes, and farmers have become accustomed to regard electricity supply as essential to meet the difficulties of scarcity of labour, there is no divergency of opinion or experience as to the uses of electricity for industrial purposes. Consumers generally have little difficulty nowadays in realising the advantages of an external supply of electricity. They are glad to be relieved from responsibility and capital expenditure on generating plant of their own. To them it is a decided inconvenience to attend to the generation of power, the operation of boilers and steam engines, the buying of fuel, etc., wherefore a reliable supply is a recognised boon.

As ideas of this kind took root, the methods for the generation of power advanced rapidly towards centralisation. In some countries the development has been more rapid than in others. Very often satisfactory growth has been hampered by legislation. Enterprising private supply concerns found it difficult, if not impossible, to come to satisfactory agreements with municipalities. The latter enjoyed a monopoly inside their boundaries, and used the same to the disadvantage of the consumer. The question of cheapening the production costs was not always of primary importance to them; they felt secure with the high prices the consumer had to pay. On the other hand, the policy they had pursued made it impossible for them to offer special inducements to industrial concerns to settle in their area of supply, and many branches of the industry preferred a locality served by a supply company, with whom more business-like transactions for the supply of power were possible. In order to safeguard the sound development of centralised generation and universal distribution of electrical energy, legislative facilities must be provided to enable municipalities and companies to link up their systems on reasonable terms. Although greater facilities in this direction would be welcome, there still remain disadvantages arising from the manner in which a municipal undertaking is generally controlled. It seems impossible for a municipality to manage its electricity supply undertaking on any but political lines. The engineer or expert may be allowed to express his opinions on engineering or economical questions, but the committee's decisions are largely governed by the policy of the party to which its members happen to belong.

The management of a company presents an entirely different picture. Here experts both in engineering and in business and finance stand at the head; they have entire control, their decisions are influenced by the interests of the concern only, they can organise and renew their staff according to the ability of the individual, they are in close touch with industrial developments, engineering and economical improvements do not escape their notice.

The question of staff has become one of the most important factors in an undertaking since the industrial power load has gained such prominence. Those in responsible positions must possess very special qualifications to be able to show satisfactory results. Not only must generating and running costs be reduced to a minimum, which means that an intimate knowledge is required of every process involved, from the storage and burning of coal to the distribution and metering of energy, but difficult problems in economy have to be solved, such as are characterised by the fact that energy from the same plant may be sold at sixpence with a loss to one consumer, and at the tenth part of this amount with a profit to another consumer.

Under municipal control there is not that incentive to attain the highest possible economy as with a company; there is often a lack of keenness and business ability when canvassing for new consumers, the responsibilities of management are not centralised, questions of finance are complicated, and the facilities of a private company for raising or controlling capital are not available.

These are facts which no one can seriously dispute, and the public is confronted with the question whether it is preferable to allow private industrial concerns to take control of the supply business (on the strength of provisional orders or by way of concessions or lease), or whether a joint undertaking between company and authority offers the best solution.

In the author's opinion comparatively little importance attaches to this question. What concerns a municipal or other authority in the first instance is that energy is available for consumers at rates and on terms which are not less favourable than those of works under the very best management, and furthermore, that certain financial advantages are derived by which all ratepayers may benefit—all other questions are of a secondary nature to these. It seems, therefore, that the privileges and main objects of a municipality as regards electricity supply can be safeguarded equally well by joint ownership or by entire transfer of legal rights.

Such considerations as these do not, however, reflect a sufficiently broad policy: they lead no further than to a temporary solution of present-day problems. Looking beyond the immediate future, it seems that in order to exhaust all possible economical advantages, limitations of areas by municipal borough or even county boundaries must disappear. Most existing power stations should not be extended, and the production of energy should be confined to very large power stations in the best situations, and all joined together by high-tension mains from which both existing and future undertakings could draw their supply. This programme is far reaching both from an engineering and an economical aspect. The author developed it for the first time in 1912 at the annual meeting of the Verbandes Deutscher Elektrotechniker. The industrial development of electric power stations still lies in the future, and one can therefore well imagine that the project outlined will assume the magnitude and economical importance, for instance, of the combined railways of a country. What immediately becomes evident when following this line of thought is that any general scheme of this order cannot be carried out without State support. The method of procedure will soon be found when once the general public grasps the soundness of the idea, even should the State find reasons for withholding financial support. The development towards this end must be gradual, but now is the time for legislation and preparatory work.

The economist cannot avoid conviction on the urgency of improvements in electricity production when comparing generating costs for small power stations with those of large stations, and transmission costs with coal freight. According to Dettmar, the installed capacity in public electric power stations in Germany amounted to 1,500,000 kw., and the energy developed in 1911 was 1,600 million kw.-hours. Assuming the capital expenditure on existing power stations (without network) to have been at the rate of £25 to £30 per kw., then a sum of £30,000,000 would represent the possible saving in capital expenditure on large power stations built at a cost of £8 per kw. As there is not much difference between transmission costs and coal freight these need not be taken into consideration. A comparison of present working costs with possible costs will therefore convey an approximate idea of the saving in this direction. Taking the same example, viz., Germany, one may say that the average working costs, including interest and amortization of the existing stations, is at least ·6d. to ·7d. per kw.-hour, which is equivalent to an annual expenditure of £4,500,000. According to the author's calculations this amount would be reduced to £2,000,000, so that a saving of more than £2,500,000 could be effected every year. These are large figures; they are, however, small now in comparison to what they will be when an appreciable industrial supply sets in.

The following indicates the direction in which legislation should move in order to develop the suggested programme:—

1. The formation of large electrical undertakings for the erection of power stations on a very large scale and in the best situations. The State to participate, but the form of a company should be maintained for reasons already explained, even should the State find the necessary capital. Operation by the State is not desirable; it does not possess the necessary organisation, and should avail itself of experience gained elsewhere.

2. The undertaking shall be obliged to supply electrical energy on certain terms to existing or new undertakings within its authorised area.

3. Wayleaves shall be granted to these undertakings (powers

of expropriation). Compensation claims for transmission lines shall be determined.

4. The amount of energy to be generated in existing power stations shall be limited to their present capacity or to the capacity at the time the general supply is available. All further demands to be taken from the large undertakings.

At first sight this restriction seems to be a hardship, but in reality it is of no consequence, because the smaller undertakings would be able to obtain energy from the large works at rates which are below their own working costs. The generators in existing power stations will therefore either be stopped altogether and the whole of the energy required will be taken from the large undertaking, or a certain amount of plant will remain in commission, the surplus energy beyond this being obtained from the larger power station. Which of the two methods is adopted depends on whether the saving derived by purchasing energy is smaller or greater than the interest and depreciation of the existing plant. Should the savings be smaller, then the plant will be kept in commission until it in entirely written off.

5. Existing concerns shall participate in the surplus revenue of the large undertakings at the rate of the amount of energy they have purchased.

6. Regulations shall be drawn up with regard to linking up the undertakings. The engineering terms should be standardised; the main pressure, periodicity, limits of regulation, etc., must be uniform throughout, the network must be laid out on a uniform basis, providing facilities for linking up, balancing the load, and localising faults. The use of spare plant, etc., must be determined.

7. The maximum rates for the sale of energy for lighting and small power shall be determined.

8. Energy shall be supplied to the industry on terms allowing transmission costs, and a reasonable commission to existing undertakings (energy may be supplied direct if necessary, after having agreed upon the commission).

Should the State not desire, or find it impossible, to form such undertakings itself, then the existing concerns, whether under company or municipal control, should have power to take financial shares in the large undertakings. The idea would be that the capital which becomes available, when their own power stations are not further developed, is used for participation in the large undertakings.

There are two ways of satisfying any claims the State may put forward: one is by determining the right of taking over the undertaking (an agreement to this effect should not hamper the development of the undertaking) after a certain period (forty years); secondly, the State might participate in the revenue. This could, for instance, be arranged by deciding on a standard method of preparing the balance-sheet, and distributing any revenue above 7 per cent., to the extent of one-third to consumers, one-third to the State, and one-third to the company. The latter should participate in this surplus in order to give the management an incentive to develop the undertaking on the most economical lines.

II. ENGINEERING DEVELOPMENT.—The more extensive use of electrical energy in industrial works has induced a greater economy in the generation of power. That in this direction considerable improvements are still possible, is clearly shown by the well-known method of separating capital costs into constant and variable costs, and by the recent method of dividing losses into fixed losses and variable losses. Means for reducing capital expenditure are, more efficient use of materials, reduction in weights (but not at the cost of reliability), smaller buildings, and reduction of areas covered by buildings. Salaries and wages are reduced by automatic operation (coal haulage and ash removal), stoking, feed water regulation, devices for cleaning and automatic switching. The constant losses are reduced by reducing cooling surfaces, power for auxiliaries (condensing plant), iron losses, etc.

A very large number of improvements have been introduced in the last few years. Some of those taken alone do not affect the operation to any great extent. The combined result has, however, entirely remodelled the power station, the appearance of which is to-day totally different from what it was even a few years ago.

Whether any radical change may be expected in the immediate future, and which part of the plant will be affected, it is difficult to say. Tests and calculations made with the Bonecourt system of surface combustion in connection with steam production for power station purposes have not yet warranted its general adoption, although high efficiency and low capital cost seem to be its characteristic features. There is certainly a tendency to obtain more out of coal than hitherto, and to extract by-products before raising steam or to use waste gases for combustion in boilers. Developments in this direction may be expected, and economical advantages are probable for large power stations working with a very high utility factor, or in power stations where plant can be run at a high load factor. The methods by means of which a higher economy is ensured in the transformation of energy from coal to electricity are briefly the following:—

Coal stored outside boiler houses. Coal bunkers in boiler houses should be done away with or reduced as much as possible. Uninterrupted movement of coal right into the fire instead of intermediate storage and transport at intervals. Automatic stoking in place of stoking by hand. Boilers and economisers should be built together; the latter should be of wrought iron instead of cast iron, in order to keep capital expenditure low and reduce the cooling surfaces. One economiser for each boiler instead of combined economisers. Separate chimneys instead of a common chimney. Iron chimneys take the place of brick chimneys. Artificial draught (most frequently ejector draught) instead of natural draught. Resistance inside boilers and economisers should be reduced as much as possible in order to obtain a large output for natural draught, and to reduce the consumption of energy through running fans as much as possible. A larger average evaporation in boilers without increasing the maximum evaporation where the gases are hottest. A high super-heat, with automatic temperature regulation and automatic feed water supply. Reduction of water capacity of boilers in conjunction with rapid fire and draught regulation. Large increase in steam speed in pipes, and the reduction in length of pipes between boilers and prime movers. Reduction in pipe resistance by reducing the number of valves (slide, rather than screw-down valves). Improvements in boiler and pipework lagging (packed flanges). Steam turbines and generators of larger capacities at normal speeds. Greater overload capacities for short periods. Modifications in mechanical design, and insulation to withstand short circuits and pressure surges. In the condensing plant the highest vacuum should be obtained for the least possible consumption in auxiliaries. Removal of air in feed water. Syphon action for cooling water pumps, short path for cooling water, and large sections for the canals and pipes. Steam driven auxiliaries for the condensing plant to ensure greater reliability.

Evidence of sound developments in the last few years is also found in switch plant. The uniform factor of safety and standard forms of insulators for all parts. Large spacing between conductors, cable terminals with protective devices, etc., bus-bars and switchgear on separate floors. Danger of oil fires eliminated by placing transformers and switches in separate compartments. Danger from burning oil is eliminated by using closed pipes. A serious effort is also being made towards better arrangements for switching, by improving and re-designing switches (specially for large capacities and overhead lines). The unrelinquished study of pressure surges has already produced arrangements for reducing the danger. Modifications in switchgear will follow in this direction in the next few years (resistance switching is being reintroduced).

Greater distances and larger outputs have led to the introduction of larger line pressures, with the unexpected result of greater reliability. Further improvements are aimed at by increasing distances between supports, by introducing devices for the protection of birds, and the protection against atmospheric discharges.

A large amount of attention is also given to means for showing up high-tension conductors in order to remove the danger to aerial navigation.

A great deal still remains to be done to improve the outward appearance of power stations and transformer substations. The architect of these buildings should not attempt to hide the purpose for which they are intended; on the other hand, they should be adapted in appearance to the locality as much as possible.

LARGE ELECTRIC POWER STATIONS

CHAPTER I.

PRINCIPLES FOR THE CONSTRUCTION OF LARGE ELECTRIC POWER STATIONS.

THE load conditions in public electricity works can be determined in advance with fair accuracy, since they are dependent on the nature of the supply to consumers. Similarly, the change of load from one stage to another is known beforehand; it may be seen from the load curve, in which there is not very much difference from day to day. The shape of the curve is influenced by the nature of the consumption and by the time of year; generally for similar periods during consecutive years the curves show but insignificant differences. Power station engineers have long recognised the fact that important economic advantages may be obtained by altering the shape of the curve, and by introducing ingenious tariffs they have sought to flatten the peaks. The Upper Silesia Electricity Works (Agthe Tariff) have led the way as pioneers in this respect. The economic advantages secured by altering the curve are greater than those obtainable by any other technical means; they should be given special attention on this account. The calculations contained in this book give an idea to what extent improvements are possible.

In cases where the consumption curve is regarded as fixed, power station engineers still have the choice of various combinations for generating the energy required; they can employ different machines and boilers at different times, and can vary the distribution of the load among the generating sets as desired, within wide limits. Thus the possible combinations of plant in the power station seem almost unlimited and can be varied for every stage of the load; one of these combinations must give the best results from an economical point of view, *i.e.*, for every condition of the load there must be a certain grouping of plant, and a certain distribution of the load which entails the lowest working costs. Considerations of this kind result in a definite programme for operating the power station, and if this is followed, the efficiency will always be a maximum and will vary only according to the load.

In practice it is, however, not always possible to adapt the plant to the most satisfactory combination for each change of load. With sudden and temporary load fluctuations—traction work, for example—no attempt can be made to alter the plant in commission, although the change in load could be dealt with more economically by a different grouping of the plants. One naturally prefers to obtain the energy rushes from the plant that happens to be in operation, and to subject it to temporary overloads of short duration, because through starting up and shutting down plant, greater thermal losses are caused than by leaving the plant unchanged when the temporary fluctuations come on, although the combination of plant may not be the most economical. There are, however, exceptional conditions which need not be dealt with here—we are concerned with fundamental principles only.

1. FUNDAMENTAL TERMS.

a. Total Connections, Hours of Full Use, Load Factor, Diversity Factor, Utility Factor, Running Factor.

The definitions of the terms used are :—

1. Total connections = capacity in kw. of all plant supplied with energy from a power station.

2. Hours of full use of power station = ratio of kw.-hours per annum supplied to feeders, to peak load of power station in kw.[1]

3. Load factor referred to power station = ratio of kw.-hours per annum generated, to highest peak load of power station in kw. × 8760 = ratio of average load generated, to peak load of power station.[1]

4. Load factor referred to consumer.

a. Ratio of kw.-hours sold per annum, to peak load on feeder × 8760 = ratio of average load sold, to peak load on feeder.

b. Ratio of kw.-hours sold per annum, to consumers' installed capacity × 8760 = ratio of average load sold, to consumers' installed capacity.[2]

5. Diversity factor = ratio of peak load on feeders, to sum of consumers' or groups of consumers' maximum demands.

6. Utility factor of power station = ratio of kw.-hours generated per annum, to capacity of plant installed in power station × 8760 = ratio of average load generated, to installed capacity.[3]

The utility factor is determined by the load factor and the available standby plant. It is reduced each time an extension is made, and will become equal to the load factor when the whole of the installed plant is made use of and no spare plant is left.

7. Running factor[4] = ratio of sum of hours per annum during

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[1] Either the term under 2, or that under 3, will suffice to characterise load conditions. In England one generally uses load factor, whilst in Germany it has become customary to calculate with the hours of full use.

[2] In order to avoid errors, a careful distinction must be made between *a* and *b*; the former expresses the consumers' load factor based on the maximum load of feeders, whilst the latter is based on installed capacity.

[3] It is found desirable to introduce this term because it defines conditions which it is essential to take into consideration in calculations of efficiency. The term should not be confused with the ratio of the peak load on a power station to the installed capacity with or without standby plant.

[4] The running factor is a new and useful term for calculations of economy, because it helps to increase the degree of accuracy. The running factor can always be obtained from power station statistics where the hours of running of every machine are recorded. In the case of new schemes, one can determine the running factor from the diagram showing the demand. Its value is largely affected by the number of sets that have to be running simultaneously at the time of peak loads. As generally at least one of the largest sets is a standby, the running factor will be reduced accordingly. With only two sets in a

which the plant was running, to the possible maximum; the latter is obtained by multiplying the number of sets installed by 8,760.

b. Characteristic Consumption Curves.

Figs. 1A to 1F are a few characteristic daily load curves for existing power stations; they show the influence of the predominating forms of consumption on the load.

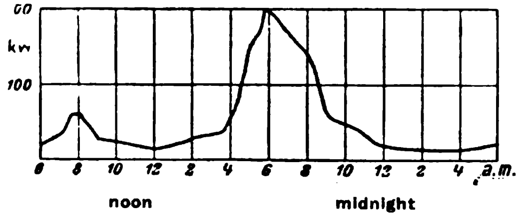

Fig. 1A.—Winter Curve of a small town (Wolfenbüttel), Lighting Load predominating, small Motor Load, no Industrial Load.

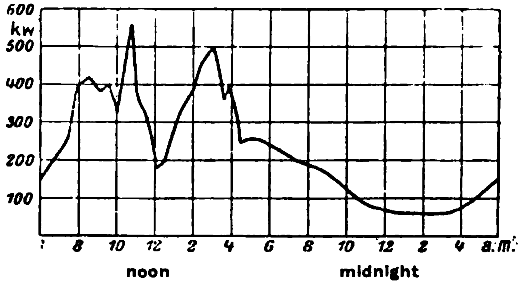

Fig. 1B.—Autumn Curve of an agricultural overland transmission station (Birnbaum, Meseritz, Schwerin), Agricultural Motors and Lighting.

Any special conditions of the load must be taken into consideration when designing the station in order to obtain the best economy. The following points must also be borne in mind:—

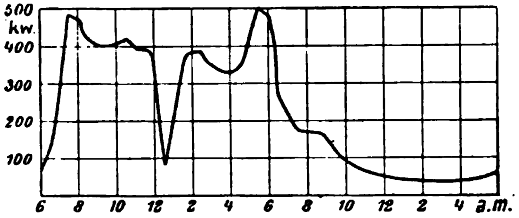

Fig. 1C.—Winter Curve of a small town with an Industrial Load (Lahr).

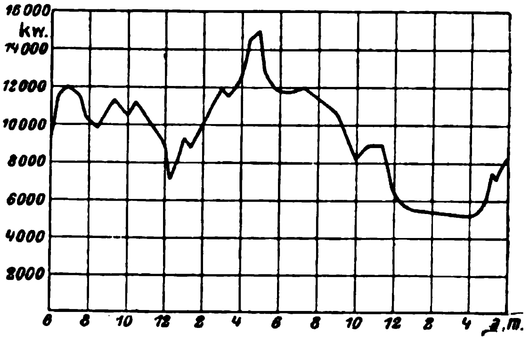

Fig. 1D.—Winter Curve of a large industrial district (Upper Silesia Electricity Works), Industrial Load predominating, comparatively small Lighting Load.

The total annual costs consist partly of cash payments and partly of indirect expenses.

power station the running factor will, therefore, be 0·5 under these conditions; where there are three sets the running factor will be above 0·33, but lower than 0·67, with four sets it is above 0·25 and below 0·75; furthermore the running factor can never be below the load factor.

The former include the expenditure on fuel, coal, oil, waste, etc., staff, repairs, insurance, penalties, etc.

c. THERMAL CHARACTERISTIC.

The greater part of the thermal characteristic represents fuel consumption. To what extent this consumption depends on the load factor may be ascertained from the fuel or thermal characteristic of the power station.

As explained at length further on, the fuel consumption, according to station load, moves approximately along a straight line within the limits of load existing in a certain power station. This line cuts the ordinate axis at a point representing the fuel consumption necessary for keeping the station running on no-load and therefore for supplying the constant part of the energy losses.

d. ECONOMIC CHARACTERISTIC.

Similarly, the expenses for oil, waste, etc., and up to a certain point, the staff expenses, are dependent on the load on the station. A proportion of the repair costs are likewise constant and independent of the load, the remaining part being proportional to the latter. The total cash payments can thus be separated into a constant part and a part proportional to the load, and, therefore, to the hours of full use or the load factor.

The indirect expenses consist of the amount allowed for depreciation of the plant and the sum required for providing the interest and amortisation on the capital expenditure.

The amounts to be written off are as a rule definitely determined in advance according to the probable life of the different parts of the plant.

It would be more correct to write off larger sums on account of those parts subjected to considerable stresses and to determine them on the actual hours of use or on the load factor. Frequently a system is adopted of writing off an average amount on the entire plant including the network, and not on separate parts of the undertaking. In consideration of the high second-hand value of the supply mains a sum of from 3 to 4 per cent. is regarded as ample under normal conditions.

The sums required for interest and amortisation on capital expenditure are classed with the constant costs, so that all indirect costs are a constant sum which is independent of the load on the station.

If the curve for the total working costs and that for the load are combined an approximately straight line is obtained, and this represents the economic characteristic of the power station. It cuts the ordinate axis at a point for costs which is independent of the load.

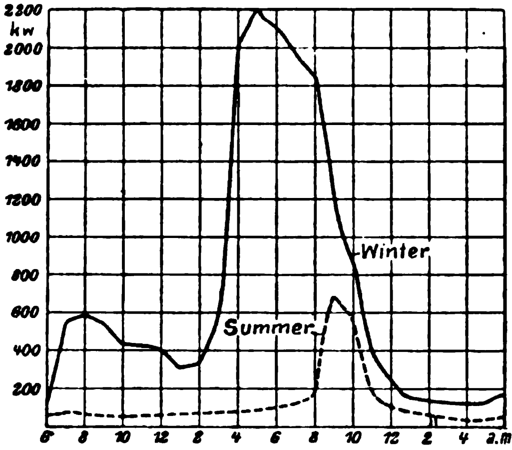

Fig. 1E.—Maximum Winter Curve and Minimum Summer Curve (Sunday) of a large city (Königsberg), without Tramway Load, Lighting Load predominating, small Motor Load, no Industrial Load.

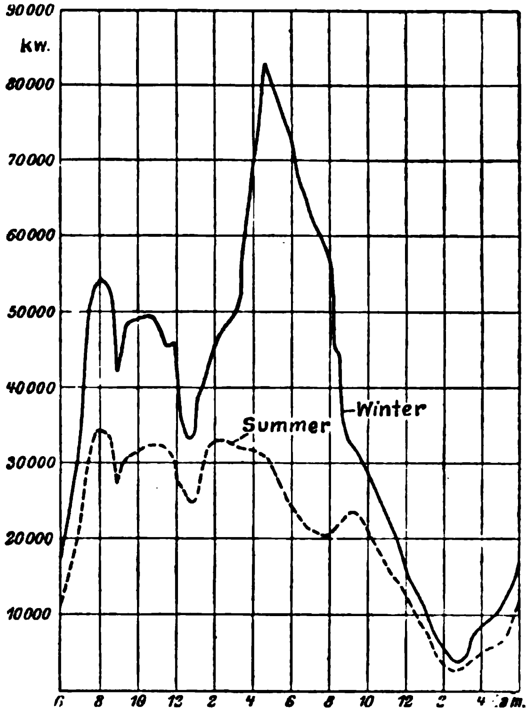

Fig. 1F.—Winter and Summer Curves of a large city (Berlin), heavy Lighting Load, Industrial Load, heavy Tramway Load.

When the daily load curve is known, that for working costs can be plotted with the assistance of the economic characteristic; the area of the working costs diagram gives the generating costs for the day in question (Fig. 2).

The generating costs per annum are obtained in Fig. 3 by combining the economic characteristic with the annual load curve.

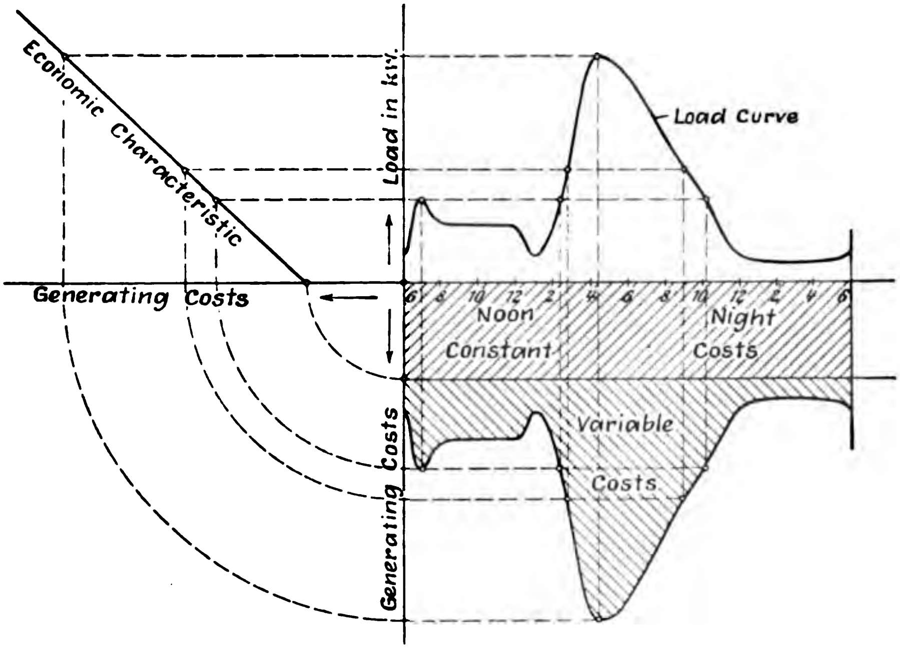

Fig. 2.—Economic Characteristics and Daily Working Costs.

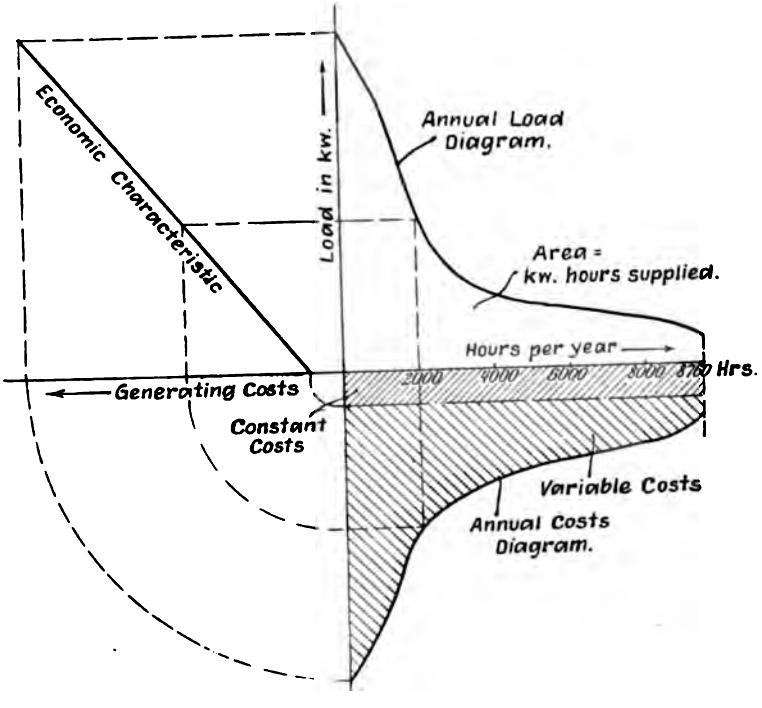

Fig. 3.—Annual Costs.

The latter is obtained from the daily load curves by taking each separate load stage as a function of that number of hours per annum applying to the particular stage. In designing new stations, this curve can be obtained in a simple manner from the estimated consumption, and the hours of full use at the same time, taking the diversity factor in consideration.

The smaller the utility factor is, the greater will be the influence of the constant costs, whereas the full load efficiency of parts of the plant, which is frequently regarded as an important criterion for the quality of the latter, only influences the generating costs to a slight degree.

In order to obtain high economic results in a power station, care must therefore be taken that each of the three factors—capital expenditure, constant working losses, and operating costs—is reduced to a minimum, more especially so in cases where the utility factor is low.

Economy in capital expenditure should, of course, be aimed at only by way of design and arrangement of the plant, but not at the cost of quality or reliability.[1]

2. ENGINE ROOM.

a. SELECTION OF GENERATING SETS.

The advent of the steam turbine has forced the design of power stations along new paths, and has reduced the generating costs to values formerly unheard of. This result is not due to the higher economy of the steam turbine (the steam consumption of well-designed steam engines on full load, at all events, is not inferior to that of steam turbines); it is due solely to the great reduction in the constant parts of the costs. The steam turbine is not only appreciably cheaper in itself than a steam engine for the same output, but large units are simpler and easier to construct. Whereas, formerly, stationary

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[1] The most promising lines on which to work seems to be to generate the constant part of the load with plant working as economically as possible, whilst the variable part is obtained from plant involving low capital expenditure. A combination of gas engines or Diesel engines with steam turbines, or of water-power plant with steam stations, may be recommended in some cases on these grounds.

steam engines with outputs of 5,000 to 6,000 H.P. (as for example those in the Berlin Electricity Works) were looked upon as the largest of the kind, 10,000 H.P. steam turbines are to-day a standard size, and output in single sets of 25,000 to 30,000 H.P. are by no means uncommon. The manufacturing costs for these generating sets have at the same time fallen to less than half the figures for the old type of plant. A further appreciable reduction in the installation costs is obtained from the small space required and the possibility of being able to erect very large sets.

Another important point is the fact that the constant losses in turbo-generators are less than those for steam engines and their generators, a circumstance which leads to the employment of larger units, since the difference in the average economy of large and small units is less than in the case of steam engines. Finally, stress must be laid upon the great reliability in operation and the lower costs for attendance, oil and waste. A numerical comparison can be dispensed with here, in view of the number of comparisons of a similar nature that have been made elsewhere. What seems more important is to discuss other improvements which can be effected in new turbine installations.

b. STEAM PRESSURE, TEMPERATURE, SPEED.

Standard steam pressures and temperatures are to-day 170 to 200 lbs. per square inch and 570° to 620° F. including superheat. A higher temperature at the turbines is not desirable at present on account of the boilers.

Higher steam pressures would not afford any advantages, since the greater part of the energy is obtained from the low pressure portion of the steam curve, and difficulties would arise the removal of which would in no wise be proportional to the gain secured.

The direction in which an advantage can be gained from an economic point of view is an increase in capacity at the normal speeds (3,000, 1,500, 1,000). The difficulties which are certainly encountered here lie less in the turbine than in the generator in which the dissipation of heat is limited by the comparatively small cooling surface.

Improvements in ventilating devices call for special attention on this account; they will, no doubt, lead to higher outputs from standard sets.

A low final pressure at which the steam exhausts is essential for high economy; this is limited by the temperature and quantity of the available cooling water. The question of size of condenser must, therefore, be investigated with particular care when the water temperature is relatively high; the power required for pumping the cooling water is also of importance in this connection. Comparative calculations frequently show that the employment of larger quantities of water is more economical than the installation of large condensers.

The question as to which type of turbine should be given preference cannot be gone into here.

Assuming each type to have the same reliability in operation, the same life, and to occupy the same space, then the decision will depend upon price and steam consumption. These figures, however, vary in a certain inverse ratio to one another: the greater the number of turbine wheels, up to a certain limit, and the larger the condenser, the lower will be the steam consumption, and the higher the price of the plant.

The most suitable type must, therefore, be determined by considering the average annual load and the cost of fuel. Where cheap fuel is available (as, for example, in brown coal power stations), and where a low load factor prevails, a cheap type should receive preference, whereas expensive coal and the high load factor call for a low steam consumption, and therefore for more expensive plant.

c. GENERATORS.

The possibility of employing bar windings should determine the pressure at which generators supply current; thus alone are simplicity in design and reliability in operation secured. That part of the plant which is exposed to great danger, *i.e.*, high-tension windings, should be provided for in separate apparatus. Wire-wound generators for 10,000 and 15,000 volts have been constructed, but they cannot be recommended, particularly in connection with overhead transmission lines.

The principal disadvantage of these high-tension generators is that in the event of frequency or pressure surges, stresses are set up between adjacent turns which exceed normal values many times and may cause the insulation to break down, more particularly so, because the insulation between turns is much less than that to earth. This danger does not exist with bar windings, the insulation of which is the same between bars as to iron. Transformers, on the other hand, are more easily protected against the effect of pressure surges than the high-tension windings of generators, furthermore the windings of the former can be renewed more rapidly at a lower cost.

Whether it is preferable to connect transformers direct to generators or to feeders, depends upon the nature of the consumption. It should be remembered, in this connection, that a part of the capital invested in extra transformers is regained, as the capacity of generators with bar windings is appreciably higher than that of generators with wire windings; an increase in the constant losses must, however, be allowed for, it is true, on account of the increased magnetisation. If the transformers are treated as a part of the generators and are switched in and out with the latter, a portion of these losses will be compensated by the lower copper losses in the generators.

Every effort is no doubt being made to obtain the greatest possible output from the material available in view of the keen competition between manufacturers. There is nothing to say against this effect of rivalry so long as it has no adverse effect upon reliability in operation. The objection frequently put forward that the characteristic of the generator will be impaired by the high stress on the iron and copper is not tenable, as the reactance in the circuit is frequently increased artificially at the present day in order to reduce the effect of short circuits. Satisfactory regulation can be obtained with a rapidly falling characteristic by means of quick-acting regulators which are necessary in circuits with heavy and sudden load fluctuations.

d. OVERLOAD CAPACITY.

It is advisable here to refer to the term, overload capacity, which has a different meaning according to English and German practice. In English specifications the plant is often required to give an overload continuously, whereas, according to German practice, the maximum continuous output thus obtained is the normal output. It has furthermore been standardised in Germany to specify an overload capacity of the plant from a cold condition. This, of course, produces no technical advantages in the operation of the set, as the temperature rise at normal load is greater and, moreover, leads to an incorrect relation between the capacity of the steam portion of the plant and that of the generator. From an operation point of view that peak load only is of interest which is obtainable from the plant for a certain short period, following a lengthy run at normal load.

The steam portion of the plant must, of course, be capable of giving this overload continuously, so that in reality one obtains a generating set with a capacity for the steam plant which is only temporarily obtainable from the generator.

The overload requirements are sometimes met by allowing live steam to enter the low-pressure part of the turbine. This measure enables a comparatively small turbine to be selected at the expense of worse steam consumption. For this reason it recommends itself for plants with a low load factor, or for which cheap fuel is available.

e. SIZE OF THE GENERATING SETS.

The size of generating sets is, of course, determined principally by the estimated consumption. A frequent experience is that, as the result of excessive caution, the generating sets installed are too small.

First and foremost the future development must be borne in mind, and must be given very careful consideration, when the first lay-out is decided upon. In any case the probable profits should be determined for future extensions as well as for the present lay-out. One will thereby find out to what extent the utility factor can be reduced, particularly for concerns for which a rapid increase in connections is anticipated.

A modest amount of profits in the initial stages is often rewarded by better results after a very short time.

An exhaustive calculation is also necessary in order to determine whether a special small generating set for dealing with light loads should be installed. This provision is greatly favoured at the present day with the idea of effecting economies. A comparative calculation prepared with proper care will, however, generally show that the additional interest and depreciation exceed any economy that may be secured in the operation of the smaller plant.

The desire to reduce capital expenditure leads to the installation of machines of the largest size. The price per kw. is not appreciably reduced for sets exceeding 5,000 kw., but a saving can be effected in the space occupied and in the cost of the engine room and the auxiliary equipment.

Large sets on the one hand have a lower steam consumption at heavy loads and entail lower costs for attendance, whereas on the other hand a larger number of smaller sets can be better adapted to load fluctuations. The ultimate decision, therefore, depends upon the load factor and the shape of the load curve, and careful calculations, based on the steam consumption characteristic, should be made beforehand.

f. STEAM CONSUMPTION CHARACTERISTIC.

The total steam consumption within the limits of load may be represented approximately by a straight line, which cuts the ordinate axis at a value under the actual no-load consumption when steam turbines are used.

The steam consumption Q may thus be represented with sufficient accuracy by the formula $Q = a + b \times L$, where a is the constant part of the steam consumption, b the specific load consumption, and L the load. The importance of the value a for high economy will be the greater the smaller the load factor is.

Fig. 4 shows the steam consumption per annum derived from the load curve and the steam consumption characteristic.

Power stations for the supply of two forms of electric energy, three-phase and continuous current, are, as a rule, so arranged that different generating sets are employed exclusively for either one or the other form of energy; further, at least one generating set is designed as a double set, so that both forms of energy can be taken from it simultaneously. This set serves as a common reserve, and can be used for taking up the supply at light load. This scheme is generally wrong, although, unfortunately, it is frequently adopted. It is unquestionably preferable to generate one form of energy only, and to obtain the second from the first by conversion. It is true that for a large portion of the supply, the converter losses, by no means inappreciable, have to be provided.

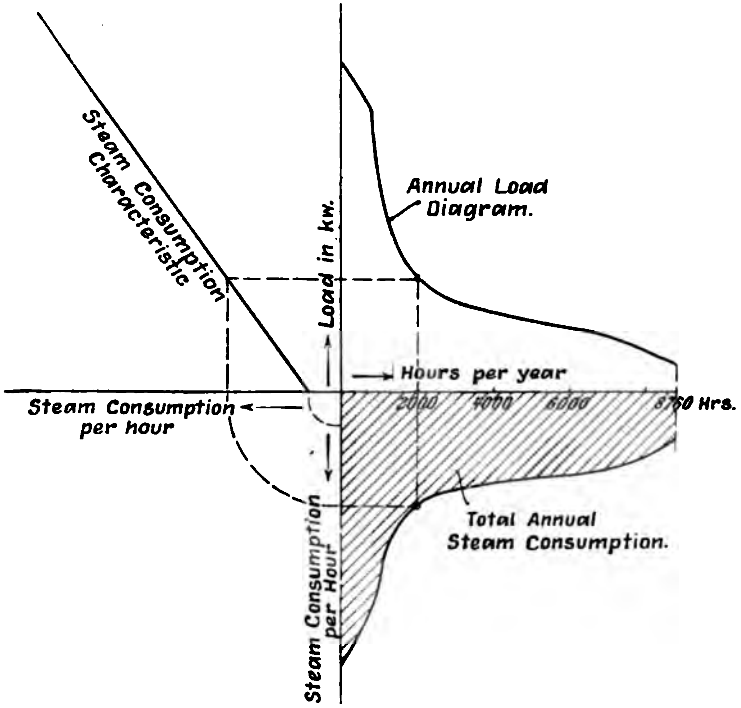

Fig. 4.—Annual Steam Consumption.

But these losses are generally more than compensated by the greater efficiency and economy of the larger generating sets that can be employed. In the first place, a smaller number of large generating sets is required, and one need not run more sets than may be required to cover the total consumption. One can therefore select the most suitable sets for the purpose. With the customary arrangement, on the other hand, it is necessary to run as many generating sets of each category as may be required to cover the maximum demand of each system. The converter losses may then be compensated by the steam economy due to the more favourable load distribution with large generating sets. Calculations made for given instances, taking the running factor in consideration, prove the economic advantage of the arrangement suggested.

g. EXCITATION ENERGY.

According to the fundamental principles laid down in the beginning, the efficiency of the generators should not be highest at the maximum load, but at the actual average load;[1] the energy for excitation and the iron losses both being constant losses are of all-important influence in this connection.

The arrangements for generating the excitation energy are thus of great importance. According to American practice, special steam sets are frequently provided for the purpose in large power stations, which at the same time supply the energy for other auxiliary services.

The question of reliability in operation is given great prominence by American engineers. It is unquestionably preferable, however, in the interest of reliability, to couple the exciters directly to the main sets. If, on the other hand, economy is regarded as the more important point, the capital expenditure must also be looked into. It will then be found that the latter depends on the speed of the main sets, and that for high-speed sets (steam turbines) direct coupling is preferable. In power stations containing slow-speed sets, particularly when water power is used, it is European practice to obtain the excitation energy by conversion, a battery serving as a reserve.

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[1] The exceptions are low-pressure water-power plants without storage, where the water flows away unused at light loads.

For water-power plants with high-pressure storage, the same point of view applies as in the case of steam plants.

h. AUXILIARY MACHINERY.

The plant included under this heading, of which air, cooling water, and feed pumps are the most important, calls for very careful thought. The energy consumption for condensers is to a great extent independent of the load, and should therefore be added to the constant losses, the costs of which must be reduced as far as possible.

The cheapest method of driving auxiliary machinery is, undoubtedly, to take the energy required from the main sets, as it represents a load on the latter, the steam or coal consumption of which is extremely low.

i. ELECTRICALLY-DRIVEN AUXILIARY MACHINERY.

In the case of power stations containing steam turbines the above argument as regards cost naturally leads to electric driving of auxiliary plant; the energy is then taken from the bus-bars of the station, an arrangement against which no objections exist as long as an uninterrupted supply is ensured, and provided different forms of energy are generated simultaneously (combined continuous current and three-phase stations or special batteries). When, however, only one form of energy is available, the auxiliary machinery is in danger of being brought to a standstill under heavy pressure fluctuations, and considerable time elapses before the station can be started up again. In some English stations this disadvantage is supposed to be overcome by obtaining energy for auxiliary machinery through separate transformers direct from the terminals of the generators (see Fig. 5). The advantage secured is that the auxiliary machinery starts up again with the corresponding generating set when the generator is excited. With this arrangement electric coupling takes the place of mechanical coupling, and its reliability is still dependent upon faults or pressure fluctuations at the bus-bars. The sole advantage secured is, that it takes less time to put the plant in commission, and that sections of the auxiliary plant are independent of one another.

In small generating stations, the drawbacks appertaining to the electric driving of auxiliary machinery for condensers can be overcome in the case of an emergency by the installation of main exhaust valves and atmospheric exhaust pipes for the turbines. This arrangement does not, however, commend itself for medium size stations because the boiler plant is not capable of giving the increased quantity (100 to 120 per cent. more) even temporarily when running non-condensing; in large stations the idea is altogether impossible.

The majority of station engineers rightly prefer greater reliability in operation to higher economy; from this point of view the auxiliary plant should be driven from independent sources of energy. In America, even comparatively unimportant drives, such as the movement of the grate, are frequently obtained from special small steam engines. Other auxiliary machinery is driven electrically; but the energy is supplied by a separate generating set, which is in no way connected with the other machines. In very large generating stations, where the total power required for auxiliary plant is so great that it can be generated with the same economy as that of the main machines, this idea may find justification.

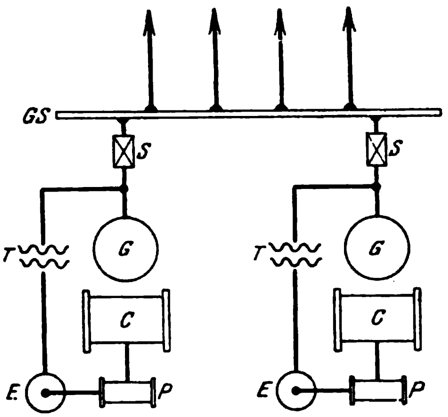

Fig. 5.—Diagram of Connections for Electrically-driven Condenser Pumps.

GS = Generator Bus-bars.
G = Generator.
E = Electric Motor.
S = Switches.
T = Transformer.
C = Condenser.
P = Condenser Pump.

k. Steam-Driven Auxiliary Machinery.

Modern European practice is to introduce steam drive for auxiliary machinery on account of reliability in operation, simplicity, and rapid setting to work. The question now arises whether it is advisable to centralise the whole of the auxiliary machinery. A scheme of this nature would involve the installation of air, lift, and cooling water pumps, and possibly also of feed pumps, all in one group. The size of this plant would be determined solely by the requirements of the whole station (allowing for the necessary reserve), and not by the size of individual generating sets. The immediate effect is a smaller number of auxiliary machines and a more economical service. The points against centralisation of this kind are, however, the very much more expensive and complicated pipework and the more difficult control of the plant; furthermore, the reliability in operation would be less. In the end this scheme is therefore not practicable unless very special conditions prevail (difficulty in procuring cooling water, etc.). The final conclusion is in favour of separate auxiliary machines for each generating set, all plant for one set being installed as close as possible to its set.

Since central condensation entails too heavy pressure losses, the most natural solution is a separate condenser with its own auxiliary machinery for each generating set. What remains to be considered is whether the auxiliary machinery can be driven by one prime mover. Here again every effort must be made to keep the constant losses as low as possible.

There is nothing against a combination of those auxiliary machines which must be in operation at the same time, viz., the air pump, the lift pump for condensed steam, and the circulating water pump. As the quantity of condensed steam (apart from unavoidable losses) is equal to the quantity of boiler feed water required, a boiler feed pump for each set may be included in such a combination. Each generating set would therefore have its own auxiliary set, consisting of an air and lift pump, a feed pump, a circulating water pump, and the prime mover. In Germany a combination of this extent has not yet been installed. Favourable reports, however, have been received on this combination of plant in a power station in England.

The desire to do away with reciprocating masses and valve gear in the interests of simplicity, has led to the design of high-speed rotary auxiliary machines driven by steam turbines.

The disadvantage of higher steam consumption is to a great extent compensated by the use of the remaining kinetic energy of the exhaust steam in the low-pressure stages of the main turbine.

The dimensions of these rotary sets become so small, that they can be erected immediately in front of the condenser without increasing the size of the engine room. This position gives the shortest possible connections. Further advantages are the possibility of drawing denser tubes from either end because the pumping set is low es no obstruction, also supervision from the engine room and use of the main travelling crane through openings in the floor (see Figs. 6 and 7).

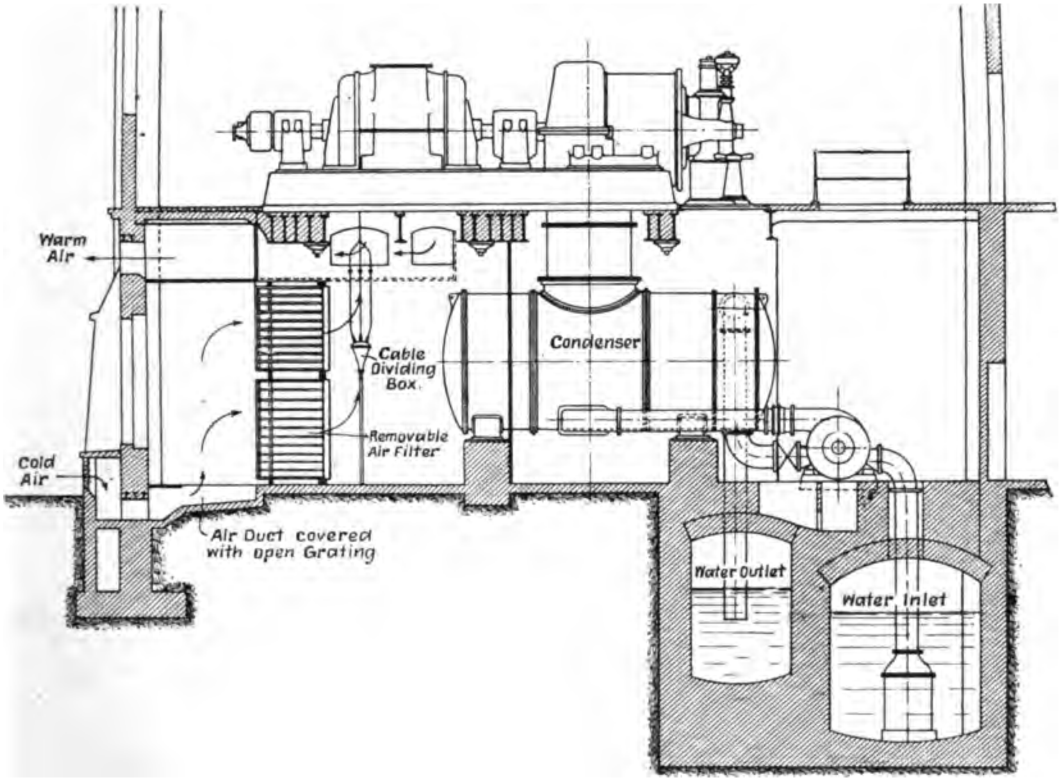

Fig. 6.—Cooling water inflow and outflow and cooling air inlet and outlet for a steam turbine. The air filter can be withdrawn. On removal of the air filter the condenser tubes can be drawn out. The closed high-tension compartment for cables and terminals is between the air filter and condenser. Light for auxiliary machinery comes through opening in engine room floor; the air filter is in daylight.

We will now consider in which direction a further reduction of the constant losses of such an installation may be obtained.

The cooling water pump requires the least amount of energy when all joints are perfectly watertight, and the friction losses are reduced to a minimum, thus all pipes should be as short and large as possible, and the inflow and outflow channels should have a large cross section, so that no appreciable losses in head occur here (see Fig. 6).

All the cooling water pump will have to do is to overcome small friction losses within the condenser; the power it takes is thus reduced to the lowest possible value.

Air and lift pump for condensed steam.—The air pump work depends to a great extent upon the quantity of air in the exhaust steam; some of this air may have penetrated through leakages in the turbine and condenser, and the pipe connection between them. A particularly weak point in this respect is the gland between the steam turbine and condenser. By means of a water seal, one can keep this joint airtight, a method which is frequently employed at the present day.

Large quantities of air can enter the boiler through the feed water. This is undesirable not only on account of the work to be done by the air pump, but also on account of corrosion inside the boiler, and every care must therefore be taken to prevent the admission of air. As the condensed steam leaving the lift pump is practically free from air, the latter can only enter the feed water on its way from the lift pump to the feed pump.

With reciprocating feed pumps special attention must be given to the flow of water, as the irregular suction may create a vacuum, which is sufficiently powerful to draw in air through leakages in the suction pipe and the pump. If the lift pump is capable of dealing with medium head, the condensed steam should first be raised into a feed tank with a small exposed water surface, so as to prevent air absorption. From here the water would flow with a certain head to the feed water pumps, the admission of air being avoided thereby. By using high-pressure centrifugal pumps for feeding the feed tank can sometimes be dispensed with. When these rotary feed pumps are driven by steam turbines, the steam consumption must necessarily be high, but this disadvantage is of slight importance since most of the heat contained in the exhaust steam from the pump turbine can be used for heating the feed water. By coupling the feed pump to the turbine driving the air and water pumps, the

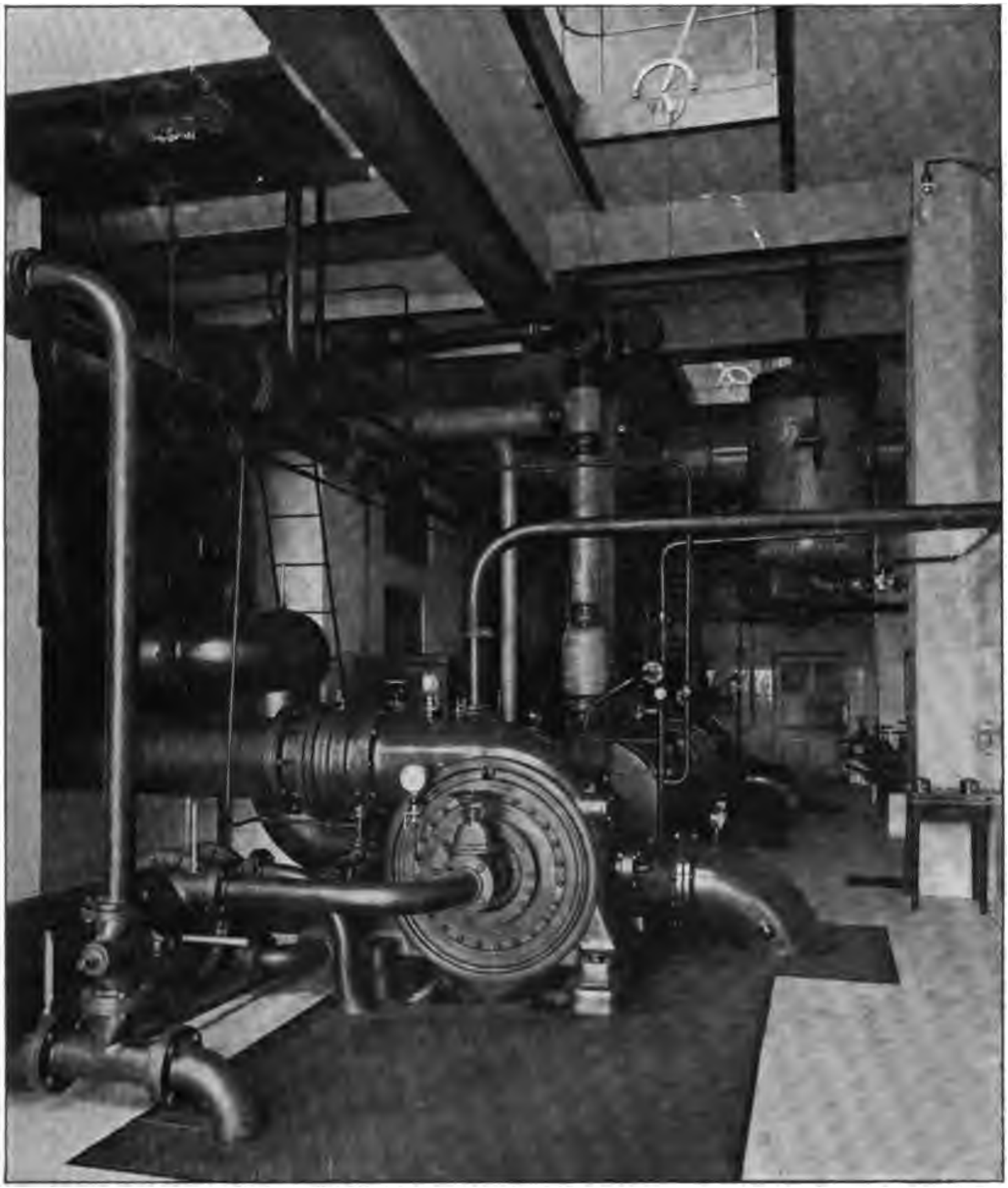

Fig. 7.—Condensing Plant.

losses are reduced to a minimum. The pumps and auxiliary turbine must be installed with the shortest possible pipe connections in order to reduce pressure and thermal losses; this is a condition which it is not difficult to comply with, when adopting the illustrated lay-out.

l. POSITION OF GENERATING SETS IN ENGINE ROOM.

The principal point to be kept in view when determining the position of generating sets in the engine room is the effect of the proposed lay-out on the building costs. What largely influences these costs is the area, dependent to a great extent upon the size of the ground to be covered by the building and the span of the iron work (roof and travelling crane).

Three positions have to be considered for generating sets :—

1. Parallel to one another and at right angles to the axis of the engine room.
2. In tandem and parallel to the axis of the engine room.
3. In two rows in tandem and parallel to the axis of the engine room.

Arrangement 1, with the pumps placed in front of the condensers, is generally the best, since it entails the lowest building costs, and affords the following advantages :—

Attention to the steam turbines and condenser pumps is simplified, both being situated at the same side of the engine room. By means of a partition in the basement the steam and electrical parts of the plant can be separated from one another. The steam pipes can be arranged in the basement in a very simple manner; they are approximately the same length for all sets.

Inlet and outlet channels run in a straight line under the floor of the basement quite close to the pumps. The length of these channels may, however, be somewhat greater under certain conditions than in arrangement 3. Air filters and air ducts for the generators can be placed in convenient positions.

In arrangement 2 two sets are placed with the steam sides towards one another in order to simplify the attendance. The pumps can then be installed either in front of the condensers or at the side close to the foundation blocks of the turbine. Arrangement 2 gives a long and narrow engine room. It does not offer particular advantages, excepting perhaps in the case of very large sets, and may recommend itself in certain cases owing to the space required by the boiler house.

Arrangement 3, with four sets with their steam sides towards one another and the pumps in front of the condensers, is exceptional; the economy in space is not greater than in arrangement 1, and there are great disadvantages as regards the length of the pipes and channels.

3. BOILER HOUSE.

a. BOILERS AND ECONOMISERS.

The design of the boiler house generally presents greater difficulties than any other part of the installation.

When the fundamental principles given in the opening paragraphs of this book are accepted, it will be found that very great care in the selection of plant to be installed here becomes essential. What helps in this connection is that the two requirements, low capital expenditure and low losses, are synonymous as regards the construction.

All station engineers attach great importance on obtaining the highest possible efficiency in plant in the engine room, while, as a rule, an amount of energy is wasted in modern boiler houses on which only very vague ideas exist. Here again insufficient attention is given to constant losses. In the boiler house the losses may also be divided into a constant part which is independent of the load, and a variable part which is about proportional to the load.

The constant losses are caused by thermal conduction and radiation from the exposed surface of the boiler and in the flues, etc. A small part of the heat carried off with the gases in the chimney must also be included, although by far the greater part of this heat is dependent on the load, and is therefore included with the variable losses.

The latter losses caused by eddy currents, pressure losses, etc., of the waste gases in the flues, must be added, as well as those due to imperfect combustion.

The efficiency of boiler houses is further reduced by the losses due to the firing of boilers on starting up. These losses vary with the time of the year; they depend upon the shape of the daily load curve, and will be all the greater the more pronounced the daily peak, *i.e.*, the smaller the load factor is. With unity load factor, on the other hand, boilers are fired only after having been shut down for overhaul and inspection purposes. The coal consumption per annum for losses and firing is therefore largely dependent on the load factor and the size of boilers. It can be ascertained by calculation, with due consideration to the running factor.[1]

As the firing losses are dependent on the total weight, and the constant running losses chiefly on the total surface of the boiler, the boiler and economiser with their flues, etc., should be designed as light as possible and for the smallest amount of space; thus also one will meet the requirements of minimum capital expenditure.

An increased output should not be obtained by an excessive strain on the heating surface. A higher specific output in steam should be arrived at solely by improvements in the design and dimensions.

Information for this purpose can be obtained by means of a curve (Fig. 8), showing the conditions prevailing when the boiler is at work. The temperature of the gases will be seen to drop as they pass through the various parts of the plant; the

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[1] The introduction of the running factor for the calculation of boiler economy has no important influence on the result, as in the case of generating plant, since the number of boilers in large stations is always very much greater than the number of generators. The greater the number of boilers, however, the closer will it be possible to get to the ideal condition of having none but satisfactory boilers in commission. No great mistake is therefore made by neglecting the running factor, the firing losses being expressed in the efficiency. This is the basis of the following calculations.

temperature of the walls with which the gases come in contact is also given.

The temperatures in the diagram are equal to about normal conditions.

Since the quantity of steam generated per unit of surface is dependent on the temperature difference between the gases and the surfaces with which they come in contact, the greater portion of the steam is produced in the first part of the path of gases, while that produced in the latter part falls to very low value.

If we assume the flues in a boiler to be cut off at "*a*" the remaining part of the boiler would not be affected, and the stresses would remain the same. The average load would, however, be appreciably greater, and the efficiency would fall, as the gases would escape at a temperature of 660° to 760° F. instead of 480° F. In consequence of this reduction in size the price of the boiler would be reduced. The temperature differences between the gas and the water in the economiser would be greater, and the falling off in boiler efficiency can be counterbalanced by a slightly larger economiser receiving gases at a higher temperature and delivering hotter feed water.

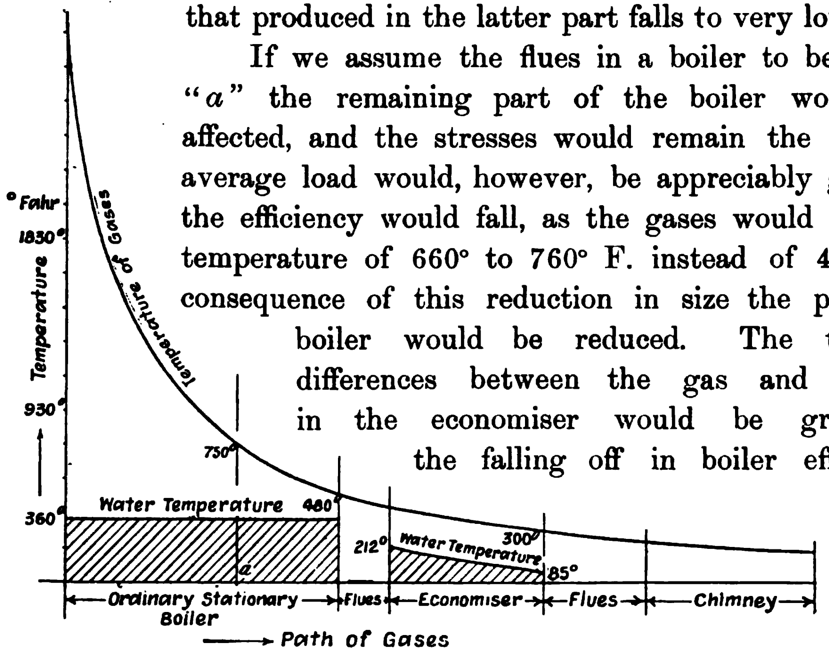

Fig. 8.—Temperature Diagram for Standard Boiler Plant.

The idea outlined above is to substitute for a comparatively large and ineffective part of the boiler a small but effective enlargement of the economiser. When ordinary coal is used, and under economic conditions as regards size of the boiler and the economiser, the gases should leave the boiler at a temperature of 750° to 840° F. The feed water will then enter the boiler at a temperature up to 280° F.

Boilers can be shortened with the same object by reducing the length of the path of gases through a standard boiler, and at the same time by increasing the grate area and combustion chamber. The result is a greater average stress on the boiler with the same maximum stress for surfaces exposed to the greatest heat.

It follows from the foregoing that by reducing the constant losses one obtains smaller surfaces exposed to continuous cooling. As the production of an adequate draught (with natural draught) necessitates a certain minimum temperature of the waste gases on entering the chimney, the surface losses in the flue must also be included in the above losses. The principles for designing the boiler plant may accordingly be summarised as follows :—

1. Small specific surface area of the boiler obtained by raising the average stress without affecting the maximum stress on the first part of the boiler surface exposed to the fire.

2. Avoidance of excess of air at low loads by reducing the effective grate area (partially covered grate).

3. Prevention of leaks on the boiler when not in commission; the remedy is iron casing and avoidance of damper leaks.

4. Effective lagging.

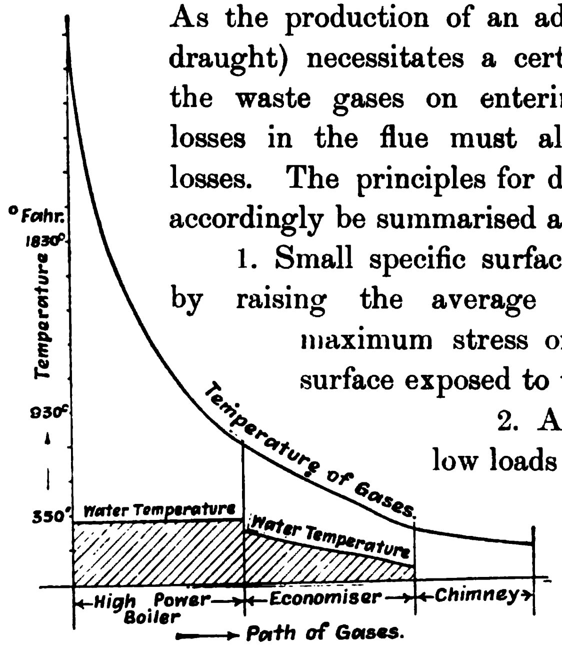

Fig. 9.—Temperature Diagram for Boiler Plant designed by the Author. (Victoria Falls and Transvaal Power Co., Markische Electricity Works, etc.)

5. Reduced resistance in the boiler flues to obtain the necessary draught (also with natural draught), and at the same time the greatest possible thermal drop up to the chimney.

6. The shortest possible flue between boiler and economiser.

7. The principles enunciated under 1 to 5 are also applicable to the economiser.

8. The shortest possible flue between the economiser and the chimney.

By due attention to the above points further considerable

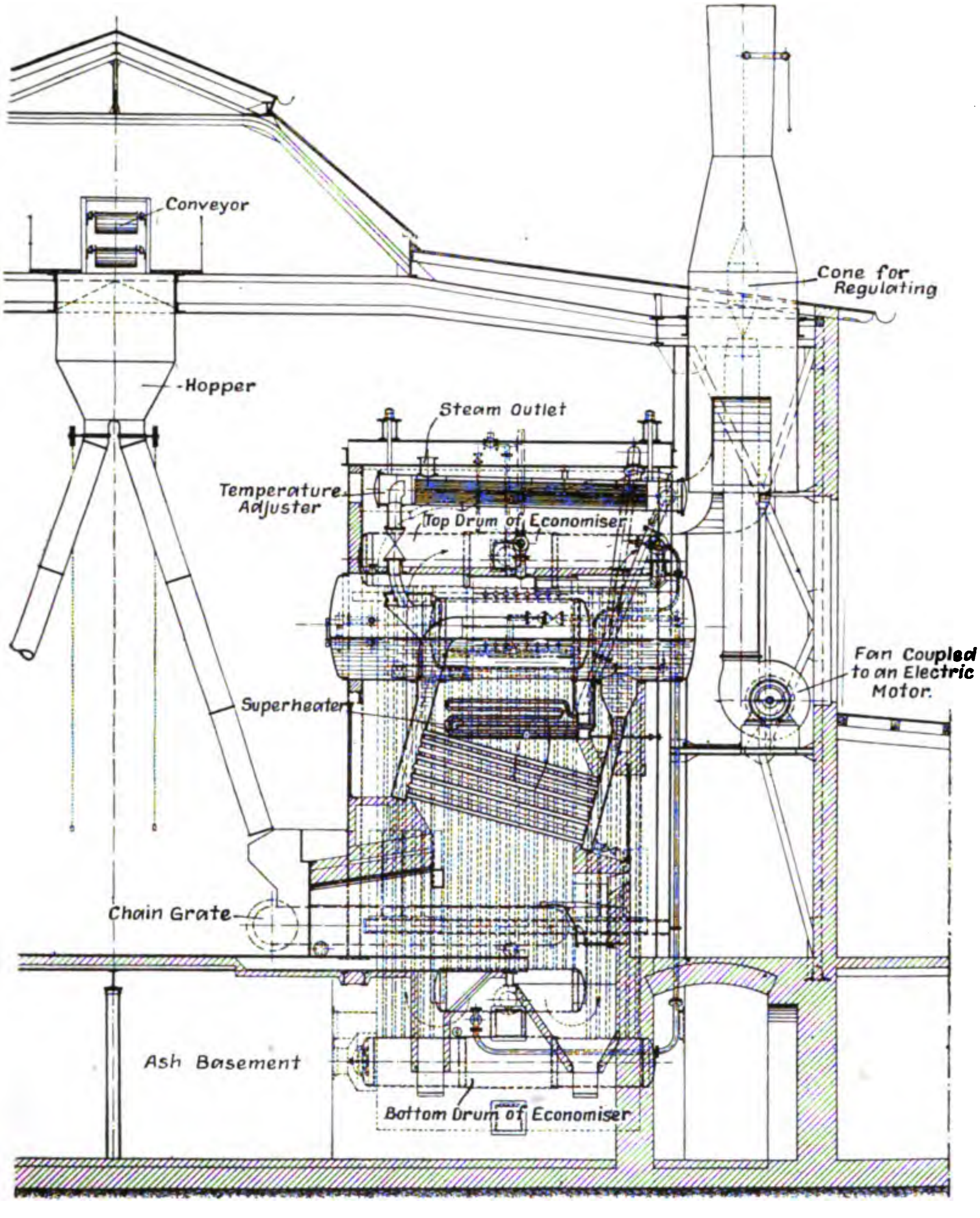

Fig. 10.—High Power Boiler with Self-contained Economiser and Artificial Draught, constructed by the firm of Steinmüller for the Breitungen Electricity Works.

Maximum steam output, 33,400 lbs. ; Heating surface of boiler, 3,710 sq. ft. ; heating surface of superheater, 1,160 ; heating surface of economiser, 3,120 ; grate area, 146 sq. ft. ; water capacity, 1,367 cub. ft. ; steam pressure, 215 lbs. per sq. in. ; steam temperature, 660° F.

The boiler is a combination of an inclined water tube (two-header) boiler and two upright tube boilers. The latter are placed on either side of the inclined tube boilers. In the four corners of the boiler, on the end plates of the upright tube boiler, four nests of economiser tubes are inserted, which are connected by drums located above and below the drums of the upright tube boiler. The gases rise up through the inclined tube boiler, pass through the superheater, then through the economiser from the bottom to the top. The temperature regulator, which is constructed in the form of a tubular feed heater, enables the superheat to be reduced by passing the superheated steam round the nest of tubes for saturated steam, the latter thereby being dried.

advantages may be realised from the fact that the area covered by the boiler houses, and the length of the pipes between boilers and the engine room, can be reduced appreciably, whereby a further saving is secured in the constant losses. A number of iron chimneys

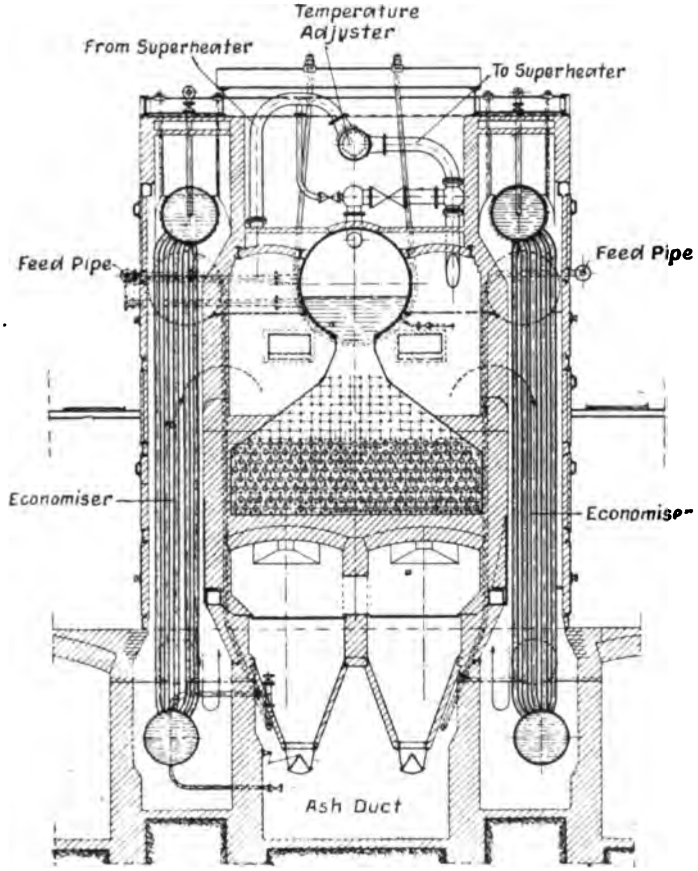

Fig. 10A.

The resistance in the path of the gases is kept low when the passage from the grate to the chimney is as free from bends as possible, as the resistance set up by bends is several times that of straight sections owing to eddy currents.

Boilers of the high power type conform best to the foregoing principles, when the economiser is built on top of the boiler, and when each boiler has its own chimney close up to the economiser, so that boiler, economiser, and chimney form a compact unit. This arrangement reduces the exposed surfaces and also the resistance to a minimum. The result is the temperature diagram shown in Fig. 9.

A disadvantage of this system is the necessity for constructing a large number of iron chimneys, the repair costs for which are higher than for brick chimneys ; a further disadvantage arises from the use of wrought-iron economisers, which are more expensive to repair and require more men for cleaning.

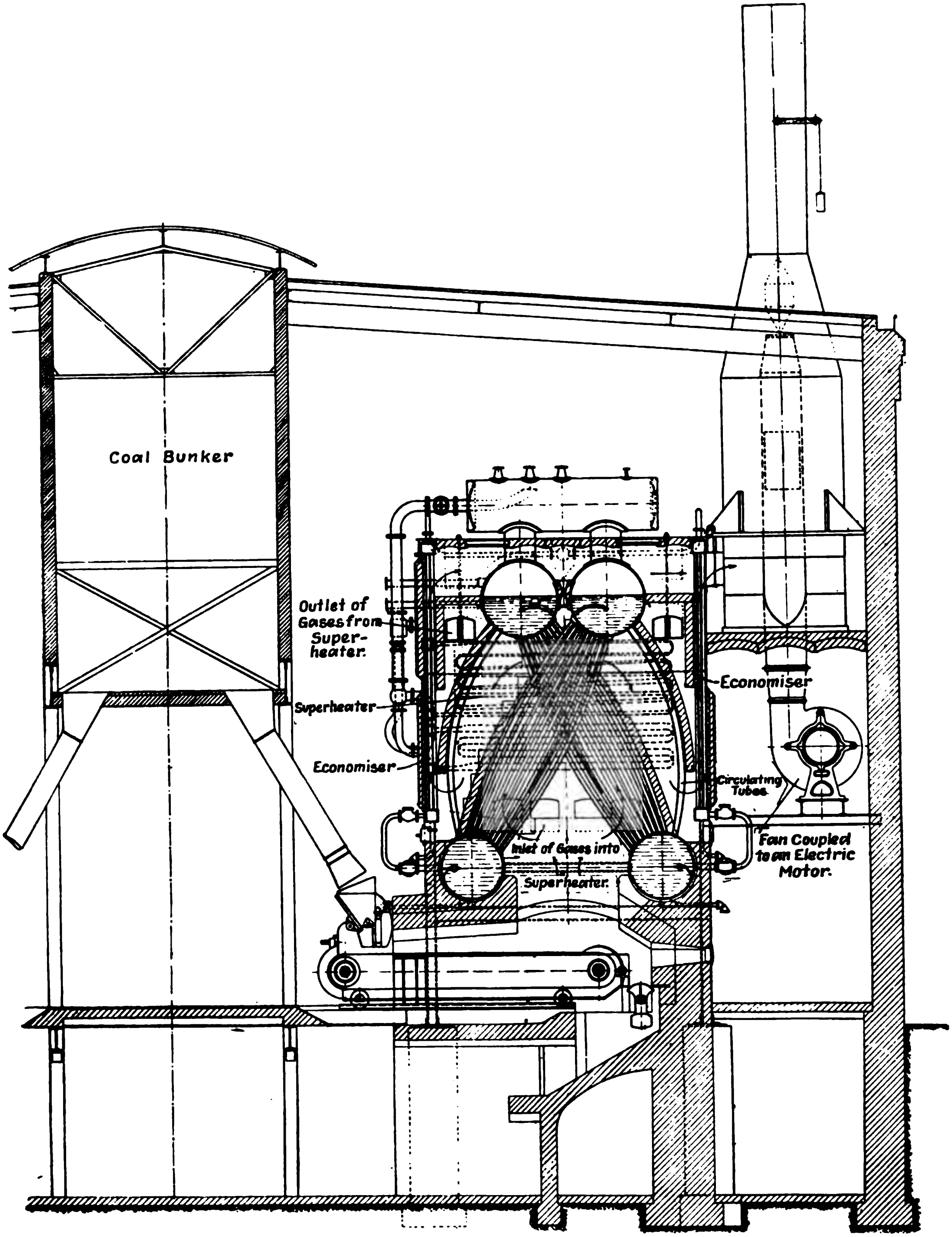

Fig. 11.—High Power Boiler with Self-contained Economiser and Artificial Draught, constructed by the firm Jaques Piedboeuf for the Königsberg Electricity Works, Prussia. Erected in existing boiler house; coal bunkers already installed.

Maximum steam output, 33,000 lbs. per hour; heating surface in contact with water, 3,760 sq. ft.; heating surface of superheater, 1,665 sq. ft.; economiser heating surface, 2,420 sq. ft.; grate area, 194 sq. ft.; steam pressure, 200 lbs. per sq. in.; steam temperature, 660° F.

The economiser, which can be drawn out in front, is placed in the centre of the boiler, and is heated in parallel with the boiler tubes. Part of the gases pass through the openings shown in the centre superheated chamber, and leave the latter at the top through similar openings which are controlled by dampers; they here join the other gases, and then pass along the front of the vertical economiser.

avoid the drawbacks associated with brick chimneys and flues, which, for the first lay-out, must be made large enough for later extensions, and even then sometimes turn out to be a hindrance (see Figs. 10, 11, 12).

b. Artificial Draught.

The development in the size of power stations has produced difficulties in the construction and operation of brick flues and chimneys. The possibilities of regulation are limited, and the amount of draught depends on the load. In the present forms of boiler construction these faults are avoided by employing artificial draught, which enables the maximum output of the boiler to be raised considerably. The importance of diminished efficiency and of the extra power required decreases with the utility factor, since a stronger draught is only required for meeting the peak loads, and for blowing up the fire after the boiler has been working light.

The fans should be driven by electric motors with automatic starters; they are frequently started and stopped.

The question whether induced draught or ejector draught is preferable requires investigation; it must be considered in conjunction with the arrangements for automatic stoking and ash removal.

Contrary to the customary practice on board ship, suction draught is generally employed for boilers on land in Europe, as the usual arrangements for mechanical stoking, controlling the fire, and for the removal of clinker can be retained. In America, on the other hand, one frequently sees boilers with air under pressure being passed over the grate; in isolated cases, compressed air at a fairly high pressure is forced through hollow grate bars in order to cool the latter: the depth of the layer of fuel may then be very great. In hand-fired boilers the pressure of the air sometimes just balances the resistance offered by the layer of fuel, so that the pressure over the grate is the same as that of the outer air; the object is to prevent the entrance of cold air when the furnace doors are opened.

The adoption of direct or indirect suction is decided by local conditions. With direct suction or induced draught the fan is in the

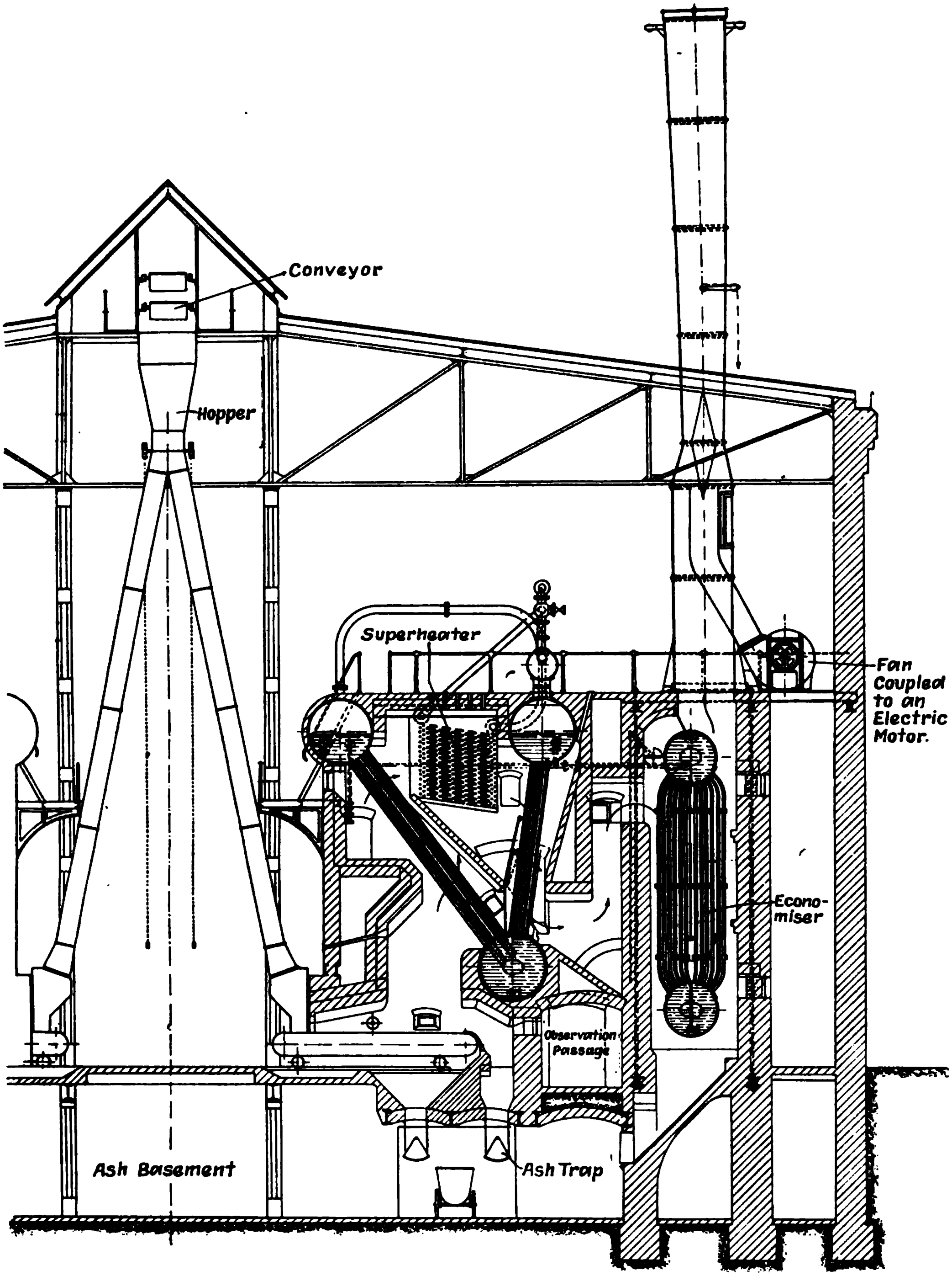

Fig. 12.—High Power Boiler with Self-contained Economiser and Artificial Draught, constructed by the firm Hartmann & Co., Chemnitz, for the Elbtal Power Station.

Maximum steam output, 24,640 lbs.; heating surface of boiler, 3,760 sq. ft.; superheater, 1,774 sq. ft.; economiser heating surface, 3,225 sq. ft.; grate area, 108 sq. ft.; water capacity, 1,165 cub. ft.; steam pressure, 213 lbs. per sq. in.; steam temperature, 660° F.

The boiler is composed of two separate upright elements, with separate upper headers and common lower header. The water circulation in each upright element is complete in itself; the water rises in the narrow tubes, and flows back to the lower header through wide tubes which are protected from the fire by brickwork. The gases first pass along the front tube element in the same direction as that in which the water flows; they next pass through the superheater, and then through the back tube element in a contrary direction to that of the water circulation, and finally reach the economiser, moving in the same direction as the water. The steam generated in the front upper header passes through the back upper header and a steam collector mounted on top on its way to the superheater.

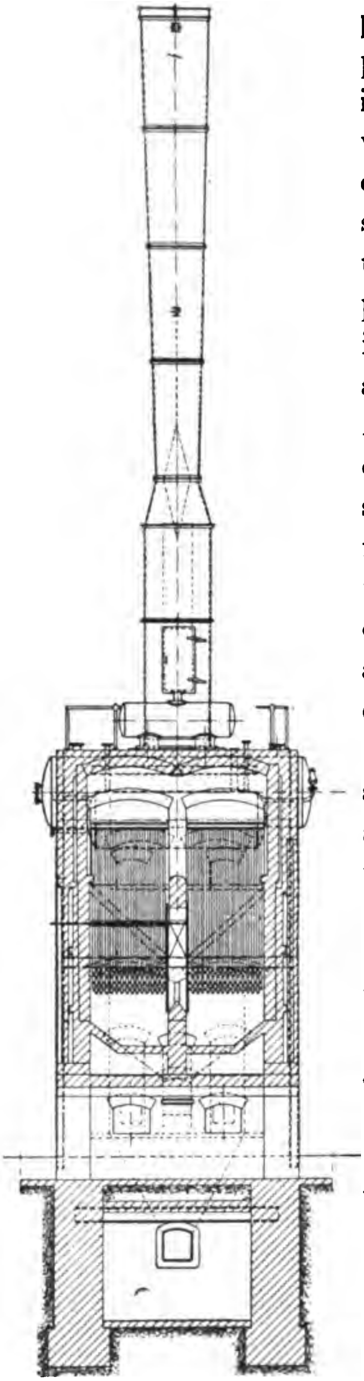

Fig. 12A.

path of the gases. This system requires less power than when ejector or indirect draught is employed. To enable the boiler also to work with natural draught, a short by-pass closed by dampers is necessary. The ejector system (Figs. 10, 11, 12), notwithstanding the larger amount of power it requires, possesses the advantage that the fan draws in cold air and can be made conveniently accessible independently of flue gases. Attempts have been made of late to reduce the amount of power taken in this system by withdrawing flue gases with the fan before they enter the chimney, and using them in place of air to produce the ejector action. The lack of dampers is the advantage of this system compared with direct suction draught.

On the assumption that the water resistance inside the boiler is sufficiently small, and that there are no corners which the gases cannot reach, the maximum steam output of the boiler in pounds per hour can easily be increased from forty to forty-five times the number of square feet of water-touched heating surface, when the above arrangement is adopted, whereby the output obtainable with a natural draught may be increased from twenty-eight to thirty times.[1]

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[1] Official tests were carried out in the beginning of October 1912 with a boiler constructed by the firm of Jaques Piedboeuf, similar to that shown in Fig. 11. The boiler was tested under ordinary working conditions without being specially prepared.

As the steam turbine to which it was supplying

Automatic stokers are, of course, an essential condition. Their arrangement depends to a very large extent on the nature of the fuel. In addition to easy regulation, the surplus air should be reduced to a minimum (partially covered grate).

It must further be possible to adapt the coal conveyor to load fluctuations. In conjunction with an artificial draught, speedily controlled, it is then possible to produce an almost instantaneous increase in the amount of steam generated. The small quantity

steam was working on tramway service, the load fluctuated between the limits of 24,200 lbs. and 34,100 lbs., corresponding to a mean stress on the heating surface of 6·4 to 9 lbs. per square foot. The days on which the test was carried out were preceded by an uninterrupted period of service of 1,000 hours.

RECORDS AND TEST RESULTS.

Boiler heating surface	3,760 sq. ft.
Economiser ,, ,,	2,420 ,,
Grate area	194 ,,
Duration of test	8 hours 1 min.
Total coal consumption	30,424 lbs.
Total water consumption	233,650 ,,
Thus 1 lb. of coal evaporated 7·68 lbs. of water.	
Feed water temperature on entering the economiser	118° F.
Feed water temperature on leaving the economiser	290° F.
Steam pressure	206 lbs. per sq. in.
Temperature of superheated steam	650° F.
Heat generated by saturated steam	2,660 B.Th.U.
Heat generated by superheated steam	320 ,,

$CP = 0{\cdot}554.$

Heat utilised in boiler, 21,626 B.Th.U. At the calculated thermal value of the coal (26,290 B.Th.U.), the efficiency of the boiler would be approximately 82 per cent. This result was obtained with an average evaporation of 7·7 lbs. water per square foot of heating surface; as mentioned above, the evaporation varied from 6·45 to 9·1 lbs. per square foot.

The temperature of the flue gases, at the end of the boiler system, *i.e.*, behind the economiser, averaged 557° F. The average draught, also measured behind the economiser, was only ·59 in.; the fan consumed 12·5 kw.; the average amount of carbonic acid in the waste gases was 12 per cent. The test was satisfactorily conducted; the grate did not become excessively hot. Notwithstanding the great fluctuation of the load, there was no priming; the superheat temperature remained practically constant during the test, readings at the turbine being taken every five minutes.

of water in high power boilers or their low thermal value need, therefore, not cause any anxiety. Automatic feed water supply has given excellent results in plants of this kind.

c. SUPERHEATERS.

There is no difficulty now in obtaining the desired steam temperatures at full load, since it has become customary practice to place the superheater into the path of the hottest gases. What is not quite so easy is to produce a sufficient amount of superheat at light loads, because the temperature drop of the flue gases is considerable at the point where they come into contact with the superheater. A high superheat is, however, particularly desirable at light loads, as the temperature losses in the pipes increase when the velocity of the steam drops, and the steam consumption of the turbines becomes worse in consequence. Provisions for securing a high superheat at low loads are therefore of value from an economic point of view. However, a superheater that may be correctly dimensioned for light loads will give too high a superheat at full load.

The methods most generally resorted to for regulating the superheat are to add saturated steam or to divert the hot gases, and to bring them into contact with the saturated steam when they are cooler (see Fig. 10).

It is not advisable to surround the superheater with brickwork in power stations with widely fluctuating loads. When a heavy load of steam consumed is reduced suddenly its temperature will rise in consequence of reduced steam velocity and of the heat stored in the brickwork; under certain conditions temperatures might thus be reached which would endanger the running of the turbines. The superheater should therefore be placed in that part of the boiler which is below the water line.

d. POSITION OF BOILERS.

In order to economise in the building costs, and to avoid unnecessary losses in pipe connections, it is customary to place the boiler house up against the long side of the engine room; thus in old steam power stations the boilers were situated in a long row along the engine room wall.

This design was the best with respect to low cost, accessibility, and simplicity in the arrangement of the pipes. Coal-conveying plant could be adapted to the large floor space required by steam engines with the small installed capacity obtainable per yard run of the engine room.

The advent of the steam turbine has altered these conditions. Even with small sets the available space is utilised so much more satisfactorily, that the corresponding boiler output cannot be obtained within the limits of the engine room otherwise than by erecting a second row of boilers.

With large steam turbine power stations, on the other hand, a boiler house with two rows of boilers parallel to the engine room is no longer feasible. With sets from 4,000 to 15,000 kw. and the best arrangement of engine room, an output of 700 to 1,400 kw. per yard run of the engine room should be obtained, whereas with high power boilers having heating surfaces from 3,200 to 5,400 sq. ft., an output of 200 to 320 kw. at the most can be obtained per yard run of single boiler frontage. This makes it necessary to erect a larger number of boilers in a row at right angles to the axis of the engine room, where regulations prohibit the practice of placing the boilers above one another which is frequently followed in America.

As the space in front of boilers with mechanical stokers must be of sufficient width to enable the grate to be drawn out entirely, the best arrangement seems to be to place the boilers in rows face to face (Fig. 13).

In large steam turbine power stations a number of double row boiler houses are erected side by side at right angles to the engine room. The accompanying advantages are numerous, and short connections to the engine room and to condensing plant, in addition to the great reliability obtained by dividing the total steam production amongst several boiler houses which are independent of one another.

In power stations with sets up to 6,000 kw. placed in parallel the best arrangement will be found to be to have two rows of boilers for three sets. For larger sets, up to about 12,000 kw., one row of boilers must be installed for each set. With sets beyond this capacity a satisfactory arrangement is to place all sets parallel with the

Fig. 13. -Arrangement of Coal Hoppers and Shoots in the Obererzgebirg Electricity Works.

axis of the engine room, a double row of boilers being provided for each set.

e. COAL BUNKERS.

The situation and size of the coal bunkers have an important influence on the design of the boiler house. The now favourite practice of installing large bunkers in the boiler house is not justified when sufficient space can be obtained cheaply for storing the coal outside. They cut off all daylight, and increase the cost of the installation considerably by the heavy and expensive constructional work and foundations that become necessary.

Irregular coal transport, danger of strikes, and local conditions are inducements for storing a much larger quantity of coal than can be accommodated in the bunkers of the boiler house. Coal is then usually stored outside, and is brought into the boiler house by mechanical transport. The reliability of well-designed coal conveyors is, however, such at the present time, that at all times an uninterrupted delivery of coal into the boiler house can be assured. With plant of this description it is therefore sufficient to design the boiler house with bunkers for an hour coal supply.

The bunkers then become so small and light that they can be attached to the roof without having to strengthen the construction of the latter very much, and no supports in the form of columns in the boiler house are required (Fig. 13).

The extent to which the weight of the ironwork in boiler houses can be decreased by reducing the floor space of boilers and by using small bunkers is illustrated by the power station of the Märkische Electricity Works (see page 108).

The boiler house has a maximum output of 93½ tons of steam per hour, and the ironwork only weighs 95½ tons, *i.e.*, about one-fifth of the weight of the iron which would have been necessary for large bunkers and boilers of standard size. It will thus be realised that a very considerable economy can be effected—moreover, an economy that has no adverse influence on the reliability of the plant.

f. PIPEWORK.

Owing to the pulsating character of the steam supply to reciprocating engines, it was formerly necessary to keep steam velocities low (about 82 ft. per sec.) to allow ample sectional areas when steam collectors were not placed in the branches to the engines.

This restriction has now been removed in view of the steady steam flow into turbines. Taking economy alone into consideration, the steam pipes would have to be dimensioned in such a manner that the annual expenses for interest and amortisation, together with the cost of losses (pressure losses and thermal losses), are kept as low as possible. This leads to steam velocities which the vibration of the pipes on changes of load would alone make prohibitive; moreover, the great drop in pressure from the boilers to the turbines at these speeds would be an impossibility from an operating point of view. It is advisable not to exceed maximum steam velocities of 262 ft. per second.

Formerly very little importance was attached to thermal losses in the pipes, although they should not be overlooked, because they are constant losses.

If, for example, they amount to 2 per cent. of the thermal consumption of the fully loaded plant (which is easily possible with badly insulated pipes), then with a load factor of 20 per cent. the coal to be burnt for meeting these losses will be as much as 10 per cent. of the total coal consumption.

Recently more efficient thermal insulation of the pipework has been aimed at, and more attention is now also being given to flanges, steam separators, valves, etc.

By taking these precautions it has become possible to reduce the radiation losses to 224 and 335 B.Th.U. per square foot and per hour,[1] so that they have practically no influence on the economic result.

The pressure losses in the pipework are of no importance as far as the energy losses they present are concerned. But as they

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[1] See Eberle, *Zeitschr. d. Ver. Deutsch. Ing.*, 1908, p. 481.

determine the difference in pressure between boilers and turbines they must be kept as low as possible, to enable the boilers to work in parallel satisfactorily in the event of load fluctuations. As, furthermore, the pressure losses increase with the length of the pipes, and at the same time great speed of the steam is desired, all pipe connections should be made as short as possible.

For these reasons also it is desirable for the boiler house to adjoin the engine room. High pressure losses are caused by valves, the resistance of which is approximately equal to that of a pipe 18 yds. in length and of the same bore. For cutting off the steam in live steam pipes, one should therefore only use slide valves, the resistance of which may be neglected.

All complications in the pipework should be avoided, and it should be remembered that the shortest and simplest pipework is the cheapest and most reliable in operation. Defects occur now and again in stop valves and flanges, but the pipes themselves very rarely give trouble from defective material. The smaller the number of valves the greater will be the reliability in operation. The same applies to expansion joints, the use of which can frequently be avoided by a skilful arrangement of the pipes.

The ring system of pipework, to meet an old rule, had to be dimensioned so that every part could carry the entire steam supply; pipes with very large sections and a great number of valves were therefore required. These are reasons why a ring system cannot be recommended. Duplicate pipes are worth considering when it is not desirable to pass the whole of the steam through one pipe for reason of safety in operation. If higher pressure losses are not objected to when one of the pipes is cut off owing to a defect, the dimensions necessary are not unfavourable from an economic point of view.

In double row boiler houses placed at right angles to the engine room duplicate pipework is not necessary; one pipe main (of different sections) along each row of boilers is sufficient. A limited reserve can then be obtained without appreciable additional cost by joining the two pipe mains near the dead ends by an auxiliary pipe sufficiently large to carry the steam from two or three boilers.

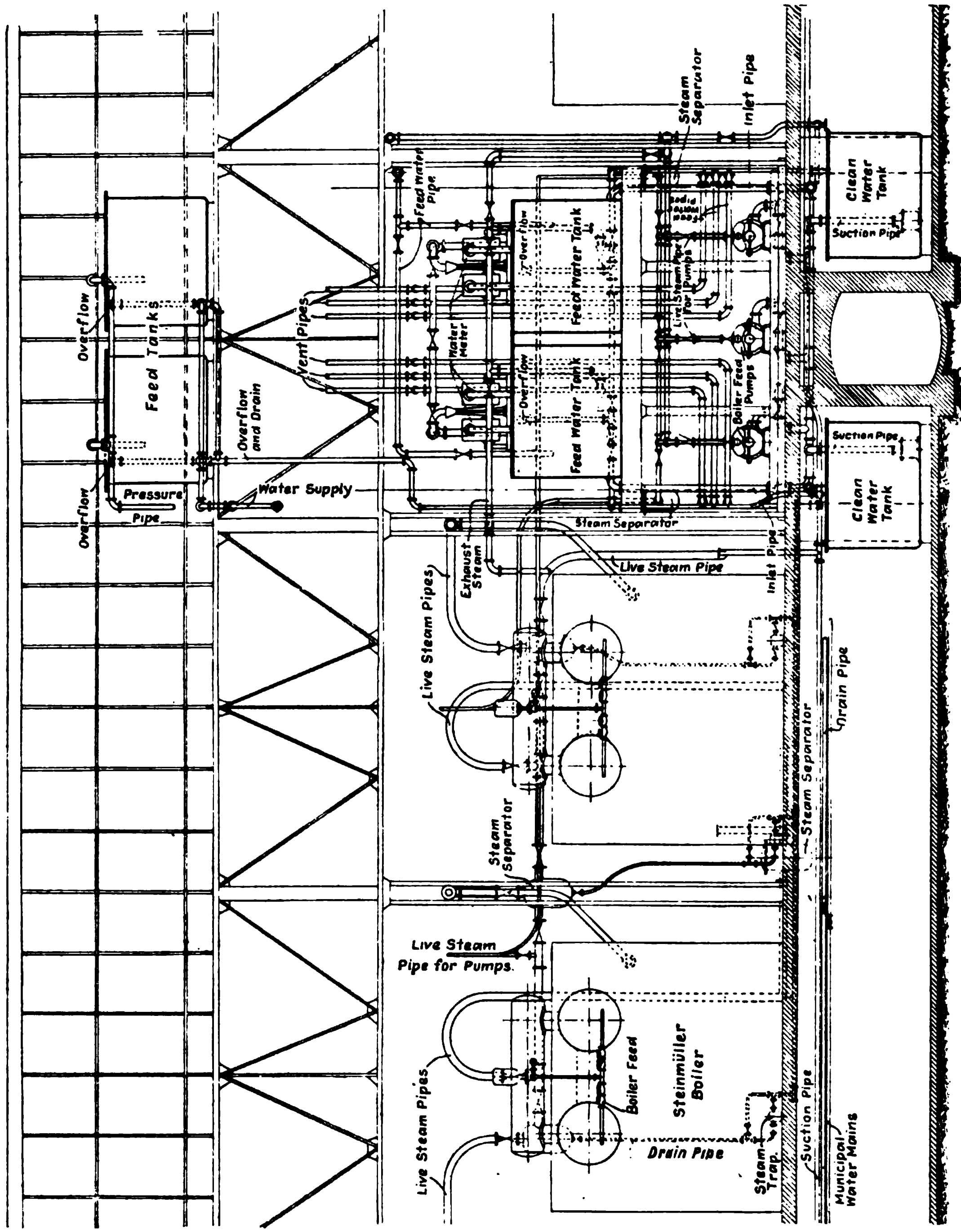
Overflow
Feed Tanks
Overflow
Pressure Pipe
Overflow and Drain
Water Supply
Vent Pipes
Feed Water Pipe
Water Meter
Overflow
Feed Water Tank
Overflow
Feed Water Tank
Steam Separator
Inlet Pipe
Live Steam Pipe for Pumps
Boiler Feed Pumps
Clean Water Tank
Suction Pipe
Suction Pipe
Clean Water Tank
Steam Separator
Live Steam Pipe
Inlet Pipe
Exhaust Steam
Live Steam Pipes
Drain Pipe
Steam Separator
Steam Separator
Live Steam Pipe for Pumps
Live Steam Pipes
Boiler Feed
Steinmüller Boiler
Drain Pipe
Steam Trap
Suction Pipe
Municipal Water Mains

Fig. 14.

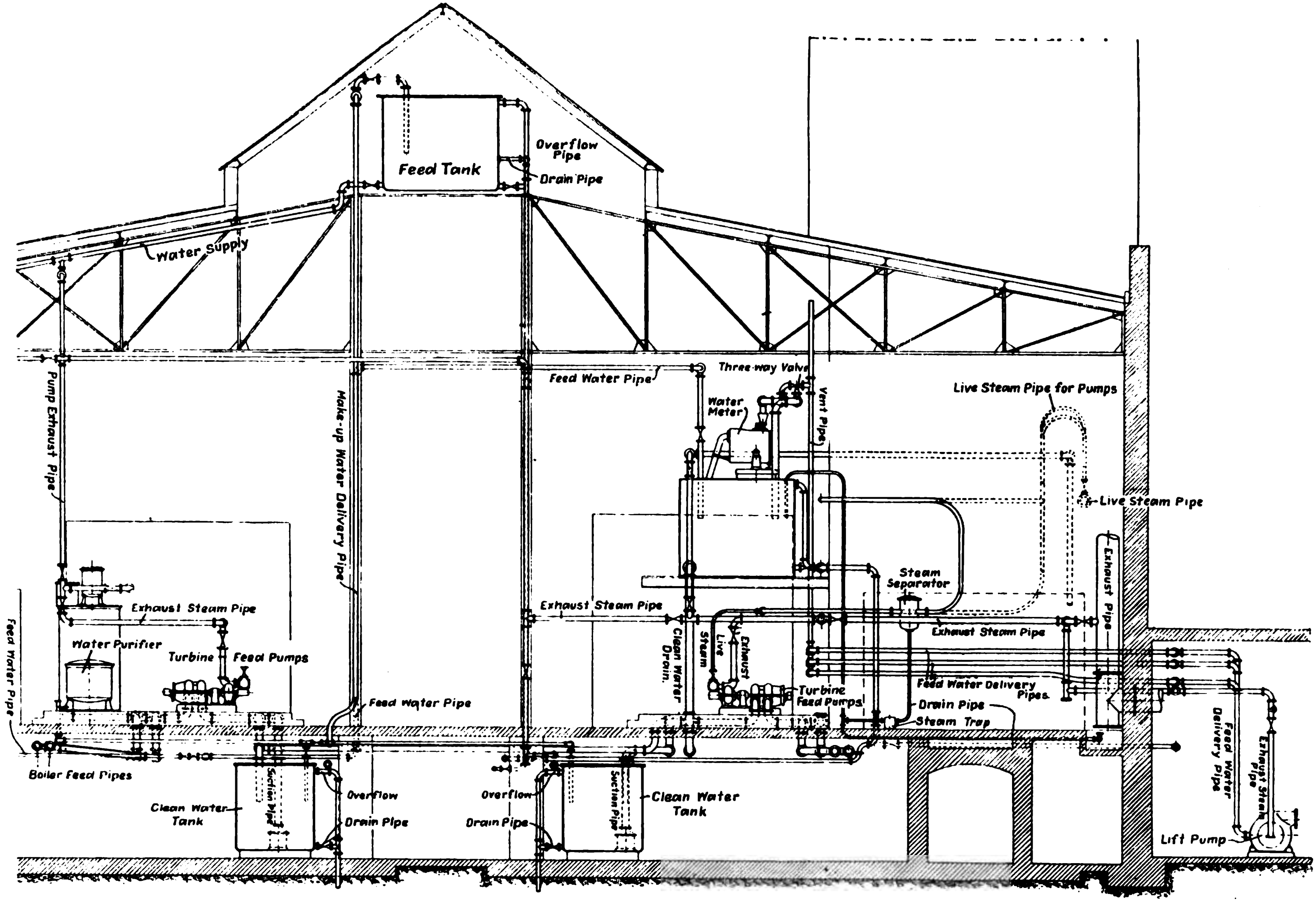

Fig. 15.

Figs. 14 and 15.—Feed Water Supply System in the Power Station of the Hamburg Elevated Railway. The make-up water flows from two raised tanks to the water purifier. After treatment the water is collected in tanks in the basement, and is pumped into the feed water tanks above the boiler feed pumps as required. A special pressure pipe for the condensed steam passes from each set to the condensed feed water tanks, and to the water meters above. In addition, each boiler is fitted with a disc water meter, thereby bringing both condensed steam and feed water under permanent observation. The feed water delivery pipes are arranged in such a manner that the steam consumption of any turbo-generator can be determined while it is in commission.

In large power stations, where one row of boilers is provided for each turbo-generator, the pipe mains are led directly to the turbines. A connecting pipe, with a stop valve, should be provided between the pipe mains. The section of this connecting pipe, however, may be comparatively small, since it will be required for the steam of only one turbine.

If the number of turbines is not the same as the number of rows of boilers, the turbines must be connected to a collector pipe. In both cases it is advisable to have steam separators at the ends of the pipe mains from the boiler house; they should be used as fixed points for the pipework. The collector pipe is then arranged as a connection between these separators, and should be flexible. The necessary movement could be obtained in an ordinary stuffing box, because the ends of the connecting pipe are rigidly fixed in the separators, which are anchored.

g. MEASURING APPARATUS.

In order to keep a daily record of the coal consumed and water evaporated in the boiler house, it is necessary to employ coal and water meters. The simplest and most satisfactory position for the latter is between each condenser and the feed water tank; a special water meter is also employed for measuring the make-up water. Thus the steam consumption of each set is ascertained in addition to the total consumption (see Figs. 14 and 15). Where it is desired to measure the steam output of each boiler, steam meters in addition to the water meters may be desirable.

Where a daily check on the coal consumption is desired and large bunkers are provided, automatic weighing machines are built into the coal shoot for each boiler. This arrangement is somewhat complicated, and reduces the available space, which is by no means ample, with large bunkers. If, on the other hand, there is no coal store worth mentioning in the boiler house, one single weighing machine placed in the track of the conveyor will suffice for ascertaining the daily coal consumption. The accuracy of this method is quite reliable, provided the small bunkers and shoots in the boiler house are filled completely every day at the same time (whilst the plant is running on light load). This cheap and reliable arrangement has given excellent results as a check on the coal consumption and on the boiler house staff.

4. STORAGE AND TRANSPORT OF COAL OUTSIDE THE BOILER HOUSE.

Even when an uninterrupted supply of coal can be relied upon under normal conditions, it is necessary to provide for storage, sufficient for at least two months, as a safeguard against strikes. The quantity of coal stored must be even greater in the case of water freight, as a spell of severe frost may make delivery by this means impossible.

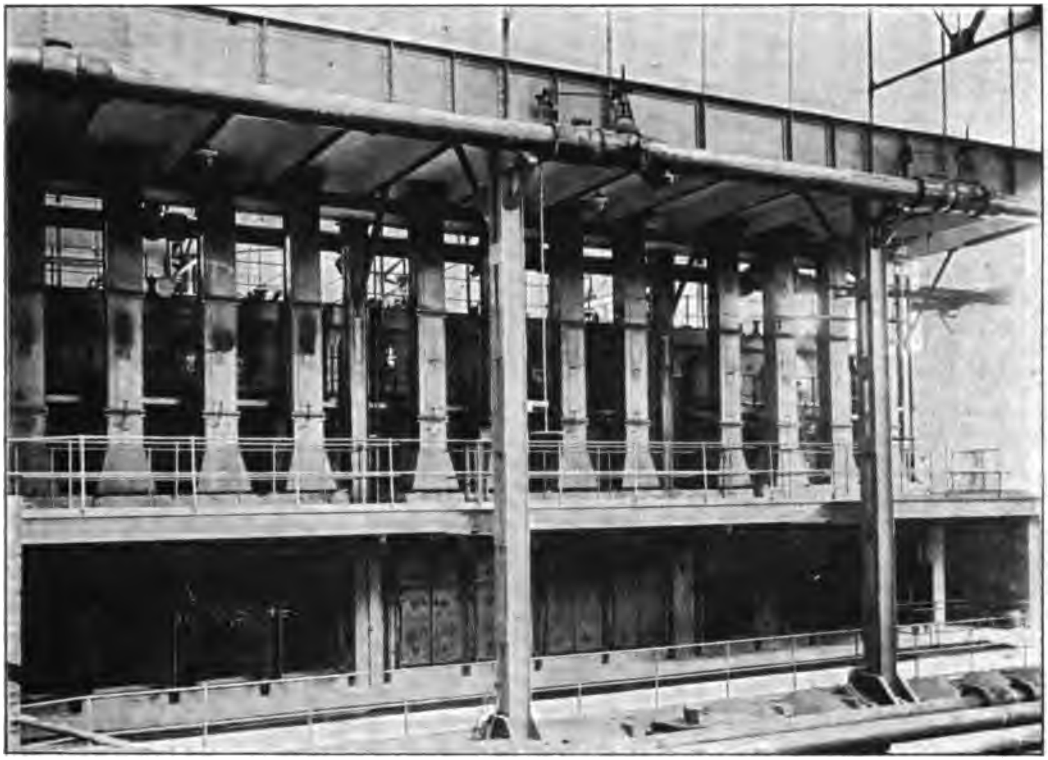

Fig. 16.—Brown Coal Bunkers and Shoots in the Fortuna Power Station.

Open air storage is preferable when sufficient space can be secured at a reasonable price, as it entails the lowest capital costs; it is true that coal stored in the open air is exposed to the effects of the weather, and deteriorates in quality in the course of time. But the loss in thermal value is, as a rule, not large enough to justify storage in covered bunkers. This form of storage is of interest only under certain conditions—for example, in densely populated districts where storage of brown coal or very dusty coal in the open is not permissible.

If the coal cannot be stored in the open for other reasons, one can determine by estimate whether it is better to store in the boiler house bunkers, or to erect separate covered bunkers (see Figs. 17, 18, and Fig. 19, Plate I.).

Where small coal hoppers in the boiler house are decided upon, the provision of a transporting device which enables an uninterrupted supply of coal from the storage yard to the hoppers is essential. No special attendance should be necessary for such a device; this condition is fulfilled when the coal hoppers in the boiler house are fitted with automatic arrangements which prevent overcharging, by diverting the supply, when a hopper is full, and by stopping the conveyor altogether when all hoppers are fully charged.

The coal conveyor between the storage yard and the boiler house should be so designed that the coal falls on to it from the yard by gravity. When the coal is stored in the open, a satisfactory solution of this problem is to mount the conveyor in passages underneath the storage yard, and to enable the coal to fall on to it through openings in the ground (Fig. 20).

All unnecessary handling of coal on its passage from the store to the boiler house must be avoided. On this account bucket conveyors are preferable to belt conveyors. Only one endless bucket chain and one motor are required for each boiler house, and this type of conveyor is therefore cheap to install and occupies very little space (Fig. 20).

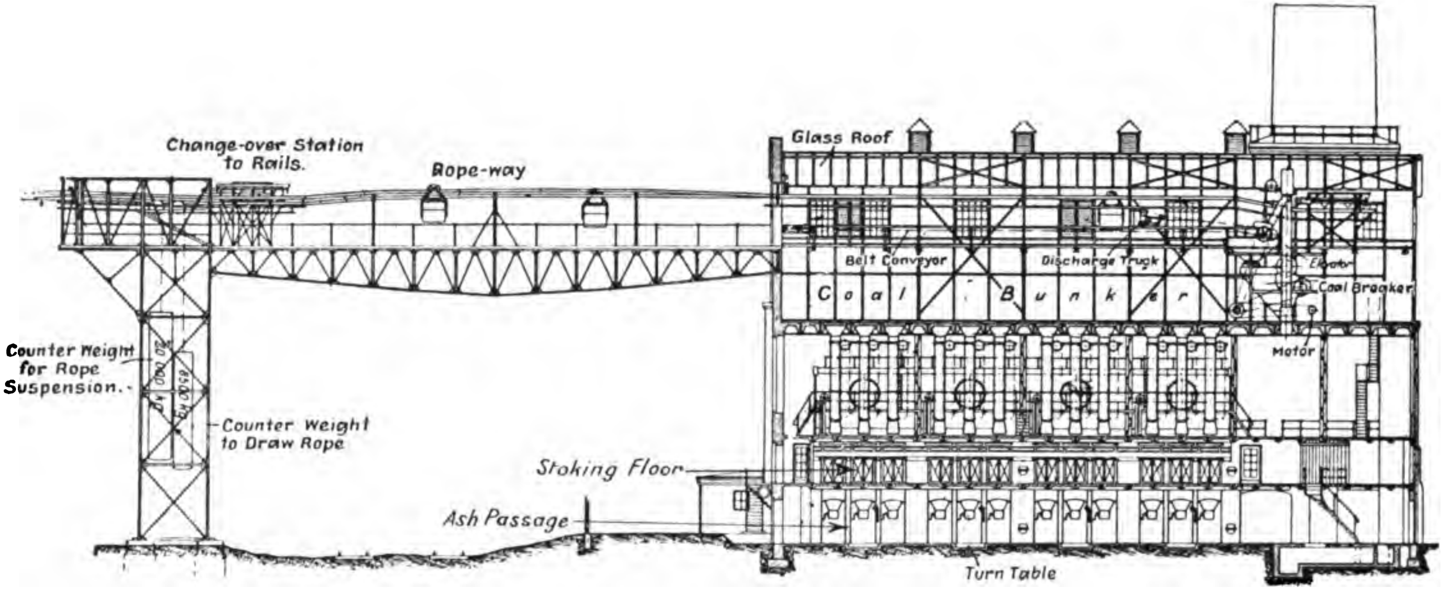

Fig. 17—Arrangements for Coal Transport at the Hirschfelde Electricity Works (brown coal power station). Rope telpher. Large coal store above the boilers. Storage capacity, 19,420 cub. ft. The rope telpher runs direct into the coal store, and incoming trucks can be discharged automatically at any desired point. Length of the telpher, 1,430 yds. Power required, 11-13 H.P. Boiler house, 12 water tube boilers manufactured by the firm of Steinmüller, with self-contained economiser and natural draught. Maximum steam output, 1,210 lbs. per boiler. Heating surface in contact with water, 2,656 sq. ft. Superheater surface, 765 sq. ft. Economiser heating surface, 2,687 sq. ft. per pair of boilers. Grate area, 132 sq. ft. Steam pressure, 205 lbs. per sq. in. Steam temperature, 645° F.

5. ASH REMOVAL.

The work of removing ash and clinkers from the basement of the boiler house and further transport varies in proportion to the percentage of ash contained in the coal. Attempts have frequently been made in large power stations to introduce an automatic device, but where the ashes are removed in open receptacles this kind of plant has not given satisfaction. The idea of using the coal conveyor for the removal of ashes is tempting, and the chain of buckets is often made to pass through the ash pit for handling the ashes as well as the coal. The wear in this case is, however, unusually heavy, since the flinty articles of the clinkers injure the moving parts of the conveyor. Automatic devices for removing the ashes pneumatically in closed tubes are more successful. When the ash is fine (brown coal ash), the principal wear takes place at the bends in the ducts and can be

Fig. 18.—Coal Bunker. Ropeway and belt conveyor to carry the coal to bunker.

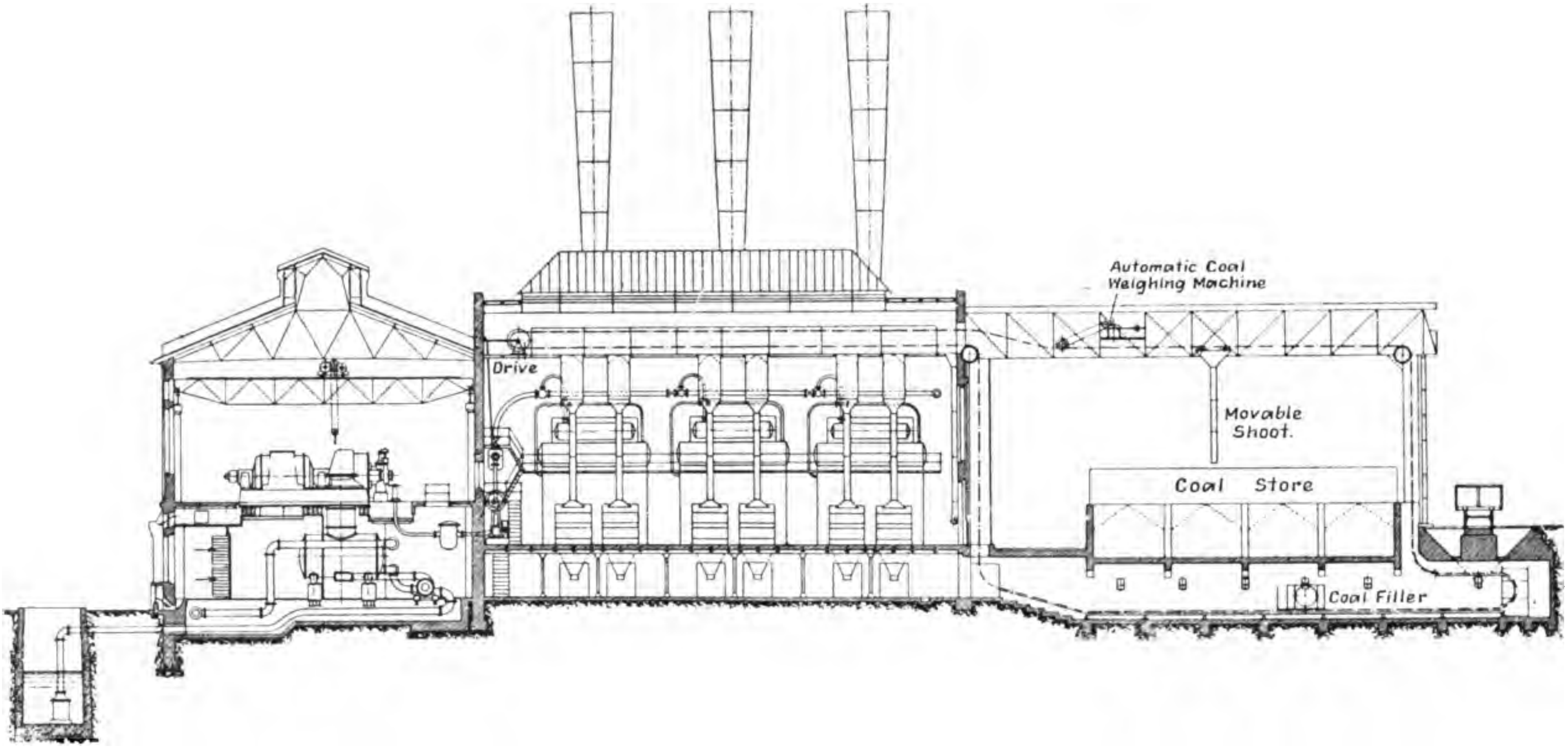

Fig. 20.—Arrangements for coal transport at the Obererzgebirg Electricity Works. Endless chain bucket conveyor used for unloading the railway trucks, discharging coal in the storage yard, drawing the trucks to the coal hoppers of the boiler house, and conveying the coal from the storage yard to the boiler house, with travelling discharge shoot. The bucket chain is driven by a 5 H.P. electric motor. The capacity of the coal store is 35,300 cub. ft.

Present output of the power station, 8,000 kw.

For the present it seems therefore advisable to employ trucks running on rails, which are raised without discharging from the basement by means of a lift or an inclined moving plane.

kept within reasonable limits. Results obtained up to the present with the ash from bituminous coal are conclusive. The system of ash disposal usually adopted on ships by means of a stream of water from a centrifugal pump, cannot be adapted to stationary plants, as the volume of water required is too great, being several times that of the ash.

Fig. 21.—Arrangements for the Removal of Ashes in the Basement of the Hirschfelde Electricity Works.

Installations of the above nature have given satisfactory results when adequate lighting and ventilation is provided in the basement (see Figs. 21, 22, 23). It is not advisable, however, to give access to the basement from the boiler house through openings in the floor, because the boiler house would then soon become very dirty.

Fig. 22.—Stoke Hole in the Hirschfelde Electricity Works.

Fig. 23.—Ash Tunnel under the Boilers in the Hirschfelde Electricity Works.

6. SWITCHGEAR.

As the outputs of power stations and electric transmission pressures have increased, the strains put upon switchgear have become greater, and the former tendency to economise in capital expenditure and space in this part of the plant has had to be abandoned in the interest of reliability in operation.

a. Type of Apparatus.

The working conditions are very much more unfavourable in switchgear installations than in other parts of the station. On the one hand, the whole of the energy generated in the power station is concentrated here, and any breakdown of the apparatus may mean shutting down the entire station; on the other hand, it seems impossible in any installation to avoid short circuits in the network, and pressure surges, with their accompanying mechanical and electrical stresses far in excess of anything that may occur under normal conditions.

All apparatus and constructional parts of which the switchgear installation is composed should be designed in accordance with standards approved for general engineering purposes. The following would be the most important requirements:—

(1) The factor of safety, from an electrical point of view throughout, should be high enough to enable the plant to withstand any pressure surges that may occur. The factor of safety of inaccessible parts should be greater than that of the more accessible sections.

(2) With respect to mechanical strength, the apparatus should be capable of dealing with the conditions that may arise when the whole power station is short circuited; capability of keeping on the service should not be affected thereby.

The observance of the first condition is more easily controlled when the same insulator is used throughout, including switches, isolating switches, current transformers, etc. (Figs. 24 and 25).

With insulators of the correct sizes, and a standard clearance between live parts and to earth, the factor of the degree of safety for each section of the plant may be determined in advance.

What degree of safety is desirable depends on the surges to be expected due to switching operations, short circuits, etc. The value of these surges is influenced largely by the current, and to a lesser degree by the working pressure. The higher the working pressure the lower will be the surge pressure in comparison, so that as the working pressure goes up the factor of safety may be reduced.

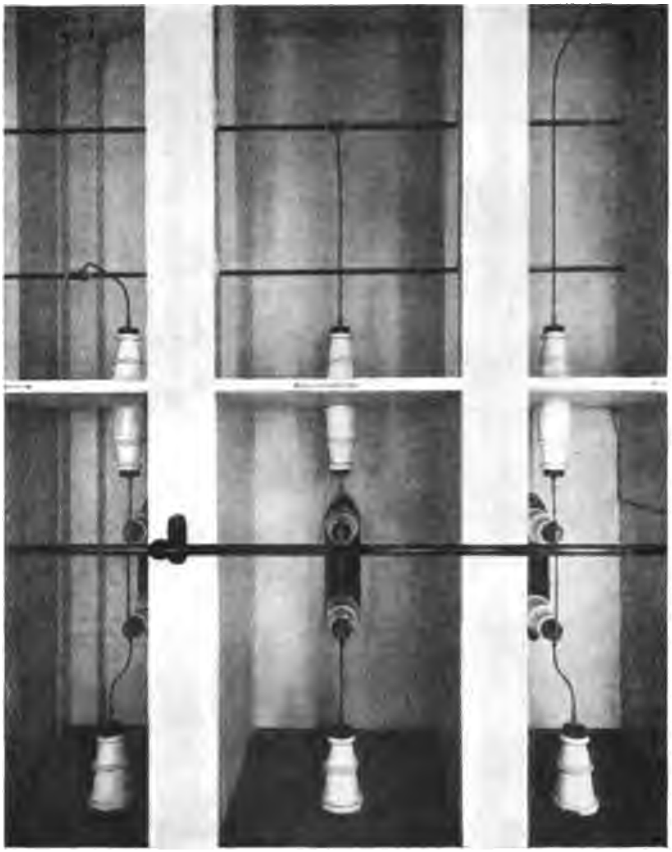

Fig. 24.—Insulators for Isolating Switches, and Bus-bars in the Hirschfelde Electricity Works. 40,000 Volts.

For medium working pressures (10,000 to 20,000 volts) and power station capacities, a factor of safety of 5 is ample, whereas for 100,000 volts a factor of safety of 2 is, as a rule, sufficient.

Insulators with a smooth shape are easier to keep clean, and do not collect so much dust as insulators with many corrugations (Figs. 24 and 25). The pressure at which the insulators flash over should be considerably lower than the puncture pressure. The break-down pressure of enclosed apparatus, such as that for the windings of current transformers to the tank, should also be higher than the flash-over pressure of the insulators. Under these conditions the insulators form may be looked upon as a safety spark gap across which, in the case of an emergency, a discharge may take place without endangering more important parts of the apparatus.

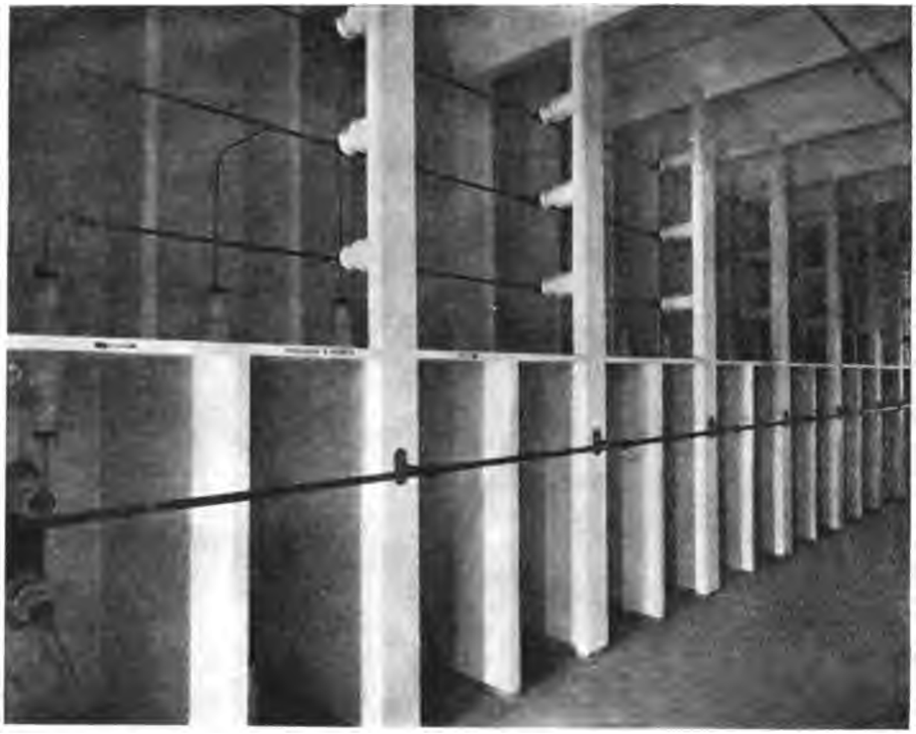

Fig. 25.—Bus-bars in the Hirschfelde Electricity Works. 40,000 Volts. Partitions of Duro Plates. No Partitions between Bus-bars.

The smaller the amount of high-tension apparatus used the greater the reliability in operation. Nothing but what is absolutely necessary should therefore be installed. Current and potential transformers should be large enough in capacity for working four or five instruments each.

The number of instruments that can be installed is then not limited unnecessarily.

It is important to obtain accurate measurements of the output generated and distributed.

Meters should be installed for each generator as well as for each feeder circuit, so as to obtain a check on the readings.

In addition, recording instruments giving a constant record of the station pressure and the load on each feeder circuit are necessary for a proper management of the undertaking.

The part of the installation which is subjected to the greatest stresses are the oil switches connected direct to the main bus-bars; in cases of an emergency they have to break the short circuit energy of the entire power station, and should be capable of doing so rapidly, and without any danger of failure. No apparatus has yet been designed to fulfil this condition in stations with a very large capacity, and it seems doubtful whether the principle of breaking under oil is the right one to follow to the exclusion of other ideas. Attempts are now being made to lighten the duty of switchgear by reducing short circuit currents (time limit in the operation of switchgear, reactances, switches with resistance or reactance steps, sectionalising the supply). The conditions of operation are particularly difficult for switching at a small power factor (overhead transmission lines, furnaces, etc.). Considerable improvements are possible by increasing the speed at which switch contacts separate.

Only one size of switch should be connected to the bus-bars. Its capacity should not be determined by the load on feeders, but rather by the capacity the power station may ultimately have after all extensions are completed.

Large outputs call for single pole switch elements with automatic and remote control. In plants of medium size, at least, the generator switches should be electrically controlled, because it makes synchronising easier. Switches in feeder circuits, on the other hand, can be operated by hand, being used less frequently.

b. Overloads and Pressure Surges.

The system of protection against excessive overloads must be designed in such a manner that the faulty feeder can be cut out without disturbing the supply elsewhere. If the generators can withstand short circuits with full excitation, the best protection for them are reverse current relays for instantaneous operation. The reverse current, which would flow into a defective generator, would then be switched off immediately.

The differential protective (Merz-Price) system is the best for outgoing feeders and overhead transmission lines, particularly for ring mains (see *E.T.Z.*, 1908, pp. 316-321, 329-333, 361-365). It can be made so sensitive that the conductor is cut out at both ends simultaneously, immediately the fault occurs, and other parts of the network are not affected. The switch can also be set to operate with a time limit, if it is not considered advisable to switch out during the first rush of heavy current.

Next to the differential system, preference should be given to maximum relays with independent time adjustment, rather than to devices in which the time limit is influenced by the value of the current. Reliable time adjustment is unobtainable with the latter apparatus, the time of release being too short on heavy overloads. If, for example, a short circuit occurs in a feeder which is not on load, it frequently happens that another feeder working on full load is cut out first.

In order to be able to switch out a short circuit to earth, the neutral of one of the generators in commission should be earthed through a suitable resistance ; it is then necessary to protect all the phases of the feeder.

Opinions are still divided as to which is the best system of protection against pressure rises, and it is not the intention to discuss this subject exhaustively here. It should, however, be emphasised that protection is best obtained by a high factor of safety, by transformers with extra insulation on the first turns, by earthing the neutral point, and by large clearances between phases of high-tension conductors. The fact is frequently overlooked that the extra money spent on apparatus of ample dimensions is counterbalanced by a simpler protective system.

As a protection against lightning, good results have been obtained with one or more earthed steel wires of sufficient sectional area over the main conductors of an overhead line. These wires form an effective protection against lightning discharges into the line, and prevent static charges to a certain extent.

c. Bus-Bars.

The double bus-bar system is superior to the older ring system. The chief advantages are: convenience and absence of danger for cleaning, the possibility of dispensing with isolating switches in the main bus-bars, freedom in arranging generator and feeder panels, and the possibility of connecting each generator to any feeder when an independent supply is wanted.

In a large power station, with a great number of outgoing feeders for comparatively small output, the following modification is advisable, since it permits an economy in space and capital expenditure without adversely influencing reliability.

Four to six feeders are combined to a group with their own set of bus-bars; each of these groups is connected to the main bus-bars through a special section oil switch. Although the main bus-bars must be dimensioned to carry the full short circuit energy of the power station, the group switches may have a smaller capacity.

No apparatus should be in the circuit between bus-bars and oil switches, because when such apparatus becomes defective the bus-bars are short circuited. The correct sequence of the apparatus is, therefore, cable terminals, isolating switch (a bench for protective devices and potential transformers), current transformers, oil switches, isolating switches, bus-bars.

d. INSTALLATION OF SWITCHGEAR.

The high-tension apparatus can be installed in the order given above, either side by side on the same floor, or separately on different floors. The latter arrangement is generally preferable, since it entails lower building costs and shorter leads.

To prevent crowding of apparatus three floors should be provided in high-pressure installations, one for the bus-bars, another for oil switches, and a third for the cable sealing boxes or transmission line terminals (with all protective apparatus). Where feeder cables alone come into question, the bus-bars are placed on the top floor (see Fig. 27); for overhead transmission lines, the middle floor is more suitable for this purpose (see Figs. 28 and 29).

Fig. 26.—Operating Passage for the Oil Switches in the Rheinfelden Electricity Works. In the floor to the right and left are cover trenches for the control wires; the bottom part of panels consists of removable metal plates covering the terminals for the apparatus leads; it is not necessary to enter the high-tension chambers to inspect these leads.

The operating gear for oil switches should be in an operating passage, which is separated from the actual high tension by a switch chamber (Fig. 26).

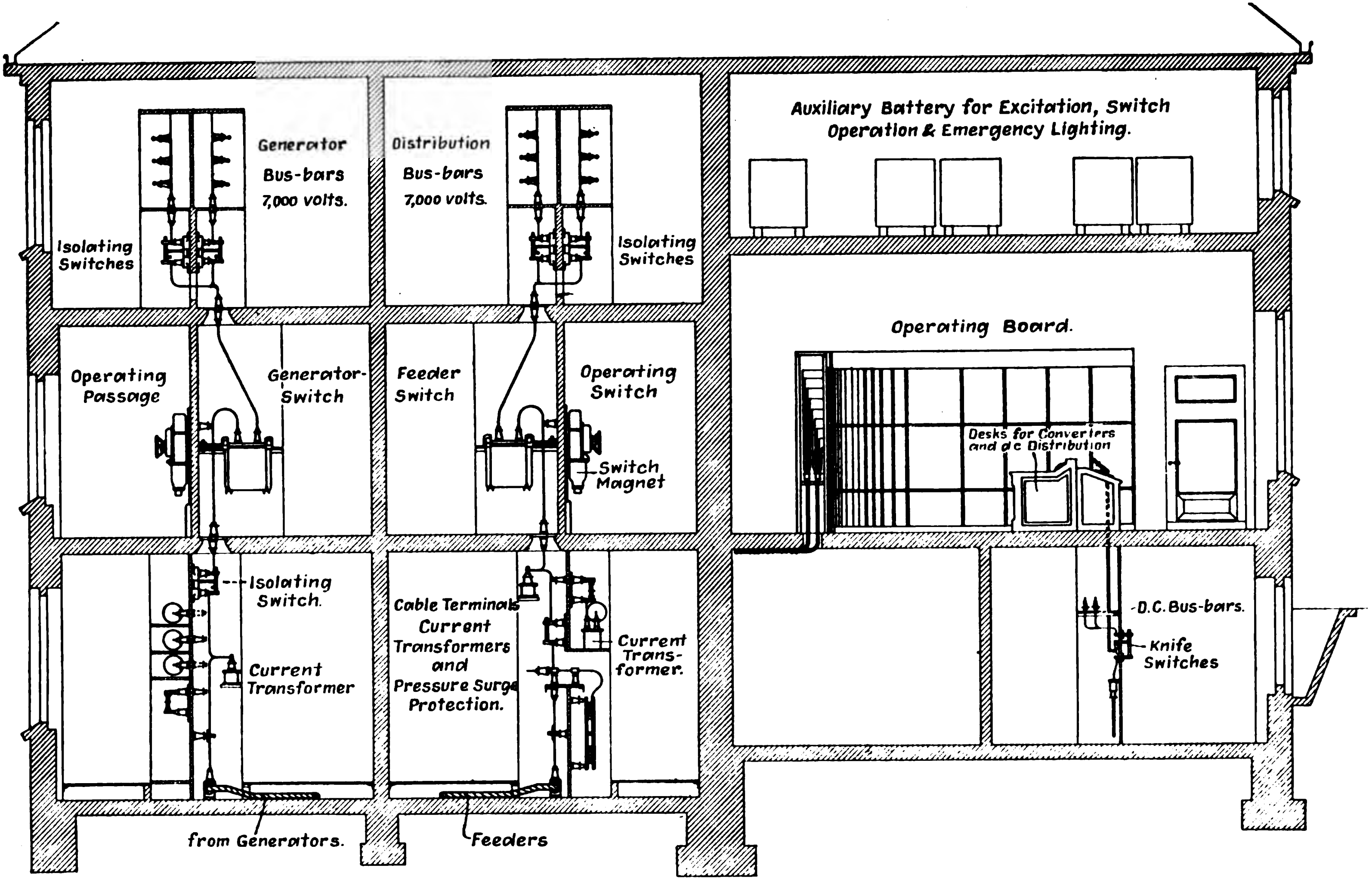

Fig. 27.—Switch House for the Bremen Electricity Works. 7,000 Volts. Complete Separation of the Phases from Cable Terminals to Bus-bars.

Special care must be taken to make the installation fireproof. The formation of arcs must be prevented by large clearances between conductors, and between the latter and earth.

On the other hand, the system of separating the phases by partitions does not possess the great value (even in the case of bus-bars) which is still frequently attributed to it.

Its adoption is only justified where large quantities of oil (single pole switches) might cause serious conflagrations.

In the remaining part of the installation it is sufficient to separate the entire panels of generators and feeders from one another by solid walls, so that repairs can be carried out without danger and without interrupting the remainder of the service.

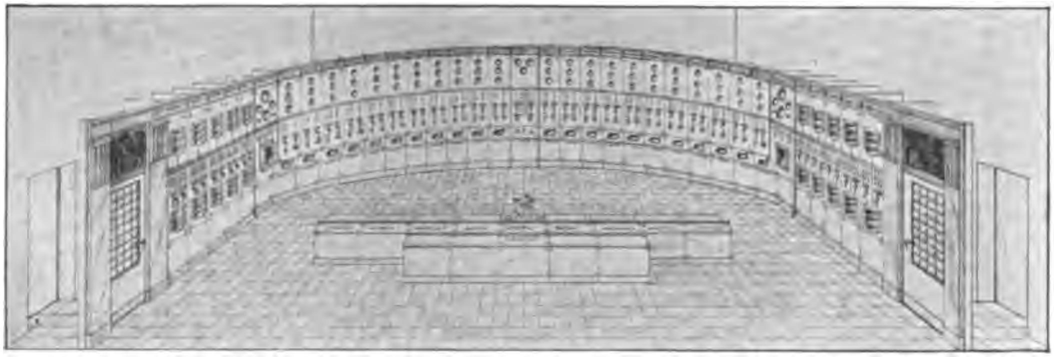

Fig. 27A.—Operating Board in the Switch House of the Bremen Electricity Works. Generating Panels in the centre, Feeder Panels on the right and left. Desks for Converter and Auxiliary Service Switches.

The stories of the building must be made fireproof to prevent a fire spreading from one floor to another.

All conductors should therefore pass through insulators and not through openings in the floor.

e. Oil Cleaning and Drying.

The quantities of oil used in transformers, oil switches, instrument transformers, etc., for insulating and cooling purposes, represent such considerable sums of money in large plants that it is important to make provision for cleaning and drying the oil at some central points.

Of late, Russian mineral oil, free from acid and moisture, has largely been employed for transformers and apparatus: this oil has a freezing point below 4° F., and a flash point exceeding 300° F. The length of time a transformer can be operated without renewing the oil depends to a great extent on the average temperature of the oil. This again depends on the load conditions and on the arrangements made for cooling the transformers. Under ordinary conditions the oil in transformers should be examined about every one or two years. If some device is available for easily changing the oil, more frequent cleaning is advisable for the sake of securing increased reliability.

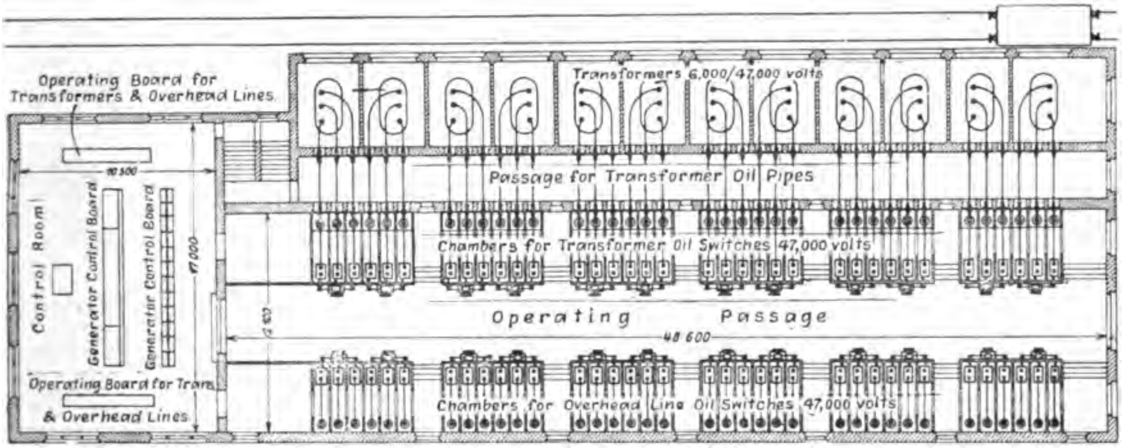

Fig. 28.—Plan of the Switch House for the Laufenburg Electricity Works. (Dimensions in metres.)

The life of oil in switches will depend on the energy which the latter have to break. When an overload or short circuit has been switched off, some of the oil will become carbonised, and it is advisable to examine it after the switch has operated not more than twice under such conditions. The carbonised layer will be found at the top and must be removed, as it decreases the insulation and breaking capacity of the switch. In the case of fire, it must be possible to allow the oil to run off quickly in order to prevent the fire from spreading.

The plant for oil treatment (see Figs. 31 and 31A) must also include an iron reservoir, which is placed outside the building, and sunk below the level of the ground in brickwork. The capacity of the tank must be greater than that of the largest transformers;

it must be connected by large pipes to the transformer tanks; and one should be able to empty the largest of these completely in ten minutes. A second reservoir of the same size is required for the

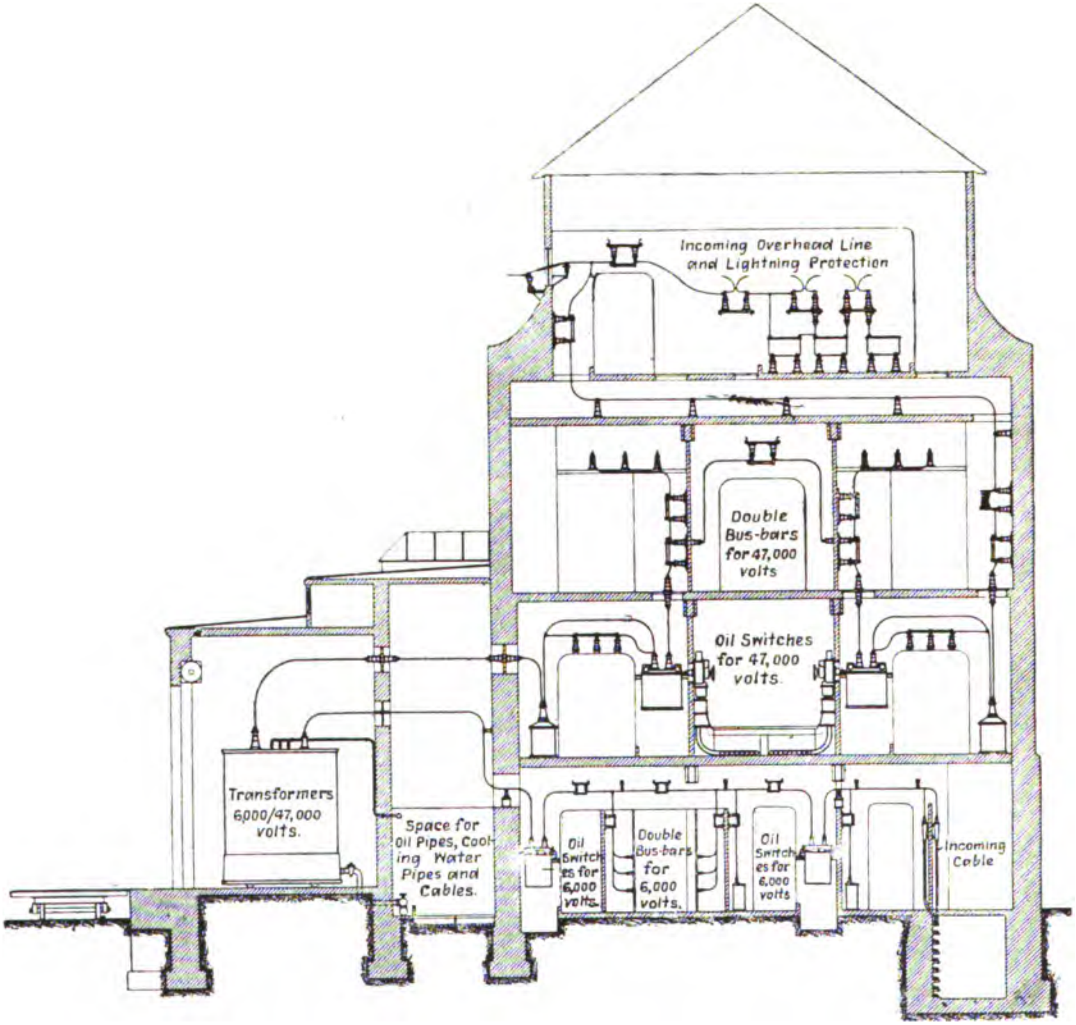

Fig. 29.—Section through the Switch House for the Laufenburg Electricity Works, equipped at the present time for ten sets of 5,000 kw. each, and ten transformers; also two reserve panels each. Generator pressure transformed from 6,000 to 47,000 volts; six outgoing transmission lines for 47,000 volts. All operating panels are situated in the switch house. The cables between the engine room and switch house are laid in an underground trench. The transformers are installed in special chambers attached to the main building; they can be rolled direct on to railway trucks. A passage is left between the transformer chambers and switch house for the oil and cooling pipes, and the cables to the engine room. The oil-handling plant is similarly constructed to that shown in Figs. 31 and 31A.

clean oil. The floor of the transformer chambers is constructed so that oil escaping from leaky flanges, etc., can drain away, and is provided with special pipes connected to the reservoir.

The dirty oil can be used again after having been filtered and boiled. For this purpose it is taken from the reservoir, where it leaves a certain amount of sediment, and is passed through a strainer (0·12 in. mesh), in a chamber outside the reservoir. From here it is pumped to a filter in a room in the transformer house; after leaving the filter it flows to the clean oil tank. A filter capacity of 220 galls. per hour will, as a rule, suffice, and as the loss due to pressure is about 4·3 to 5·7 lbs. per sq. in., a pump taking about 0·5 H.P. will be ample for this purpose. In order to prevent an undesirable rise in oil pressure it is advisable to install a vent pipe about 12 ft. in height, through which at the same time any air in the oil can escape. The clean oil tank is equipped with a heating coil, the heating surface of which in square feet should be about equal to the capacity of the tank in cubic feet. The coil is heated with steam from the boiler house, and the oil should reach a temperature of about 250° F.

In order to keep up the circulation of oil during the drying process the use of a small pump is recommended, designated "the clean oil pump" in the illustration. The velocity of the flow of oil in the pipes should not exceed 1·5 to 2·5 ft. per sec., and the oil must not be pumped back into the transformer tank at a speed exceeding that at which it can flow out through the overflow.

The clean oil is pumped into the transformer tank through an inlet at the bottom. When the oil level reaches the overflow, the oil will run back into the clean oil tank. This arrangement enables the transformer windings to be dried in the transformer tanks. The drying process can, of course, be shortened by passing current through the primary and secondary windings, and thereby heating them electrically.

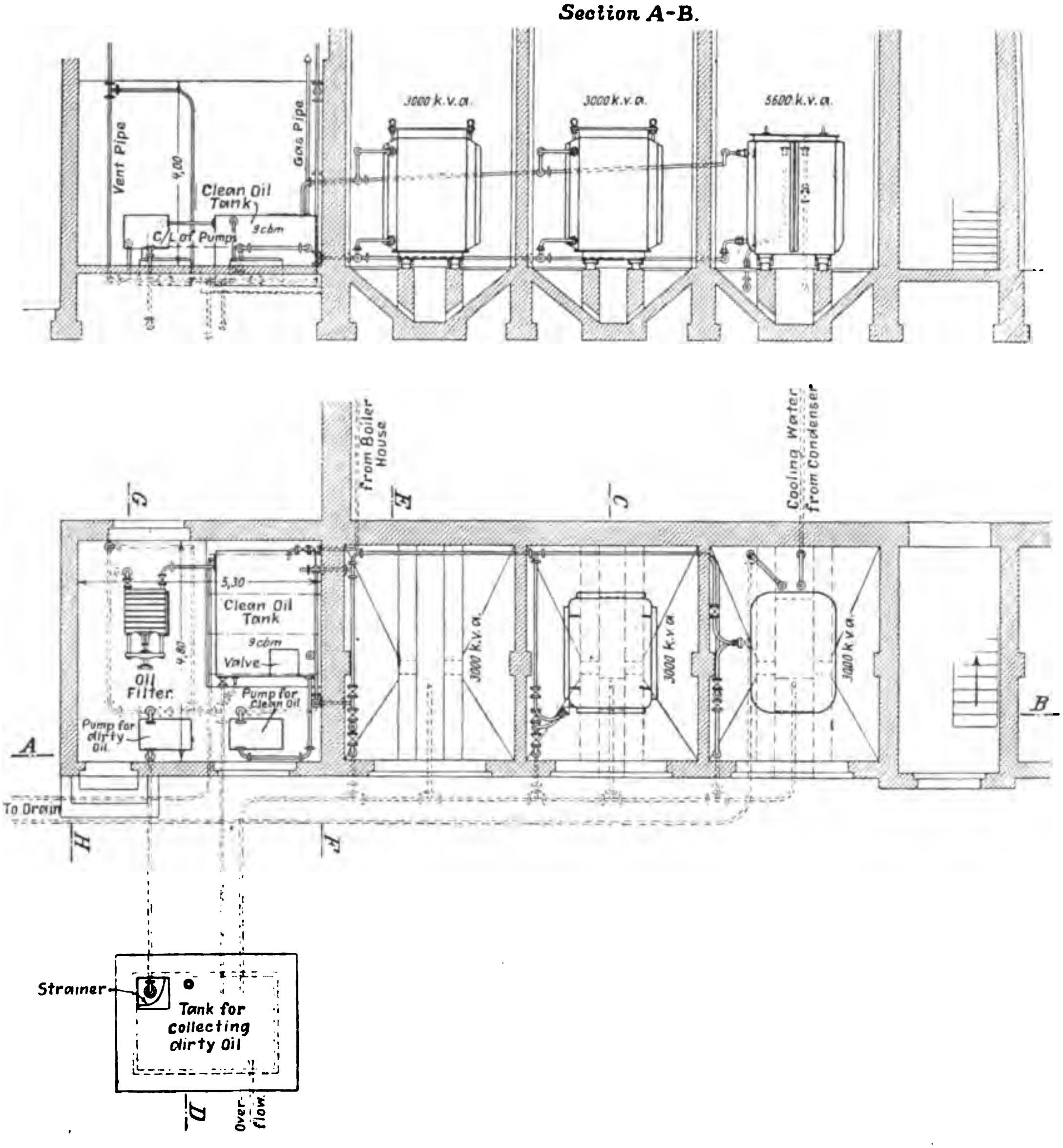

Fig. 31.—Plant for Oil Cleaning in the Switch House of the Breitungen Electricity Works. Plan and Sectional Elevation. (Dimensions in metres.)

f. Arrangement of Control Board and Switch House.

The control board should be situated where it can be conveniently overlooked from one point, and should be suitably connected with the inspection passage for the high-tension gear (Figs. 27A to 32).

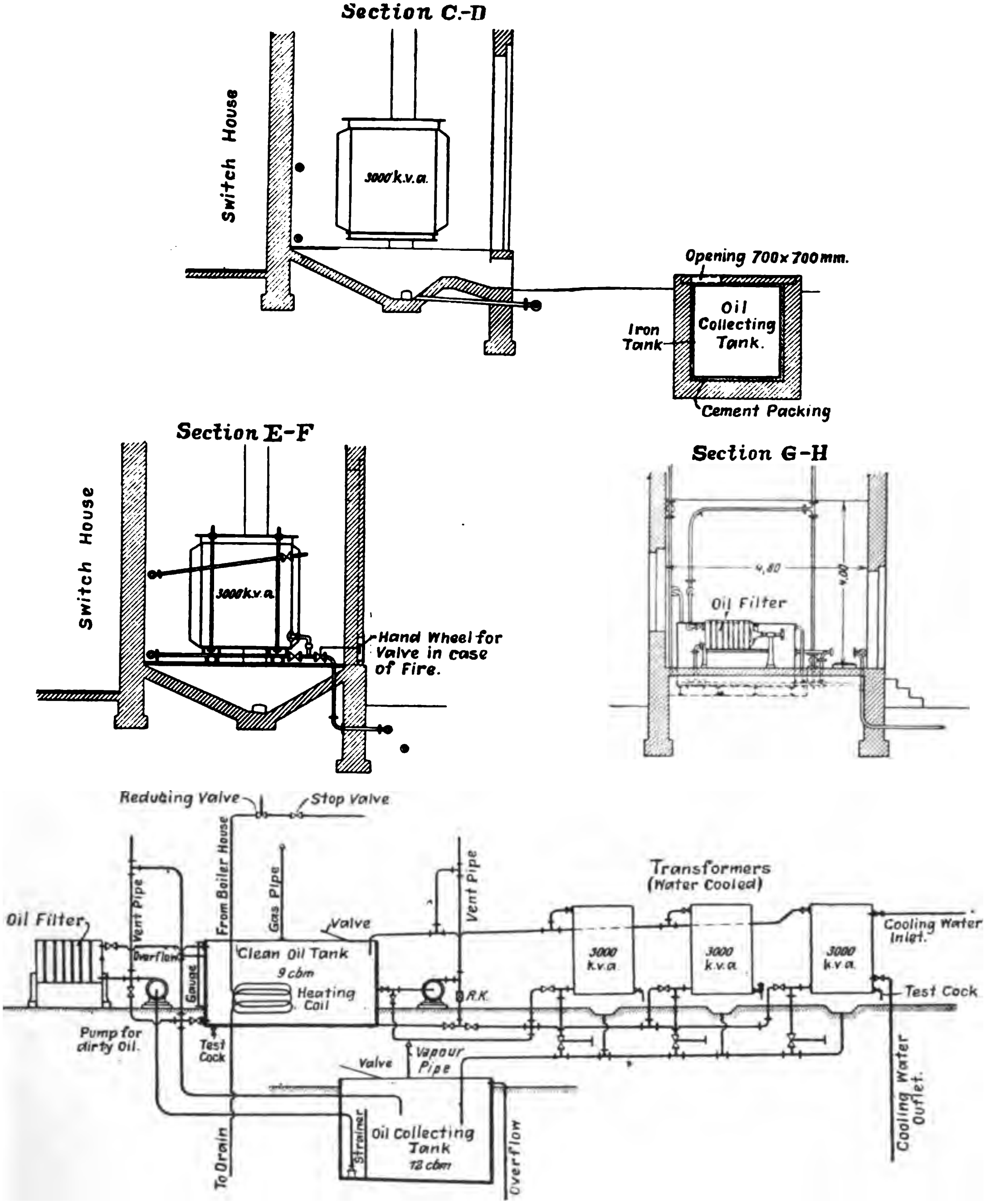

Fig. 31A.—Plant for Oil Cleaning in the Switch House of the Breitungen Electricity Works. Section through transformer chambers and oil cleaning chamber. Lay out of pipework. (Dimensions in metres.)

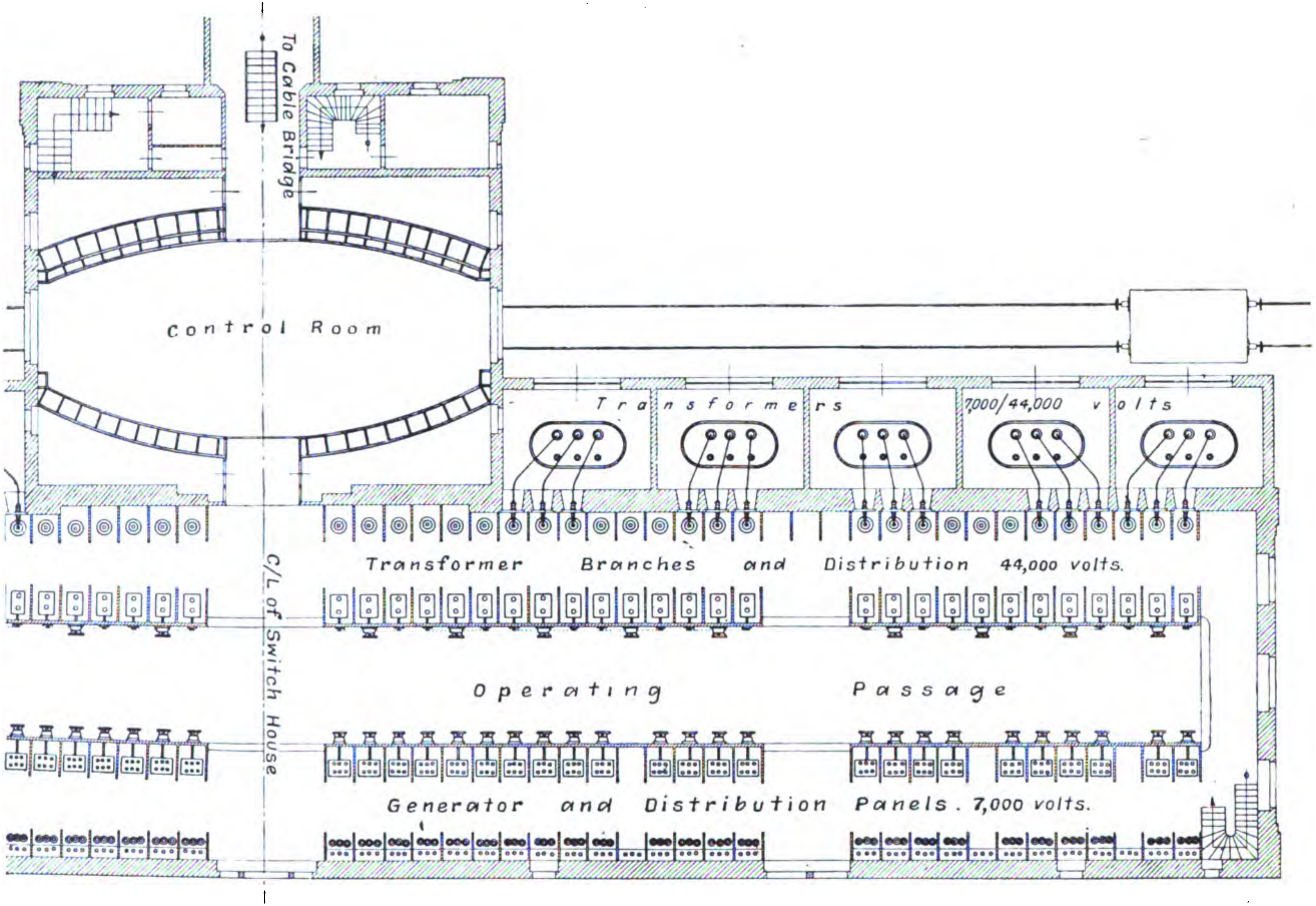

Fig. 32.—Plan of Switch House in the Wyhlen Electricity Works.

If a separate building is erected for the switchgear, it should be connected to the end of a passage leading to the engine room, or should be built into this passage (Figs. 38 to 41, Plates III., IV., V., VI.). In arrangements on the panels, it must be borne in mind that the intimate organic connection of apparatus should be plainly indicated.

The operating leads and those for the measuring instruments should preferably be laid in trenches with removable covers to make them conveniently accessible for inspection purposes (see Fig. 26).

Fig. 33.—Control Board in the Switch House of the Wyhlen Electricity Works. Generator panels on the right, feeder panels on the left. Panels constructed of polished blue marble. Diagrams of connections shown on the panels by strips of polished brass.

Should the switch house immediately adjoin the engine room, or should a separate building be erected?

Only one point can be put forward in favour of erecting the two buildings immediately adjoining one another, namely, that of capital cost, but even this is somewhat doubtful. There are, on the other hand, many decisive reasons to commend a separate building, provided sufficient space is available. The only extra expenditure is that due to one extra outside wall and a connecting bridge. The cost of these is by no means heavy, and can be compensated to a certain extent by savings in other directions. Two further sides of buildings exposed to direct light from outside are obtained, a point of great importance for the engine room basement as well as for the switchgear. Light in basement and at the back of the switchboards is a matter which is frequently overlooked (see Fig. 6). This system further allows the exterior of the building to be designed quite independently of conditions prevailing in the engine room, such as the height of floors, the position of columns, roof construction, etc. In the event of making extensions to the plant at a future date one is not hampered in any way, and can add to existing buildings in any desired direction (see Figs. 38 to 41, Plates III., IV., V., VI.).

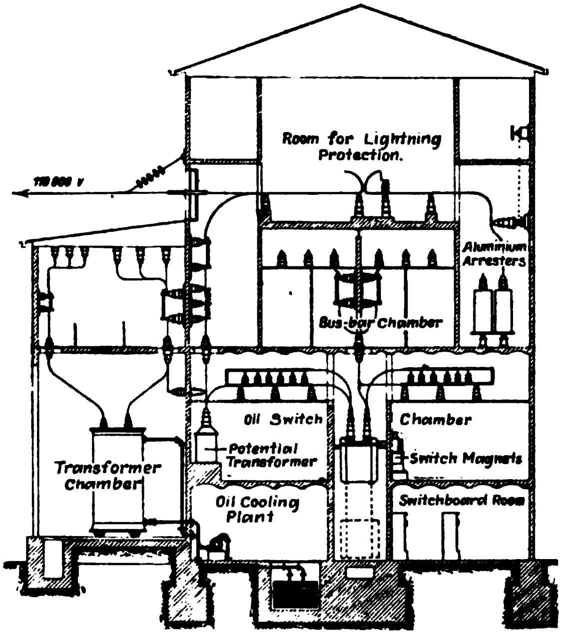

Fig. 34.—Section through the Gröditz Transformer Station of the Lauchhammer Power Transmission Plant. Overhead transmission lines, 110,000 volts. Oil switches with two resistance steps; the resistances for the same are placed above the oil switches on insulators; the oil tanks can be lowered to the floor beneath. Double bus-bars arranged horizontally. Equipped for three transformers, 110,000, 15,000 volts, 3,000 kw. each, and one transformer, 110,000 to 60,000 volts, 7,000 kw.

Why it is still sometimes asserted as untenable that the switchgear must be as close to the engine room as possible it is difficult to understand, because all switchgear, excepting apparatus controlling the generator pressure, forms a part of the network, rather than of the generators (see also Fig. 30, Plate II.).

The argument that the switchboard attendant should be able to see the generating sets can also be dismissed. It is far better for the attendant to be some distance away from the generating plant, so that he is not influenced by the noise in the engine room, and concentrates all his attention on the reading of the instruments. Cases are known where sudden breakdowns of generators confused attendants, with the result of incorrect operations being made at the switchboard.

Communications between the engine room and the switch house are limited entirely to questions of starting and stopping generating sets and to conditions of load.

These simple communications can best be transmitted by means of signalling apparatus; it is therefore better to place the operating switchboard in the switch house also in order to obtain short connections to the other parts of the switchgear.

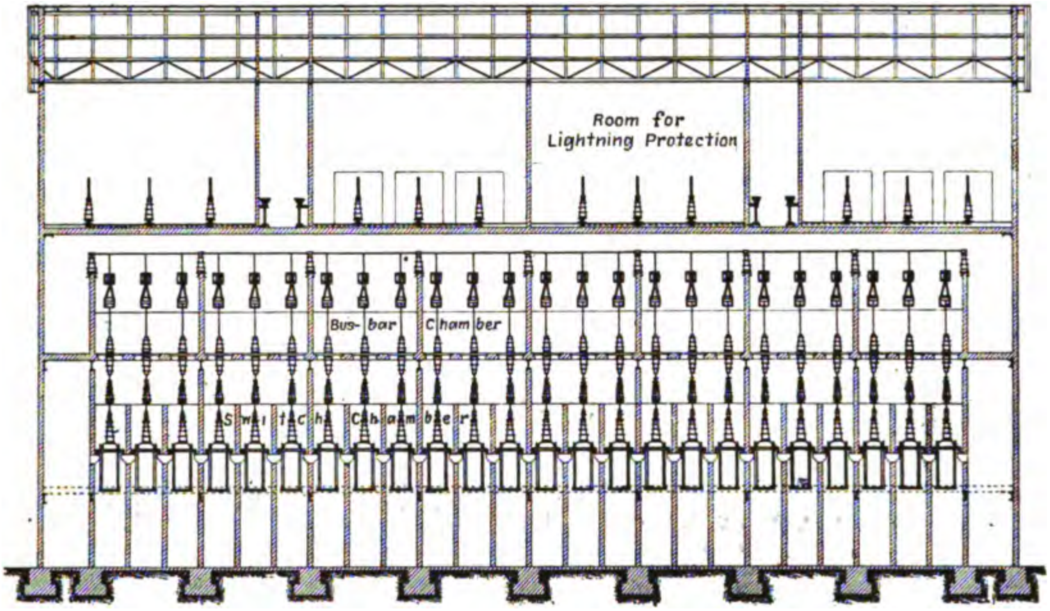

Fig. 35.—Longitudinal Section through Gröditz Transformer Station.

7. POSITION OF POWER STATION.

Generally the station should be situated as nearly in the centre of the supply area as possible, owing to the costs involved by long distance power transmission. Economic considerations of another kind, relating principally to the cost of the land, nature of the ground, the possibility of obtaining coal and water, are often brought to bear

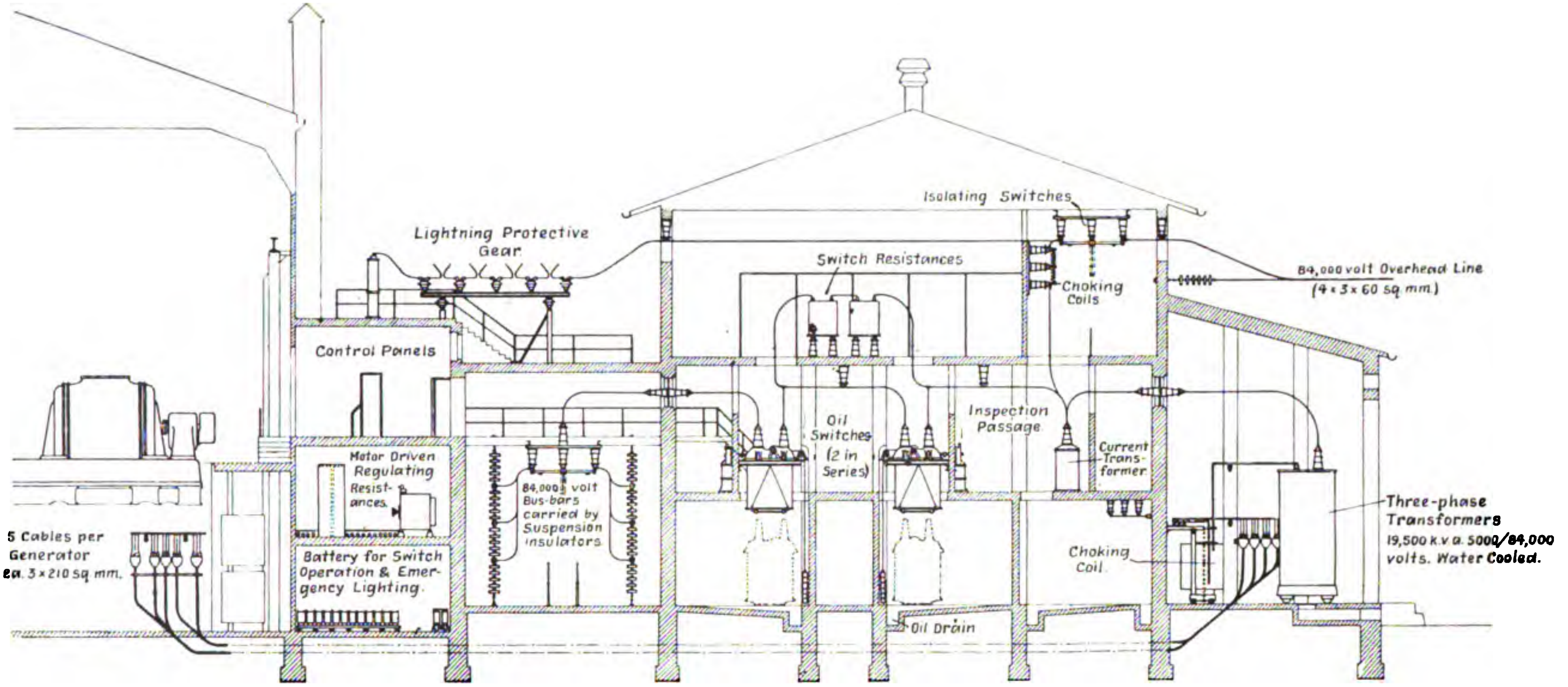

Fig. 36.--Section through the Vereeniging Switch House of the Victoria Falls and Transvaal Power Co., South Africa. Four generators, 18,000 K.V.A. each. Four transformers, 5,000 to 84,000 volts. Two oil switches in series for each field, one of which has a protective resistance for limiting short circuit currents; the oil switches can be lowered complete to the floor beneath. Bus-bars mounted on suspension insulators. Choking coils without iron cores are connected up between transformers and generators. (Dimensions in metres.)

on this question, with the result that a site is selected which is situated at some distance from the centre of the area.

As will be shown later, the electrical transmission of energy over comparatively long distances is found to be cheaper than coal transport by rail, provided the load factor is high.

A power station burning bituminous coal cannot be situated at some distance from the centre of the supply area without adversely affecting overall economy, unless a coal mine or a shipping canal is in the immediate neighbourhood, and coal freight is very low in consequence.

The large quantity of cooling water required (65-90 galls. per kw.-hour) also makes it desirable to select the neighbourhood of a river or lake for the site. Cooling plant can then be dispensed with, which is an important advantage, owing to its heavy first cost and the extra coal consumption involved. Owing to inferior vacuum and greater power taken by air and circulating water pumps the constant losses rise considerably, and may represent 18 per cent. more coal.

Having generally settled on the neighbourhood, the principal factors to be considered are the nature of the ground, ground water level, and the possibility of floods. The area is determined by the probability of extensions, the quantity of coal to be stored, and the space required for the storage of other material.

The most suitable lay-out of the plant, that is to say, the relative position of the boiler house, engine room, and switch house, and the system of coal storage, must be determined separately in each case after giving due consideration to the above-mentioned points.

With respect to the level, it is desirable to aim at a small suction lift of the cooling water pumps without introducing very heavy excavations. Convenient access must be provided to all parts of the building, stairs being avoided wherever possible. A satisfactory arrangement is obtained when the floor of the condenser room is on the same level as that of the boiler house, both being on the ground level.

It is then possible to pass from the centre passage in the boiler house straight into the condenser room, and from the floor of the engine room to the gallery in the boiler house, from which convenient staircases should lead to the floor of the boiler house.

When the boiler house floor is on the ground level, the basement for ash removal is easily connected to the passages under the coal store outside.

The main control boards should be practically on the same level as the engine room floor, whether the switch house joins the engine room or is erected separately (see Figs. 38 to 41, Plates III., IV., V., VI.).

Fig. 37.—Operating Switchboard in the Electricity Works of the Hamburg Elevated Railway.

8. ARCHITECTURE.

The design of the power station buildings in many cases follows wrong ideas altogether, and one seldom sees applied the important maxim that the shape of the building should be subservient to its use.

The fact must not be lost sight of that a power station in reality is nothing more than a factory for producing electricity, and as in the case of other factory buildings, there is no need to disguise its character. Many power station buildings resemble theatres more than anything else, and this is particularly so when the architectural plans are prepared by municipal architects. The beauty of power station buildings, as in the case of machinery, should lie in the simplicity of the design, and in proper proportions. Where special constructional material is employed, such as ironwork in the boiler house, iron roof ties in the engine room, etc., it should not be covered, but allowed to appear at the same time; the outline should be quite simple. A false ceiling in the engine room, for instance, for concealing the roof construction is quite unnecessary. One forgets that an ordinary visitor does not really expect to see more than the room of a factory on entering an engine room, and certainly not a lecture theatre which happens to contain machinery.

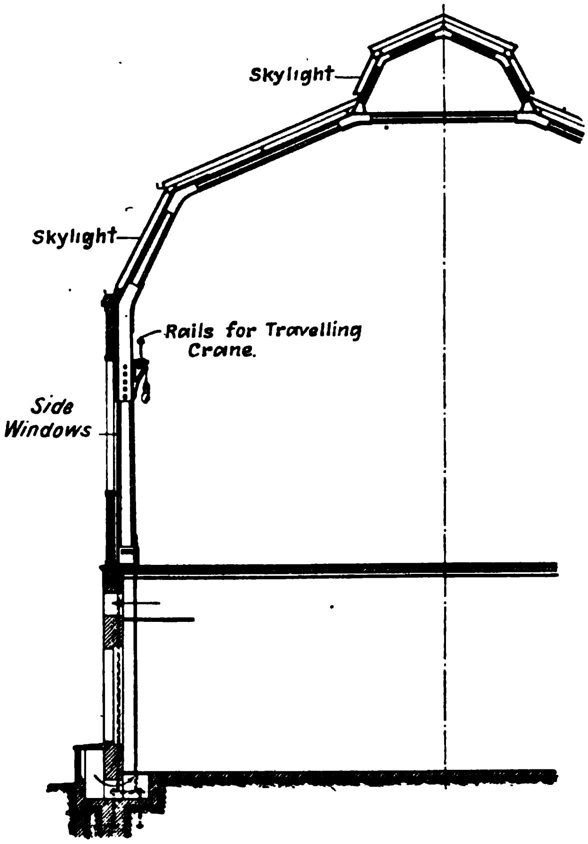

Fig. 42.—Architectural Example: Rigid Frame Construction for Engine Room.

It is none the less possible, after taking all these points into consideration, to find suitable designs even for the ironwork for engineering buildings, which cannot be mistaken for anything else, and yet present a fine if not elegant appearance.

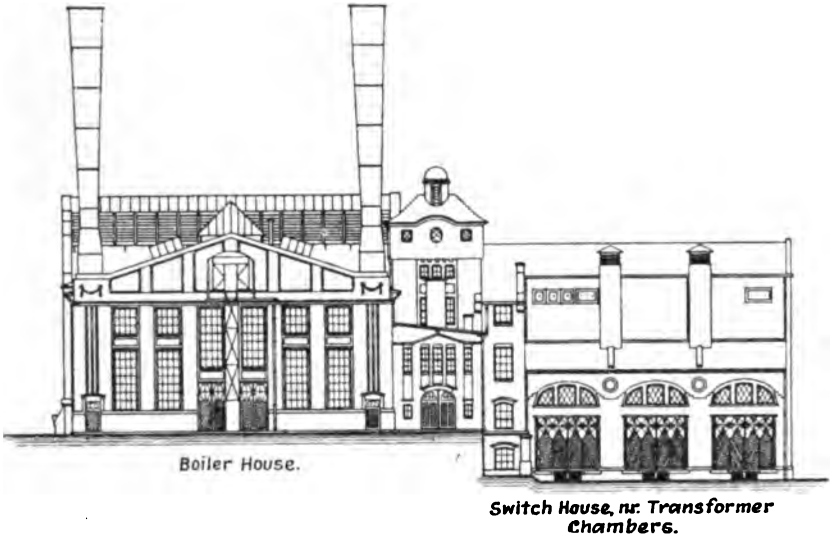

Fig. 43.—Architectural Example—Façade of the Obererzgebirg Electricity Works.
Architect, Dr W. Klingenberg, Berlin.

Fig. 44.—Architectural Example—Obererzgebirg Electricity Works.
Architect, Dr W. Klingenberg, Berlin.

As already mentioned, with a separate house for the switchgear, the lighting conditions and the architectural lay-out of all buildings are considerably improved.

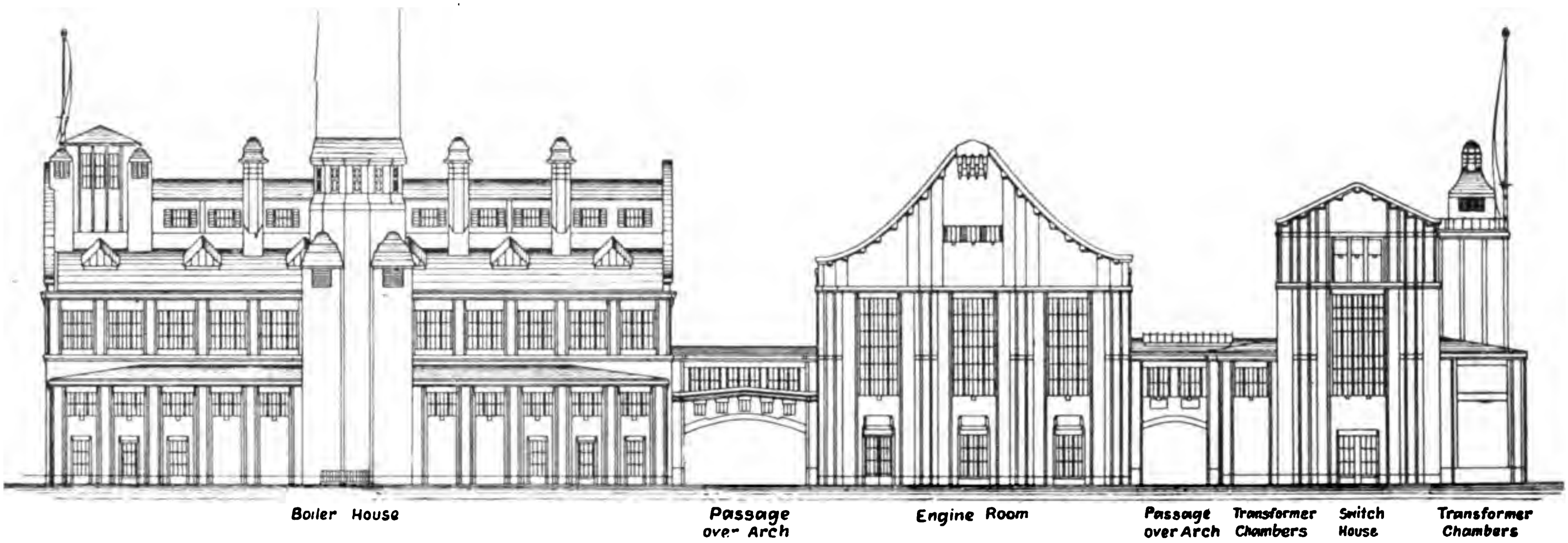

Fig. 45.—Architectural Example—Façade of the Fortuna Electricity Works.

Architect, W. Issel, A.E.G., Berlin.

It is most important that the light in all rooms is ample during daytime. It is impossible to provide too much light; experience has shown that it is much easier to keep the plant clean and in good order, or to detect faults, when it is well lighted. The best

Fig. 46.—Architectural Example—Fortuna Electricity Works.
Architect, W. Issel, A.E.G., Berlin.

direction for the light to come from in the boiler house and the engine room is through a skylight, as it does away with all shadows. In the boiler house a skylight can be adopted throughout when there are no coal bunkers. In the engine room the rigid frame construction is a very effective design from an architectural point of view, and offers the best possibilities for obtaining light from above (see Fig. 42).

As already mentioned, with a separate house for the switchgear, the lighting conditions and the architectural lay-out of all buildings are considerably improved.

In designing the façades, all superfluous cornices, horizontal projections, etc., should be avoided, as they rapidly become soiled by the soot and ash which settles on them, with the result of a very unattractive appearance. Simple vertical lines and pillars, which are necessary for constructional reasons, will indicate the nature of the building, and the fact that it houses powerful machinery (Architectural Examples, Figs. 43 to 48).

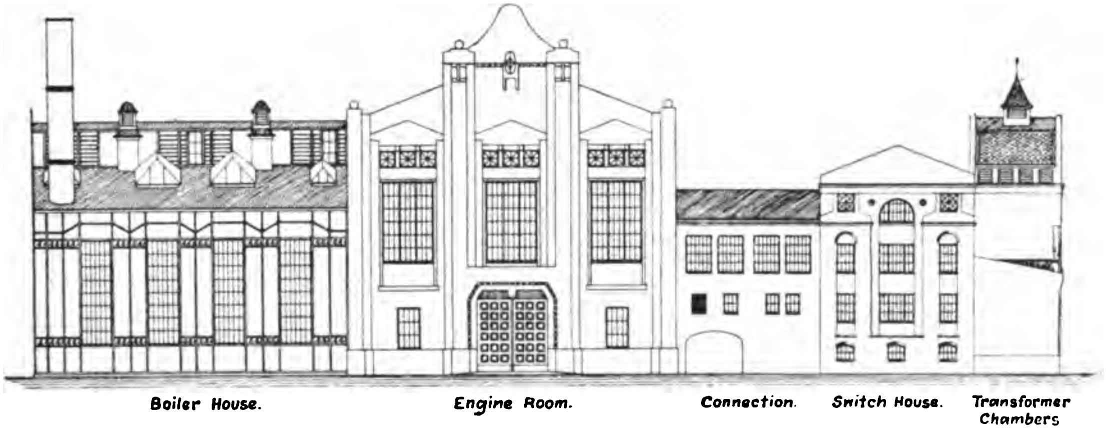

Fig. 47.—Architectural Example—Façade of the Hattingen Electricity Works. *Architect*, Dr W. Klingenberg, Berlin.

The interior finish of all rooms should be on similar principles. It is desirable to paint the walls a light colour, in order to increase the reflection of the light; all decorative painting, outlining, etc., should be avoided, as it is out of place in a factory. Distinctive colours should only be employed where different constructional material is used; thus, for example, the ironwork and wood panelling should be painted a different colour to the walls.

The walls of the engine room, the switch house, control rooms and condenser basements should be lined with plain coloured glazed tiles to the height of 9 or 10 ft., and the walls of the condenser room and other small rooms, where natural light is scarce, should also be painted white.

Fig. 48.—Architectural Example—Hirschfelde Electricity Works.

For the floor of the engine room it is advisable to use tiles which, contrary to those lining the walls, should have a pattern, as oil stains show up too conspicuously on plain tiles. Tiles of a somewhat light colour should be selected for this purpose—light grey for example—slightly different shades being used, but the contrast in shades should not be very great.

Sometimes the sets are surrounded by a special pattern. This should not be done, because it spoils the appearance of the engine room.

9. SUMMARY, ENERGY DIAGRAM.

The foregoing suggestions for different parts of a power station may be combined into a comprehensive whole, from which an important general principle evolves. A survey of the process of power production from coal, as outline, shows how the transport and conversion of energy moves along a straight line; all auxiliary processes branch off from this line at right angles. The idea underlying all suggestions for improvements in that straight line of conversion, as well as the branches for auxiliary processes, should be shortened as much as possible (see Diagram, Fig. 49).

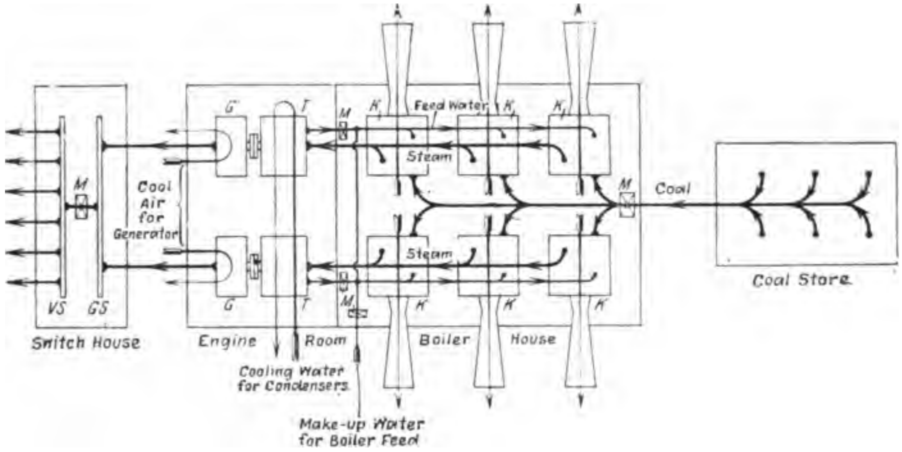

Fig. 49.—Diagrammatic Scheme for a Power Station.

K = Boiler. T = Turbine. G = Generator. GS = Generator Bus-bars. VS = Distributing Bus-bars. M = Consumption Meter.

Starting from various points in the storage yard, the energy in the form of coal runs in a straight line along the axis of the boiler house, and is distributed amongst the various boilers, where the first conversion into steam energy is accomplished. It now runs on in the same direction from the boilers to the turbines, where it is changed into mechanical energy, and then passes to the generators in which the conversion into electrical energy takes place. Continuing in the same direction, it comes to the generator bus-bars in the switch house, and finally enters the feeder cables.

The auxiliary processes take place at right angles to this direction, each branch being made as short as possible. These processes include: leading the air for combustion to the boilers (this air being drawn from the boiler house), and the rapid distribution of the waste gas from above through separate vertical chimneys, leading the exhaust steam downwards through the condenser at right angles to the main direction, admission and discharge of the cooling water through channels vertical to the main direction, admission and discharge of the cooling air for the generators vertically downwards, and the shortest possible connection with the outer wall of the engine room. The only exception is found in the course of the feed water, which must flow backwards, as one is obliged to use the condensed steam.

CHAPTER II.

COMPARISON OF COSTS FOR ELECTRICAL TRANSMISSION OF ENERGY AND TRANSPORT OF COAL (BITUMINOUS COAL AND BROWN COAL).

It is very likely that most power stations would not have been erected on the sites on which they are to be found now had it been possible to foresee future developments, and to have due regard to conditions that affect the position of a power station. It seems, therefore, desirable to enter into discussion of the principle which should determine any decision as to the position of a power station.

The whole question has increased in importance since, in many cases, the area of supply is very extensive, necessitating the transmission over long distances. In this connection it is interesting to ascertain how the cost of the transport of coal by mechanical means (railways or waterways) compares with electrical transmission, and also what influence the load factor exercises on the generating costs.

Although the following calculations deal with the subject in general only, they possess a certain amount of direct value when it is desired to investigate the influence of certain conditions, and they can in this case easily be applied to conditions met with in actual practice.

Two kinds of power stations must be considered, one situated in the centre of the area of supply and the other situated at a distance therefrom, necessitating long distance transmission of energy. Comparing the two power stations, it will be seen that in the latter case we get:—

1. An increase in indirect expenditure, in consequence of a larger capital expenditure due to:—

   (*a*) The cost of the transmission line.

(*b*) The cost of a transformer station and, in the case of long distances, an intermediate station.

(*c*) The cost of a larger power station, of a capacity to meet the maximum losses that occur in the transmission line.

2. An increase in the direct working expenses owing to :—

(*d*) The cost of transmission lines losses (copper or corona losses).

(*e*) The cost of transformer losses in the additional transformer substation required.

(*f*) The cost of repairs and inspection of transformer lines and transformer substation, etc.

The greater expenditure outlined above was taken into consideration in the following manner :—

1. The extra indirect expenditure is calculated at the rate of 10 per cent. of the extra capital expenditure to cover expenses, renewals and depreciation (due regard was given to the value of conductors).

(*a*) Cost of transmission line. This was estimated in each case per mile and is based on the principal standard cross sections and pressures.

Each line of masts is assumed to have two sets of wires and the cross sections are sufficient to carry the energy required over one set of wires in an emergency. The prices per mile are given in the following table :—

PRICE OF ONE MILE WITH DOUBLE SET OF WIRES.

		£	$
		(Approximately.)	
60,000 volts.—	2 × 3 × 0·0542 sq. in.	880	(4,224)
	2 × 3 × 0·0775 „	1,020	(4,896)
	2 × 3 × 0·108 „	1,180	(5,664)
80,000 volts.—	2 × 3 × 0·0542 „	920	(4,416)
	2 × 3 × 0·0775 „	1,088	(5,222)
	2 × 3 × 0·108 „	1,256	(6,029)
100-110,000 volts.—	2 × 3 × 0·0775 „	1,127	(5,410)
	2 × 3 × 0·108 „	1,288	(6,182)
125-150,000 volts.—	2 × 3 × 0·108 „	1,320	(6,336)
	2 × 3 × 0·1472 „	1,624	(7,795)
	2 × 3 × 0·1866 „	1,872	(8,986)
	2 × 3 × 0·2325 „	2,120	(10,176)

As it is impossible to transmit a very large amount of energy along a single row of masts, the calculations were not extended beyond 50,000 kw.

(*b*) The costs of transformer substations are approximately as follows:—

Output of Stations.	10,000 kw.	20,000 kw.	50,000 kw.
	£ $	£ $	£ $
At 60,000 volts -	6,750 (32,400)	13,000 (62,400)	31,000 (148,800)
„ 80,000 „ -	7,750 (37,400)	14,500 (69,600)	35,000 (168,000)
„ 100,000 „ -	8,500 (40,800)	15,500 (74,400)	38,000 (182,400)
„ 125,000 „ -	9,000 (43,200)	16,500 (79,400)	40,000 (192,000)

Intermediate substations were estimated at £2,000 to £3,500 ($9,600 to $16,800) according to pressure and energy passing through the substation. It was assumed that intermediate substations would be required as follows:—

In 30 miles length of transmission line, no intermediate substations.
„ 60 „ „ „ 2 „ „
„ 125 „ „ „ 4 „ „

(*c*) The increase in power station capacity was estimated as follows:—

	£. s. d.	$
For 10,000 kw. - - -	9 15 0 per kw.	(46·80 per kw.)
„ 20,000 „ - - -	9 10 0 „	(45·60 „)
„ 50,000 „ - - -	9 0 0 „	(43·20 „)

2. Increase in direct working expenses.

(*d*) The cost of transmission line losses was taken at 0·177d. (0·354 cent) per kw.-hour for bituminous coal power stations, and 0·088d. (0·176 cent) per kw.-hour for brown coal power stations.

The following are the values taken for copper losses at different working periods:—

8 per cent. of the full load losses at 1,000 hours.
22 „ „ „ „ 2,500 „
55 „ „ „ „ 5,000 „
100 „ „ „ „ 8,000 „

The value of the corona losses was estimated at 0·3 kw. (at 6,000 volts and 70 sq. mm., or 0·108 sq. in.) up to 1·0 kw. (at 125,000 and 70 sq. mm., or 0·108 sq. in.), according to the pressure and the size of conductor, and for an annual period of 8,760 hours.

(*e*) The cost of transformer losses is also calculated at the rate of 0·177d. and 0·88d. (0·354 cent and 0·176 cent) per kw.-hour respectively. The no-load and copper losses were taken at 0·6 per cent. each of the full load capacity. The latter depends on the time value in the same way as the conductors.

(*f*) The costs for repairs and inspections were taken at a rate of 1·5 per cent. of the extra capital expenditure, because, in the case of transmission lines, there is no relation between this expenditure and the time value.

The above figures give the basis on which were calculated the transmission costs per annum for 10,000, 20,000, and 50,000 kw. at 80 per cent. power factor over distances of 30, 60, and 125 miles, with a utilisation of 1,000, 2,500, 5,000, and 8,000 hours. The following is an example based on 125,000 volts, 50,000 kw., 125 miles, 2,500 hours.

PRESSURE AND SECTION OF CONDUCTORS, 125,000 volts, 2 × 3 × 70 sq. mm. (0·108 sq. in.).

Price per mile	**£1,300 ($6,240)**
Maximum loss in line (12·5 per cent.)	**6,250 kw.**
Corona losses (1·6 kw. per mile)	**200 ,,**
Maximum total losses	**6,450 kw.**

CAPITAL EXPENDITURE.

	£	$
125 miles of transmission line at £1,300 per mile	**162,500**	**(780,000)**
6,450 kw. power station capacity at approx. £9 per kw.	**58,050**	**(278,400)**
Transformer station for 50,000 kw.	**39,200**	**(188,200)**
Four intermediate substations	**13,250**	**(63,800)**
Total extra capital expenditure	**273,000**	**(1,310,400)**

EXPENSES.

1. Cost for losses:—

Transformer no-load losses	1·9 mill. kw.-hours.
Transformer copper losses	0·5 ,, ,,
Corona losses: approx.	1·8 ,, ,,
Copper losses in line	11·0 ,, ,,
	15·20 mill. kw.-hours.

	£	$
At the rate of 0·177d. per kw.-hour (0·357 cent) (bituminous coal) - - - - -	11,200	(53,800)
2. Interest on capital, 10 per cent. on £273,000 -	27,300	(131,040)
3. Repairs and supervision, 1·5 per cent. on £27,300 -	4,100	(19,660)
Total expenses for the transmission line -	42,600	(204,500)

with 50,000 × 2,500 = 125 million kw.-hours supplied at the end of the overhead line, *i.e.*, 0·082d. (0·164 cent) per kw.-hour.

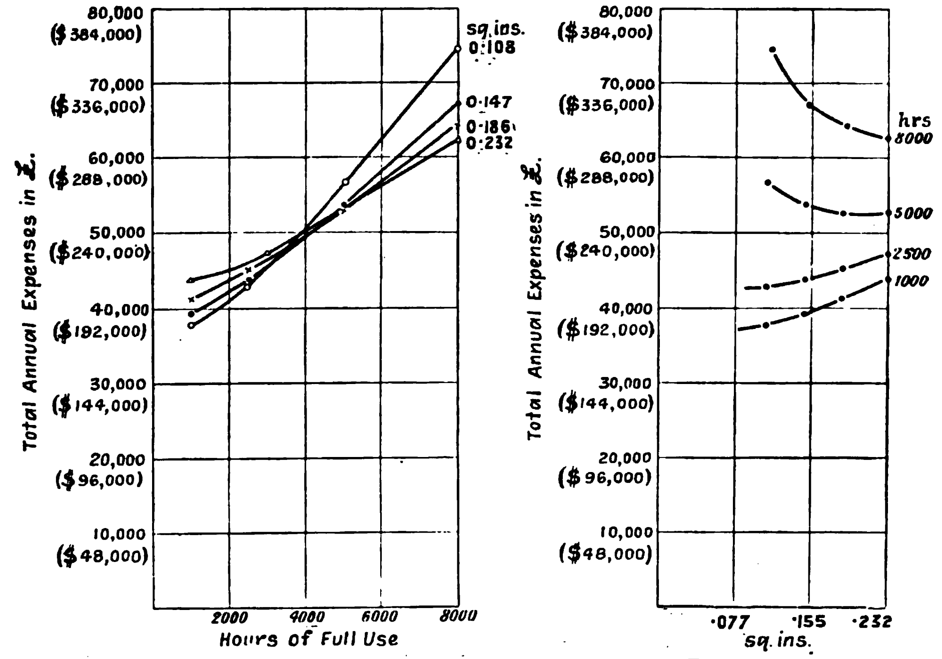

Fig. 50. Fig. 51.

Figs. 50 and 51.—Annual Expenditure in relation to Hours of full use and Size of Conductors for transmitting 50,000 kw. over a distance of 125 miles. (Power Station burning Bituminous Coal.)

There are certain conditions for all energies and distances that give the most favourable results, from an economical point of view, and these conditions were determined in the manner shown in Figs. 50 and 51, which refer to the transmission of 50,000 kw. over a distance of 125 miles.

The total annual expenditure for a power station burning bituminous coal is shown in Fig. 52, and that for brown coal power stations in Fig. 53. In each case the results are given for various outputs and distances, and refer to the hours of full use.

The most economical transmission line pressures and sizes of wires are marked in the curves by the letters *a* to *h*.

Figs. 54 and 55 show the cost of transmission per kw.-hour supplied at the end of the overhead lines, and in relation to the powerful influence the hours of full use have on the economy of an installation.

In order to obtain a comparison of the costs of coal transport, the transmission costs were referred to the cost per ton of bituminous coal and brown coal consumed in a power station of a similar capacity, and with the same hours of full use, but situated within the area of supply. The results are given in Fig. 56 for bituminous coal, and in Fig. 57 for brown coal.

The coal consumption of this power station was assumed to be as follows :—

	Power Station Burning Bituminous Coal.	Power Station Burning Brown Coal.
1,000 hours of full use - -	3·08 lbs. per kw.-hr.	9·9 lbs. per kw.-hr.
2,500 " " - -	2·53 " "	8·16 " "
5,000 " " - -	2·2 " "	7·05 " "
8,000 " " - -	1·98 " "	6·39 " "

With an output of 50,000 kw. to be transmitted 125 miles during 2,500 hours of full use, the total expenses involved by the transmission line would, according to the above, amount to £42,580 ($204,534) per annum for bituminous coal.

A power station situated within the supply area and giving the same output of $50,000 \times 2,500 = 125$ million kw.-hours, would consume : $125,000,000 \times 0{\cdot}00115 = 144,000$ tons of coal.

The long distance transmission costs based upon a ton of coal will therefore amount to

$$£42,580 \div 144,000 = \text{about 6s. per ton.}$$
$$\$204,384 \div 144,000 = \text{about \$1·42 per ton.}$$

If under similar conditions the freight of coal delivered at a power station in the area of supply, including loading and unloading, is less than six shillings per ton, then it would be cheaper to transport the coal to the power station than to transmit electrical energy.

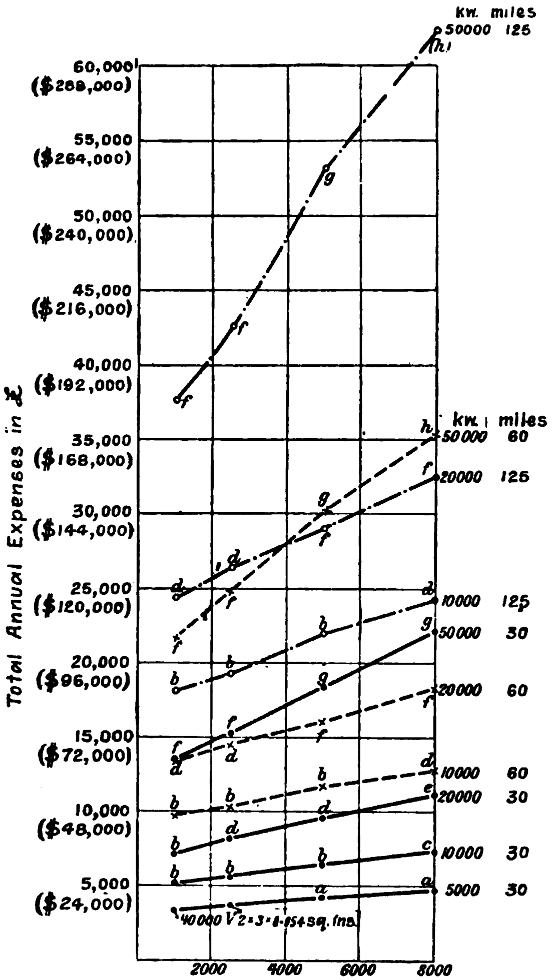

Fig. 52.—Annual Total Costs for Power Transmission. (Bituminous Coal Power Station.)

a = 60,000 volts 2 × 3 × 0·0542 sq. in. (35 sq. mm.)
b = 80,000 „ 2 × 3 × 0·0542 „ (35 „)
c = 80,000 „ 2 × 3 × 0·0775 „ (50 „)
d = 100,000 „ 2 × 3 × 0·0775 „ (50 „)
e = 100,000 „ 2 × 3 × 0·1085 „ (70 „)
f = 125,000 „ 2 × 3 × 0·1085 „ (70 „)
g = 125,000 „ 2 × 3 × 0·1866 „ (120 „)
h = 125,000 „ 2 × 3 × 0·2325 „ (150 „)

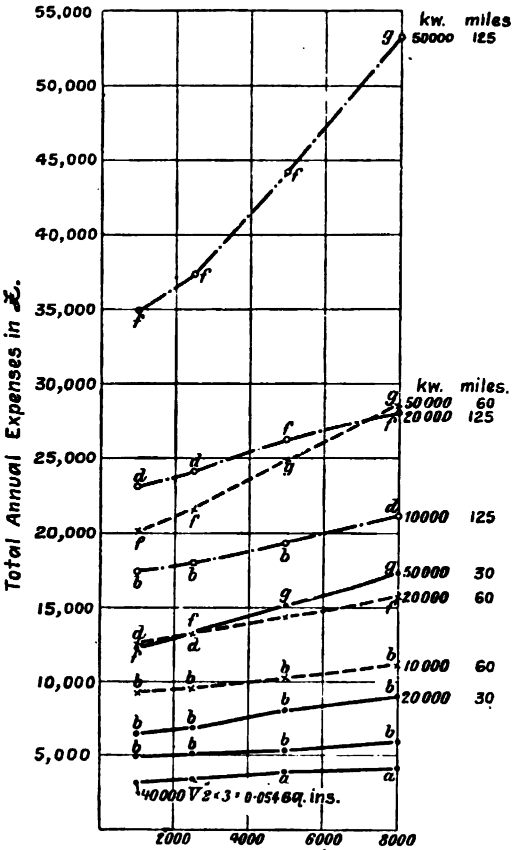

Fig. 53.—Annual Total Costs for Power Transmission. (Brown Coal Power Station.)

a = 60,000 volts 2 × 3 × 0·0542 sq. in. (35 sq. mm.)
b = 80,000 „ 2 × 3 × 0·0542 „ (35 „)
c = 80,000 „ 2 × 3 × 0·0775 „ (50 „)
d = 100,000 „ 2 × 3 × 0·0775 „ (50 „)
e = 100,000 „ 2 × 3 × 0·1085 „ (70 „)
f = 125,000 „ 2 × 3 × 0·1085 „ (70 „)
g = 125,000 „ 2 × 3 × 0·1085 „ (120 „)
h = 125,000 „ 2 × 3 × 0·2325 „ (150 „)

Figs. 56 and 57 will be found convenient for comparing the economy of the two methods of dealing with this problem.

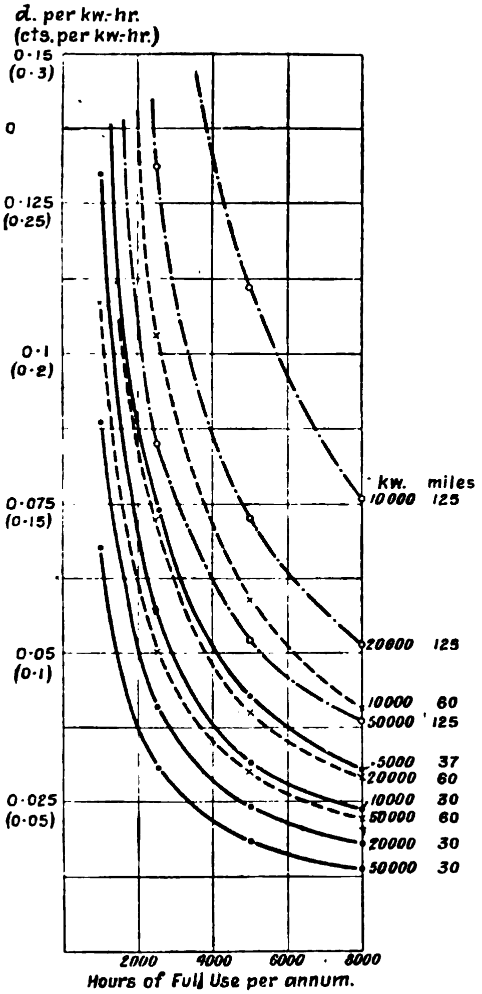

Fig. 54.—Costs for Power Transmission in Pence per kw.-hour (Bituminous Coal Station).

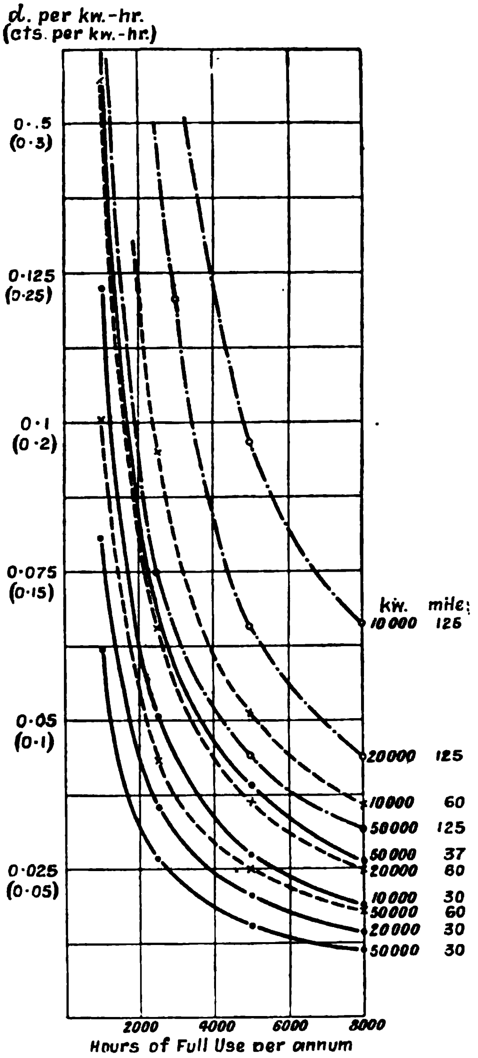

Fig. 55.—Costs for Power Transmission in Pence per kw.-hour (Brown Coal Power Station).

It is difficult to arrive at any general conclusion with regard to the advantages of one or the other method in the case of bituminous coal as will be shown from the curves, Fig. 56, which also include the bare freight costs for railway transport only (indicated by the letter

F). It is evident that in many cases such costs as those for loading, discharging, and for carrying the coal from the railway station to the power station will alone be able to turn the balance in economy from one method to the other.

Long distance transmission of electrical energy will, as a rule, be more economical, however, than the transport of coal by railway where one has to deal with large outputs and more than 2,500 hours of full use.

When the fuel consists of brown coal (Fig. 57) the transmission of electrical energy will, almost without exception, be cheaper than railway transport of fuel; even low water freight of brown coal will in many instances not be able to compete with electric transmission.

With the curves in Fig. 57 one can easily determine the economic operating radius of a brown coal power station when the prices of brown coal and bituminous coal are known.

In Fig. 58 the costs of long distance transmission per kw.-hour (bituminous coal) are given in relation to distance, and in Fig. 59 in relation to the output to be transmitted.

From the latter curves it may be seen that at higher outputs than 50,000 kw. and normal hours of full use one cannot expect an appreciable reduction in the cost of electric transmission, apart from the fact that such large outputs cannot very well be transmitted on a single row of masts.

Fig. 58 shows that for distances exceeding 125 miles the transmission costs increase practically in proportion to the distance.

From a numerical comparison of the transport of coal and electricity based on the foregoing, one cannot justify the erection of very large three-phase power stations unless brown coal, waste heat, or some other very cheap fuel is available. One must also remember when making these comparisons that railways as a rule run along a straighter line than electric transmission lines. The latter can reach their destination, but by a roundabout route on account of difficulties in obtaining wayleaves and overcoming other obstacles.

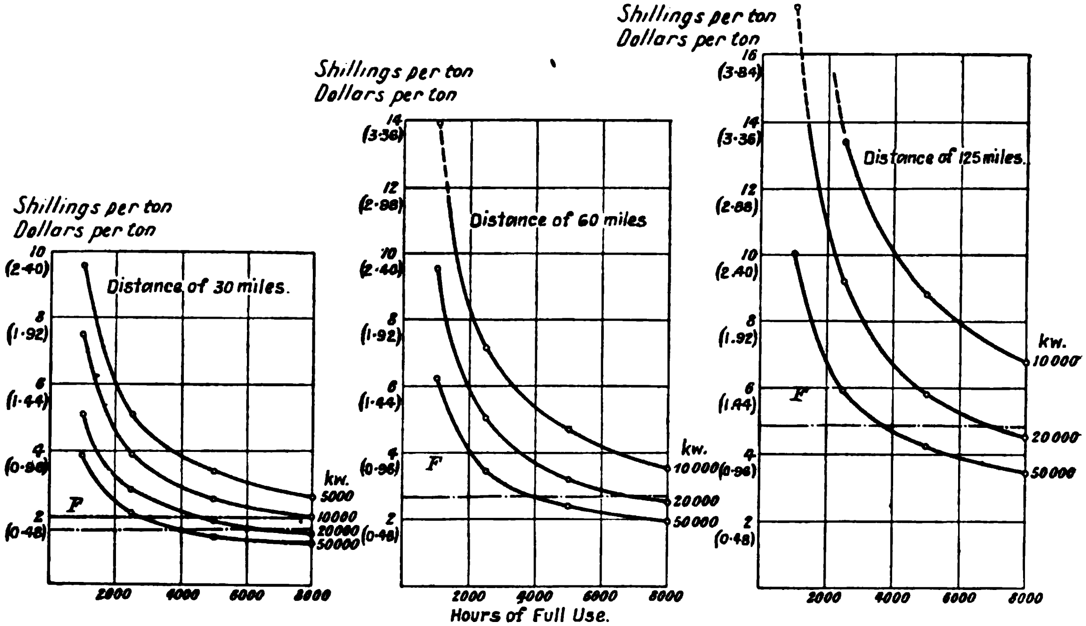

Fig. 56.—Cost of Transmission of Power in Bituminous Coal, Power Station.

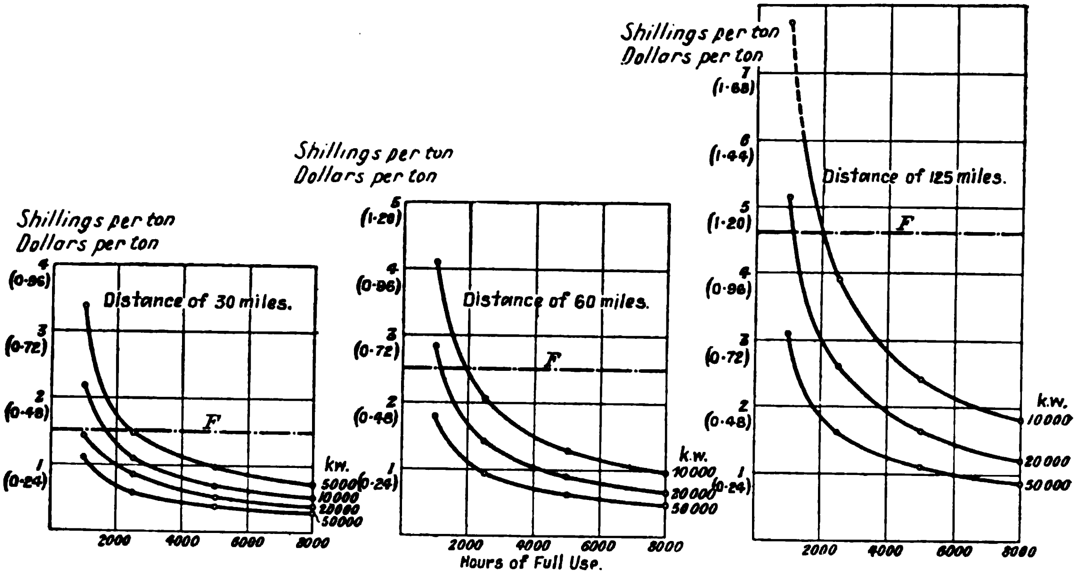

Fig. 57.—Cost of Transmission of Power in Brown Coal, Power Station.

Another point of importance, where railways are State owned, is that coal transport forms a considerable source of revenue to the

State, whereas with electric transmission the calculations are based on the bare prime cost apart from a small interest on the capital to be invested.

Finally, the fact must be taken into consideration that in railway transport certain existing conditions can be relied upon from the beginning; further, that electric conductors are not utilised at first to the extent assumed when making estimates. During the period of development the calculated results will therefore be unfavourable to electric transmission in this respect.

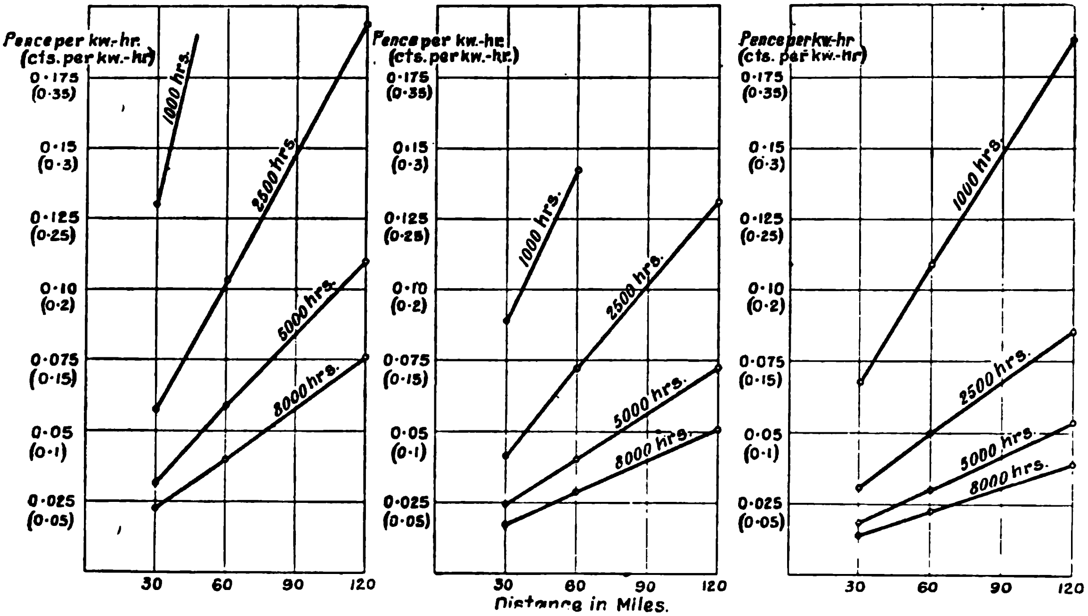

Fig. 58.—Cost of Transmission of Power in Bituminous Coal, Power Station.

Taking all these facts into consideration, one can say that the cost of transport will be the same for both forms of energy under normal conditions; the superiority of electric transmission only becomes apparent with a very high load factor. It must, however, not be deduced from the foregoing, that the erection of large three-phase power stations is not justified in itself; the advantages are to be found in other directions, as will be shown later on.

Before proceeding, however, we will again refer to the above calculations. When considerable parts of the energy are tapped off the main transmission line at intermediate points, the figures are subject to a modification in favour of centralisation, as the conditions of load along the line will then become improved; at the same time it must be borne in mind that one cannot tap off any small amount of energy from a transmission line. The high cost of the transforming stations makes it essential to distribute large amounts of energy at intermediate points. On the other hand, an area of consumption situated along the line may necessitate a deviation of the main transmission line.

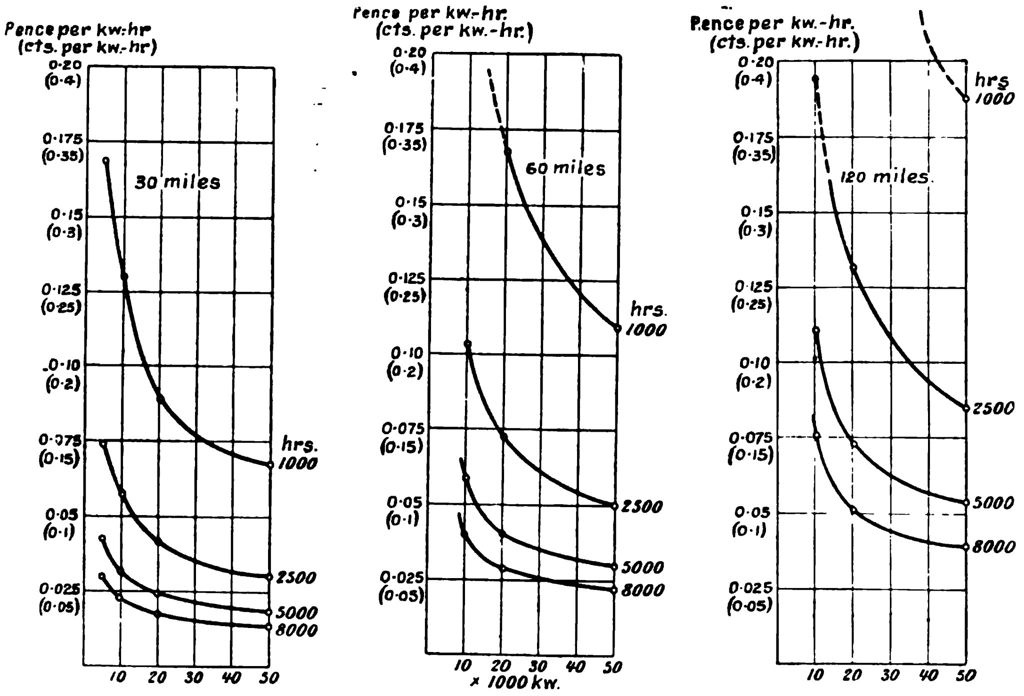

Fig. 59.—Cost of Transmission of Power in Bituminous Coal, Power Station.

The example chosen would, of course, not apply to a very extensive area along the line that may have to be opened up; a problem of this kind would perhaps be solved best by running a single set of conductors as a ring transmission main, which affords reasonable possibilities for continuity of supply.

CHAPTER III.

ECONOMY AND GENERATING COSTS IN RELATION TO CAPACITY AND UTILITY FACTOR.

1. BASIS OF CALCULATIONS.

A comparison of the transport costs of energy is seldom the only point of view to be considered when dealing with entire schemes for the supply of large areas. One must, at the same time, draw a parallel between the provision of a single station and a large number of local stations of medium size. When viewed from this aspect, such appreciable differences will be found to exist, that there can be no doubt of the great advantage of centralisation in large works.

According to present-day experience the capital expenditure on power stations may be taken to be roughly as follows:—

Medium size stations, £15 ($72) per kw. installed.

Large stations with an installed capacity of 10,000 kw. upwards, £10 ($48) per kw.

Very large stations with units of 15,000 to 20,000 kw., £7 to £7. 10s. ($34 to $36) per kw.

What also is in favour of centralisation, and reduces the generating costs of a large station below those of a number of smaller ones, is the fact that each of the local stations must be equipped for the local maximum, while a single large station need only provide for the sum of all local maxima multiplied by the diversity factor, that is to say, not more than 60 to 80 per cent. of this sum.

Several small stations must also have a larger total of spare plant than one large station. Even in power stations of medium size the distribution costs are frequently greater than the generating costs.

A comparison can be obtained from the following figures:—

POWER STATION.

A.	Units of generating plant	20,000 kw.
	„ „ boiler plant	7 for each generating set.
B.	„ „ generating plant	5,000 kw.
	„ „ boiler plant	4 for each generating set.
C.	„ „ generating plant	1,000 kw.
	„ „ boiler plant	1 for each generating set.

The following are the values to be taken into consideration in each case :—

1. Total heat consumption (W_t) in relation to the momentary load factor of machines in commission, expressed in B.Th.U. per kw.-hour.

$$W_t \frac{a_w}{m} + b_w. \qquad (1)$$

Where m = Momentary load factor

$= \frac{\text{Momentary load on the sets}}{\text{Most favourable } (=\text{full}) \text{ load}}.$

a_w = Heat consumed by boilers, with generating sets running light, in B.Th.U.'s per hour and per kw. of the total output of the sets in commission.

b_w = Additional heat consumed by boilers in B.Th.U.'s per hour and per kw. of energy supplied.

2. Average annual heat consumption (W_m) in relation to the average utility factor of the station (B.Th.U. per kw.-hour).

Where $s_1 s_2$ = Number of running hours per annum of generating sets,
$L_1 L_2$ = Full load of generating sets in kw.,
z = Number of generating sets,
n = Utility factor of station as a decimal,
= Average annual output,
a_w and b_w = As under I.

Equations for the total annual heat consumption of the station :—

$$n \times 8760 \times \Sigma \times L \times W_m = \Sigma (s \times L) \times a_w + n \times 8760 \times b_w \times \Sigma L.$$

$$W_m = \frac{1}{n} \times \frac{\Sigma (s \times L)}{8760 \times \Sigma L} \times a_w + b_w \text{ in B.Th.U. per kw.-hour.} \qquad (2)$$

When all generating sets are of the same size, then :—

$$W_m = \frac{1}{n} \times \frac{\Sigma (s)}{8760 \times z} \times a_w + b_w \text{ in B.Th.U. per kw.-hour.} \qquad (3)$$

Assuming :—

$$\frac{\Sigma\,(s)}{8760 \times z} = f = \text{Running Factor} = \frac{\text{Total running time of all sets}}{\text{Maximum possible running time}},$$

$$W_m = \frac{1}{n} \times f \times a_w + b_w \text{ in B.Th.U. per kw.-hour.} \qquad - \qquad - \quad (4)$$

Extreme Cases for f.

First Extreme Case.—$f_{max.} = 1$, that is to say there is only one set, or all sets are in commission continuously.

$$W_m = \frac{1}{n} \times a_w + b_w \text{ in B.Th.U. per kw.-hour.} \qquad - \qquad - \quad (5)$$

Second Extreme Case.—$f_{min.} = n$, that is to say, either all sets are running continuously at full load, or, in the case of a large number of sets, the load is so distributed that any set in commission runs fully loaded.

$$W_m = a_w + b_w \text{ B.Th.U. per kw.-hour.} \qquad - \qquad - \qquad - \quad (6)$$

i.e., the thermal efficiency is independent of the load factor.

3. Average annual running costs in relation to the utility factor (n) of the station in pence per kw.-hour (cents per kw.-hour).

$$K = \frac{1}{n} \times c + g \times W_m \text{ in pence per kw.-hour (cents per kw.-hour) (7)}$$

$$= \frac{1}{n}\,(c + g \times f \times a_w) + g \times b_w \text{ in pence per kw.-hour (cents per kw.-hour) (8)}$$

$$= \frac{1}{n} \times A + B \text{ in pence per kw.-hour (cents per kw.-hour).} \quad - \qquad - \quad (9)$$

$$A = c + g \times f \times a_w \text{ in pence per kw.-hour (cents per kw.-hour).} \; - \qquad - \; (10)$$

$$B = g \times b_w \text{ in pence per kw.-hour (cents per kw.-hour).} \qquad - \qquad - \; (11)$$

In equations 7 to 11 :—

c = Average annual running and capital costs (exclusive of fuel) per hour and per kw. installed, in pence (cents).

g = Cost of fuel per B.Th.U. in pence (cents).

A = Total running costs per kw. installed and per hour at no-load (no energy being supplied), in pence (cents).

B = Additional costs per kw.-hour supplied, in pence (cents).

The comparison of examples A, B, and C mentioned previously is based on the following values :—

BASIS OF COMPARISON.

No.	Item.	Size of Generating Sets. Power Station.		
		A. 20,000 kw.	B. 5,000 kw.	C. 1,000 kw.
1	Efficiency of a boiler unit at the most favourable load (= full load), including energy for artificial draught, chain grate stoker, tube cleaner, and feed pumps	78 %	76 %	75 %
2	No-load consumption of a boiler unit in accordance with 1 as a percentage of the full load consumption—			
	Boiler alone	9 %	9·75 %	10 %
	Auxiliary machine	1·5 %	1·5 %	1·5 %
	Feed pumps	0·5 %	0·5 %	0·5 %
	Total	11·0 %	11·75 %	12·0 %
3	Thermal drop for 1 lb. of steam in the turbine and condenser (185 lbs. per square inch, 570° F.)	1,250 B.Th.U.	1,250 B.Th.U.	1,250 B.Th.U.
4	Steam consumption per kw.-hr. of one generating set at the most favourable load (= full load), including energy for excitation and condensing plant	12·75 lbs.	14·3 lbs.	16·5 lbs.
5	Thermal equivalent for 1 kw.-hr.	3,410 B.Th.U.	3,410 B.Th.U.	3,410 B.Th.U.
6	Efficiency of one generating set in accordance with 4	21·5 %	19·1 %	16·6 %
7	No-load consumption of one generating set in accordance with 4 as a percentage of the full load consumption	10 %	12·5 %	15 %
8	Pipework. For determining the thermal losses all pipes are reduced to the dimensions of the live steam pipes:			
	Reduced length	492 ft.	492 ft.	525 ft.
	Diameter	15 ins.	11 ins.	$7\frac{7}{8}$ ins.
	Reduced surface	1,937 sq. ft.	1,399 sq. ft.	1,076 sq. ft.
9	Thermal losses in the live steam pipes per square foot of surface per hour	370 B.Th.U.	370 B.Th.U.	370 B.Th.U.
10	Efficiency of the pipework in accordance with 8 and 9 (throttling losses neglected)	99·8 %	99·7 %	99·6 %

BASIS OF COMPARISON—(*continued*).

No.	Item.	Size of Generating Sets. Power Station.		
		A. 20,000 kw.	B. 5,000 kw.	C. 1,000 kw.
11	Consumption in the power station itself as a percentage of the full load capacity (lighting, workshop, etc.) -	0·5 $^\circ/_\circ$	0·75 $^\circ/_\circ$	1·0 $^\circ/_\circ$
12	Capital expenditure per kw. installed - - - -	£7·10 ($36)	£10 ($48)	£15 ($72)
13	Supplies, water, taxes, etc., per kw. per annum - - -	3·5d. (7 c.)	5d. (10 c.)	7d. (14 c.)
14	Salaries per kw. per annum -	3s. (72 c.)	4s. 3d. (98 c.)	6s. (144 c.)
15	Repairs per kw. per annum (1 $^\circ/_\circ$ of capital expenditure) -	1s. 6d. (36 c.)	2s. (48 c.)	3s. (72 c.)
16	Interest and renewals per kw. per annum (12 $^\circ/_\circ$ of capital expenditure) - - -	18s. ($4·32)	24s. ($5·76)	36s. ($8·64)
17	Calorific value per lb. of coal -	13,500 B.Th.U.	13,500 B.Th.U.	13,500 B.Th.U.
18	Cost of coal per ton delivered inside the boiler house -	15s. ($3·60)	15s. ($3·60)	15s. ($3·60)
19	Cost of one thermal unit -	0·592 × 10^{-5}d. 1·19 × 10^{-5}c.	0·592 × 10^{-5}d. 1·19 × 10^{-5} c.	0·592 × 10^{-5}d. 1·19 × 10^{-5} c.

BALANCE OF WORKING COSTS.

WORKING COSTS IN PENCE PER KW.-HOUR AT FULL LOAD.

No.	Item.	A. 20,000 kw.			B. 5,000 kw.			C. 1,000 kw.		
		Constant.	Variable.	Total.	Constant.	Variable.	Total.	Constant.	Variable.	Total.
27	Coal (19-25) - -	0·0232	0·0988	0·122	0·0300	0·1110	0·1405	0·0390	0·1261	0·1651
28	Supplies, water, etc. (13) - - - -	0·0004	...	0·0004	0·0005	...	0·0005	0·0008	...	0·0008
29	Staff (14) - -	0·004	...	0·004	0·0056	...	0·0056	0·0081	...	0·0081
30	Repairs (15) - -	0·0020	...	0·0020	0·0027	...	0·0027	0·004	...	0·004
31	Interest and renewals	0·0243	...	0·0243	0·0324	...	0·0324	0·0486	...	0·0486
32	Total - - - -	0·0539	0·0988	0·1527	0·0712	0·1110	0·1817	0·1005	0·1261	0·2266

NOTE.—To obtain working costs in cents multiply the above figures by 2

THERMAL BALANCE.

Initial value, 100 B.Th.U. The figures for items 20 to 24 at the same time give the percentage efficiency.

The figures in brackets refer to items under the "Basis of Comparison."

THERMAL CONSUMPTION IN POWER STATION AT FULL LOAD.

No.	Item.	A. 20,000 kw.			B. 5,000 kw.			C. 1,000 kw.		
		Con-stant.	Vari-able.	Total.	Con-stant.	Vari-able.	Total.	Con-stant.	Vari-able.	Total.
		B.Th.U.	B.Th.U.	B.Th.U.	B.Th.U.	B.Th.U.	B.Th.U.	B.Th.U.	B.Th.U.	B.Th.U.
20	Boiler (1, 2)—									
	Input	11·0	89·0	100·0	11·75	88·25	100·0	12·0	88·0	100·0
	Output	...	...	78·0	...	...	76·0	...	...	75·0
21	Pipework (10)—									
	Input	0·16	77·84	78·0	0·23	75·77	76·0	0·3	74·7	75·0
	Output	...	...	77·84	...	...	75·77	...	...	74·7
22	Generating sets (6·7)—									
	Input	7·78	70·06	77·84	9·45	66·32	75·77	11·2	63·5	74·7
	Output	...	...	16·7	...	...	14·50	...	...	12·4
23	Bus-bars (11)—									
	Input	0·08	16·62	16·70	0·11	14·39	14·50	0·12	12·28	12·40
	Output	...	...	16·62	...	...	14·39	...	...	12·28
24	Total balance—									
	Input	19·02	80·98	100·0	21·54	78·46	100·0	23·62	76·38	100·0
	Output	...	...	16·62	...	...	14·39	...	...	12·28
25	Total balance per kw.-hr. at full load—									
	Input	3,900	16,600	20,500	5,145	18,605	23,750	6,580	21,120	27,700
	Output	...	...	3,410	...	...	3,410	...	...	3,410
26	Most favourable coal consumption per kw.-hr.	Lbs. 0·286	Lbs. 1·232	Lbs. 1·518	Lbs. 0·374	Lbs. 1·386	Lbs. 1·76	Lbs. 0·484	Lbs. 1·57	Lbs. 20·46

EQUATION CONSTANTS.

(The numbers in brackets refer to the items from which the figures are taken.)

Term.	Designation.	Symbol.	Power Stations.		
			A. 20,000 kw.	B. 5,000 kw.	C. 1,000 kw.
Thermal consumption at no-load (25)	B.Th.U. per kw.-hr. output	a_n	3,900	5,145	6,580
Additional thermal consumption (25)	B.Th.U. per kw.-hr.	b_n	16,600	18,605	21,120
Working costs exclusive of coal (32, 37)	Per kw. installed { Pence. Cents.	c	0·0308 (0·0616)	0·0414 (0·0824)	0·0615 (0·1230)
Cost of coal (19) - -	Per B.Th.U. { Pence. Cents.	g	$0{\cdot}592 \times 10^{-5}$ $(1{\cdot}184 \times 10^{-5})$	$0{\cdot}592 \times 10^{-5}$ $(1{\cdot}184 \times 10^{-5})$	$0{\cdot}592 \times 10^{-5}$ $(1{\cdot}184 \times 10^{-5})$

FINAL EQUATIONS.

No.	Term.	Designation.	Type of Power Station.		
			A. 20,000 kw.	B. 5,000 kw.	C. 1,000 kw.
1	Momentary thermal consumption	B.Th.U. per kw.-hr. output	$W_t = 3900 \times \frac{1}{m} + 16600$	$W_t = 5145 \times \frac{1}{m} + 18605$	$W_t = 6580 \times \frac{1}{m} + 21120$
4	Average annual thermal consumption	B.Th.U. per kw.-hr.	$W_m = 3900 \times \frac{1}{n} \times f + 16600$	$W_m = 5145 \times \frac{1}{n} \times f + 18605$	$W_m = 6580 \times \frac{1}{n} \times f + 21120$
5	Extreme case $f = 1$ -	B.Th.U. per kw.-hr.	$W_{m1} = 3900 \times \frac{1}{n} + 16600$	$W_{m1} = 5145 \times \frac{1}{n} + 18605$	$W_{m1} = 6580 \times \frac{1}{n} + 21120$
6	Extreme case $f = n$ -	B.Th.U. per kw.-hr.	$W_{m2} = 20500$	$W_{m2} = 23800$	$W_{m2} = 27770$
7	Average annual working costs	Pence per kw.-hr.	$K = 0{\cdot}0308 \times \frac{1}{n} + 0{\cdot}592 \times W_m \times 10^{-5}$	$K = 0{\cdot}0412 \times \frac{1}{n} + 0{\cdot}592 \times W_m \times 10^{-5}$	$K = 0{\cdot}0615 \times \frac{1}{n} + 0{\cdot}592 \times W_m \times 10^{-5}$

EXAMPLE I.

AVERAGE ANNUAL THERMAL CONSUMPTION PER EFFECTIVE KW.-HOUR. (W_m).

Utility Factor.	Extreme Case: $f=1$, $n=m$, Equation 5.			Power Station.			Extreme Case: $f=n$, Equation 6.		
	Power Station.			In Percentages of (Example A at $n=1·0$).			Power Station.		
	A. 20,000 kw. B.Th.U. per kw.-hr.	B. 5,000 kw. B.Th.U. per kw.-hr.	C. 1,000 kw. B.Th.U. per kw.-hr.	A.	B.	C.	A. B.Th.U. per kw.-hr.	B. B.Th.U. per kw.-hr.	C. B.Th.U. per kw.-hr.
1·0	20,500	23,750	27,700	100	86·1	74·0	20,500	23,750	27,700
0·9	20,950	24,400	28,480	98	84·2	72·1	"	"	"
0·8	21,450	25,105	29,410	95·5	81·9	69·6	"	"	"
0·7	22,395	26,000	30,560	91·8	79·0	67·0	"	"	"
0·6	23,150	27,205	32,080	88·9	75·6	63·8	"	"	"
0·5	24,420	28,900	34,400	84·1	71·0	59·8	"	"	"
0·4	26,400	31,575	37,600	77·9	65·2	54·7	"	"	"
0·3	29,220	35,980	43,100	69·4	57·2	47·5	"	"	"
0·2	36,150	44,350	54,150	56·7	46·4	37·9	"	"	"
0·1	55,670	70,200	87,000	36·8	29·3	23·6	"	"	"

NOTE.—The percentage values of the middle columns, when multiplied by 0·1662, give the total thermal efficiency of the works as a percentage, 0·1662 = No. 24A, p. 96.

EXAMPLE II.

AVERAGE TOTAL ANNUAL RUNNING COSTS IN PENCE PER EFFECTIVE KW.-HOUR. (K).

Utility Factor.	Extreme Case: $f=1$, Equations 5 and 7.			Extreme Case: $f=n$, Equations 6 and 7.		
	Power Station.			Power Station.		
	A. 20,000 kw. pence per kw.-hr.	B. 5,000 kw. pence per kw.-hr.	C. 1,000 kw. pence per kw.-hr.	A. 20,000 kw. pence per kw.-hr.	B. 5,000 kw. pence per kw.-hr.	C. 1,000 kw. pence per kw.-hr.
1·0	·1552	·1882	·2258	·1522	·1882	·2258
0·9	·1582	·1893	·2371	·1556	·1868	·2327
0·8	·1656	·2002	·2506	·1599	·1926	·2409
0·7	·1765	·2129	·2691	·1653	·1998	·2524
0·6	·1881	·2276	·2927	·1727	·2097	·2668
0·5	·2062	·2538	·3261	·1828	·2234	·2872
0·4	·2328	·2898	·3762	·1982	·2441	·3178
0·3	·2776	·3492	·4597	·2237	·2782	·3689
0·2	·3672	·4688	·6267	·2747	·3471	·4712
0·1	·6361	·8270	1·1277	·4280	·5531	·7777

These calculations show that the thermal or coal consumption is also dependent upon the running factor, apart from the utility factor, this being all the more the case the smaller the annual utility factor of the power station. Special attention should be given to this point, because a station superintendent is able to keep the running factor low to a certain extent by an intelligent division of the running period of the various sets, and can thus approach the most favourable coal consumption as given by equation (6). A record of the running factor (which, similarly to the utility factor, can be determined also for shorter periods) would thus offer valuable assistance in controlling the expediency of measurements adopted by the supervising staff.

The difference in thermal consumption for the two extreme cases of running factor in relation to utility factor may be seen from the table, Example I., page 98 (see also Figs. 60, 61, and 100).

From this table it will be seen that with a utility factor of 0·1, for example, the coal consumption may rise to three times the value obtainable with the most favourable load factor, if the running factor is not favourable.

2. ECONOMIC DEDUCTIONS.

The figures obtained show the superiority of large stations over medium-sized and small stations. The fact that the diversity factor falls as the supply area and consumption increases, whereas the load factor, and with it the utility factor, rise, makes the advantage of erecting large stations still more clearly evident. For example, according to the above tables a utility factor of 40, 30, and 20 per cent. may be taken for the stations A, B, and C; the average value of the generating costs between $F = 1$ and $f = n$ would then be: 0·215 penny (0·4359 cent) for A, 0·3137 penny (0·6360 cent) for B, and 0·5487 penny (1·1124 cents) for C. These large differences, which hold good for new plant, will be seen to become greater still when the above figures are compared with the prime costs of existing power stations.

If one were confronted with the task of supplying a very large district, such as the whole of Germany, for example, with electricity in the most economical manner possible, and without being restricted by political boundaries, other power stations, and municipal authorities, the problem would have to be solved in the following manner :—

A comparatively small number of very large power stations, with units of at least 20,000 kw., would be erected at suitable points. The most suitable neighbourhood for steam power stations would of course be near coal fields, but at the same time due consideration should be given to the demand that could be supplied at an intermediate pressure, and to the possibility of firing the boilers with waste coal or utilising any available waste heat. In brown coal districts a power station of this description would have to be erected directly on the coal fields, because the transmission costs do not appreciably affect the results for reasons already stated. Harbours and waterways may also be regarded as suitable localities owing to the convenience of transporting coal by water.

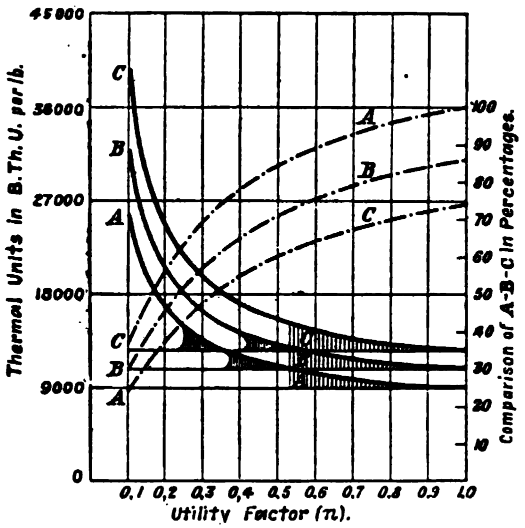

Fig. 60.

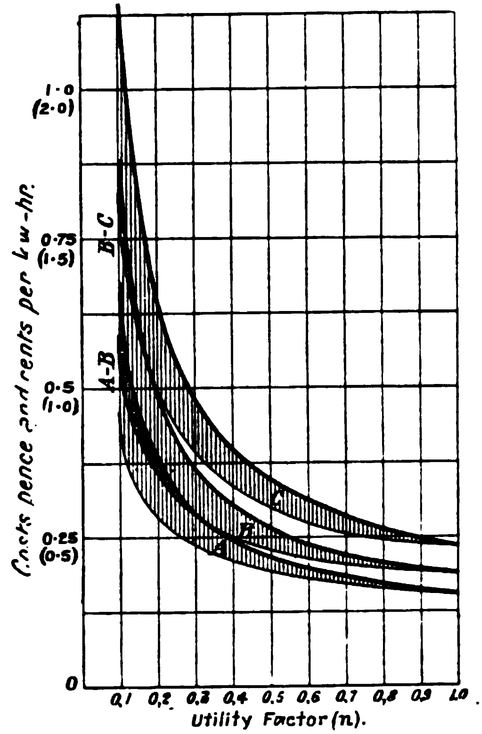

Fig. 61.

A number of such power stations would be distributed over the whole of Germany ; their size and the distances between one another would depend upon the density of the demand. The most economical distance can be calculated when the conditions are known ; such calculations are, however, seldom of much use in practice, because generally there are other considerations that decide the position of the site. Nevertheless, it would hardly be advisable to design stations for outputs exceeding 80,000 to 100,000 kw., as at these outputs two power stations of half the size would not be much more expensive to erect and to operate than one large station.

The power stations would be interconnected by high-tension lines for pressures of 60,000 to 100,000 volts, and with conductors to enable the stations to support one another to the extent of 20,000 to 30,000 kw. according to the density of the demand. Although the transmission lines would have to pass large intermediate centres of consumption, it would, nevertheless, be advisable to keep the number of tappings as low as possible. The branch feeder stations are in a sense power substations for local consumption; they would transform the pressure of the lower voltage of any large existing network—generally this should be between 10,000 and 20,000 volts. The distribution of energy for local consumption would be carried out from these mains in the usual manner. A mesh system of high-tension lines would thus be obtained, and the size of the meshes would depend upon the specific density of the demand; the distance between power stations would vary between 50 and 200 miles.

Any large existing water power station would be connected up to this network, and it would be possible to arrange for future extensions in accordance with the average quantity of water available and not the minimum quantity as hitherto.

The principle on which a system of this kind should be operated would be to keep the utility factor of the most economical stations as high as possible, while smaller and less economical stations would be employed principally for dealing with peak loads.

The foregoing considerations may be summarised in the statement that much of a profitable nature, both from a technical and an economical point of view, still remains to be accomplished in power station design. Solutions of these problems are sure to open up new fields in the application of electricity.

Further development of this extensive branch of engineering must, of necessity, finally lead to a uniform treatment of the problem of general supply outlined above. One cannot expect, moreover, a continued disregard of the possible saving in national property that might be effected by improving present-day methods of designing and operating undertakings for the production of electricity.

CHAPTER IV.

FIRST CONSTRUCTIONAL EXAMPLE: MÄRKISCHE ELECTRICITY WORKS.

1. GENERAL.

THE town of Eberswalde is situated some twenty miles to the north of Berlin, on the banks of the Finow Canal, a waterway which joins two important rivers. One of these is the river Elbe, which flows into the North Sea not far from Hamburg, and the other is the river Oder, which flows into the Baltic Sea at Stettin. The canal derives its name from the river Finow, the course of which it follows. The water power of this latter river is still utilised in a number of falls. A flourishing industry, which dates back to the time of the Great Elector, has gradually developed along its banks, favoured by the proximity of the city of Berlin.

The small amount of power obtained from the river Finow has long ago ceased to be sufficient for the demand, and it therefore became necessary to resort to steam power. At the present day the river Finow is far more serviceable as a waterway for barges for coal and other freight than as a source of power.

With the object of supplying power to this industrial district, a company was formed in 1909, and a power station, the Märkische Electricity Works, was built on the banks of the Finow Canal.

Investigations made in the early period of the scheme showed that the principal consumers would be :—

Brickworks with about 2,000 working hours per annum, and a diversity factor of about 100 per cent.

Factories with 3,000 to 7,000 working hours, and a diversity factor of from 40 to 70 per cent.

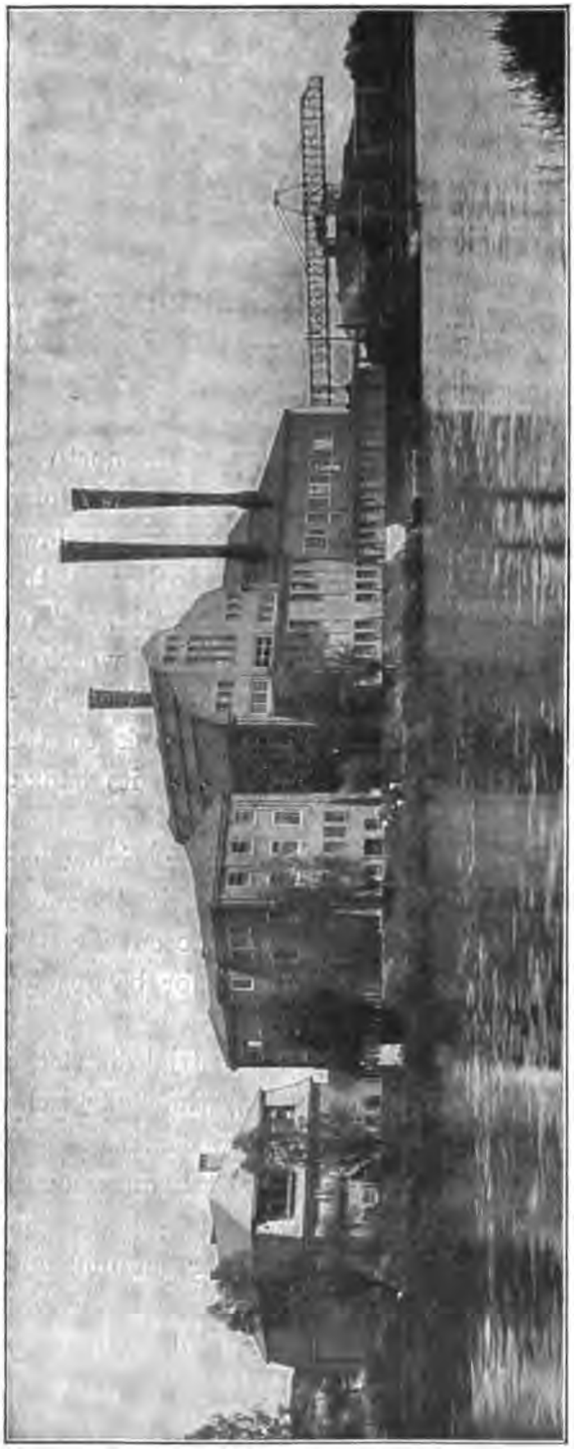

Fig. 62.—General View of Power Station.

Local authorities and farms with 150 to 1,000 working hours, and a diversity factor of about 35 per cent.

The lay-out was based on a peak load of about 3,200 kw., whereas 5,500 kw., and 8,800 were the assumed peak loads for the first and second extensions respectively. In consequence of the large proportion of power taken, a load factor of 35 to 40 per cent. was estimated for the generating station. Under the above conditions, the most suitable sizes of machines were considered to be units, each developing 3,600 kw. at 80 per cent. power factor. The engine room was accordingly designed for the accommodation of three steam turbines, and the boiler house for six boilers evaporating from 26,400 to 33,000 lbs. of water per hour. Of this plant, two steam turbines and three boilers were at first installed. The works were extended in 1912 by the addition of a turbo-generator, with an output of 8,000 kw., and three additional boilers.

A site for building the power station (see Fig. 63) was selected at Hegermühle (about two miles from Eberswalde), on the banks of the Finow Canal. This position enabled coal to be brought alongside the power station by water, and an ample supply of water for cooling purposes and for feeding the boilers was ensured.

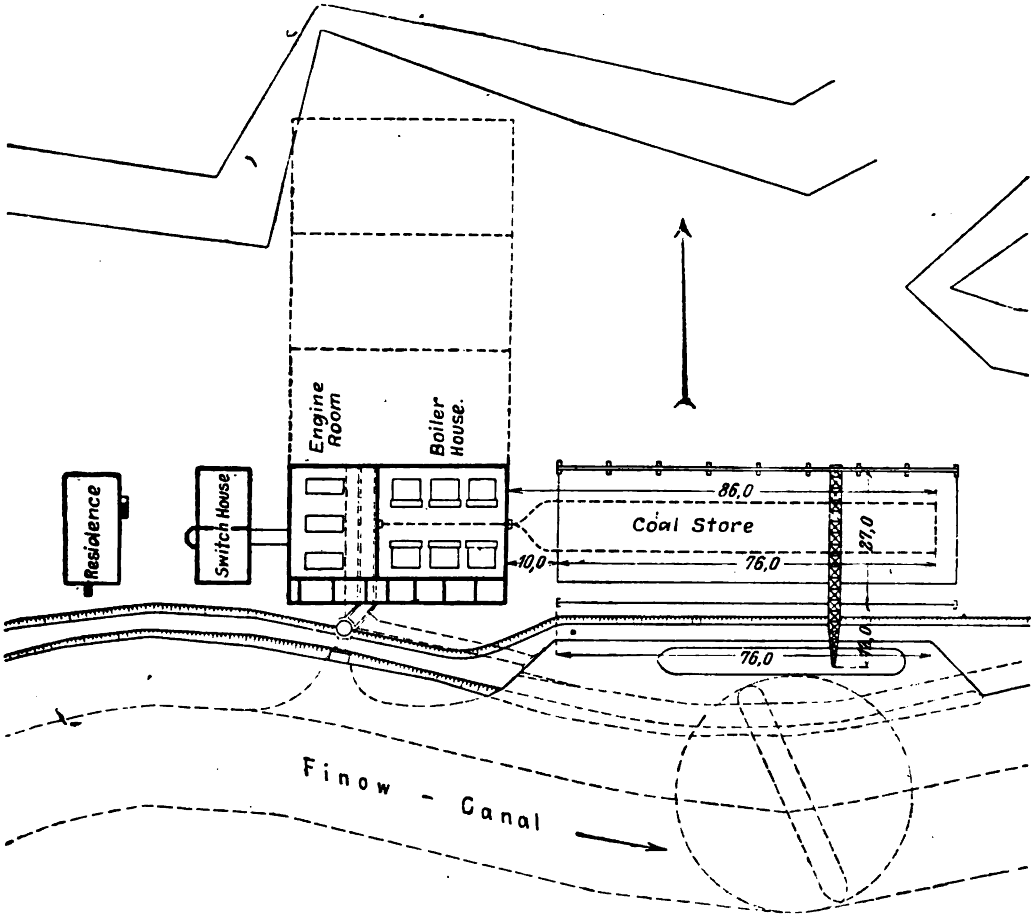

Fig. 63.—Plan of Site.
Scale, 1 to 1,500. (Dimensions in metres.)

The decisive factor in the choice of the site was that at

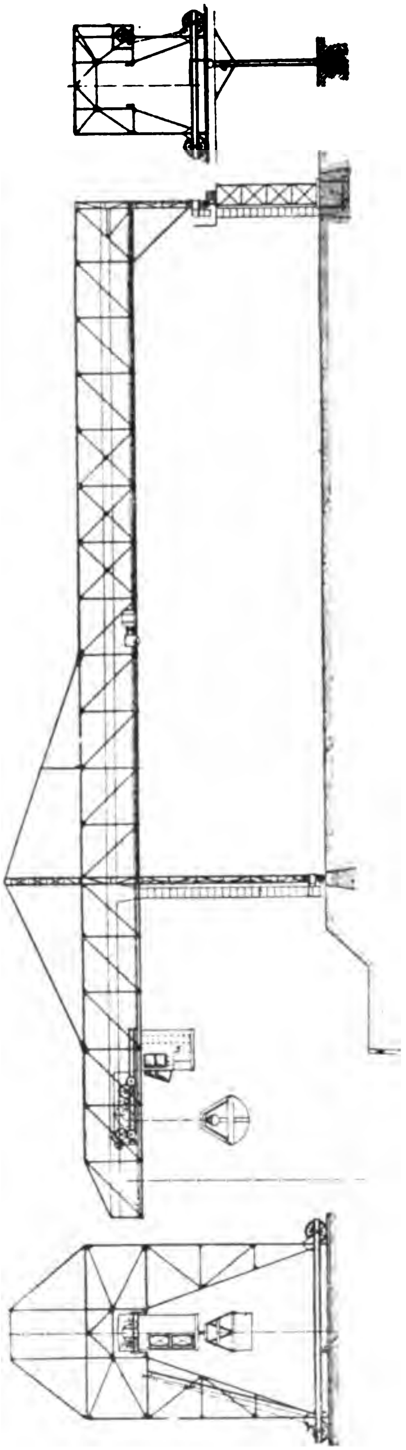

Fig. 64.—Coal Bridge. *Scale*, 1 to 300.

Hegermühle the Finow Canal runs nearest to the large waterway, which is navigable for large ships. With this site was acquired a strip of land right up to this waterway at a distance of 875 yds. The site is of ample size to allow of future extensions; it is fairly level and has a sandy subsoil.

Fig. 63 shows how the canal has been widened so as to provide for a swinging berth and landing facilities. Sufficient room has been arranged for two 200-ton barges. The coal store runs parallel to the canal immediately opposite to the point where the barges land. The boiler house and engine room are placed at one end of the coal store, in such a way that the length of the inlet and outlet ducts for the cooling water are as short as possible. It will be noticed from the illustrations that the centre line of the boiler house is at right angles to the centre line of the engine room. A separate building was reserved for the switchgear, but the engine room and switch house are connected to one another by a covered bridge.

2. COAL STORE AND COAL TRANSPORT.

The coal store is of a sufficient size to accommodate a four months' supply, because a regular supply of coal by water cannot be relied upon during severe winters. The coal delivered is suitable for use on chain grate stokers; coal crushers can therefore be dispensed with. The barges are emptied with grabs controlled from the coal bridge,[1] and discharged on to the coal store; the general arrangement of the coal bridge is shown in Figs. 64 and 65. The track for the coal bridge on the land side was constructed to support a second similar bridge for travelling over the coal store in front of a second boiler house. The idea is to connect the second coal bridge rigidly to the first one. A driver's cabin is attached to the traveller, from which the lifting and travelling movements can be controlled.

Fig. 65.—Coal Bridge.

Underneath the coal store two passages of reinforced concrete have been constructed (see Fig. 66); they contain the track for the

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[1] Coal bridge—manufacturers, M.A.N.; capacity, 40 tons per hour; span between supports, 88 ft.; projecting arm, 42 ft.; carrying capacity of traveller, 3 tons; capacity of automatic grab, 70 cub. ft.; duration of one working cycle, 110 secs.; lift, 33 ft.; travel, 130 ft.; depth of lowering, 16 ft.; drive, three-phase motors; 30 H.P. for lifting motor; 15 H.P. for travelling motor; 9·5 H.P. for bridge movement.

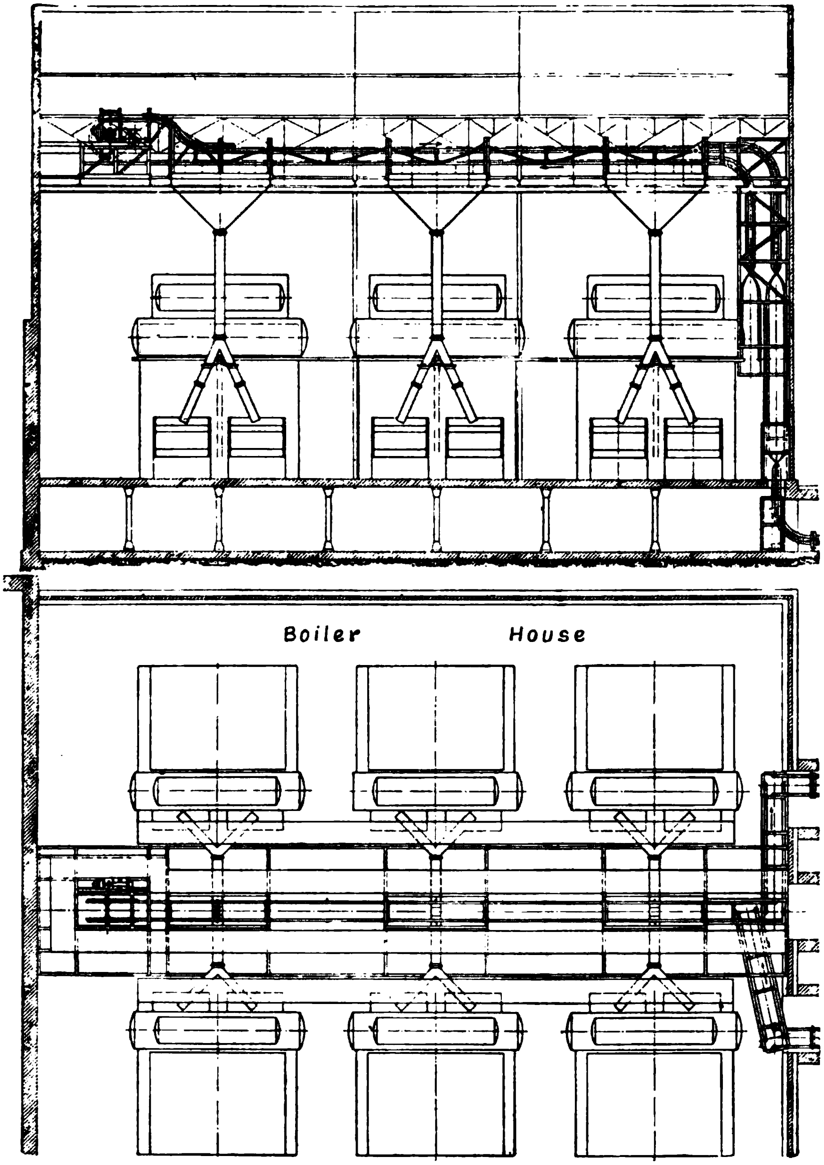

Fig. 65A.—Boiler House.

endless chain of the bucket conveyer.[1] The size of these passages

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[1] Coal conveyer—manufacturers, C. Schenk, G.m.b.H., Darmstadt. Capacity, 14 tons per hour; length of bucket chain, about 1,000 ft.; number of filling hoppers, 42; number of charging machines, 2; number of weighing machines, 1; drive, one 8 H.P. three-phase motor.

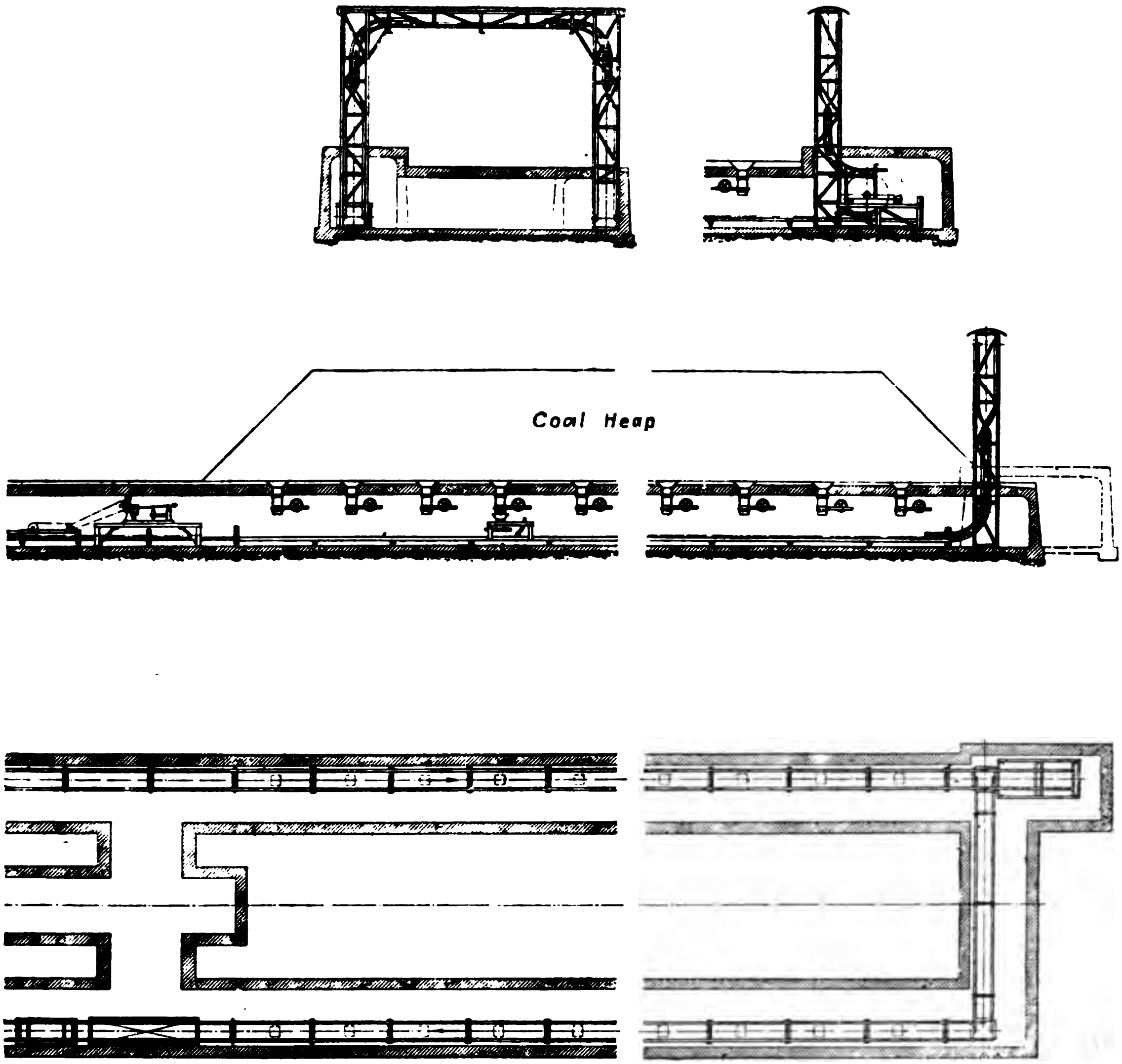

Fig. 66.—Coal Store. Arrangements for Coal Transport.
Scale, 1 to 260.

is 6 ft. 6 in. × 5 ft. 9 in. There are a number of small hoppers in the roof of these passages, through which the coal from the store reaches the conveyer buckets.

The chains travel from one passage into the other through a double spiral placed above ground. Before entering the boiler house the conveyer passes over an automatic coal weighing machine placed in the passage nearest the canal (Figs. 66 and 67) It furnishes a daily record of the consumption of coal, provided the coal bunkers are filled each day at the same time.

3. BOILER HOUSE.

a. Buildings.

The provisions necessary inside the boiler house for bringing the coal to the boilers are of light construction, and take up very little space; the conveyer is therefore placed between the roof trusses. As the coal used contains very little dust, it was not necessary to enclose the conveyer inside the boiler house. The chain of buckets is therefore quite open and readily accessible on either side from gangways (Fig. 68).

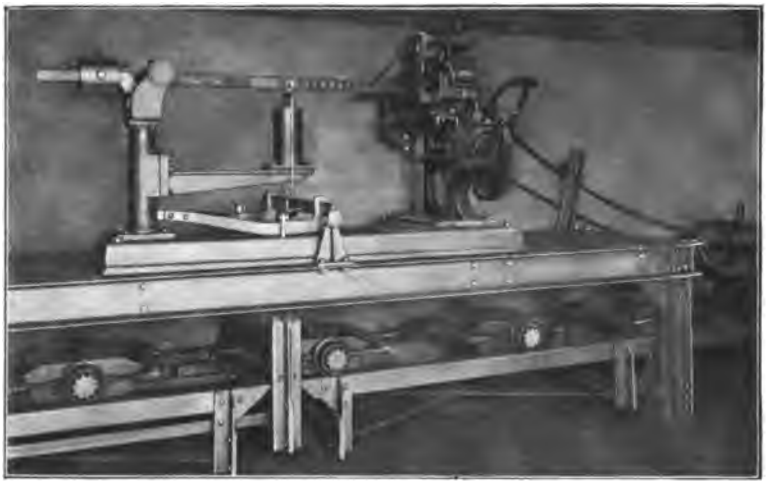

Fig. 67.—Automatic Coal Weighing Machine in the Conveyer Passage.

The buckets are discharged through automatic catches built in pairs into each filling hopper, and operated by a handle in front of the boiler near the chain grate. The bunkers were dimensioned for not more than a two hours' supply of coal, as in view of the great reliability of the coal-conveying plant the storage of coal inside the boiler house appeared superfluous. The adoption of this principle for the design of the boiler house leads to an extremely light constructional ironwork, and the advantage of being able to dispense with iron columns. When a bunker is filled the further discharge of coal is stopped automatically. When all bunkers are filled the buckets are automatically discharged on the return trips into a coal shoot situated in the front of the boiler house (see Fig. 69). As all buckets are tipped automatically when passing over this coal shoot, the weight of the coal from any full buckets moves a flap which switches off the conveyer motor.

Fig. 68.—View of Coal Conveyer in the Roof of Boiler House.
Scale, 1 to 200.

Different mixtures of coal can be obtained by filling the buckets alternately from different hoppers in the coal store.

b. Boilers and Economisers.

The boiler house (Figs. 69 and 70) is laid out for six units, each consisting of a boiler, economiser, air-draught plant, and iron chimney. It covers an area of 87 ft. x 72 ft. 3 in., equal to 6,214 sq. ft., and has a maximum output of about 209,500 lbs. of steam per hour. Three of the units mentioned were installed at first. The steam produced per square foot of the area covered for the first lay-out is about 34 lbs. The weight of the ironwork employed in the construction of the whole boiler house is 96 tons, or about 1 lb. of iron for 1 lb. maximum output in steam.

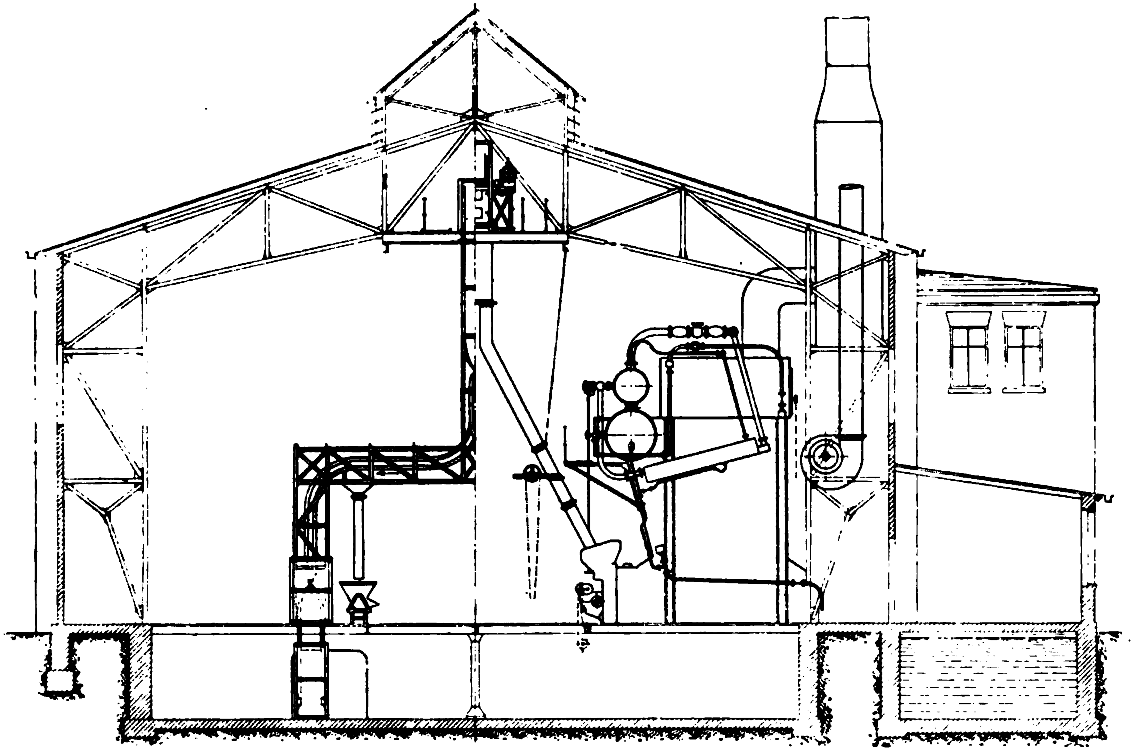

Fig. 69.—Section through Boiler House looking towards the Coal Yard.
Scale, 1 to 200.

These exceedingly low figures were obtained, on the one hand, by employing the above described coal conveyer, and, on the other hand, by the adoption of a form of boiler proposed by the author and constructed by Babcock & Wilcox, Ltd. Apart from the whole arrangement of the plant, the boiler alone gives excellent results from the point of view of thermo-efficiency, and the favourable heat characteristics obtained are largely attributable to this point.

Apart from the satisfactory utilisation of the available space, further advantages are also obtained from this construction in the low thermal losses from radiation and conduction. The entire exposed surface of the boiler and economiser becomes much smaller than in the case of the customary separate form. Good heat insulation can also be obtained easily (even when running for long periods, the temperature of the outer walls of the boiler does not exceed about 140° F.). Another very important point was the very appreciable reduction in the resistances of the entire boiler plant. All these reasons made it possible to work with naturral daught

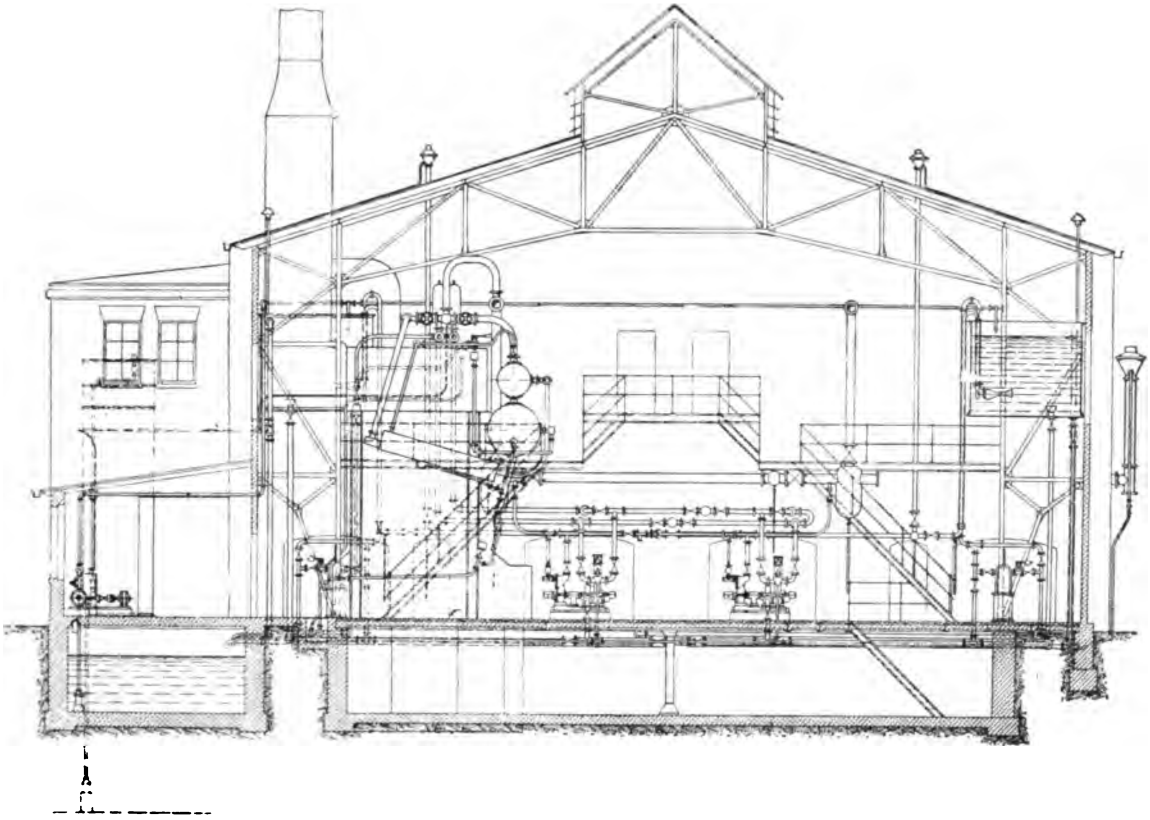

Fig. 70.—Section through Boiler House looking towards the Engine Room.
Scale, 1 to 200.

up to about two-thirds of the maximum boiler output, notwithstanding the comparatively low height of the chimneys. The fan is naturally required at times when the maximum load comes on; the small increase in power, as compared with natural draught,[1]

Fig. 71.—End View of One Boiler Unit.

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[1] Forced draught plant—manufactured by the Gesellschaft für Künstlichenzug. Dimensioned for an air supply of one and a half times the normal, gauge behind the economiser; normally, 1 in.; maximum, 1·49 in.; height of iron chimney above boiler house floor, 100 ft.; external diameter of chimney at top, 6·5 ft. Type of fan, sirocco driven by three-phase motor. Fans supplied by White, Child & Beney. Power consumption, normal, 20 H.P.; maximum, 30 H.P.

is at such times of no economical importance. The simplicity of operation, absence of reversing valves, the fact that the fan moves cold air only, and can be installed in a readily accessible position, are advantages which under similar conditions make this ejection system superior to others employing induced draught.

Fig. 72 shows a section through the boiler with the economiser mounted on top.[1] As may be seen, the complete set is self-contained, and is encased in iron, thus preventing air leakage. A large steam drum is placed on top of the main boiler drum so as to trap any water that might otherwise get into the superheater.

The ash falls through hoppers into trucks in the very spacious basement.

The boilers and economisers are so dimensioned in relation to one another that the gases enter the economiser at a temperature of about 750° F. The temperature of the feed water is raised to about 250° to 285° F.

The importance of preventing air from getting into the feed water is generally recognised, as the work of the pump for the condenser is largely affected by the amount of air in the condensed steam; moreover, the existence of air in the water exercises an injurious effect on the boiler and economiser tubes. If, as in the present case, the condensed steam from the surface condenser is used for feeding purposes, the admixture of air can be prevented when the feed water is not subject to a partial vacuum on its way to the boilers, and is stored in tanks having small exposed surfaces. Any special air eliminating apparatus can then be dispensed with.

The boilers are fed automatically by means of Hanneman's water level regulators.

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[1] Boilers—constructed by the Deutsche Babcock & Wilcox Dampfkesselwerke; normal output, 27,700 lbs. of steam per hour; maximum output, 34,700 lbs. of steam per hour. Steam pressure, 220 lbs. per square inch; steam temperature, 662° F. Heating surface of boiler, 4,410 sq. ft.; heating surface superheater, 1,450 sq. ft.; heating surface of economiser, 2,260 sq. in. Grate area of chain grate stoker, 160 sq. ft. The chain is driven by a 1·5 H.P. three-phase motor. Calorific value of coal, 12,600 B.Th.U. Total coal fired per hour normally, 4,290 lbs.; maximum, 5,400 lbs.

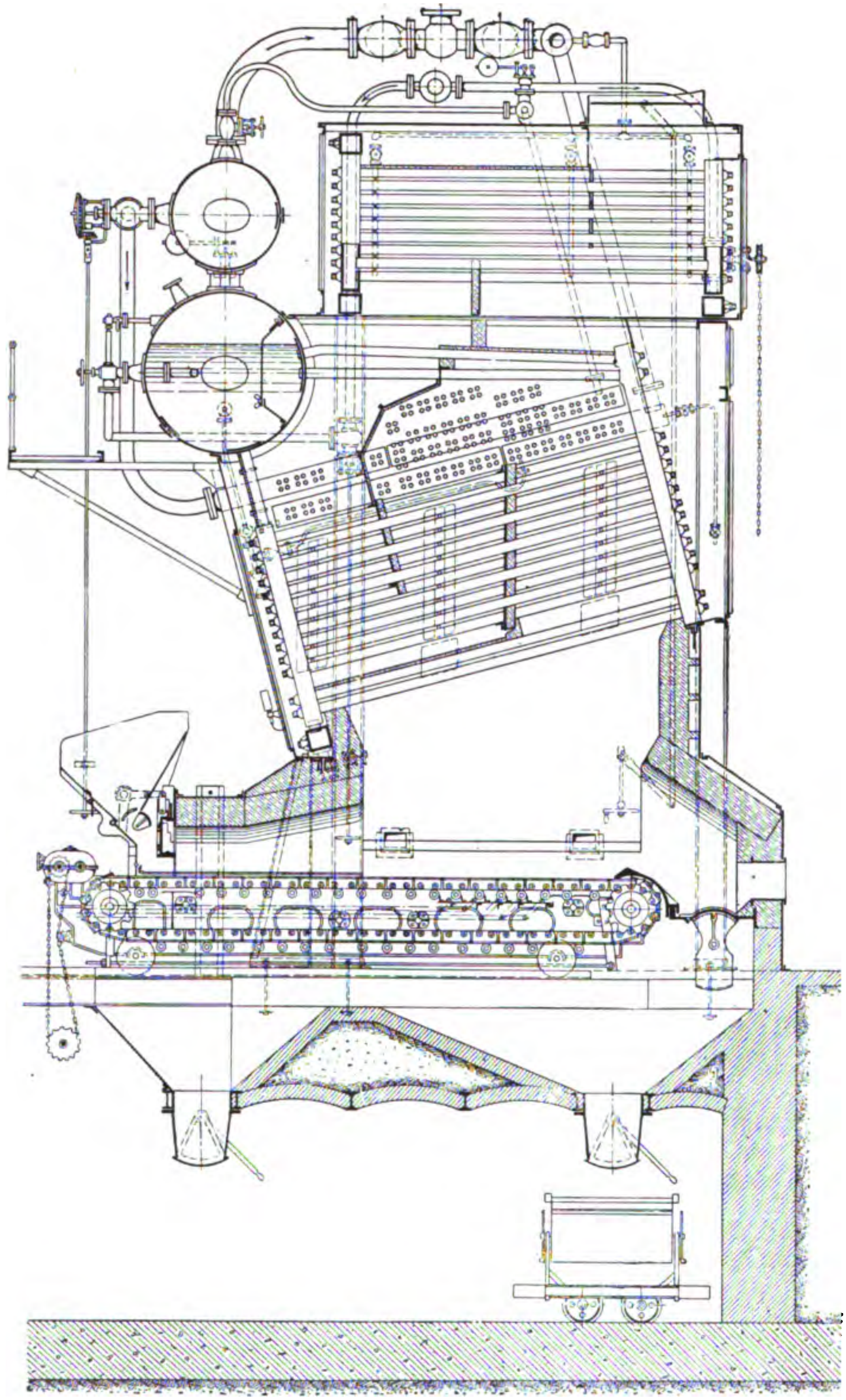

Fig. 72.—Section through the Boiler with Economiser above.
Scale, 1 to 60.

c. Feed Pumps.

The boiler feed pumps are of the turbine-driven type. They are regulated by a special governor, which controls the admission of the steam in such a manner that the water pressure remains practically

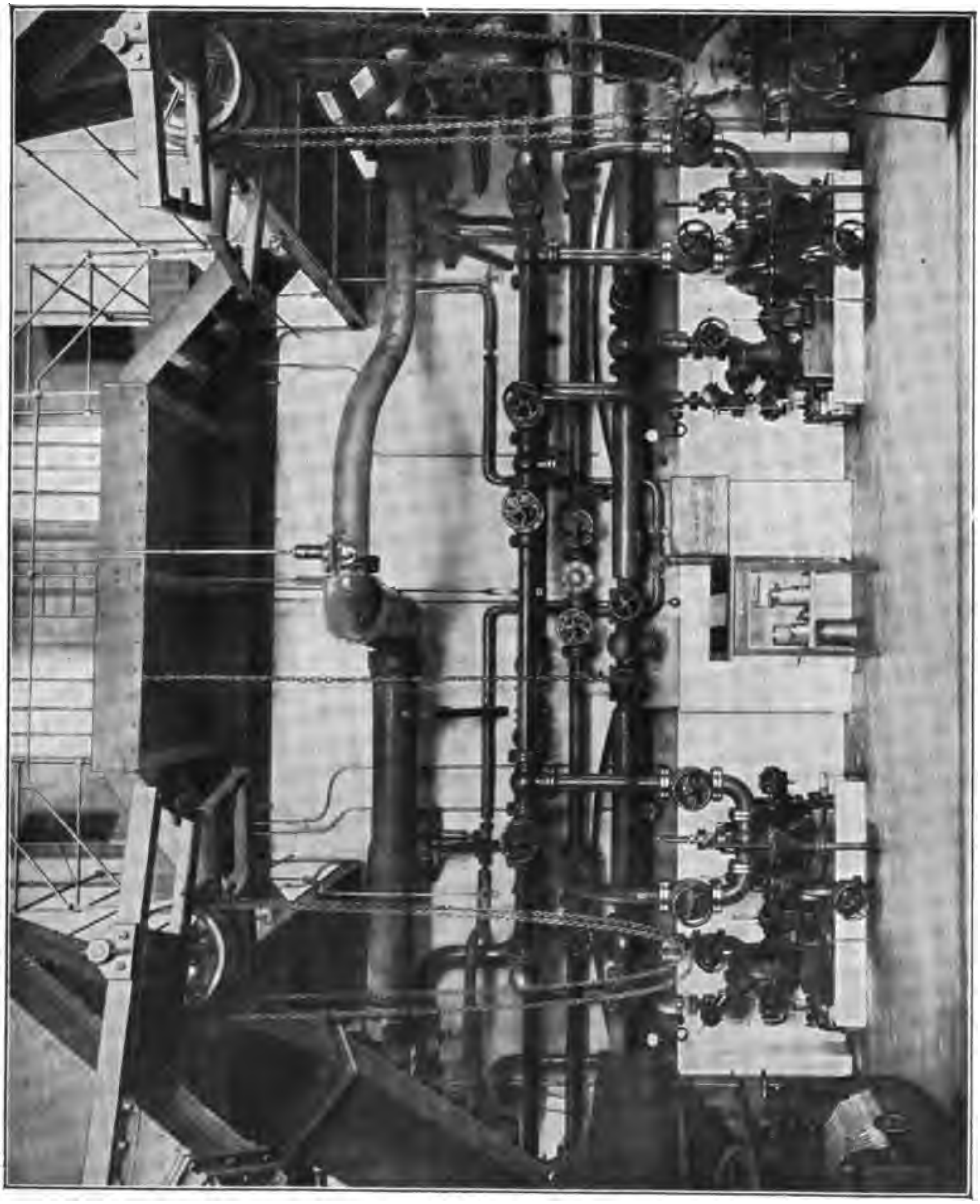

Fig. 73.—View of Feed Pumps and Pipes on the Boiler House Wall adjoining the Engine Room.

constant. Any fluctuations in the quantity of water are controlled automatically.

The stages of the centrifugal feed pumps are placed in one case. One of the pumps is sufficient for the entire water supply of the boiler house. The pumps take up a small amount of space, and are not affected by dust, consequently there is no objection to placing them inside the boiler house. Reciprocating pumps of the same capacity would have required a special room. The feed pumps are shown in Fig. 73.

d. STEAM PIPES, AUXILIARY PIPEWORK AND WATER SUPPLY.

The steam pipe connections to the small turbines for driving the boiler feed pumps are branched off from the main steam separators in the steam range in easy curves. The exhaust steam from these turbines is passed through heaters in feed tanks (see Fig. 70), where the remaining heat of the steam is used for heating the feed water. As the tanks are placed at a higher level than the pumps the feed water flows to the latter under a certain head. The delivery side of the pumps is connected to the boilers by pipes with a 4·875-in. bore. Sharp bends are avoided as far as possible in this pipe, and roller supports are provided to allow for free expansion.

The main steam piping is shown diagrammatically in Fig. 74. The main steam range consists of a steam pipe passing along each row of boilers, and connected to large steam separators fixed to the engine room wall (Fig. 70). The two steam separators thus provided are connected to one another by a steam pipe to which the branches leading to the main turbines are connected.

Before the steam enters the turbine it has to pass through a further steam separator in order to prevent the admission of water into the turbine.

A cross connection in the steam range is made between boilers 3 and 4. This connection does not produce a ring main in the ordinary sense, because its section is not large enough for carrying the whole amount of steam. It is, however, an additional security which was obtained without appreciable extra expenditure.

There are two fixed points in the steam range: one is the main steam drum on the boiler, and the other the steam separators in the boiler house. The latter are rigidly anchored by means of brackets and struts. The steam pipes running overhead are attached to the ironwork by means of slings which allow a certain movement. The inter-connecter, which contains the expansion piece between the two main separators, is supported on brackets with roller supports to allow for longitudinal expansion. The two main steam pipes in the boiler house also contain expansion pieces.[1]

The pipework consists of seamless steel pipes with cast-steel flanges and globular T-pieces, cast-steel slide valves with nickel alloy packing. All valves can be operated from the floor of the boiler house. The main valves are fitted with indicators to show whether the valves are opened or closed.

The steam pipes are lagged with siliceous compound of a thickness of 2·35 in. The flanges are protected by cast-iron covers with small drain tubes.

The selection of the most suitable steam velocity requires special consideration for all generating stations working with a bad load factor. When dividing the losses in a steam range into thermal and pressure losses it will be seen that the former, being constant, largely affects the economy of the installation, whereas the maximum pressure losses are temporary only since they occur at peak loads. It is therefore evident that a reduction of the thermal losses is of considerable importance even at the cost of greater pressure loss. The former can, however, only be reduced under otherwise similar conditions, by reducing the exposed surface. This again is determined partly by the distance between the boilers and the engines, and partly by the velocity of the steam.

The minimum length of steam piping was obtained by placing the boiler house with its axis vertical to that of the engine room, by the close proximity of the two without intervening buildings, and by the form of boiler construction introduced. Under the circumstances there

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[1] **Pipework carried out by Seyffert & Co., Eberswalde.**

is nothing against a large specific pressure loss, which can be made greater still by dispensing with valves in the main steam piping. The passage of steam is controlled by slide valves in which the pressure losses are negligible.

Provided these assumptions can be fulfilled, there is no objection to increasing the maximum steam velocity to values considerably exceeding figures that have been customary hitherto. In this installation the maximum velocity of the steam is about 260 ft. per sec.

Careful insulation is a most important point, especially in the case of flanges and valves under working conditions with a small load factor.

The water for the condenser runs through an inlet canal parallel to the engine room; at the opening of this canal a grid and strainer are provided. The cooling water pumps draw their water vertically upwards through cast-iron pipes with a bore of 17·5 in. After having passed through the condenser, the cooling water flows into a smaller canal which discharges into the Finow Canal at a point further down near to the coal wharf. The circulating water for cooling the bearings of the turbo-generators is drawn from the same source, two small pumps driven by three-phase motors placed in the basement being provided for this purpose (see plan of piping, Fig. 74).

The amount of make-up water for feeding the boilers is quite small. The losses in feed water are low, as the condensed steam delivered by the feed pumps is free from oil and can be used again. The water drawn from the Finow Canal is of a somewhat hard quality, and must, therefore, be softened before use. For this purpose the water softener[1] is employed, the water taken from the inlet canal being pumped to the softener by a centrifugal pump installed in the pump room.

The water softener (see Fig. 75) is erected in a special room adjoining the pump room. The operating gallery for the softener is on a level with the engine room floor, and is accessible through a door in the engine room.

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[1] Water softener supplied by H. Reisert. Capacity, 425 cub. ft. per hour, designed for future extensions to the power station.

After passing through a water meter the softened make-up water flows into a soft water reservoir placed underneath the pump room

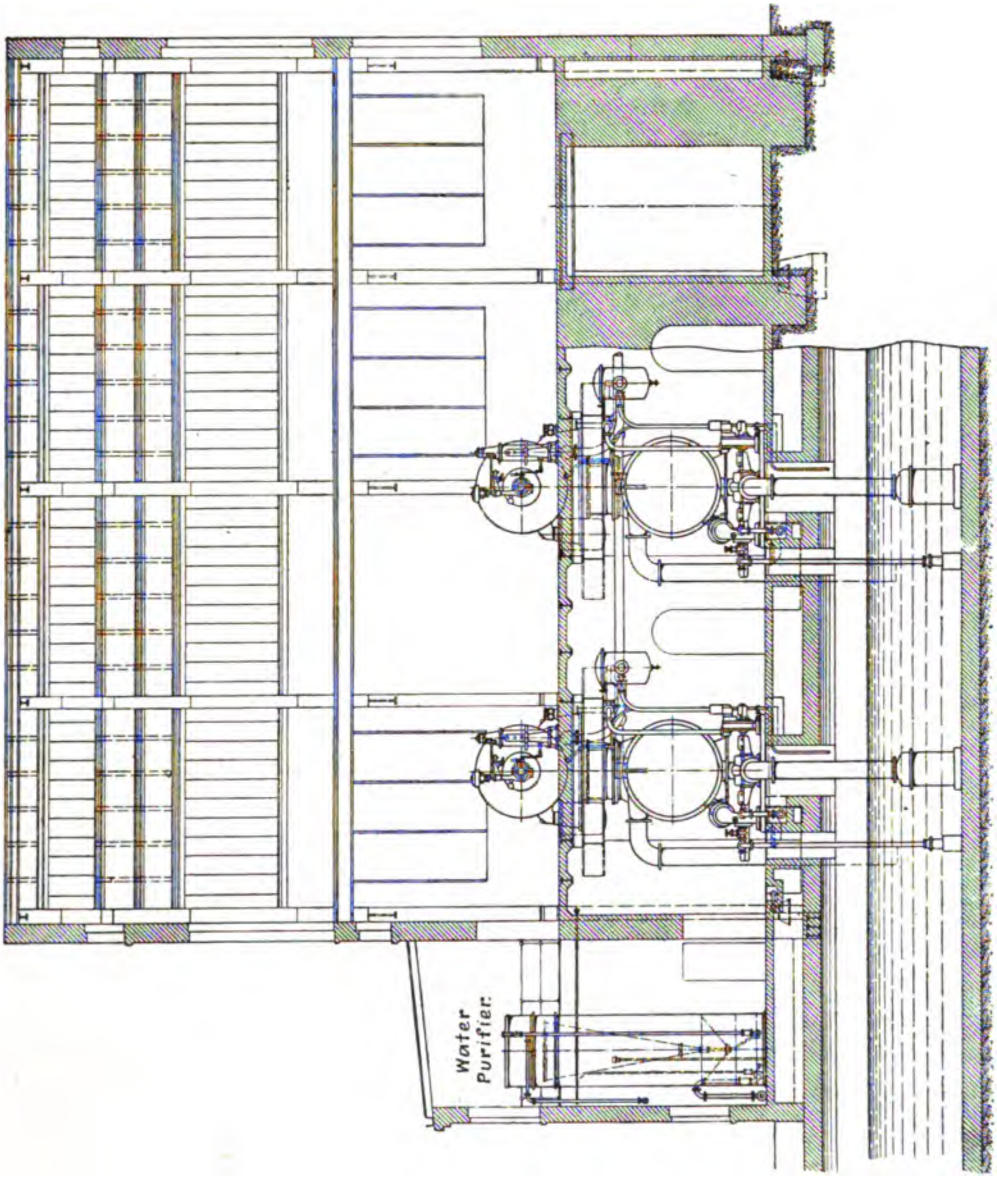


Fig. 75.—Section through Engine_Room. *Scale*, 1 to 200

and adjoining rooms. The condensed steam from the various steam separators is also discharged into this reservoir. A centrifugal pump installed in the pump room raises the softened water into the above-mentioned feed tanks. All centrifugal pumps for the water supply are fitted with steam ejectors supplied with saturated steam through a ·94-in. pipe coming direct from the boilers. The water softener is also connected to this piping.

4. ENGINE ROOM.

The principal dimensions of the engine room (see Fig. 87) are:—Length, 74 ft.; breadth, 54 ft.; height of basement, 18 ft.; height of engine room to roof, 47·5 ft.

a. STEAM TURBINES.

Steam is supplied to the steam turbines at a pressure of 190 to 220 lbs. per sq. in., and a temperature of 570° to 660° F. at the stop valve. The turbines are arranged for nozzle regulation, by means of which the steam consumption at low loads is reduced considerably. As the construction of these turbines, which are of A.E.G. design, is well known, they need not be further described here.

b. CONDENSERS.

The condensers are located immediately below the steam turbine between the foundation blocks. The pumps for the condensers are placed underneath the steam end of the turbine in front of the condenser body. The condensing plant is remarkable for compact design, the pumps take up a small amount of space, and the pipe connections are short and simple. Openings are provided in the floor of the engine room through which the pumping sets can be inspected. They are at the same time most useful during erection.

The condenser bodies are of the standard counter-flow surface type. A small steam turbine in each case drives the cooling water pump as well as the rotary air pump with which a lifting pump for the condensed steam is combined (see *Zeitschrift des Vereins Deutscher Ingenieure*, 1909, page 699). The steam from

Fig. 76.—Engine Room.

the auxiliary turbine is exhausted into one of the stages of the main turbine, where the kinetic energy it still possesses is made use of.

The condensed steam is passed through a water meter provided for each turbine, and is then raised to the feed tanks (see plan of pipework, Fig. 74). The water meter shows the steam consumption of each turbine at any moment.

Both main and auxiliary turbines are fitted with emergency governors, which come into operation and close the main stop valve immediately an excessive speed is reached.

c. GENERATORS.

The generators supply three-phase alternating current at a pressure of 10,000 volts, which is kept constant by means of a Tirrill regulator. Special attention was given to good insulation and reliability in the case of short circuits.

When the generators were warm a test pressure of 25,000 volts was applied, and the rigidity of the construction was proved in several short circuit tests carried out at full excitation.

The cable dividing boxes and cloth air filters are situated in the basement underneath the generator ends of the sets, where there is ample room between the foundation blocks. The filters are mounted on rollers, and can be drawn out for cleaning purposes.

The air required for cooling the generators enters the building through openings in the foundations of the engine room wall in the basement (see Fig. 87, Plate VII.). After passing through the air filters the air is drawn into the generators and escapes into the open through air ducts placed immediately underneath the engine room floor. A switch pillar containing an ammeter, wattmeter, voltmeter, and signalling apparatus for communicating with the switchboard attendant, is provided for each turbo-generator.

d. ARCHITECTURAL FEATURES.

The buildings are remarkable for simplicity of design. They are faced with red brick, and the roofs are covered with a double layer of roofing felt laid on wooden rafters (see Fig. 62). The columns and roof trusses in the engine room are designed on the rigid principle (see Fig. 76). The engine room walls are solid, those in the boiler house are constructed of ironwork.

The lay-out was prepared with the idea of giving access to abundant daylight, and the boiler house and engine room are therefore provided with large skylights in addition to wide windows in the walls (see Figs. 71 and 76).

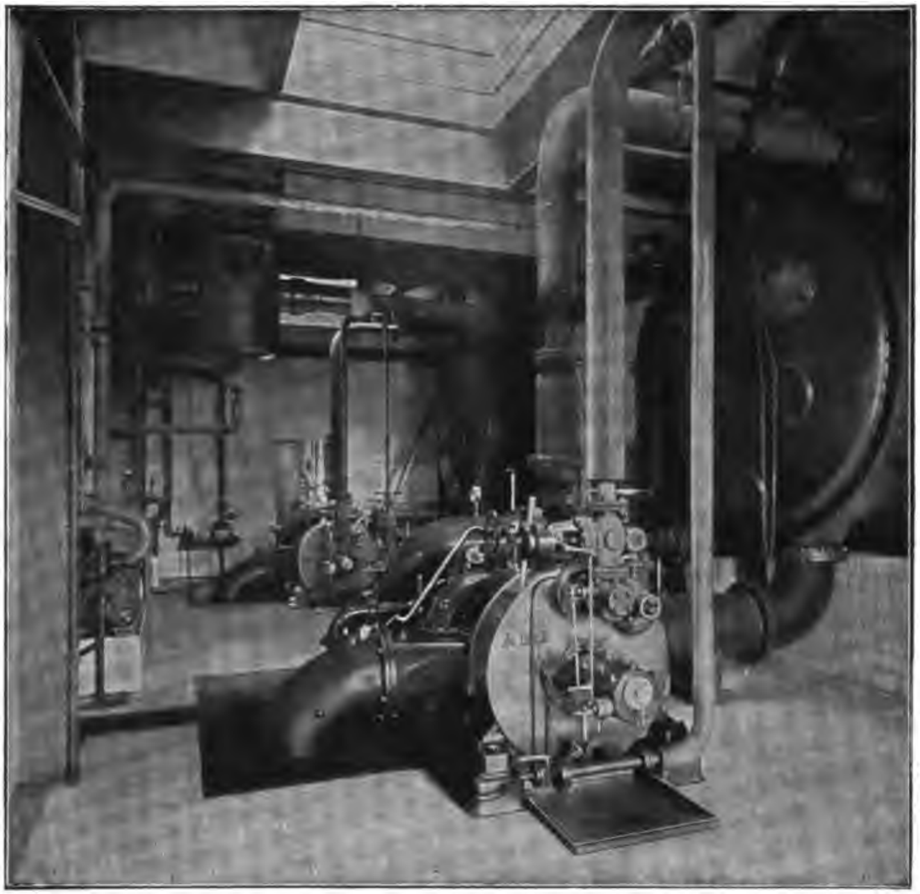
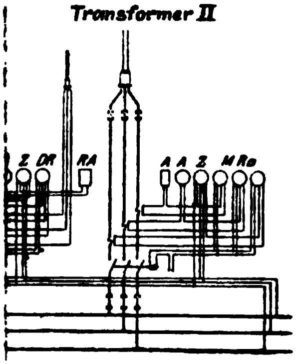


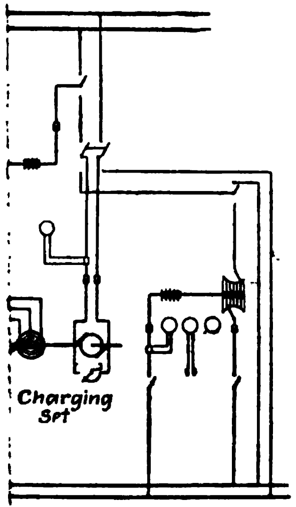
Fig. 77.—Auxiliary Pumps for the Condenser.

Owing to the omission of large coal bunkers in the boiler house the skylights there are very effective, and give a good light in the space in front of the boilers and towards the engine room wall (see Fig. 73). The walls of the engine room are lined with bright plain-coloured tiles to a height of about 9 ft. The rest of the wall is painted with a light colour. The basement is treated in a similar manner, the result being that the light coming through the openings in the engine room floor is sufficient (see Fig. 77).

The switchgear is installed in a separate building, so that direct daylight is obtainable both in the engine room and basement from the side opposite to that of the boiler house. Fig. 78 shows the air filter passage on this side of the basement. This passage forms a kind of suction chamber from which the cooling air is drawn through the air filters into the generators. The openings through which the cold air from outside passes into the passage are in the floor, and are covered by grids. Removable iron plates covering the cable trench are laid along the floor of the passage. It was considered important to obtain a convenient connection between the engine room, the basement, and the boiler house. One can pass direct from the engine room on to the boiler gangways, from which two convenient steps lead down to the boiler house. The floor of the boiler house and the basement are on the same level, and are connected by doors. The upper galleries of the water softener are, as already mentioned, at the same height as the engine room floor.

Fig. 78.—Air Filter Passage in the Engine Room Basement.





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5. SWITCHGEAR.

a. System of Connections.

The arrangement of the switchgear differs in some respects from former installations. In the first place the system of connections (Fig. 79) involves a departure from customary arrangements, inasmuch as the two ends of the distributing feeders, which are arranged as ring mains, are connected to different bus-bars. Cables 1 and 4, cables 2 and 5, cables 3 and 6, each belong to one ring. Each section is protected by the Merz-Price system. One of the two transformers is connected to each of the distributing bus-bars. The latter are joined to the double bus-bar system of the generators by group oil switches. The advantage of this arrangement lies in the fact that smaller oil switches may be used for the distributing feeders than for the machines and group switches, because, in the event of a short circuit in the cable system, only fractions of the energy come into question. In addition an increased degree of safety is obtained, since there are at least two oil switches in series for every possible short circuit.

The switch gear installation of the Märkische Electricity Works is, moreover, the first in which there is a uniform factor of safety and a uniform shape of insulators for all purposes, dividing boxes, through connections, isolating switches, etc. (Figs. 80 and 81).

The use of Duro plates for partitions, and the concentric system of wiring devised by the author, were also used here for the first time.

The generator and section oil switches are dimensioned for breaking the maximum short circuit energy, and each consists of three single pole switches. Feeders, on the other hand, are connected to three pole switches for a lower rupturing capacity.

Isolating switches are provided for connecting to sets of group bus-bars adjoining one another. Any group switches can therefore be inspected even when the group bus-bar to which it belongs is alive.

Fig. 80.—Bus-Bar Cells.

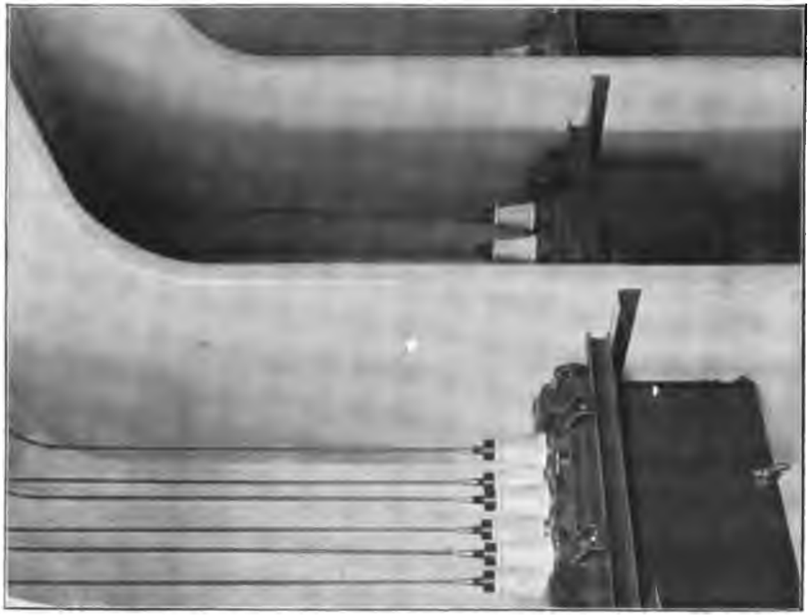

Fig. 81.—Oil Switches for Converters.

Generator and group switches are operated electrically (Fig. 82), while the feeder switches are operated by hand (Fig. 83). All switches can be released electrically.

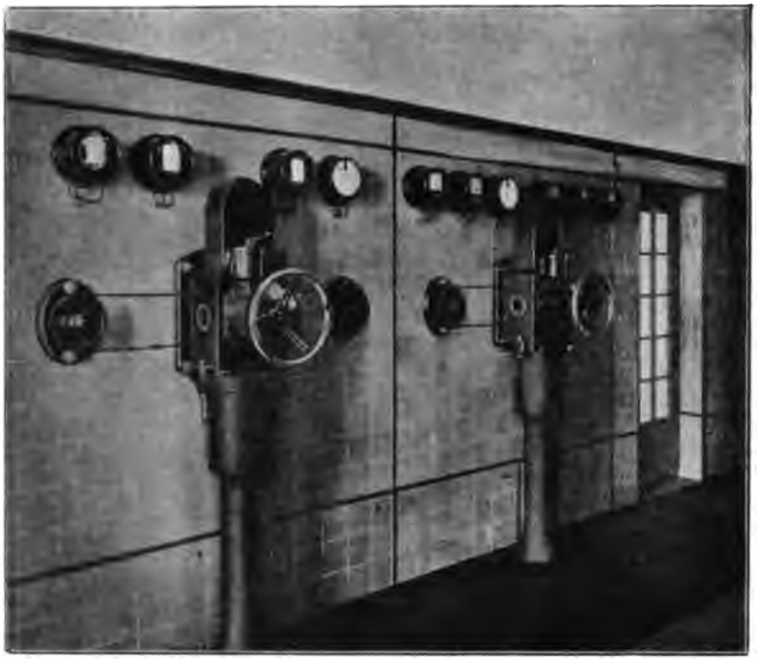

Fig. 82.—Operating Gear for Generator and Group Oil Switches.

Fig. 83.—Operating Gear for Feeder Oil Switches.

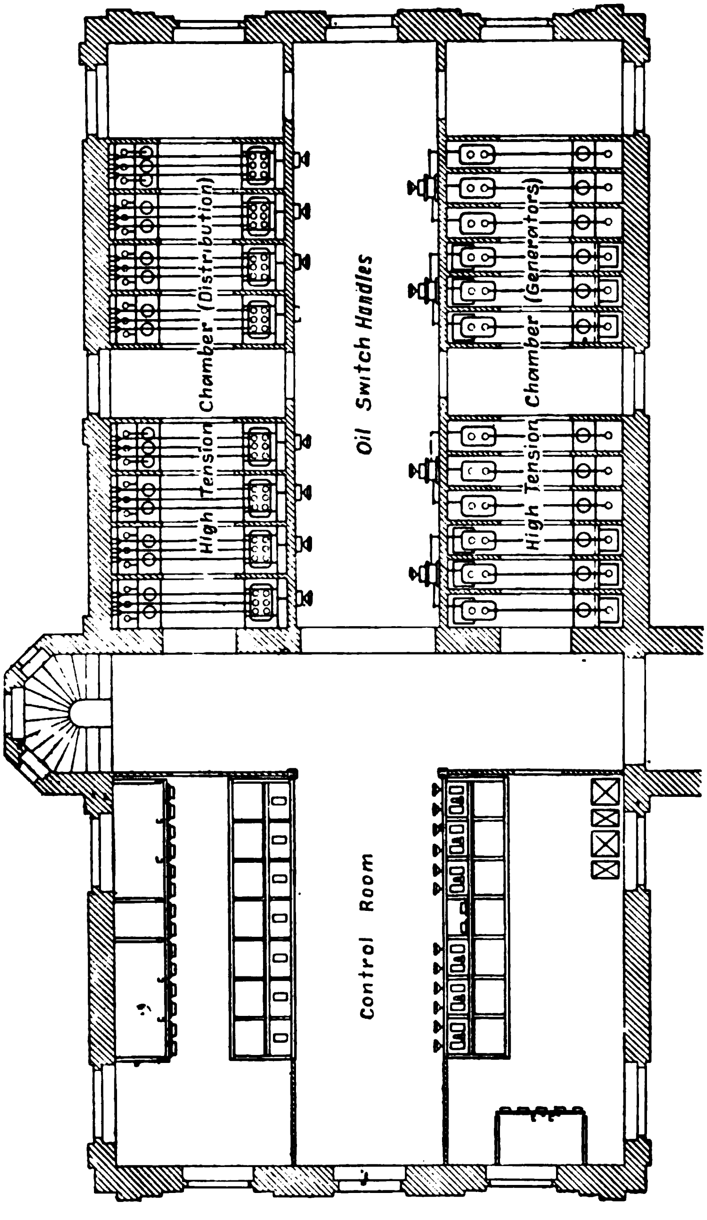

Fig. 84A.—Plan of Switch House.

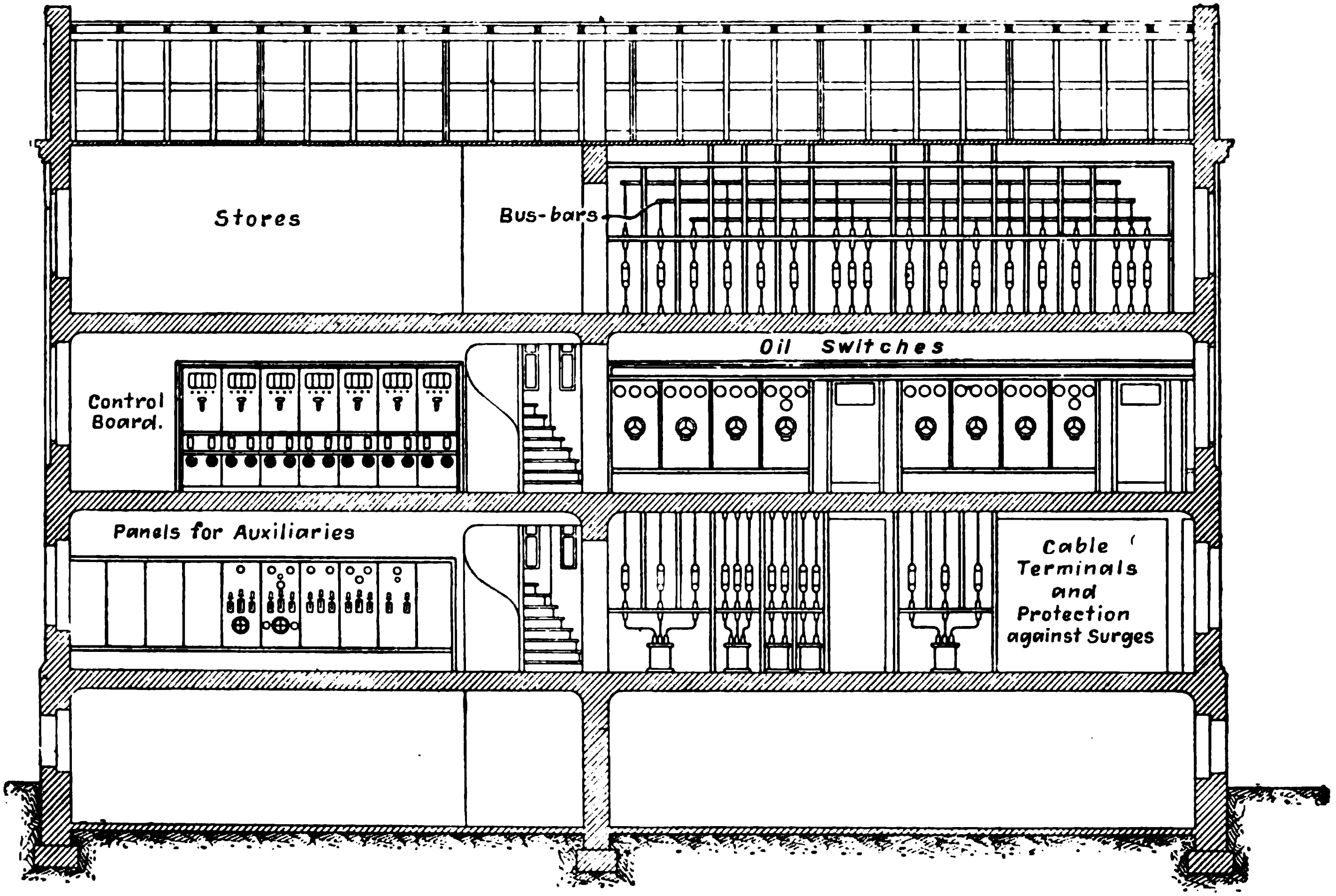

Fig. 84B.—Longitudinal Section of Switch House.

Isolating switches are provided for making each switch panel dead. The energy for the operation of the switches and for emergency lighting in the entire power house is obtained from an auxiliary battery situated on the third floor of the switch house. The batteries are charged by means of a rotary converter.

The generators are protected by reverse current and maximum current relays, the groups by time limit relays, and the feeders by the Merz-Price system.

The neutral point of each generator can be earthed by resistance, which will pass about 2½ times the amount of normal current when one of the phases is earthed. The feeder switch of a defective feeder will, therefore, be tripped by the Merz-Price relay when one phase of the cable breaks down to earth. Under ordinary working conditions only one of the generators which are in commission should be earthed. The protective arrangements against pressure surges consist of water-spray arresters and horns arranged in the usual manner.

It was considered important to devote special attention to the arrangements for measuring the energy delivered to the feeders. Each generator and each out-going feeder are provided with a meter for unbalanced loads, whereby a double check of the energy delivered is obtained.

b. ARRANGEMENT OF SWITCH HOUSE.

As already mentioned, the high-tension gear was installed in the right-hand part of the switch house. The dividing boxes and isolating switches for the generator and feeder cables, as well as the apparatus for protection against surges, are placed on the ground floor.

The current and the potential transformers are also nearly all situated on this floor.

The first floor contains two rows of oil switches, the operating gear for the latter being accessible from a central passage, which is separated from the compartments by solid walls (Figs. 82, 83, and 84A).

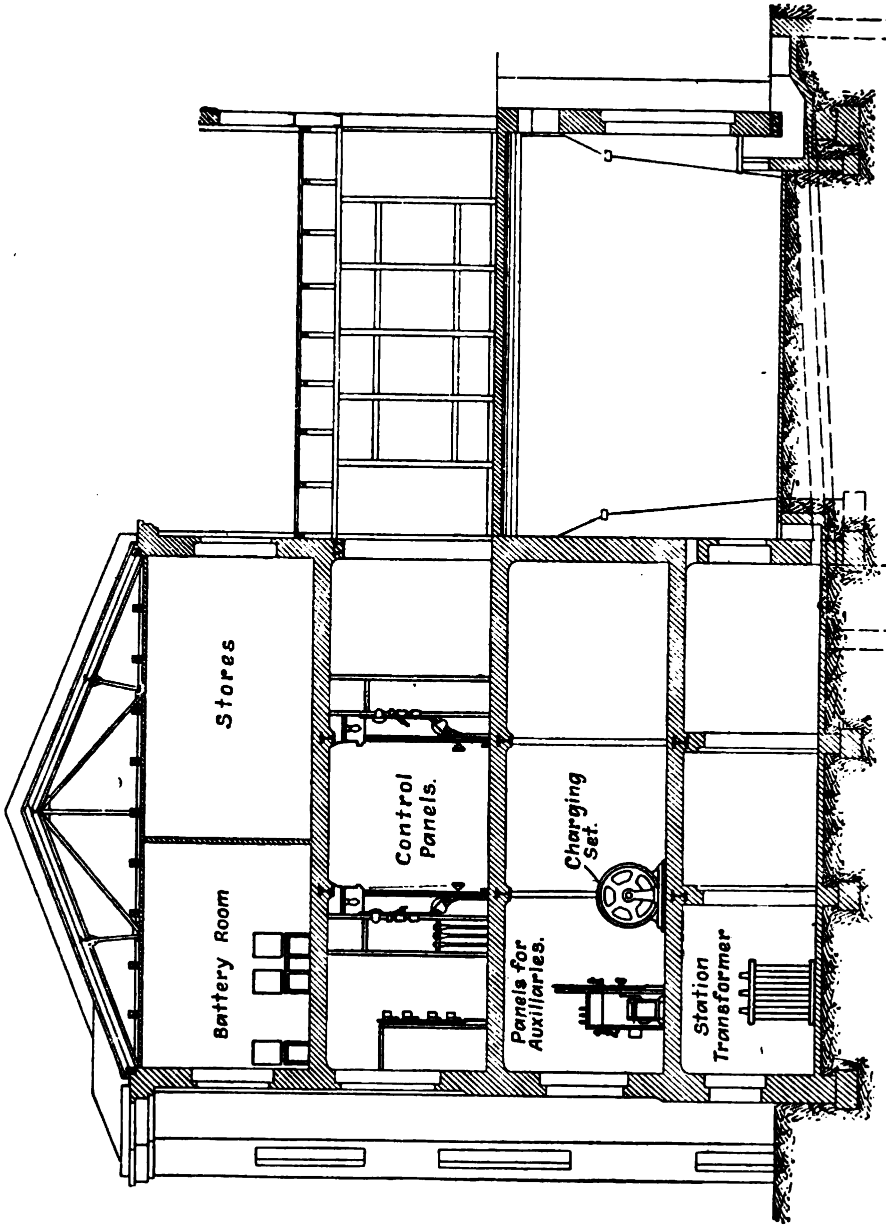

Fig. 84c.—Section, Low-Tension Part through Switch House.

The bus-bars with the necessary isolating switches are installed on the second floor. Partitions are provided to separate the phases from one another only in cases where the leads carry heavy currents. This separation of phases was omitted in the case of feeder panels, and only the panels themselves are divided. The advantage of having the generator and group panels of the same width as the feeder panels is evident from the convenient arrangement to be seen in Figs. 84A to 84D.

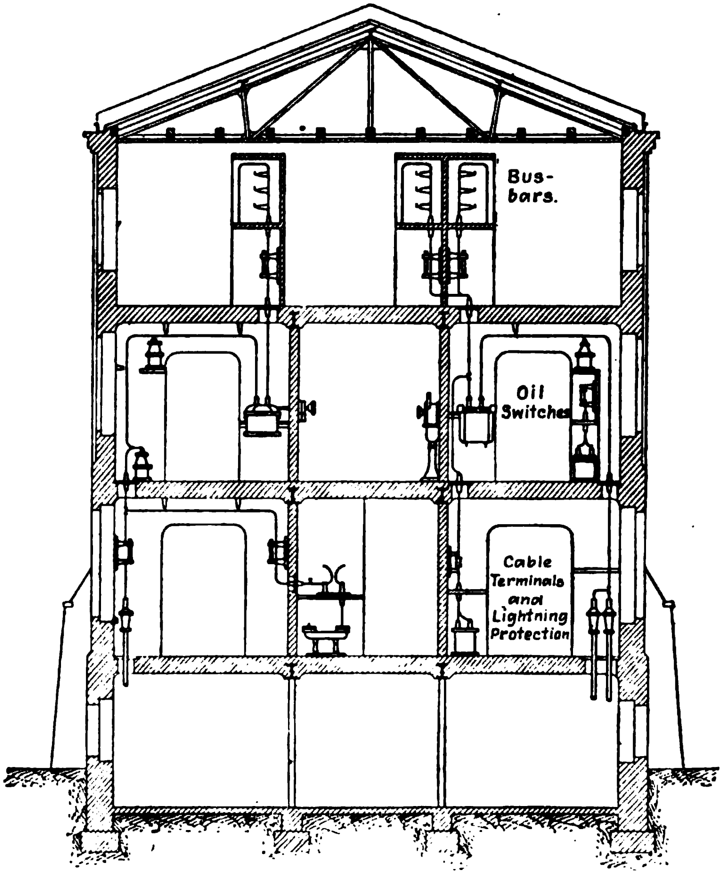

Fig. 84D. Section through High-Tension Chamber in Switch House.

All partitions and walls are constructed of fireproof plates made of Duro, which material can be cut and drilled to any size with carpenters' saws and boring bits. This is a great convenience in erection work.

The uniformity of insulators, and the system introduced for forming joints and connections, makes the installation very attractive in appearance, and adds to the facility of interchanging parts and supervising the apparatus.

The control board is situated in the central passage on the first floor. To the right of it is the operating mechanism for the oil switches, which are thus under the direct supervision of the switchboard attendant (Fig. 85).

The control board is arranged in two rows. One of these contains the Tirrill regulators and the instruments for the generators, whilst the other goes for distribution purposes. The signalling apparatus for communicating with the engine room is placed in the centre of the passage.

In the case of feeder oil switches, three single pole relays and ammeters (Fig. 83) are mounted direct on to the wall immediately above the operating gear. The instruments belonging to generator switches are in a similar position. They consist of three maximum current relays, three reverse current relays, and the group ammeter (Fig. 86).

Fig. 85.—Control Passage in Switch House.

All control leads for measuring and operating purposes are run to a terminal board protected by a detachable cover beneath the operating gear. These small leads are important, and have, therefore, been placed in a position where they can be conveniently inspected.

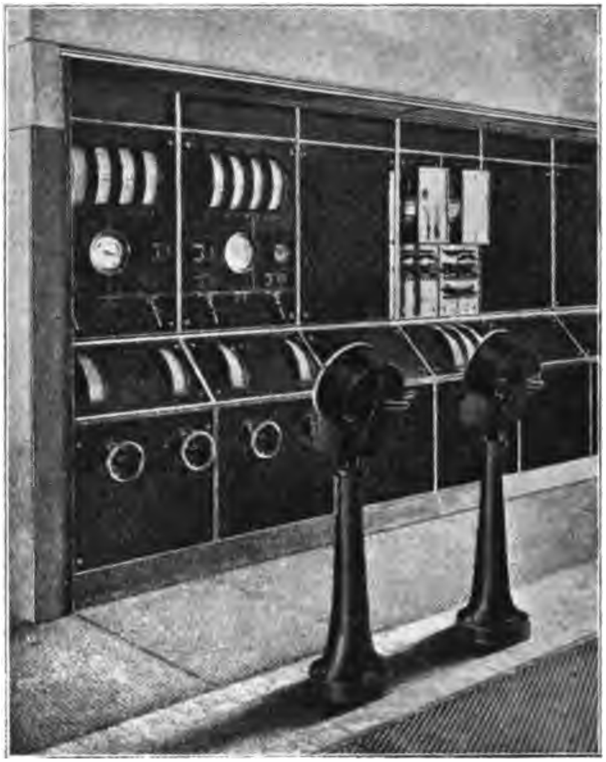

Fig. 86.—Generator Control Panel.

The power required by auxiliary plant is supplied at a pressure of 220 volts, by two three-phase transformers which have an output of 150 kw. These transformers are erected in the basement of the switch house. The distribution board for the auxiliary circuits is placed on the ground floor of the left wing of the switch house.

Each auxiliary circuit is protected by a maximum current and no-voltage relay, and the energy which flows into the circuit is recorded by meters, which will thus show the consumption in the power station itself.

6. ECONOMIC RESULTS OBTAINED IN THE MÄRKISCHE ELECTRICITY WORKS.

a. THERMAL CHARACTERISTICS.

According to what has already been stated, the coal consumption at any time, and therefore the heat consumption, will be found by a linear function of the prevailing load on the power station. If V_t equals the hourly coal consumption at any time t, and L_t is the corresponding load on the power station in kilowatts, or the output generated in kilowatt-hours during the hour in question, which is the same thing, then V_t may be represented by the equation—

$$V_t = a + b \times L_t,$$

where a and b are constants.

The total coal consumption V during any time T thus also depends in a linear direction upon the load fluctuations, which may vary during this time between the limits L_1 and L_2, and as the average output L_m during this time is—

$$L_m = \frac{1}{T}\int_0^T L_t \times dt,$$

the total coal consumption will be—

$$V = a \times T + b\int_0^T L_t \times dt,$$

and the average consumption—

$$V_m = \frac{V}{T} = a + b \times L_m.$$

The expressions for V_t and V_m are identical.

The coal consumption characteristics can thus be found from the working results if the coal consumption and the corresponding energy supplied to the feeders are determined for a given working period. If regular coal consumption measurements are made for each working day, both the coal consumption characteristics and the thermal characteristics can be deduced directly from these values. The characteristics can also be found from the figures obtained in power stations where the coal consumption is only checked once a month.

In addition to the daily statistics, monthly statistics are prepared by the management of the Märkische Electricity Works, and in Fig. 88 both daily and monthly figures are used. The daily values, which are influenced by a variety of incidental contingencies, are thus levelled up to a certain extent in the monthly statistics.

In Fig. 88 the daily coal consumption is first represented in relation to the daily energy delivered into the feeders. As the statistics extend over a period of nearly three years, the amount of work in recording the values each day would have been heavy. For this reason the relatively most favourable and most unfavourable daily values in each month were selected, so that the point along the curve will also show the maximum deviation from the curve for daily coal consumption. The latter has been drawn as a straight line from the points and represents the average. (The actual consumption values for each day, therefore, lie closer to the straight line than the points shown.) Moreover, the average monthly values have been converted to daily values, and are denoted by small circles. The values lying near the centre of the curve and deviating considerably from the latter are explained by the employment of another fuel (English coal) of lower heating value.

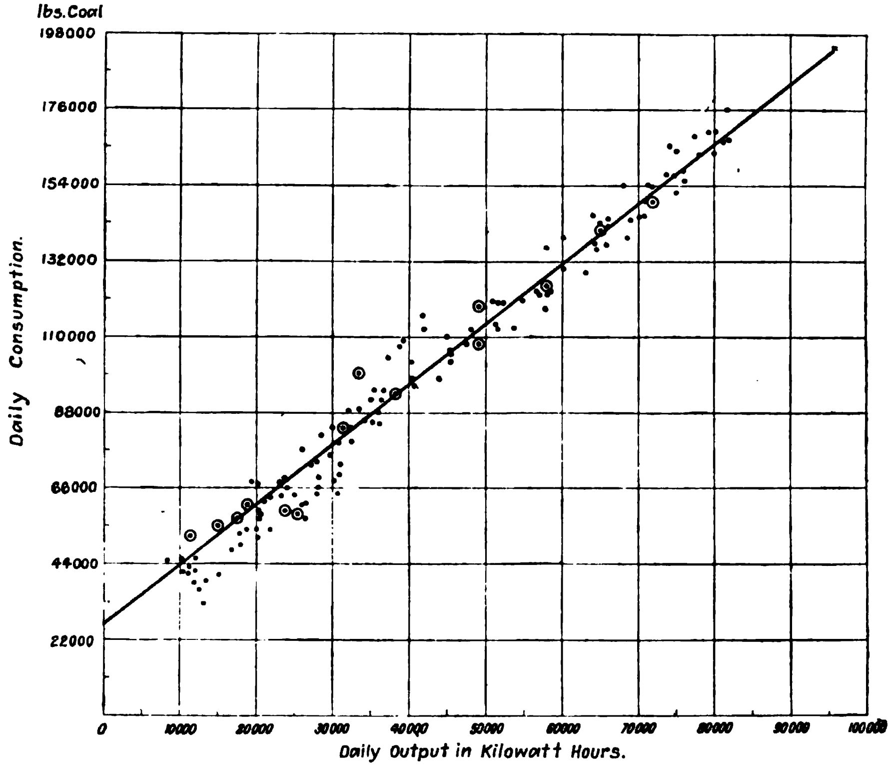

Fig. 88.—Daily Coal Consumption of the Märkische Electricity Works.

The linear nature of the curve is clearly shown; the daily coal consumption of the Märkische Electricity Works can be found with the help of this curve from the formula—

$$V = 26{,}400 + 1{\cdot}752 \times L,$$

and the hourly coal consumption, and therefore the coal characteristic, from the formula—

$$V_t = 1100 + 1{\cdot}752 \times L_t.$$

The calorific value of the coal burnt (Upper Silesian slack coal) fluctuates between 12,600 and 12,800 B.Th.U. If an average calorific value of 12,700 B.Th.U. is assumed, the thermal characteristic will be found from the formula—

$$W_t = 63{,}345{,}000 + 10{,}098 \times L_t.$$

From these formulæ the coal and heat consumption per kilowatt-hour in relation to the utility factor of the plant can be deduced. The following sets were installed in the power station before its extension: two turbo-generators with an output of 3,600 to 3,800 kw. each; the installed capacity amounts to about 7,400 kw. The utility factor is accordingly—

$$n = \frac{L_t}{7400},$$

and the coal consumption and heat consumption per kilowatt-hour respectively will be—

$$V_t = \frac{V_t}{L_t} = \frac{1100}{n \times 7400} + 1{\cdot}7512 = \frac{0{\cdot}148}{n} + 1{\cdot}752,$$

and

$$W_t = \frac{W_t}{L_t} = \frac{6{,}345{,}000}{n \times 7400} + 10{,}098 \times \frac{856}{n} + 10{,}098.$$

The following table is thus obtained for the coal consumption and heat consumption :—

Utility Factor n.	Coal Consumption, lbs. per kw.-hour.	Heat Consumption, B.Th.U. per kw.-hour.
0·5	2·050	11,810
0·4	2·127	12,240
0·3	2·251	12,960
0·2	2·495	14,391
0·1	3·245	18,684

b. Steam Consumption Characteristics.

The steam consumption may likewise be represented as a function of the average load on the power station; monthly figures reduced to the values for one day were employed for this purpose. The straight line shown in Fig. 89 is obtained from the equation :—

D (steam consumption in lbs.) $= 110{,}000 + 15{\cdot}53 \times L$; and thus the hourly steam consumption $D_t = 4576 \times 15{\cdot}53 + L_t$.

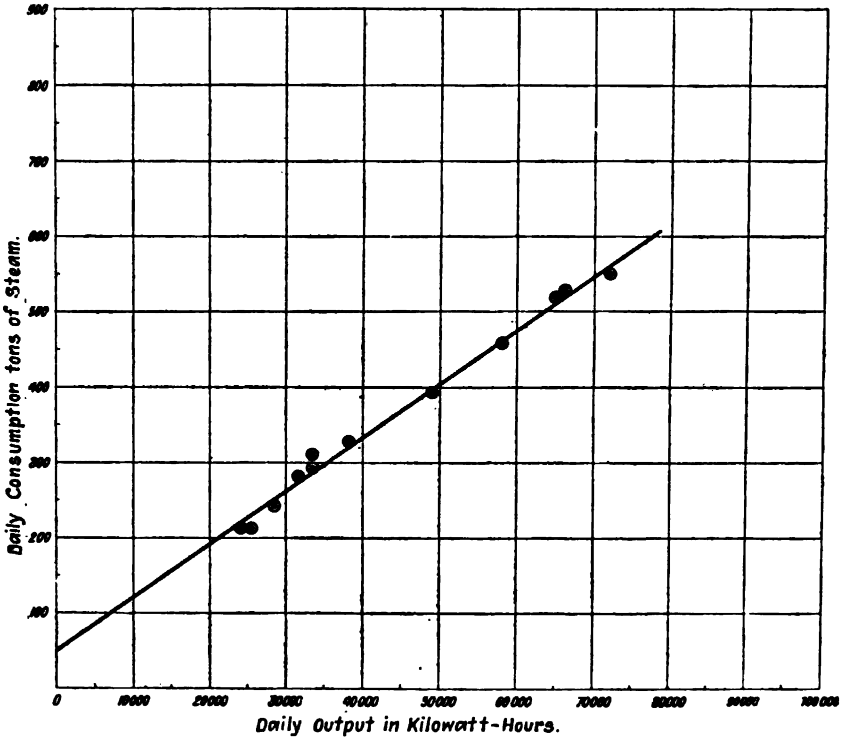

Fig. 89.—Daily Steam Consumption of the Märkische Electricity Works.

The steam consumption in relation to the utility factor of the plant is therefore :—

$$d_t = \frac{D_t}{L_t} = \frac{4576}{n \times 7400} + 15{\cdot}53 = \frac{0{\cdot}62}{n} + 15{\cdot}53.$$

The ratio of the steam consumption to the coal consumption is the figure for evaporation ; both values are combined in the accompanying table :—

Utility Factor n.	Steam Consumption per kw.-hour in lbs.	Steam Generated with 1 lb. Coal in lbs.
0·5	16·77	8·2
0·4	17·08	8·05
0·3	17·64	7·83
0·2	18·63	7·47
0·1	21·76	6·72

From the station statistics the energy consumed at the power station itself is found to be 1·5 to 2 per cent. of the energy generated; in this connection it is interesting to note that the air and lift pumps, circulating water pumps, and feed pumps are driven by steam.

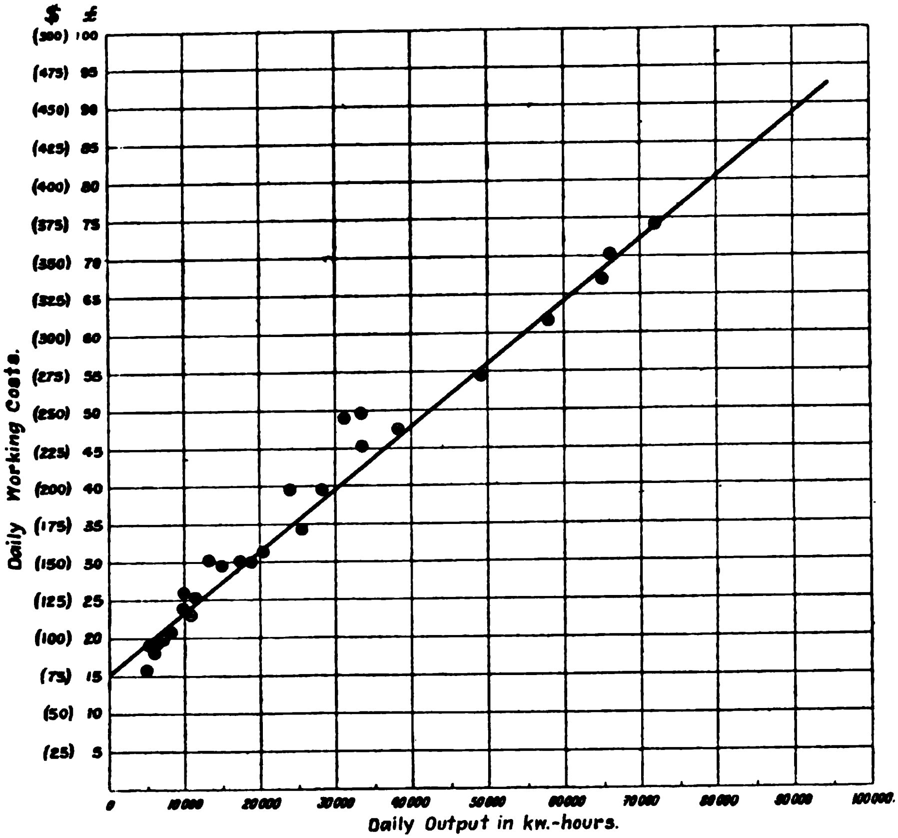

Fig. 90.—Daily Working Costs, Märkische Electricity Works.

c. Economic Characteristic.

The economic characteristic of the power station can also be obtained without difficulty from the monthly working accounts. Certain values will of course vary to a certain extent according to whether large sums for taxes, repairs, etc., happen to have been paid out during any month (Fig. 90). The monthly expenditure would agree more uniformly if the extraordinary amounts were distributed evenly throughout the year: nevertheless it is found that the hourly running costs can be expressed with sufficient accuracy from the values obtained by the formula K_t (in pence) $= 147 + 0{\cdot}192 \times L_t$ (K_t in

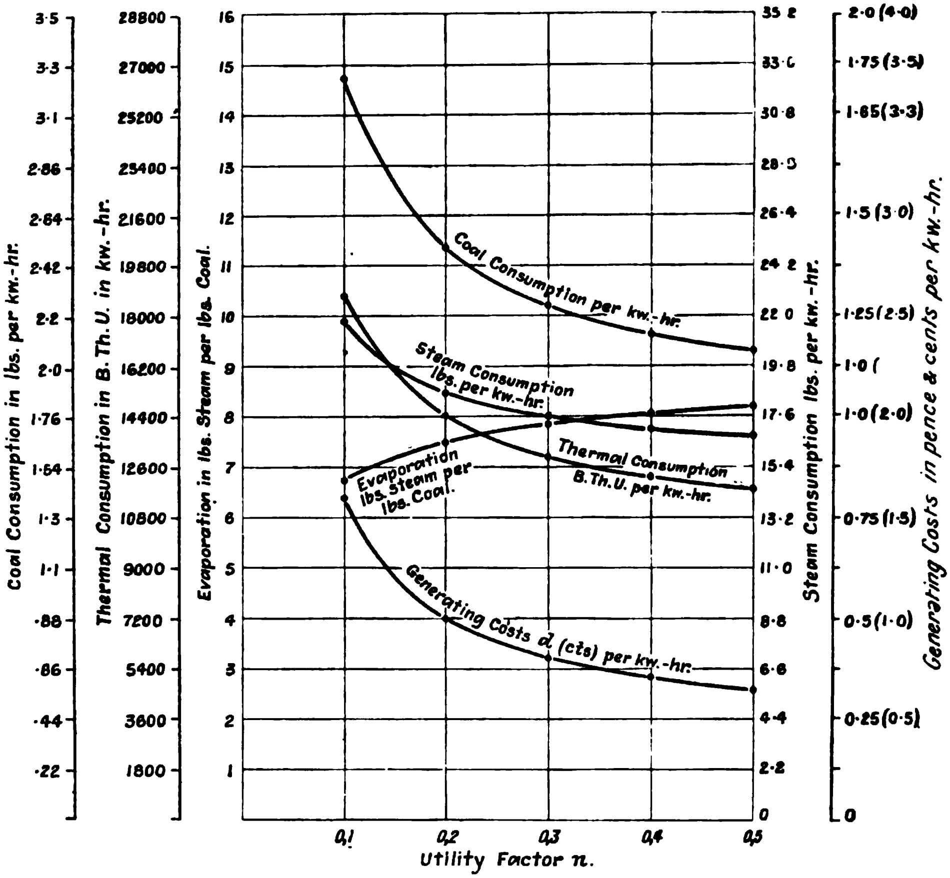

Fig. 91.—Curves for Consumption of Coal. Heat, Steam Evaporation, and Generating Costs.

cents $= 294 + 0{\cdot}384 \times L_t$). This does not include interest or amounts placed to reserve account; if 12 per cent. of the invested capital,[1] which amounts to £80,780 ($393,140) for the power station alone, is allowed for these items, the economic characteristic can be obtained from the formula:—

$$K_t = 414 + 0{\cdot}192 \times L_t \text{ in pence}$$
$$(K_t = 828 + 0{\cdot}384 \times L_t \text{ in cents}).$$

The generating costs per kilowatt-hour are thus found to be—

$$k_t = \frac{K_t}{L_t} = \frac{414}{n \times 7400} + 0{\cdot}192 = \frac{0{\cdot}056}{n} + 0{\cdot}192 \text{ (pence)},$$
$$k_t = \frac{K_t}{L_t} = \frac{828}{n \times 7400} + 0{\cdot}384 = \frac{0{\cdot}112}{n} + 0{\cdot}384 \text{ (cents)}.$$

The following table is then obtained:—

Utility Factor n.	Generating Costs per kw.-hour.	
	In Pence.	In Cents.
0·5	0·304	0·608
0·4	0·332	0·664
0·3	0·378	0·756
0·2	0·472	0·944
0·1	0·752	1·404

The coal consumption, heat consumption, water consumption, evaporating figure, and generating costs per kilowatt-hour are represented as functions of the utility factor in Fig. 91. A comparison with the example of general calculations for power stations given in the previous section shows that the actual figures obtained in the Märkische Electricity Works for heat consumption and working costs corresponds to conditions that lie between those for power station B and power station C. As the output of the sets is between

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[1] This sum includes the cost of the site (roughly £1,500 = $7,000), the regulation of the Finow Canal, the construction of a private berth, the preparation of the site, water supply arrangements, road construction, etc. The installation costs per kilowatt installed for the first section of the plant amount to:—

$$\frac{80850}{7400} = £10.\ 18s.\ (\$52{\cdot}30).$$

that given for the plant in power station B and that in power station C, one could not have expected any more favourable results, although better figures might have been obtained for heat consumption. In judging the results it should be borne in mind that the steam consumption of the steam turbines which were ordered some years ago for the Märkische Electricity Works has been improved upon with turbines of more recent designs. Nowadays steam turbines for this output would be constructed for speeds of 3,000 revs. per min., instead of for only 1,500 revs. per min. The effect would have been, apart from lower steam consumption, a smaller capital expenditure. That the difference is not due to the boiler plant is obvious from the figure given for evaporation, which now exceeds 8·2 in actual service, a figure which may be regarded as highly satisfactory. The working results compare very favourably with those obtained in other power stations of the same capacity. On completion of the extensions further improvements, both from thermo-technical and financial points of view, may be anticipated.

CHAPTER V.

FUNDAMENTAL DATA FOR THE FRAMING OF TARIFFS.

1. DETERMINATION OF PRIME COSTS.

THE generating costs may be calculated from the economic characteristic in accordance with the so-called maximum tariff, assuming that the plant without the necessary spares is fully loaded. Taking the economic characteristic of the Märkische Electricity Works as an example (Chapter IV., section 6, page 139), the annual constant costs will be $\frac{414}{240}$ penny × 8,760 = about £15,070 (\$8·28 × 8,760 = about \$72,400). When one machine is held in reserve the plant will only give an output of 3,700 kw. The costs per kilowatt per annum thus amount to $\frac{15070}{3700}$ = £4. 1s. 6d.—($\frac{72400}{3700}$ = \$19·60). With this assumption the prime costs will be £4. 1s. 6d. per kilowatt per annum, plus 193 pence per kilowatt-hour actually consumed (\$19·60, plus 385 cents); both values must be taken for the energy delivered at the power station. If it is desired, for instance, to determine the prime costs for supplying a certain class of consumers, one of whom has a peak load of 300 kw. and an annual consumption of 750,000 kw.-hours (the duration of the peak thus being 2,500 hours), the following points must be considered:—

In the first place it is necessary to ascertain what effect the peak of such consumers will have upon the power station. In this connection the maximum transmission losses and the diversity factor are of importance. With 7 per cent. for the former, and 75 per cent. for the latter, the peak for the power station will be $\frac{300 \times 0{\cdot}75}{0{\cdot}93} = 242$ kw., to which should be added the transmission losses. Supposing the maximum transmission losses of 7 per cent. to be made up as follows:—

1·0 per cent. iron losses in transforming up,
1·2 „ „ „ „ down,
4·8 „ maximum copper losses in transformers and conductors.

Total, 7·0 per cent.

The constant losses will be:—

$$\frac{2{\cdot}2}{100} \times 300 \times 8760 = \text{about } 58{,}000 \text{ kw.-hours.}$$

In order to find the variable copper losses exactly, one must know the load curve, the square of the average value of which is the determining factor for these losses. Failing this figure, the losses must be estimated; hereby one should be careful to reduce the maximum copper losses in ratio corresponding to the square of the prevailing load. If the load factor of the peak (based upon the time the consumer's plant is in operation) is known, it is not far wrong to multiply the maximum copper losses by the square of the load factor. With a working period of 3,200 hours, for instance, the load factor will be: $\frac{2500}{3200} = 0{\cdot}78$: the average copper losses are therefore $4{\cdot}8 \times 0{\cdot}78^2 =$ about 3 per cent.

Consequently 3 per cent. of 750,000 kw.-hours (= about 21,500 kw.-hours) must be added to the above constant losses, so that the total losses amount to 89,000 kw.-hours. The energy supplied by the power station is therefore:—

$$750{,}000 + 89{,}000 = 830{,}000 \text{ kw.-hours.}$$

The prime costs at the power station amount to £4. 1s. 6d. × 242 + 830,000 × 0·193 penny = about £1,650 ($19·60 × 242 + 830,000 × 0·385 cent = $7,920), or 0·478 penny (0·96 cent) per power station kilowatt-hour, and 0·528 penny (1·06 cents) per kilowatt-hour sold.

To the prime cost of the current obtained in this manner must be added the transmission costs (see Chapter II., page 80).

The results show that the generating costs are high, notwithstanding the low capital expenditure and satisfactory economic characteristic. This is due to the relation between effective output and the reserve, which is not favourable with only two generating sets. A considerable improvement is realised upon the erection of a third set, which enables the power station load to be increased to 7,400 kw. The fixed costs per annum increase by £2,500 to £3,000 (=$12,000 to $14,400), the greater part of which is required for interest and depreciation, so that the costs per kilowatt-annum fall from £4. 1s. 6d. to £2. 8s. (=$19·6 to $11·80); the additional costs are at the same time reduced to about 0·177 penny ($0·354).

The results are similar after putting into commission the fourth, fifth, and further generating sets, although the influence of later additions is not so noticeable as in the case of the first extensions to the power station.

When fixing selling prices it must be borne in mind that the assumption was that the power station operated at the most favourable (*i.e.*, full) load for the first lay-out.

The prime costs will naturally become somewhat higher for smaller loads. On the other hand, it is not essential to allow 12 per cent. for interest and depreciation from the outset; according to what has already been said, it is so important to get past the unfavourable period immediately following starting to work, by increasing the connections as rapidly as possible, that one will be inclined to arrange the prices on a basis which allows only 8 per cent. for interest and reserves. No objection can be raised to this, provided the prices are drawn up with a full knowledge of the prime costs. Unfortunately, however, there are concerns where no proper investigations are made, the calculations being merely based on the average generating costs; this naturally leads to serious errors.

2. COMPARISON BETWEEN PRIVATE SUPPLY AND SUPPLY FROM A GENERAL POWER STATION.

The cost of generating current is not the sole factor to be considered in the preparation of a tariff. The special conditions under which the consumer operates his plant must also be taken into account when deciding upon the form of tariff to be adopted and the profit to be derived. If the connections consist chiefly of industrial plants, it is indispensable in many cases to draw a comparison with the operation of the plant by heat engines, as consumers are seldom inclined to pay more for their power than it would cost them to generate themselves. This calculation is generally made by the consumer in his own interests. It is usually prepared on the assumption of an average load with average consumption figures. It yields value both for the amount of energy produced and the consumption of fuel, which are generally unfavourable with respect to the supply from a power station.

In the interests of power station supply attention must be drawn to the difference between such calculations and those made with due reference to the load factor and working conditions. The best means of illustrating this difference are to be found in the very carefully worked out comparative tables of Barth, published in Nos. 40-42 of the *Zeitschrift des Vereins deutscher Ingenieure*, 1912. Barth arbitrarily assumes the average load in small plants to be two-thirds, and in large plants three-quarters of the full output, and thereon erroneously bases his calculations for fuel, etc., ignoring the load factor entirely. It is precisely the load factor, however, which represents the fundamental value in the comparison, and one must therefore start from the load fluctuations and carry out the calculations accordingly.

A further mistake is that no advantage is taken of the most valuable property of electric energy, namely, its practically unlimited divisibility; on the contrary, it has been assumed throughout the calculations that a heat engine will simply be replaced in each instance by an electric motor of the same output. In actual practice, however, this procedure is exceptional, as it is precisely the low first cost of an electric motor that enables its advantages by an extensive subdivision of the power to be realised. A correctly prepared comparative calculation must therefore take this fact into consideration. The influence exercised by load fluctuations will now be shown.

The calculations employed for power stations (Chapter III. page 91) may be applied in principle to separate plants by taking the machines for consumers and the fuel, etc., for prime movers or electricity meters (in the case of the plant connected to power stations) as the central source of power. In making a comparison with a heat engine it should again be borne in mind that the consumption of fuel and supplies may be represented with sufficient accuracy by the formula $V_t = a \times b \times L_t$. The total consumption will then be :—

$$V = a \times t + b \times \int_{T_1}^{T_2} L_t \times dt.$$

The average load—

$$L = \frac{1}{t} \int_{T_1}^{T_2} L_t \times dt,$$

may then be found from the working diagrams of existing plants. If $L_{max.}$ is the peak load, the load factor m during the time t will be—

$$m = \frac{L}{L_{max.}} \text{ and the work } A = L \times t.$$

In order to find this value it is advisable when planning new installations to arrange the machines in groups according to their probable utility factor, and then take the maximum amount of power required by each group as a basis to work upon. If, for example, the maximum amount of power required by Group I. is L, and the hours of full use for this group is t_1, then the annual consumption of power will be $A_1 = L_1 \times t_1$. (It is also possible to work in the reverse direction, starting from the probable power consumption A_1, and finding the operating period t_1 in hours from the known output L_1.) The same method of procedure is adopted for a second and third group, and so forth; the total power used by the installation will then be—

$$A^1 = L^1 \times t = L_1 \times t_1 + L_2 \times t_2 + L_3 \times t_3 \ldots$$

If t is the working period of the installation, then L^1 will represent the average load, which may be defined as the average "useful" load.

According to the foregoing it is obtained from the formula—

$$L^1 = \frac{L_1 \times t_1 + L_2 \times t_2 + L_3 \times t_3}{t}.$$

Supposing, for example, the installation is supplied with energy from a single prime mover, then in order to find the amount of work done by this engine it becomes necessary to include the transmission losses. Assuming the average losses in transmission to be L_{T_r}, then the power per annum consumed in transmission will be $A_{t_r} = L_{T_r} \times t$, and the total output of the prime mover—

$$\begin{aligned} A &= L_{T_r} \times t + L^1 \times t \\ &= L_{T_r} \times t + L_1 \times t_1 + L_2 \times t_2 \ . \ . \ . \end{aligned}$$

The consumption in fuel, etc., per annum will then be—

$$V = a \times t + b(L_{T_r} \times t + L_1 \times t_1 + L_2 \times t_2 \ . \ . \ .)$$

A simple example will help to elucidate the above. For an installation requiring a maximum power of 150 H.P., and having a working period of 3,000 hours, Barth has found that the most satisfactory prime mover is a Diesel engine. The values calculated by him are given herewith :—

TABLE 32.[1]

150 *H.P. Tar Oil Diesel Engine* (*vertical type,* 190 *revs. per min.*).

Consumption of motor oil (tar oil) at ¾ load, ·484 *lb. per H.P.-hour.*

„ *light oil at ¾ load,* ·028 *lb. per H.P.-hour.*

	£	s.	d.	$
Capital expenditure—				
Price of the engine with all accessories - -	2,100	0	0	(10,000)
Engine room (7s. 3d. ($1·70) per square foot area) -	150	0	0	(720)
Working costs for 3,000 hours of full use per annum—				
4½ per cent. interest on £2,100 ($10,000) - -	94	10	0	(450)
Depreciation and maintenance of engine, 8 per cent. -	168	0	0	(800)
4½ per cent. interest, 2½ per cent. depreciation, ½ per cent. maintenance = 7½ per cent. on cost of buildings	11	5	0	(54)
Oil and waste - - - - - - - -	40	0	0	(192)
Cost of water, including cooling water - - -	27	0	0	(130)
Attendance - - - - - - - -	50	0	0	(240)
Cost of ignition oil, at a gas oil price, including freight of 5s. 6d. per 100 lbs. - - - - -	28	10	0	(137)
Cost of fuel, at a tar oil price, including freight of—				
1s. 10d. per 100 lbs. - - - - - -	145	10	0	(700)
2s. 3d. per 100 lbs. - - - - - -	182	0	0	(874)

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[1] *Zeitschrift des Vereins deutscher Ingenieure,* 1912, pp. 1610, 1650, 1689.

	£	s.	d.	$
Total costs per annum, with a tar oil price, including freight of—				
1s. 10d. per 100 lbs.	562	0	0	(2,720)
2s. 3d. per 100 lbs.	598	0	0	(2,912)
Cost per H.P.-hour, with a tar oil price, including freight of—				
1s. 10d. per 100 lbs.	·399d.			(0·80)
2s. 3d. per 100 lbs.	·422d.			(0·86)

Table 42.

150 *H.P. Electric Motor* (210 *volts*, 59 *periods per second*, 975 *revs. per minute*).

Consumption at ¾ load, 0·805 *kw. per H.P.*

	£	s.	d.	$
Capital expenditure—				
Price of a three-phase motor with all accessories	240	0	0	(1,152)
Engine room (7s. 6d. ($1·80) per square foot area)	17	10	0	(84)
Working costs for an operating period of 3,000 hours per annum, 4½ per cent. interest, 6 per cent. depreciation and maintenance = 10½ per cent.	25	4	0	(120)
4½ per cent. interest, 2½ per cent. depreciation, ½ per cent. maintenance = 7½ per cent. on cost of building	1	6	0	(6·30)
Oil and waste	0	7	0	(1·75)
Attendance	0	15	0	(3·60)
Meter rent	1	16	0	(8·65)
Cost of energy at a price of—				
·6d. per kw.-hour	679	4	0	(3,270)
·95d. per kw.-hour	1,076	15	0	(5,170)
1·2d. per kw.-hour	1,358	9	0	(6,500)
Total costs per annum at a price of—				
·6d. per kw.-hour	708	12	0	(3,411·26)
·95d. per kw.-hour	1,108	3	0	(5,311·26)
1·2d. per kw.-hour	1,387	17	0	(6,711·26)
Costs per H.P.-hour at a price of—				
·6d. per kw.-hour	·494d.			(1 cent)
·95d. per kw.-hour	·776d.			(1·6 „)
1·2d. per kw.-hour	·964d.			(2·4 „)

If the estimate is based on a tar oil price of 2s. 6d., and a price of ·8d. per kilowatt-hour, the cost of running the plant with a Diesel engine will be £592. 10s. ($2,840), and with an electric drive £979. 8s. ($4,700) per annum; the electric drive is therefore 65 per cent. more expensive.

This comparison should be correct for all installations having a consumption of 150 H.P., and with 3,000 hours of full use per annum. The failure of taking the load factor into account, which in most cases is estimated too high at 75 per cent. (three-quarter load), and the further mistake involved by calculating an amount of fuel consumption corresponding to the average load leads to incorrect results. The error is increased by basing the comparison not on the actual work the consumer wants done, namely, the useful horse-power per hour at the shaft of his machines, but the power developed by the prime movers.

The following calculations will explain the above more fully. Let us take as an example the power plant of a machine factory working ten hours a day during 300 days; it will therefore be 3,000. The machines employed are driven from three transmission shafts[1] only, between which the power is divided fairly equally, so that each shaft transmits a maximum of approximately 50 H.P. The first line shafting drives several large machines, each taking between 5 and 15 H.P.; the second shaft drives machines requiring 2 to 5 H.P. each, whilst all smaller machines are driven from the third. The full use of the first group (t_1), based on the maximum power consumption, is 500 hours, that of the second group (t_2) 1,000 hours, and that of the third group (t_3) 2,000 hours.

The average losses of the three transmission shafts, together with the gearing they drive, may be taken as 8 per cent. each of the maximum output transmitted (4 H.P. each), and the losses in transmitting the power from the prime mover to the three shafts may be assessed at 4 per cent., viz., 6 H.P., so that the total average transmission losses will be 18 H.P., or 12 per cent. of the maximum output. The consumption of the machines driven from the line shafting is—

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[1] Factories of this class have, as a rule, a larger number of transmission shafts.

For Group I. - - - -	50 × 500 =	25,000	H.P.-hours
For Group II. - - - -	50 × 1,000 =	50,000	„
For Group III. - - - -	50 × 2,000 =	100,000	„
		175,000	H.P.-hours
During a working period of 3,000 hours the transmission losses amount to -	18 × 3,000 =	54,000	„
Total - - - - - -		229,000	H.P.-hours

The full use referred to the total connections is—

$$\frac{229{,}000}{150} = 1530 \text{ hours};$$

the load factor is—

$$\frac{229{,}000}{150 \times 3000} = 0{\cdot}51.$$

(This figure is in accordance with actual experience; in small machine factories connected to power stations and working 3,000 hours per annum one can assume a full use of 1,400 to 1,500 hours based on the total connections.)

Where the prime mover is a 150 H.P. Diesel engine, the fuel consumption at full load and per effective horse-power-hour (with a margin of 10 per cent.), according to the Maschinenfabrik Augsburg-Nürnberg, will be 0·462 lb. with tar oil; at three-quarter load, 0·473 lb.; at half load, 0·539 lb.; at a quarter load, 0·682 lb.; to the foregoing must be added the consumption of ignition oil (18,000 B.Th.U.) of 3·3 lbs. per hour, the latter being independent of the load.

If the total consumption for every load resulting from these values is plotted as dependent upon the load, the consumption at the average load will be found from the formula $V = 15{\cdot}4 + 0{\cdot}378 \times L_t$ (lbs.) (the value for quarter load is somewhat lower, while that for fuel load is somewhat higher than the values represented by these straight line expressions); to the foregoing must be added a consumption of 3·3 lbs. for ignition oil, which is independent of the load.

One must therefore insert in the calculations $a = 15{\cdot}4$ lbs. of tar oil + 3·3 lbs. of ignition oil. We then have—

$$V = a + t + b(L_{T_r} \times t + L_1 \times t_1 + L_2 \times t_2 \ . \ . \ .)$$

$$V = 15{\cdot}4 \times 3{,}000 \text{ lbs. tar oil} + 3{\cdot}3 \times 3{,}000 \text{ lbs. ignition oil} + 0{\cdot}378 \times 229{,}000 \text{ lbs. tar oil.}$$

$$V = 132{,}630 \text{ lbs. tar oil} + 9{,}900 \text{ lbs. ignition oil.}$$

If the price of tar oil is taken at 2s. per 100 lbs., and ignition oil at 5s. 5d. per 100 lbs., delivered free at the works, the costs for fuel will be—

	£	s.	d.	$
1328·8 × 2 =	132	14	6	(646)
+ 99 × 5·45 =	26	18	6	(130)
Total -	159	12	0	(776)

The costs for attendance are estimated by Barth in this instance at £50 ($240). One must, however, consider that the machines are worked 3,000 hours, and that the engine driver will have to work three-quarters of an hour every day for starting and stopping the engine four times daily, including lubrication, etc., and that it will also be essential from time to time to carry out extra work (such as the cleaning of cylinders, reseating of valves, etc.) which must be done when the plant is out of commission. To account for this it is necessary to allow for a working period of 3,300 hours, and for this class of work wages at the rate of 6d. to 7d. an hour are certainly not too high. At the rate of 6d. an hour a sum of £90 ($433) is obtained. Even should the driver be employed on other work, while the plant is in operation, such additional work is not very great in value; it will, as a rule, consist of attending to transmission shafting and gear, and should be amply covered by a sum of £20 ($96) per annum, so that a sum at least of £70 ($337) per annum still remains for the care of the prime mover.

When making calculations for the same plant, but with electric drive for purposes of comparison, the following points must be considered.

The machines in Group I., the power consumption of which lies between 5 and 15 H.P., as well as those of Group II., with a power consumption between 2 and 5 H.P., would certainly be equipped for an individual drive, while for the smaller machines in Group III. group driving by means of a 50 H.P. electric motor would appear recommendable. The work done by motors between 5 and 15 H.P. (Group I.) may be found from the formula—

$$V = 0{\cdot}07 \times L_{max.} + 1{\cdot}06 \times L_t$$

Where $L_{max.}$ represents the maximum output, and
L_t the load on the motor in H.P. at any time.

For motors from 2 to 5 H.P. we also have the formula—

$$V = 0{\cdot}08 \times L_{max.} + 1{\cdot}07 \times L_t$$

and for 50 H.P. motors—

$$V = 0{\cdot}05 \times L_{max.} + 1{\cdot}04 \times L_t.$$

The losses in transmission between motor and machine may be assessed at 5 per cent. of the maximum output; the losses in the line shafting for Group III. at 4 H.P., and those for the transmission of power from the 50 H.P. electric motor to the shafting at 4 per cent., the same as those in the case of the prime mover. We then obtain the following values:—

Transmission losses for the machines in Group I.—

5 per cent. of 50 H.P. - - - -	$= 2{\cdot}5$ H.P.
Constant H.P. used by electric motors installed $= 0{\cdot}07 \times 50 = $	$3{\cdot}5$ „
Total - - -	$6{\cdot}0$ H.P.

The full use averaged 500 hours, but the period of use will be somewhat higher, since machines with an individual drive are not always fully loaded; for this purpose an addition of 20 per cent. will be ample. The losses will then be—

$6 \times 500 \times 1{\cdot}2 =$	3,600 H.P.-hours
To this must be added the work done by electric motors - - $= 25{,}000 \times 1{\cdot}06 =$	26,500 „
Total - - -	30,100 H.P.-hours

Similarly for Group II.—

$$2{\cdot}5 + 0{\cdot}08 \times 50 = 6{\cdot}5 \text{ H.P.}$$

$$6{\cdot}5 \times 1200 + 50{,}000 \times 1{\cdot}07 = 61{,}300 \text{ H.P.-hours.}$$

Group III. (a full use, 2,000 hours and 3,000 working hours)—

$$4 + 2 + 0{\cdot}05 \times 50 = 8{\cdot}5 \text{ H.P.}$$

$$8{\cdot}5 \times 3000 + 100{,}000 \times 1{\cdot}04 = 129{,}500 \text{ H.P.-hours}$$

Total work - 220,900 H.P.-hours

A loss of energy of 1·5 per cent. in conductors must also be added, so that the total consumption of power at the meter will be 224,200 H.P.-hours or 165,000 kw.-hours.

If a price of £3 ($14·40) per kw. of maximum demand

(150 H.P. = 110 kw.) + 0·36 penny (0·72 cent) for the actual kilowatt-hour consumed is charged, the consumer would have to pay—

	£	s.	d.	$
110 × £3 =	330	0	0	(1,606)
$165{,}000 \times \frac{0·36}{240} =$	247	10	0	(1,202)
	577	10	0	(2,808)

or $\frac{577}{165{,}000} \times 240$ = about 0·84 penny (1·68 cents) per kilowatt-hour.

The remaining figures in Barth's comparative calculation we will use as they stand, although the interest on invested capital (4½ per cent.) is not really high enough for present-day conditions in industrial works.

Our comparison is as follows:—

(a) *For a* 150 *H.P. Tar Oil Diesel Engine.*

	£	s.	d.	$
4½ per cent. interest on £2,100 ($10,000)	94	10	0	(457)
Depreciation and maintenance of engine, 8 per cent.	168	0	0	(800)
4½ per cent. interest, 2½ per cent. depreciation, ½ per cent. maintenance = 7½ per cent. on the cost of buildings	11	5	0	(54)
Oil and waste	40	0	0	(192)
Water, including cooling water	27	0	0	(130)
Attendance	70	0	0	(336)
Fuel at a tar oil price, including freight or 2s. per 100 lbs.	159	17	0	(766)
	570	12	0	(2,735)

Cost of 1 H.P.-hour - $\frac{570·6}{175{,}000} \times 240 = 0·782$ penny (1·56 cents).

(b) *For Electric Motors having a Combined Output of* 150 *H.P.*

	£	s.	d.	$
4½ per cent. interest, 6 per cent. depreciation and maintenance = 10½ per cent. on £240 ($1,152)	25	4	0	(120·96)
4½ per cent. interest, 2½ per cent. depreciation, ½ per cent. maintenance = 7½ per cent. on the cost of buildings	1	6	0	(6·30)
Oil and waste	0	7	0	(1·75)
Attendance	0	15	0	(3·60)
Meter rent	1	16	0	(8·65)
Electrical energy	577	10	0	(2,772)
	606	18	0	(2,913·26)

Cost of 1 H.P.-hour - $\frac{606·9 \times 240}{175{,}000} = 0·83$ penny (1·67 cents).

If instead of 4½ per cent. interest, 6 per cent. is allowed, the working costs in the case of a Diesel engine become £609. 7s. ($2,883·80), and in the case of electric motors £610. 14s. ($2,931·80).

It may be argued against this comparison that the costs for interest, depreciation, and maintenance of the electric plant have been estimated too low, since the employment of several electric motors, notwithstanding the fact that they have approximately the same total output, is somewhat more expensive than the installation of a single motor. Against this one may say, however, that two transmission shafts, as well as the necessary intermediate gearing and the transmission drive of the Diesel engine for two shafts, can be dispensed with. On the other hand, the transmission drives from the motors to the machines must be included, but they do not entail very heavy costs; furthermore, large machines can always be adapted for individual drive without difficulty. Any small surplus remaining may be regarded as adequately compensated by the advantages gained in the abolition of shafting, counter-shafting, and gearing, and the danger connected therewith.

COMPARISON OF THE RESULTS OBTAINED.

	Load Factor.	Working Costs per Annum.					
		Diesel Engine, 150 H.P.			Electric Motor, 150 H.P.		
		£	s.	$	£	s.	$
Barth - - - - - - -	0·75	592	10	(2,840)	979	8	(4,700)
Example with 4½ per cent. interest -	0·51	570	12	(2,728)	606	18	(2,913·26)
„ „ 6 „ „ -	0·51	609	7	(2,888·80)	610	14	(2,931·80)

The foregoing calculations require to be supplemented before one is able to decide which is the most suitable system of driving.

The assumption made in the comparison that the output of 150 H.P. will just be sufficient for the service, and that the peak load is not appreciably higher or lower, forms the exception in plants of the kind under consideration. As a rule, the power user orders a prime mover giving 20 to 30 per cent. more power than he requires at the time of purchase, with a view to the future development of his works. If the economic development is checked by unforeseen obstacles, due to unfavourable market conditions or other circumstances, the plant may but slowly adapt itself to the output of the prime mover; until this occurs the prime mover will be loaded less favourably than at first assumed. The same thing occurs when it is necessary to cut down the work owing to bad markets or for other reasons; in this case also a machine which is otherwise working under a satisfactory load may possibly have to run for a shorter working period or with an inferior load factor. Again, in the case of normal development, a time will be reached when the output no longer suffices for 3,000 factory hours. As long as the increased demands can be met by working overtime, this way out of the difficulty will be followed; eventually, however, such means will become exhausted, and extensions to the power plant may become necessary. When the plant is duplicated by the addition of another 150 H.P. engine, which at once becomes well loaded, then the working conditions will remain practically the same. If, however, as is probably the case, the demand for additional power is small at first, the comparison will not be in favour of the engine.

To give an approximate idea of the effect of a heavy or light load on the plant, calculations are given for the following cases:—

1. The output of the machines connected up is reduced by 20 per cent.
2. During one year it is necessary to work with half of the machines for 1,000 hours' overtime.

In case 1 the power consumed will be—

For Group I. - - -	20,000 H.P.-hours
For Group II. - - - -	40,000 ,,
For Group III. - - - -	80,000 ,,
	140,000 H.P.-hours
The transmission losses remain unaltered	54,000 ,,
	194,000 H.P.-hours

The fuel consumption will be—

V = 15·4 × 3,000 lbs. tar oil + 3·3 × 3,000 lbs. ignition oil + 0·378 × 194,000 lbs. tar oil

= 119,532 lbs. tar oil + 9,900 lbs. ignition oil, the price of which will amount to £146 ($720); that is to say, the cost of running the plant will be £160 - £146 = £14 ($68).

For an electric drive the comparison will be as follows:—

Group I.

Losses, 5 per cent. of 40 H.P.	= 2 H.P.	
Constant consumption of motors, 0·07 × 40	= 2·8 „	
Total	4·8 H.P.	
During 600 hours		2,880 H.P.-hours
Additional consumption, 2,000 × 1·6		21,200 „
Total		24,080 H.P.-hours

Group II.

Losses likewise	= 2 H.P.	
+ 0·08 × 40	= 3·2 „	
Total	5·2 H.P.	
During 1,200 hours		6,240 H.P.-hours
Additional consumption, 40,000 × 1·07		42,800 „
Total		49,040 H.P.-hours

Group III.

The constant losses are the same as before:—

8·5 × 3,000 = 25,500 H.P.-hours.

Additional consumption, 80,000 × 1·04 = 83,200 H.P.-hours	108,700 H.P.-hours
Total	181,820 H.P.-hours
1 per cent. losses in conductor	1,800 „
Total	183,620 H.P.-hours

= 135,000 kw.-hours.

The peak load of 110 kw. is also reduced 20 per cent., and amounts to 87 kw.

The cost of electrical energy will then be :—

	£	s.	$
87 × £3 - - - - =	261	0	(1,252·80)
+ 135,000 kw.-hours at 0·36 penny =	202	10	(972)
Total - - -	463	10	(2,224·80)

Compared with the former cost of £577. 10s. ($2,808), a reduction of £114 ($584) is effected in expenditure on energy, that is to say, the electric drive is about £64 ($324) cheaper in this case than a Diesel engine drive.

In case 2 (1,000 hours' overtime with half load) the consumption of the machine during overtime will be one-sixth of the annual consumption (1,000 hours instead of 3,000, half load instead of full load), namely $\frac{175,000}{6} = 29,200$ H.P.-hours.

The transmission losses remain unaltered, they will be 18 H.P. × 1,000 hours = 18,000 H.P.-hours; the output of the Diesel engine will then be 47,200 H.P.-hours.

The consumption of fuel amounts to

$V = 15{\cdot}4 \times 1,000$ lbs. tar oil + $3{\cdot}3 \times 1,000$ lbs. ignition oil + $0{\cdot}378 \times 47,200$ lbs. tar oil = 36,540 lbs. tar oil + 3,300 lbs. ignition oil.

	£	s.	d.	$
The working costs amount to - - - -	42	12	0	(205)
Another 1,000 hours at 6d. each must be allowed for attendance - - - - - -	25	0	0	(120)
The additional costs thus amount to - - -	67	12	0	(325)

Electric Drive

For Groups I. and II. the consumption and constant losses are also reduced to one-sixth, viz. :—

Group I.	$\frac{30,100}{6}$	= 5,020 H.P.-hours	5,020 H.P.-hours
Group II.	$\frac{61,300}{6}$	= 10,220 ,,	10,220 ,,
Group III., useful load	$\frac{100,000}{6}$	= 16,670 ,,	...
Constant loses, 8·5 × 1,000		= 8,500 ,,	...
Additional output, 16,670 × 1·04		= 17,350 ,,	25,850 H.P.-hours
The total consumption is thus			41,090 H.P.-hours
Line losses, ½ per cent.			205 ,,
Total			41,295 H.P.-hours

This is equal to 30,400 kw.-hours, chargeable at the rate of 0·36 penny; the cost for working overtime will thus be £45. 12s. ($219), or approximately £20 ($96) less than for the Diesel engine service.

COMPUTATION OF INTEREST.

From the above and former calculations it will be seen that the percentage rate of interest taken on capital expenditure exercises a considerable influence on the result. The question arises whether a rate of interest of 4½ per cent. is sufficient, or whether the manufacturer, from general business interests, will not find it preferable in certain instances to pay a higher price for electrical energy and thereby avoid the investment of further capital on an engine.

The nature of the industrial service is of decisive influence here, as the manufacturer must consider whether the capital invested in his own business cannot be made to give a better return than that represented by 4½ per cent. Should the business itself give a return of 4½ per cent. or less, the manufacturer will even then not feel inclined to invest money in power plant, but will prefer to utilise the means at his disposal for developing his business.

The rate of interest in individual cases must be left to the manufacturer's judgment; he must ask himself whether he is prepared to incur an extra expense which, under the most favourable circumstances, would not yield more than 6 or 6½ per cent.

SUMMARY.

From the foregoing investigations it follows that comparative calculations for determining the form of energy to be adopted should proceed on similar lines to those introduced for comparing power stations. In making comparisons the following points should be observed:—

1. Load factor. This must be ascertained according to the nature of the work for which the electrical energy is required.
2. Working hours.
3. The consumption should be determined from the fuel characteristic of the prime movers and not from the consumption at the average load, which is usually estimated incorrectly.
4. In large power plants the diversity factor must be taken into consideration, and the hours of full use also, when several machines are erected.
5. The interest to be charged on capital expenditure must be determined in each case; $5\frac{1}{2}$ per cent. should be the minimum.
6. The comparative calculations should as a rule include conditions in which the actual load is smaller than may be assumed under ordinary circumstances.
7. The influence of overtime on the working costs must be ascertained.
8. In cases where early progressive development may be expected, the effect of an increase in the power demand must be considered. The following additional points refer to comparisons with a supply from a power station.
9. The output follows the prevailing demand. In cases where the power is somewhat small at the outset, small motors may be installed; when more power is required later on, the increased demand can be met without difficulty.
10. One must consider the loss in revenue that is likely to occur in the event of breakdowns. Power stations are generally provided with spare boilers and generating sets, so that a reduced supply from here is of the rarest occurrence. Arrangements are generally made

for some reserve also in the distributing network. Motors for low pressures very seldom give rise to stoppage; furthermore, where an individual drive is adopted, only a very small part of the service is affected. Any breakdowns occurring can be remedied in a short time. In a factory driven by engines without any reserve a possible loss in revenue in consequence of breakdowns must be allowed for, as the stoppages are of somewhat longer duration.

11. The transmission losses must be ascertained with great care. The assumption made in the foregoing calculation that in a factory with a power demand of 150 H.P. only three transmission shafts are required is too optimistic.

12. The maximum demand tariff should always be used as a basis for comparative calculations; that is the only tariff that leads to a correct comparison of generating costs. It must not be forgotten here that lower energy costs are obtained by basing the calculations on other premises, and in particular by assuming a better load factor. If the working conditions are unalterably fixed, or contracts have been made relating to hours of full use or to load factor, another form of tariff can of course be adopted.

CHAPTER VI.

SECOND CONSTRUCTIONAL EXAMPLE: THE INSTALLATIONS OF THE VICTORIA FALLS AND TRANSVAAL POWER COMPANY, LTD., IN SOUTH AFRICA.

1. HISTORY.

ANYONE writing the history of the development of large electricity works will allot a prominent position to those works whose task it is to supply large districts and industrial areas, since they have to overcome the most difficult economic and technical conditions, and their development is hampered by both public and private opposition to an extent not generally experienced with municipal works.

The rapid growth of electricity works in large towns is not at all surprising in view of present-day knowledge of electro-economic questions. These works generally have the advantage of a position of monopoly, and an area with a high density of consumption. The rivalry of their only competitors, the gas-works, can be overcome without much difficulty, particularly in the direction of supply to small power plants. The undertakings whose chief business it is to give an industrial supply are in a less favourable position, inasmuch as the consumer they desire to connect up to their mains is himself a competitor, since he is already accustomed to generate his own power, and therefore knows exactly what the generating costs will be. The works possess one advantage over him in the fact that they usually generate their energy with large generating sets, but this advantage is often counteracted by the distribution costs they have to bear. The sole justification for the existence of such works from an economic point of view is found in the diversity factor, *i.e.*, their peak output is appreciably smaller than the sum of the peaks of the industrial plants on the system. The difficulties in securing any industrial undertaking, as a consumer, naturally increase with the size of the plant in question, and at the present day, with one single exception, the largest industrial works in Germany have refused to take their current from overland power transmission stations, and prefer to generate their own power. It is unnecessary to discuss here the question as to how far this position has been dictated by the desire to obtain economic independence in individual cases; it is significant, however, that consumers could have been secured in many instances if it had been possible to offer sufficient economic advantages. The correctness of this assertion is proved by large water-power plants, where no difficulties have been encountered in securing even the largest industrial works as consumers.

The most important German industrial power transmission works, such as the Oberschlesischen Elektrizitätswerke, the Rheinisch-Westfälische Elektrizitätswerk, and also the large works which have been erected in the North of England under the engineering control of Merz, have, amongst others, slowly developed from small beginnings.

A unique position is occupied by the Victoria Falls and Transvaal Power Company in South Africa; this has existed for nearly four years, and has reached an output of half a milliard (500,000,000) kw.-hours yearly, and before long will reach an output of a full milliard.

These are the largest power works in the world; the energy generated is used for various industrial purposes, but a large part is used to compress air for use in driving mining and other machinery up to approximately 80,000 H.P. It is worth while, therefore, to go into the history of this gigantic undertaking more closely, since the unusual growth of the plants can only be appreciated with a thorough knowledge of the conditions of power consumption prevailing at the time the plant was installed.

The rapid advance of industrial concerns in the confined district on the Rand, near Johannesburg, where gold is mined, together with the development of electric power transmission, had for a long time evoked efforts to centralise the energy supply in order to secure the benefits accompanying the generation of power with large economical machines. As early as 1905 three electrical power stations existed. The first of these, the Rand Central Electric Works, Ltd., generated current for the town of Johannesburg, and also supplied a limited amount of energy to adjoining mines. The plant, which at first returned no profit, was subsequently improved and a satisfactory surplus was obtained during the last few years of its existence. A second similar station likewise depended chiefly upon a town supply for its maintenance. This was erected by the General Electric Power Company in the neighbourhood of Germiston, which, besides supplying the town, also transmitted energy to the Consolidated Gold Fields, Simmer, Jack and Knights Deep. The third station was the Farrer plant, which had an output of approximately 8,000 kw., and was erected by the Farrar group for the operation of its mines.

In order to study the prospects of supplying energy to the districts covered by these works, the Allgemeine Elektricitäts Gesellschaft, in connection with the Dresdner Bank, commissioned two engineers, Loebinger and Dr Apt, to carry out exhaustive investigations of the power demand and other conditions upon which the centralisation of a power supply depended.

It is of importance here to take a retrospective view of the position of the gold mining industry, as it stood at the time the Victoria Falls Power Company was formed. The following particulars are taken from the reports of the two gentlemen mentioned above.

The gold fields of the Witwatersrand, which extend in an easterly and westerly direction from Johannesburg to a total length of about fifty miles, and a width of six miles, must unquestionably be numbered amongst the most important industrial districts of the world. On 30th June 1905 there were sixty-six gold mines in operation, which, during the twelve months from 1st July 1904 to 30th June 1905, handled 9,567,993 tons of ore. The value of the gold output was £17,557,350. The output of the machines employed reached a total of more than 200,000 H.P.

From a financial point of view, the number of gold mines united in single groups constantly increased. The principal groups at that time were :—

1. The Eckstein group.
2. Consolidated Gold Fields.
3. J. B. Robinson.
4. The Barnato group.
5. The Albu group (General Mining and Finance Corporation).
6. The Farrar group.
7. The Goerz group.
8. The Neumann group.

The mines in the Rand district are either outcrop mines or deep level mines according to the formation of the gold deposit. In outcrop mines the reef appears more or less near the surface; vertical shafts of little depth, sunk for the purpose of extending the workings, are also included under outcrop; mines in which the reef does not come to the surface at any point, but can only be reached by sinking a vertical shaft of more than 200 ft., are classified as deep level. As a rule an outcrop mine is found in the neighbourhood of a deep level mine. In the year 1905 the majority of the mines were outcrop mines, their number amounting to forty-six, while there were only twenty deep level mines. In the meantime, however, this proportion has constantly altered in favour of deep level mines, as the mines recently started belong to this group to a preponderating degree. The gold is worked in all mines on a similar system with slight differences. The hard quartz containing the gold is mined entirely by blasting; the drill holes are made for the greater part by means of compressed air drills, the amount of hand drilling being very small. Dynamite is employed exclusively as the explosive. The ore raised, after being roughly sorted from the waste rock, is broken up in crushers, and then passes to the stamp mills where it is ground to a fine sand.

The stamp mills are erected everywhere in batteries up to a maximum of 200 heads, provided with a combined drive.

Each stamp mill works about five tons of ore per day on the average. The sand, which is mixed with water, is then run over amalgamating plates, which retain the greater part of the gold. The remainder, according to the fineness of the sand or slime, is subjected to the cyanide process in large tanks; from the cyanide solution containing the gold the metal is finally precipitated on zinc shavings by a special chemical process. The principal auxiliary machinery required in working the gold consists of compressors, hoists for vertical and inclined shafts, crushers, stamp mills, and various forms of pumps for the cyanide process. Another form of crushing machine which has recently come into use is the ball mill, by the introduction of which the output of the stamps has been appreciably raised.

The form of energy used for working the mines in the early days was principally steam. Out of a total of 200,000 H.P. only 25,310 H.P. represented the proportion of electrically-driven machines, the remainder consisting almost exclusively of steam plants.

Calculations of the actual prime costs per H.P.-hour under the working conditions then prevailing had only been made by a few mines. A price of ·8d. per indicated H.P.-hour was obtained as the average value for twenty-four mines. Converted into electrical units, and assuming the efficiency of the steam engines to be 85 per cent., a price of 1·26d. per kw.-hour was calculated.

The difference in the cost of power for different mines was due not so much to the varying quality of the machine equipment, as to the price of coal, which is varied according to the locality of the mine. Good statistics are kept, and they are easily obtained. They show that the average working costs of the steam plants amounted to 3s. per ton of ore mined. The total costs of power generation for working 9,567,993 tons were therefore £1,450,000 under the conditions existing in 1905. With 8,000 hours full use the costs per H.P.-hour per annum would amount to £26. 13s., or approximately £41. 10s. per kw.

The generation of power for developing mines is very much less economical than for mines working regularly with a high annual load factor. In the former type, a greater part of the power is required for sinking purposes. The costs here amount to approximately 6d. per H.P.-hour, *i.e.*, they are more than seven times higher than in the case of mines working regularly.

These figures show that the working conditions prevailing on the Witwatersrand made it imperative in this instance, more than in any locality, to centralise the generation of power. The density of the consumption area and the high load factor, which could scarcely be obtained under any other conditions, here presented a particularly favourable opportunity for distributing energy from one very large power station. Although the generation of power in one large station had already been shown to be appreciably cheaper than a power supply from various isolated stations, the special conditions ruling in South Africa made this fact still more clearly apparent. The reduction in the staff permitted a considerable reduction in the high general expenses necessitated by the costly living conditions on the Rand. Coal, the price of which is very high in some cases, can be obtained on more favourable terms by purchasing large quantities. A further advantage for the mines, apart from a cheap power supply, was secured in the saving of the capital for new plant, which would otherwise have been necessary, a fact of the greatest significance, particularly in times of financial depression.

It will thus be readily understood that the proposal for a general power supply on the Rand was taken up almost simultaneously by the different parties interested. The scheme was first worked out by Robeson, who was at that time chief engineer of the Eckstein group; this scheme provided for the transmission of compressed air and electricity. The main power station was dimensioned for an output of 70,000 H.P., and in addition to the mines of the Eckstein group was also to supply power to the Consolidated Gold Fields. The price for energy proposed was ·45d. per kw., at which it would have paid to replace any existing steam plants by an electric drive. The compressed air was to be generated in one large compressor plant, and distributed to the mines through a network of piping at a pressure of 115 to 150 lbs. per sq. in. It was to be used for driving rock drills and other machines, particularly small underground winches, while all other machinery was to be driven electrically. The power was to be transmitted by overhead lines.

Robeson claimed as the advantages for this scheme that the direct transmission of compressed air could be accomplished with a better efficiency than the transmission of electric energy for driving a number of small compressors at each mine by electric motors.

According to the Annual Report of the Government Mining Engineer, the total output of the machinery erected in the mining districts amounted to 200,000 H.P., of which 60,537 H.P. was driven by compressed air. Half of these machines were rock drills, the remainder consisted of pumps, fans, winding engines, and other hoists.

A wide field was opened to electricity on the Witwatersrand for driving the various auxiliary machinery required by each mine. The advantage of the electric individual drive was soon recognised for driving machines such as hoists, belt conveyors, water-wheels, machine tools, fans, and pumps, which at that time were driven by belts and ropes from long transmission shafts; compressed air was also employed in some cases.

Up to the present time comparatively little attention has been given to the ventilation of the mines, and in the majority of cases the exhaust air from the drills has sufficed for ventilating purposes. As the depth of the shafts increases, however, the difficulty encountered in the ventilation becomes greater; the mines will therefore be obliged in course of time to resort to artificial ventilation in order to counteract the high temperatures prevailing at great depths.

The output of the pumping machinery in the gold mines during the year 1905 was approximately 32,000 H.P., of which 6,100 H.P. was driven electrically. The greater part of the pumping machinery, namely, about 16,000 H.P., was employed for raising water from the mines, approximately 6,000 H.P. being used for the pumps required in the reducing plants, and the remainder for the general water supply, the high-pressure water supply, and drainage.

It was to be expected that the number of underground pumping plants would increase as the deep level mines developed. Even at that time some trouble was experienced at individual shafts in dealing with the water, and the deeper the new shafts were driven, the more difficult it became to dispose of the water.

The appreciable lifts (4,000 to 5,000 ft.) made an electric drive imperative from the outset.

The ventilating and pumping plants include machines which work practically throughout the entire year without interruption, and as the quantity of air or water pumped is always the same, the machines form an excellent constant load for power stations.

More important in this respect were, however, the crushers, whose task it is to crush the ore after it is raised to the surface. According to the official statistics in the year 1905, the power required for driving crushers was approximately 5,500 H.P., and 28,000 H.P. for stamp mills. Although mining engineers held different views with regard to the most advantageous form of mechanical drive, they were unanimous in their opinion that the electric driving of the mills was superior to a steam engine drive.

The stamp mills are generally arranged in batteries of 200 or 400 in very large plants. The power required for a battery of 200 stamps is from 600 to 800 H.P., according to the size of the stamps. As the stamps had been driven hitherto almost exclusively from long transmission shafts, the efficiency of energy transmission was very low, and an auxiliary engine had to be provided as a standby in case the entire battery was shut down, due to a defect in the main driving engine. With the exception of a few mines in which the batteries were stopped on Sundays, an annual working period of 8,000 hours could be allowed for the mills. As the ore is distributed very uniformly, no load fluctuations were to be anticipated.

These plants, therefore, constituted ideal consumers for electricity works as regards the nature of the load and length of time for which it was required.

A less steady load is that of winding engines. But the frequent peaks of these machines, it was assumed, would be less perceptible in the load curve of the power station in consequence of the large steady load. Even the load for winding engines becomes fairly uniform as the number of winding engines on the system increases.

Mining engineers are in many cases not favourably disposed to the introduction of electricity for winding plants, and apart from the

Eckstein group, not many of the outcrop mines with winding engines above ground could be expected to take a supply. The conditions are different, however, in the case of deep level mines, where winding engines must generally be erected underground, and steam or compressed air is unsuitable in consequence of the depth. There was no other alternative than to adopt electricity, wherefore one could expect the electric drive to be introduced rapidly, particularly for inclined shafts.

Notwithstanding the unsatisfactory results of existing small power stations, the suggestion to combine the generation of energy in one undertaking laid out on a very large scale was by no means inappropriate at this stage, owing to the fact that a number of overland power stations depending on an industrial load of a like nature were already being operated with financial success in Europe and America.

On the occasion of the annual meeting of the British Association in Johannesburg, Hammond read a paper before the Engineering Section on August 30th, 1905, on electric power transmission on the Rand, in which he came to the conclusion that under the conditions ruling, a large electric power station erected on the Rand would be able to earn a dividend of 10 per cent. without difficulty. Hammond estimated the annual consumption at 300,000,000 kw.-hours, with total connections amounting to 82,000 kw., and a power station output of 60,000 kw. The price for current was to have been ·7d. per kw.-hour.

This estimate was based upon the assumption that with such a low price for current it would be possible to persuade all the mines already working with steam plants to exchange the latter for an electric drive. This assumption, however, proved later on to be incorrect.

Even at this time the question was raised by Hammond as to whether it would not be better to erect the station in some other locality where coal and water could be obtained more cheaply than on the Rand itself.

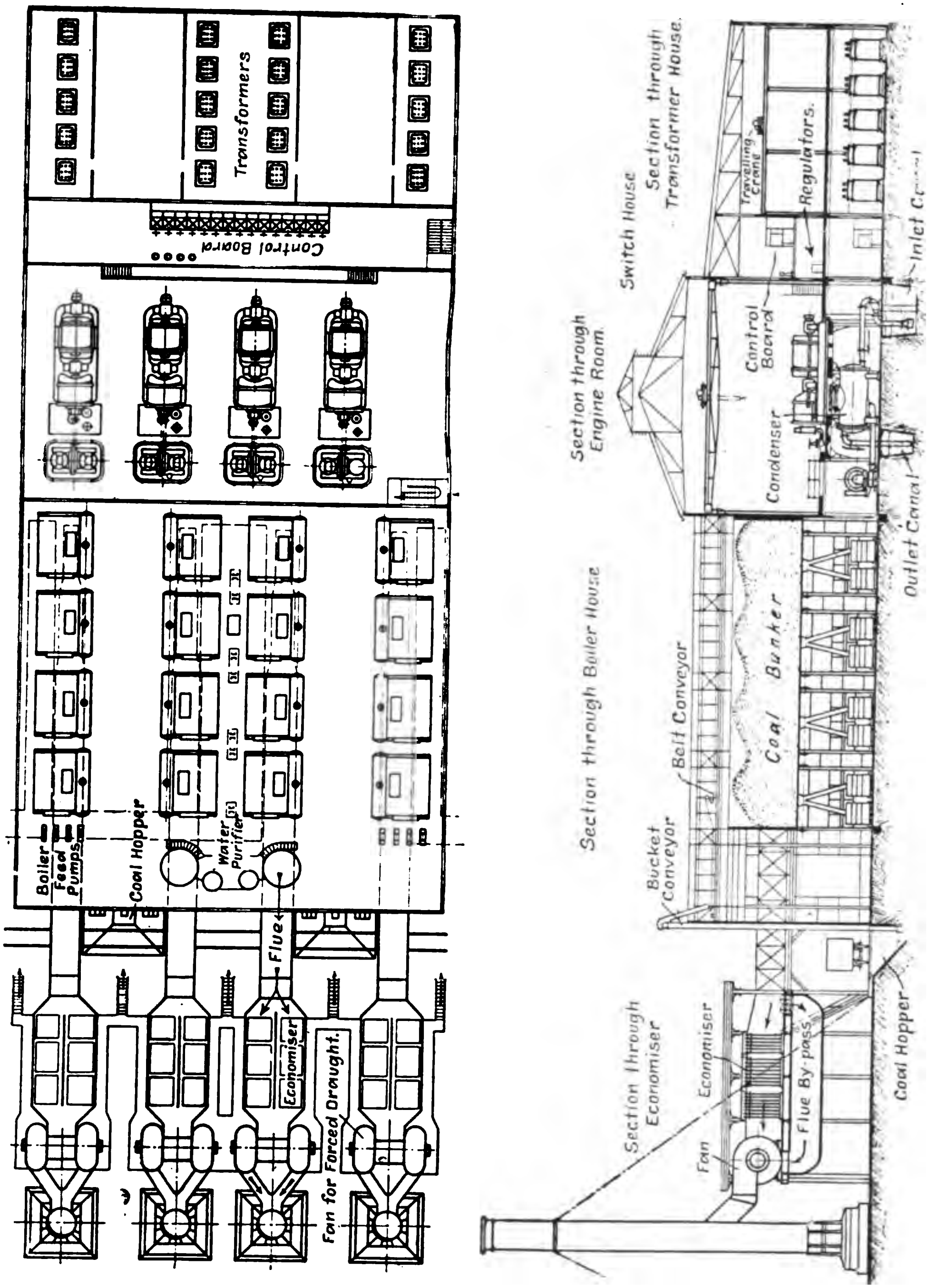
The price of these two materials is no doubt of primary importance in the selection of the site, and this fact is nowhere more clearly apparent than on the Witwatersrand, where the price of coal varies considerably in consequence of the high railway rates, and where water has a high value owing to its scarcity on the South African tableland.

The scheme worked out by the A.E.G., after preliminary investigations, provided for a power station with an output of 30,000 kw., of which 15,000 kw. were to be erected immediately at one of the large dams on the Rand. Comparative calculations made between this situation and another on the Vaal river in Vereeniging, thirty-five miles to the north, proved the site on the Rand to be superior in view of the coal prices prevailing at the time. Other considerations were the uncertainty in transmission of power over the long distance from Vereeniging and the serious consequences of any interruptions in the supply, apart from engineering difficulties.

It is interesting to compare the plans drawn up at that time with those prepared in accordance with later ideas; it will be seen, notwithstanding the short interval that has elapsed, that it has been possible to introduce great improvements in many parts of the scheme. Figs. 92A, 92B, 92C show a section and plan of the power station proposed at that time.

Simultaneously with the A.E.G., but independently of the latter, the British South Africa Company under its energetic manager, H. W. Fox, also studied the question of power supply on the Rand, with the object of utilising the enormous water power of the Victoria Falls on the Zambesi river, which belong to them. To this end H. W. Fox founded the African Concessions Syndicate, which acquired the right from the British South Africa Company to erect a power station with an output of 250,000 H.P. at the Victoria Falls. The necessity for carrying out searching investigations to determine the most satisfactory system from a technical and economical point of view for transmitting this amount of power over the great distance of 700 miles, led to the formation of a committee of experts, which included Blondel, Paris; Gisbert Kapp, Birmingham; Lord Kelvin, London; and Tissaut, Basle.

Although this scheme could not be carried out on political grounds, and was eventually abandoned for the time being, it is



Figs. 92A and 92B.—Design for a Power Station on the Rand (1905). Output, 15,000 kw. Plan and Section. *Scale*, 1 to 600.

nevertheless interesting to note from the reports submitted that the transmission of high-tension direct current was recommended by the above-mentioned experts, and it was proposed to adopt a so-called series transmission system in which the current is constant and the pressure variable. The output was to be varied by automatic regulation of the pressure, the highest value of which was estimated at 100,000 volts. The disadvantage of constant copper losses, which would have been particularly noticeable at light loads, did not come under consideration here, as a load factor of more than 80 per cent. could be expected and water in abundance was available, which could be allowed to run to waste at times of light load.

Later, Ralph Mershon, America, and the author were consulted in the same connection; both proposed high-tension three-phase power transmission, independently of each other, the frequency in Mershon's scheme being 12½, and in that of the author 10 periods per second. Calculations made at higher frequencies showed such an unusual distribution of pressure at fluctuations of the load, that the idea of adopting higher frequencies had to be abandoned altogether; satisfactory values were secured, however, at the frequency proposed. Both engineers recognised an advantage over direct current transmission, inasmuch as the generation of high-pressure three-phase electric energy could be accomplished in a more perfect manner technically with plant which had already passed the development stage, whereas the same cannot be said of high-tension direct current, which involved the complete insulation of each generator, and the insulation of the couplings to

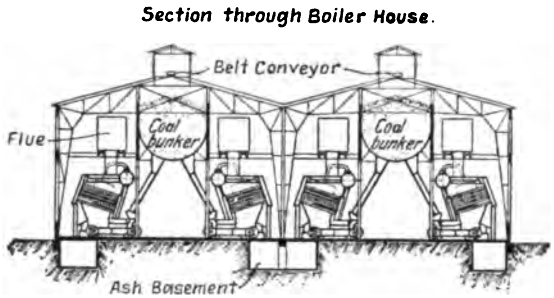


Fig. 92c.—Design for a Power Station on the Rand.
Section through the Boiler House.

prime movers for the full working pressure. The suggestion of employing silk band couplings appeared even more questionable than the erection of large machines on porcelain insulators.

In the subsequent negotiations between H. W. Fox and the author a general scheme was agreed upon. Eventually the Victoria Falls Power Company was formed, with a capital of £1,640,000, of which £815,000 were issued in debentures. This sum was subscribed in Germany under the direction of the Dresdner Bank.

The A.E.G. undertook the engineering of the scheme and the installation of the entire plant. Ralph Mershon and Arthur Wright, London, then proceeded to South Africa to obtain further important details. On their return the plans were finally passed, and the erection of two power stations with a total capacity of 18,000 kw. was begun. The smaller station, containing two 3,000 kw. sets, was to be erected at Brakpan to work in conjunction with the Rand Central Electric Works, while the larger station was built at Simmerpan, and was to have an output of 4 × 3,000 kw. At that time these were the only places where the necessary water supply was obtainable, two large artificial lakes being available for the purpose.

On the formation of the Victoria Falls Power Company the stations of the Rand Central Works and the Driehoek Electricity Works of the General Electric Power Company were taken over. The company was also successful in making a contract with the Consolidated Gold Fields for a supply of 3,000,000 kw.-hours. By this means it temporarily occupied a position of monopoly, as the power station of the Farrar group only supplied current to the mines of the latter.

2. FIRST SECTION — BRAKPAN AND SIMMERPAN POWER STATIONS AND HERCULES SUBSTATION.

A. Brakpan Power Station.

(a) *Situation of the Works.*

The Brakpan power station (see plan, Fig. 93) is situated at the extreme east of the Rand, and supplies the mines of the Brakpan district, including the Brakpan collieries, the Brakpan gold mine, and the Geduld mine. The Waterfontein mines, which have recently been taken over by the Eckstein group, have also been connected up. The capacity of the works was restricted from the outset by the water supply conditions, as the area of Brakpan Lake, which is not very deep, is reduced in summer to 645,600 sq. ft., and there is no prospect of any other source of water.

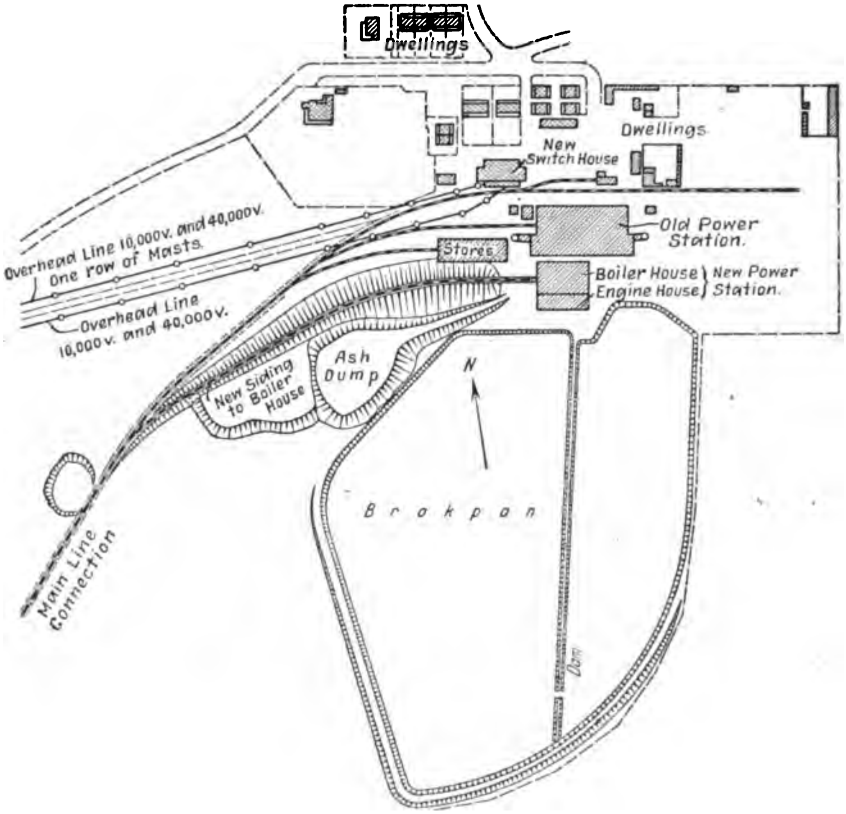


Fig. 93.—Brakpan Power Station. *Plan scale*, 1 to 5,000.

(*b*) *Engine Room.*

The plant consists of two turbo-generators, each having an output of 3,000 kw. and running at a speed of 1,500 r.p.m.; the sets are arranged along the centre line of the engine room (Figs. 94, 95, 96, 97). The generators were originally wound for a pressure of 10,000 volts, but were later rewound with bar windings for a low voltage and connected up to transformers, as the high-tension winding was subjected to excessive stresses from violent atmospheric discharges, whereas the high-tension windings of transformers can be made safer in this respect. By using bar windings the capacity of the generators could be increased by 10 per cent., so that the extra costs were for the greater part counterbalanced.

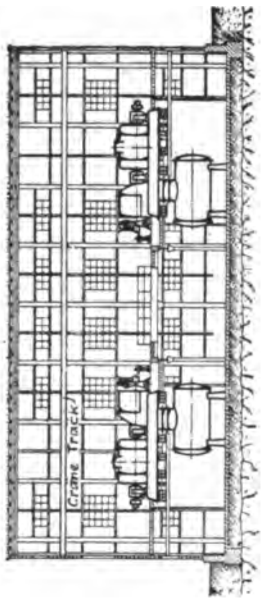


Fig. 95.—Brakpan Power Station. Longitudinal Section through Engine Room. *Scale*, 1 to 500.

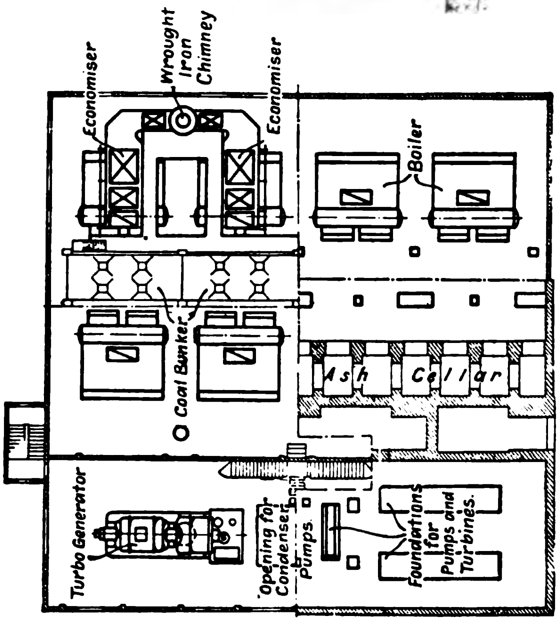


Fig. 94.—Brakpan Power Station. Plan of Engine Room and Boiler House. *Scale*, 1 to 500.

The boiler house and engine room are arranged parallel to one another and are of the same length. This arrangement was selected on account of the fact that future extensions are improbable owing to the limited supply of water; under these circumstances the area covered is comparatively small. The air and lift pumps and circulating water pumps are each driven by direct coupled electric motors (Figs. 98, 102, and 103).

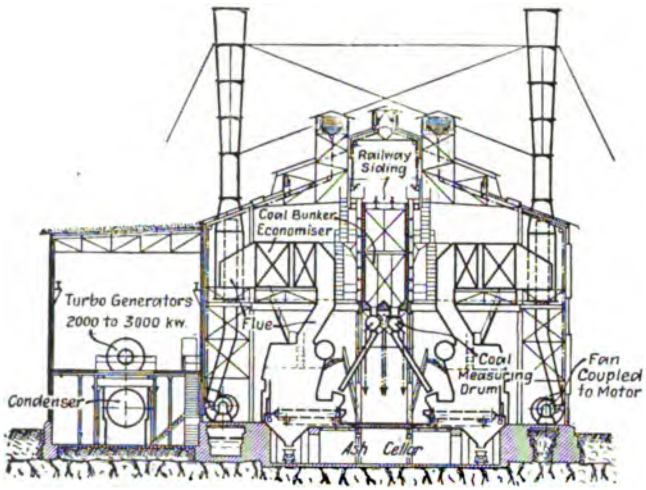


Fig. 96.—Brakpan Power Station. Section through Engine Room and Boiler House. *Scale*, 1 to 500.

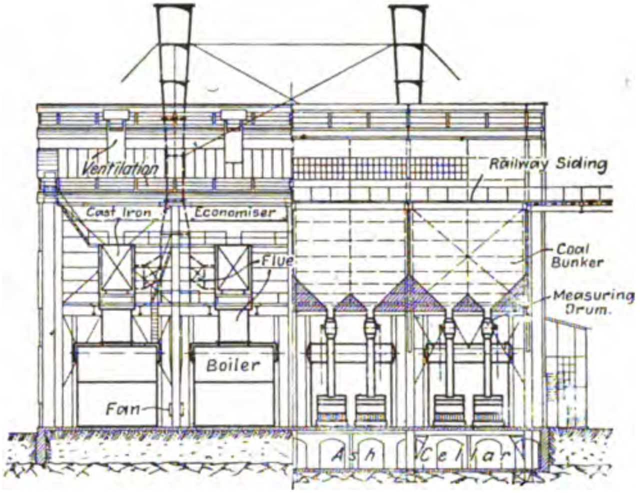


Fig. 97.—Brakpan Power Station. Longitudinal Section through Boiler House. *Scale*, 1 to 500.

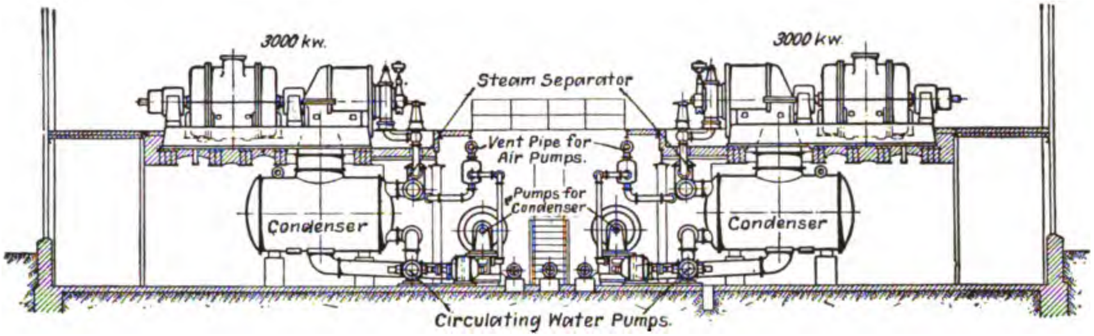


Fig. 98.—Brakpan Power Station. Condenser Plant. Longitudinal Section. *Scale*, 1 to 250.

In order to increase the cooling effect of the lake, a special dam was constructed which distributes the water as uniformly as possible (Fig. 93). The maximum temperature of the lake could thus be reduced to 86° F. in summer (views of buildings, Figs. 99 to 101).

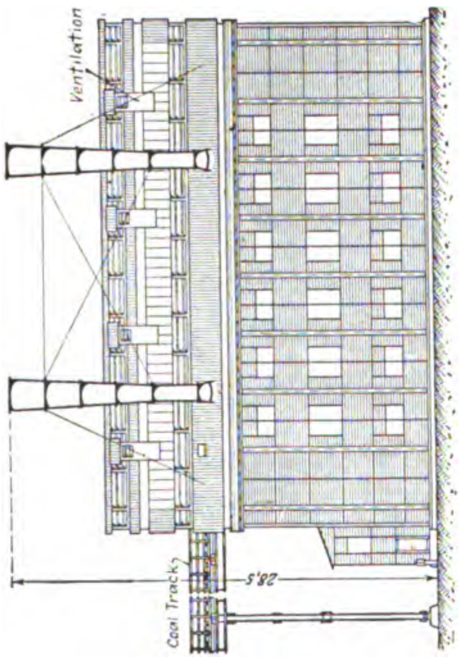


Fig. 99.—Brakpan Power Station. View of the Longitudinal Side of the Engine Room. *Scale*, 1 to 500.

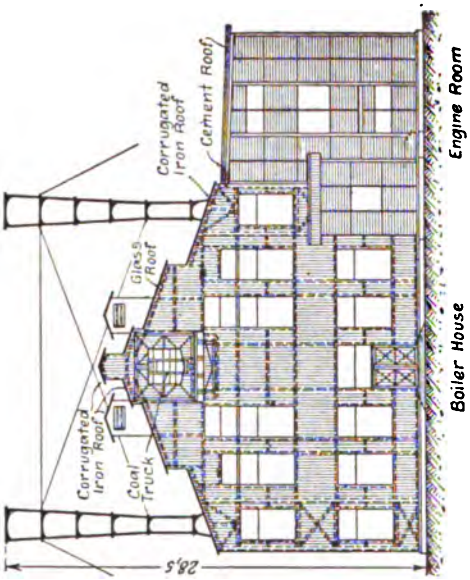
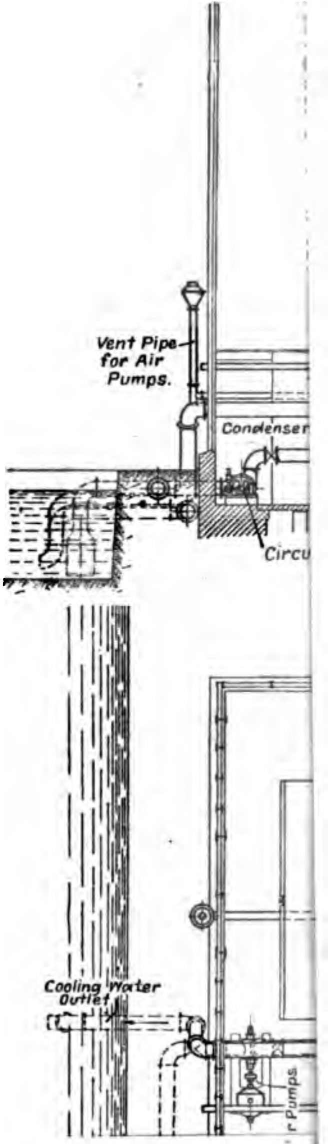


Fig. 100.—Brakpan Power Station. View of the End of the Boiler House and Engine Room. *Scale*, 1 to 500.

(Dimensions in metres.)

(*c*) *Coal Transport and Boiler House.*

Owing to the raised position of the railway siding, the coal trucks could be run directly into the boiler house above the elevated bunkers (Figs. 96, 97, 98, 100, and 101). The coal transport is thus greatly simplified, but the installation costs were somewhat heavy, since in addition to the high railway embankment, massive ironwork was necessary for supporting the bunkers, the cost of which was further increased as the result of the severe conditions for safety and taking up the shock caused by the application of the brakes on the railway trucks. The boiler plant comprises eight Babcock & Wilcox marine type boilers, each having a water-touched heating surface of 3,830 sq. ft., grate area of 156


Vent Pipe for Air Pumps.
Condenser
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Cooling Water Outlet
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sq. ft., and superheater surface of 1,370 sq. ft., which supply 17,600 to 22,000 lbs., and a maximum of 28,600 to 30,800 lbs. of steam per hour at a temperature of 615° F. The cast-iron economisers constructed by Green (Figs. 96, 97) are placed on a separate floor above the boilers; each pair of boilers has a wrought-iron chimney with artificial draught on the ejector system. The efficiency obtained in practice is between 77 and 80 per cent. With an experimental plant in Glasgow an efficiency of 83 per cent. was obtained on normal load before the erection of the works. The fans are driven by direct coupled electric motors; they are erected on the boiler house floor behind the boilers in an accessible position (Fig. 96). The artificial draught is regulated by dampers. The natural draught suffices for 40[1] per cent. of the boiler output. The fuel used is coal dust, with which a small quantity of small coal is mixed; the calorific value of the fuel is 9,000 to 10,800 B.Th.U. The ash is removed mechanically by rope conveyors and separate trucks (Fig. 101), which are raised by hand to the works entrance. The ash is dumped into a valley close by (Fig. 93), so that no hoisting is necessary.

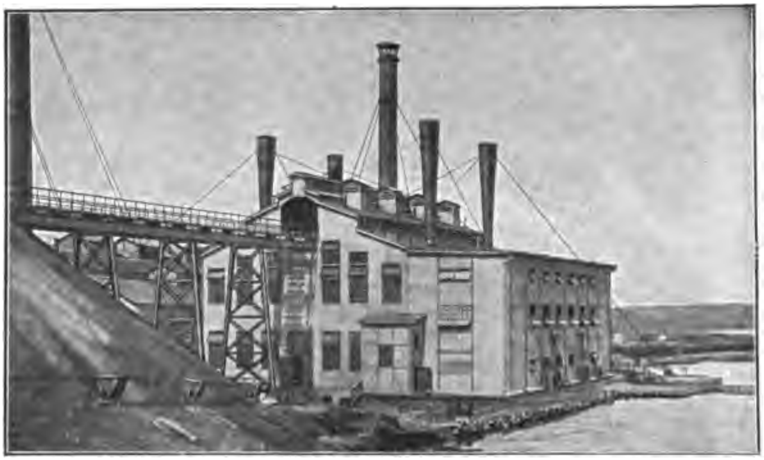

Fig. 101.—Brakpan Power Station.

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[1] This figure can be considerably improved by further reducing the resistances in the boiler, economiser, and flues (see Figs. 10, 11, 12, 38, 72, 73).

(*d*) *Switch House.*

A special switch house is erected at a distance of approximately fifty yards from the engine room; it contains the operating panels as

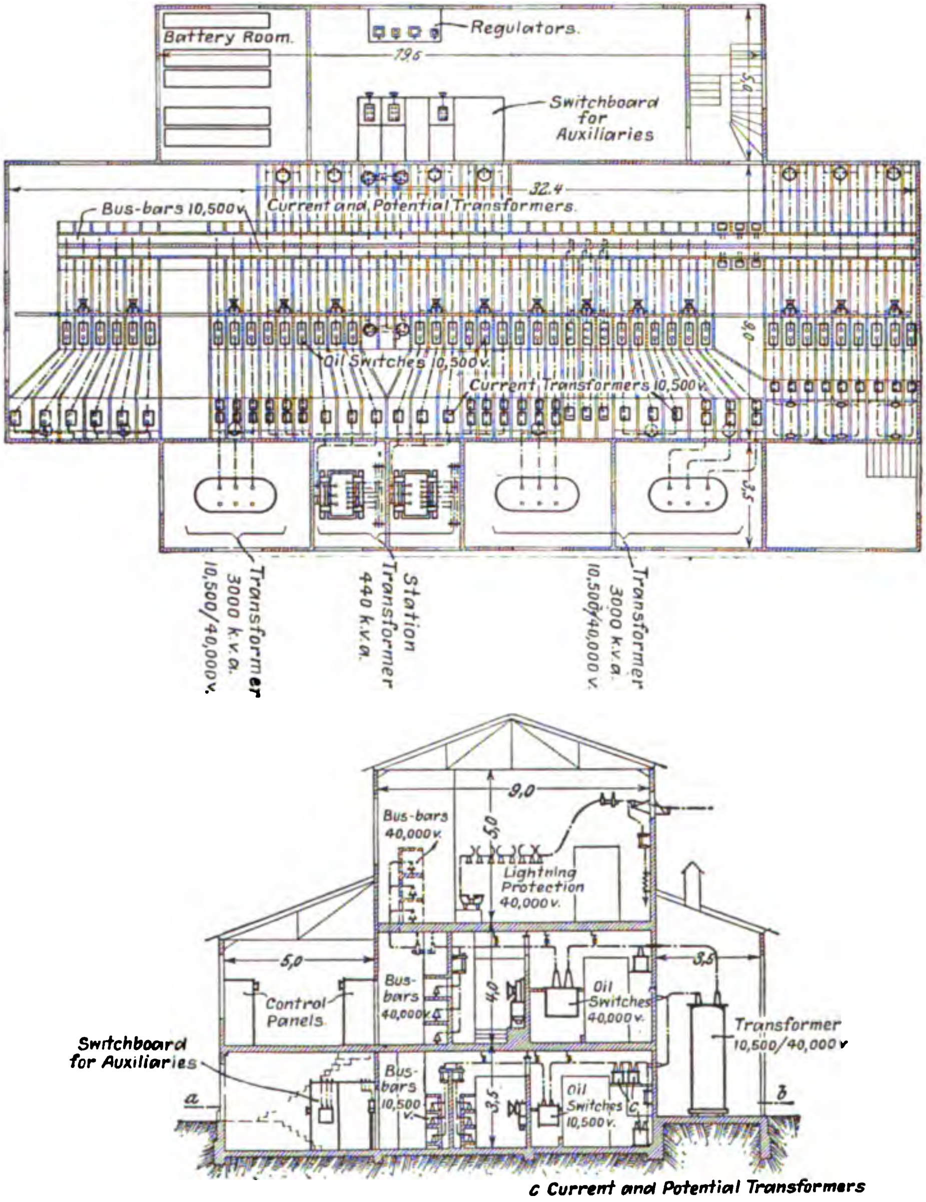

Fig. 105.—Brakpan Power Station. Plan and Section of the Switch House. *Scale* 1 to 250. (Dimensions in metres.)

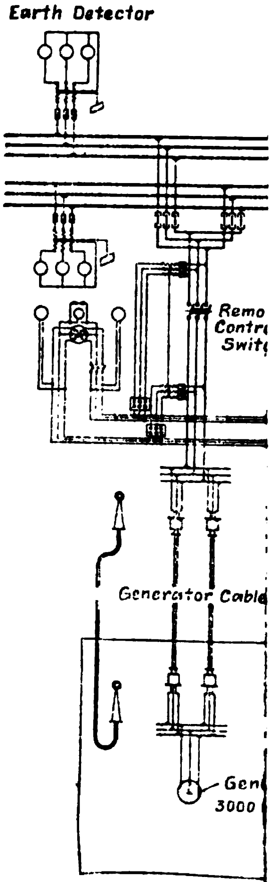

Diagram of co
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Simmerpan. One
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well as all other gear. All switchgear is operated by remote control (see diagram of connections, Fig. 104).

The switchboard attendants can communicate with the engine room by means of loud-speaking telephones. The transformer compartments are made fireproof and adjoin the long side of the switch house (Fig. 105). The pressure is transformed from 10,000 up to 40,000 volts, the current is transmitted exclusively by overhead transmission lines, the pressure being 10,000 volts in the neighbourhood of Brakpan, and 10,000 and 40,000 volts for Simmerpan, two double lines carried on special masts being employed for the latter. The switch house also contains a battery for the operation of the switches and for emergency lighting; it is charged by a small three-phase direct current converter in the same building.

B. Simmerpan Power Station.

(See plan, Fig. 106, and general view, Fig. 107.)

(a) *Coal Transport.*

The coal conveying plant includes bunkers placed outside immediately above the ground, so that the coal can be discharged from the trucks direct. The bunkers are situated in front of the boiler houses at right angles to the same, and the coal is removed by means of bucket conveyors which discharge their contents into further large bunkers above the boilers (Figs. 108, 110). The conveyors are fed by a transverse conveyor, which passes under the coal store, so that coal can be conveyed from any bunker into any of the boiler houses. This arrangement is necessary in view of the different kinds of coal used, which have to be mixed with one another to ensure satisfactory combustion on the chain grates. The conveyor plant can be so adjusted, for example, that every second hopper is filled from a certain bunker, the intermediate hoppers being filled from other bunkers. The coal store has a capacity of 1,600 tons, and the bunkers in each boiler house can take 650 tons of coal.

(*b*) *Boiler Houses.*

The boiler plant (Figs. 108, 110) consists of two boiler houses, each containing eight boilers. Each of these boilers evaporates 20,000 lbs. of water per hour, the water-touched heating surface is

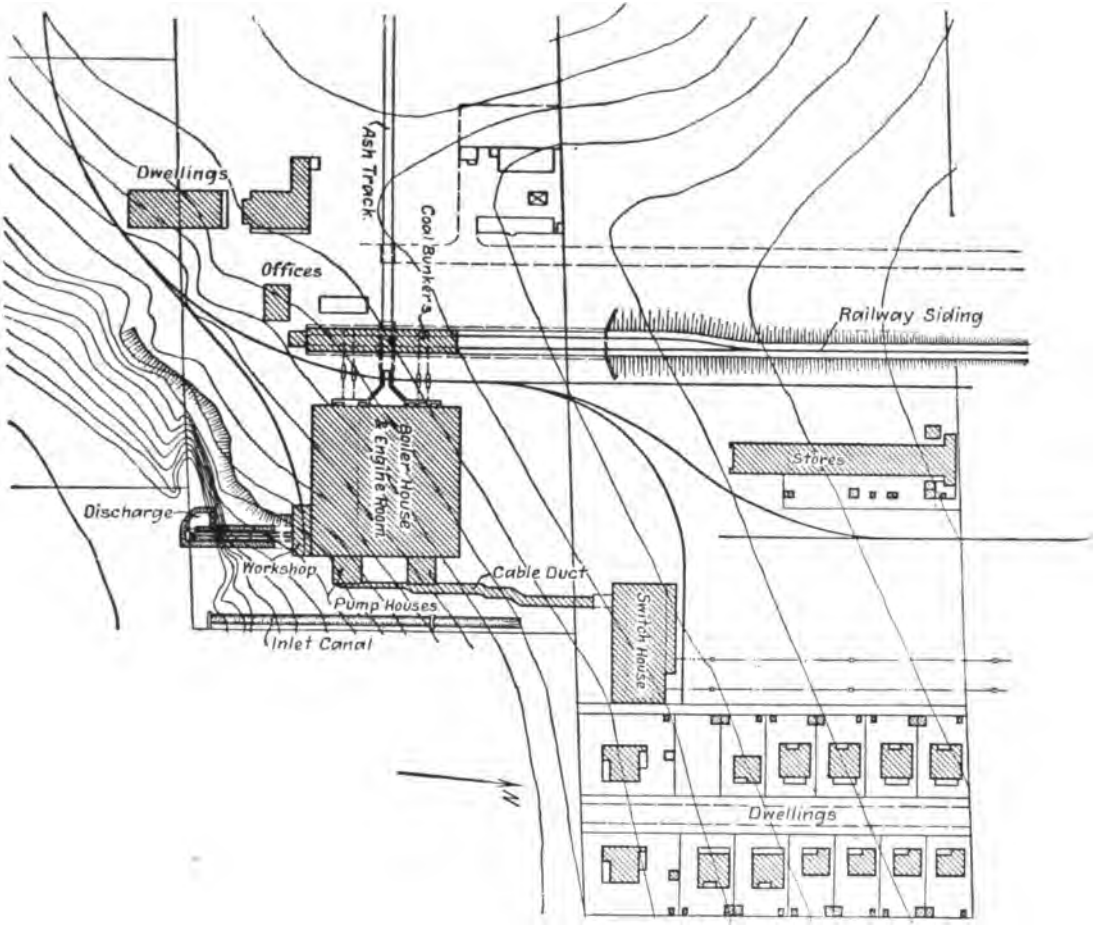

Fig. 106.—Simmerpan Power Station. Plan.

3,850 sq. ft., and the grate area 156 sq. ft. Contrary to Brakpan station, the centre line of the boiler houses here is at right angles to the centre line of the engine room. The steam from one boiler house suffices for two turbo-generators of the same size as those installed in Brakpan station, including a steam reserve of approximately 20 per cent. The boilers and economisers are of the same construction as those in the Brakpan station. The main steam pipework in each boiler house is constructed as an open ring; the ends of the ring are connected up to a collector pipe, which runs along the ash basement on the outside of the engine room; the connections to the turbines are branched off from this pipe (see lay-out of piping, Fig. 111, also Figs. 112 to 114). It is worth mentioning here that the normal steam separators inserted in the branches were not adequate, in consequence of the short circuits and heavy rushes of load which were of so frequent occurrence during the early period, and caused water to be carried over from the boilers, thus endangering the turbines. They were later replaced by separators fitted with somewhat heavy trough-shaped attachments; the latter not only retain any water carried over, but also serve as thermal reservoirs and evaporate this water.

Fig. 107.—Simmerpan Power Station. General View. Management offices in foreground; the coal bunkers may be seen in front of the boiler houses.

(c) *Engine Room.*

The engine room contains six turbo-generators, each having an output of 3,000 kw.; all sets are mounted in parallel to one another (Figs. 108, 115. First lay-out: four generating sets). The arrangement of the condensers is standard; the auxiliary pumps are driven electrically as in Brakpan station. A channel has been constructed for the cooling water supply; it runs along the outer wall of the engine room directly into the Simmerpan. The circulating water pumps, which are vertical, are placed in wells connected with the channel by pipes with suitable valves (Figs. 106, 109, 112, and 115).

The channel and wells are at such a depth that water will always flow into the pumps, even at the lowest level of the pan. The connection to the pan was blasted out of the rock as far as the water level permitted during the time building was in progress. Blasting operations will be resumed when the water level has receded further, so that later the lowest level of the channel will be connected with the pan direct; the chief object here was to avoid the erection of costly dams, which would of necessity have been very extensive, as the banks of the pan are somewhat flat, and the rock forming them is porous. After passing through the condensers, the cooling water runs through two lines of pipes along the engine room, with an outlet in the pan below

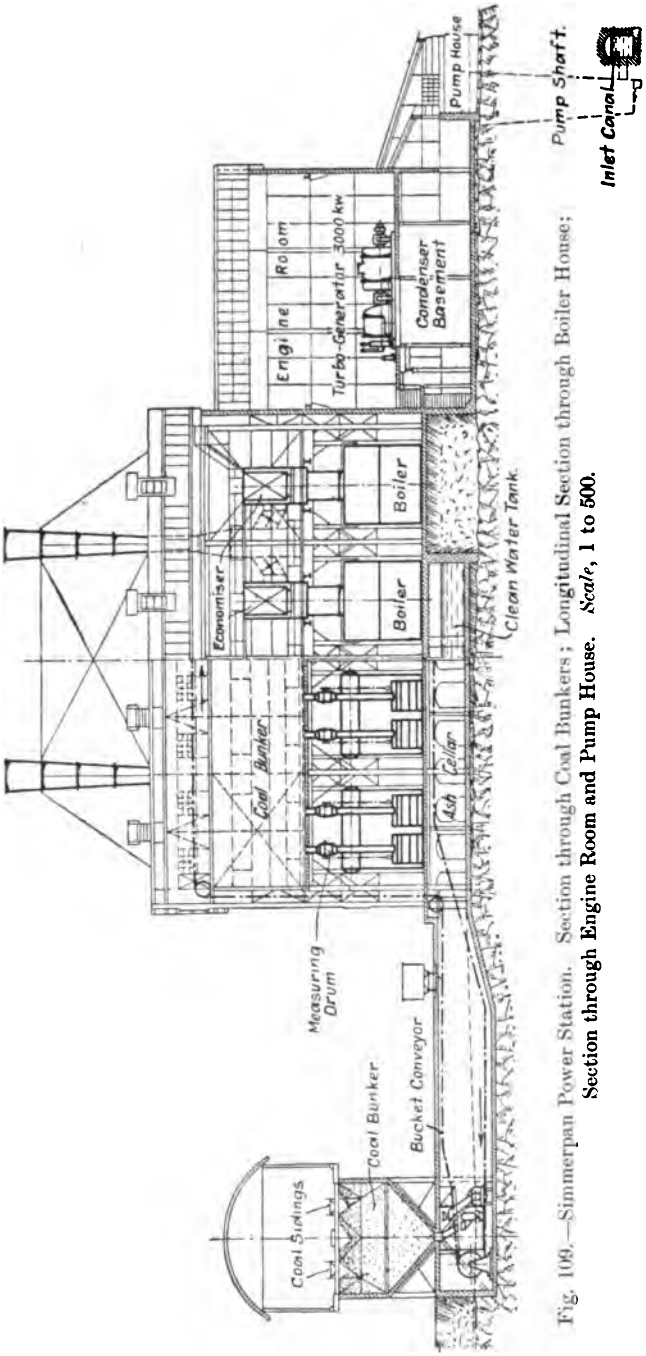

Fig. 109.—Simmerpan Power Station. Section through Coal Bunkers; Longitudinal Section through Boiler House; Section through Engine Room and Pump House. *Scale*, 1 to 500.

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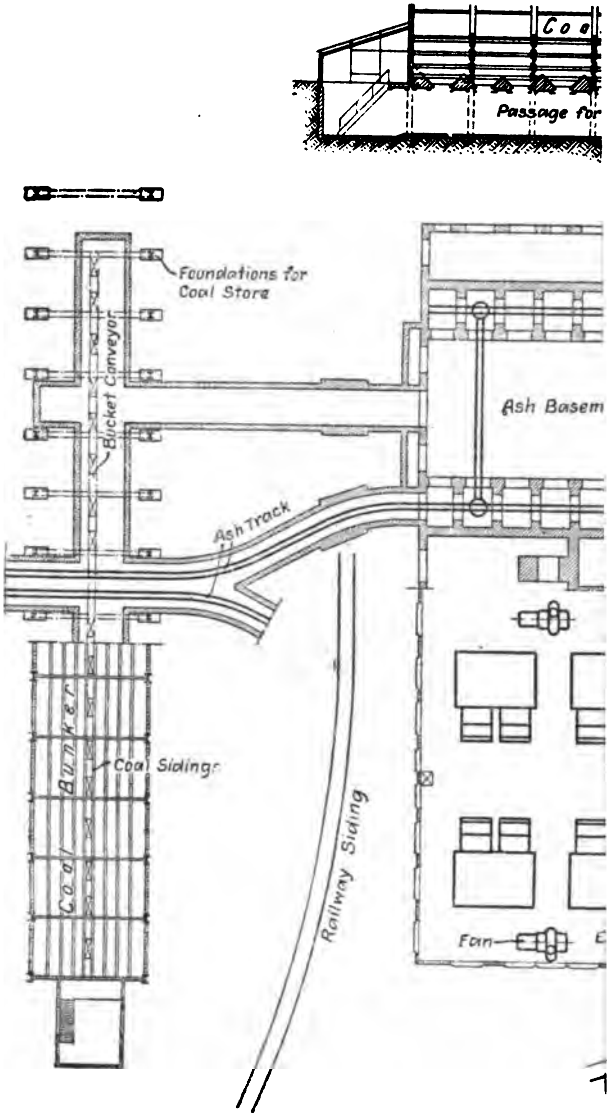

Fig. 108.—Simmerpan Power Station. Plan of Co
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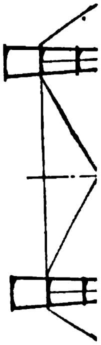

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the surface of the water, so that all leakage is avoided, and the power taken by the circulating water pumps is limited to what is required for overcoming friction losses. The electric motors driving the pumps are erected on the same level as the basement of the engine room, and are conveniently accessible for inspection purposes.

(*d*) *Switch House.*

The switch house (Fig. 116), as in Brakpan station, is separate from the machine installation, being connected to the latter by an accessible cable trench (Fig. 106); the interior equipment is the same as that for Brakpan, the departures being solely due to the greater size of plant. There are two double sets of bus-bars for 10,000 volts (distributing network) and 40,000 volts (feeders).

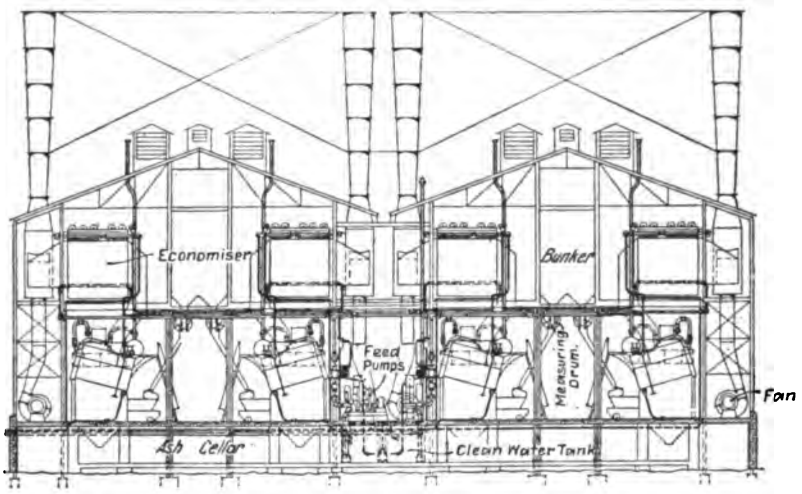


Fig. 110.—Simmerpan Power Station. Section through Boiler Houses.

The motor generator for charging the battery is driven by a synchronous motor which, in the event of a breakdown, is fed from the battery, and runs as a generator for supplying current to auxiliary motors. For this purpose the battery is dimensioned for a large output of short duration. The arrangement has given good results, and its adoption is recommended where auxiliary machines are driven electrically, and where no other independent source of supply is available.

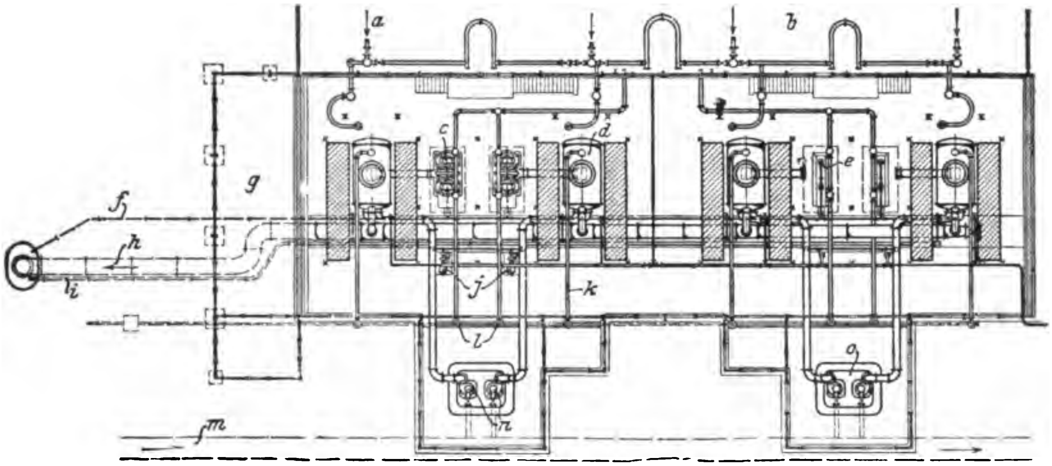


Fig. 112.—Simmerpan Power Station. Plan of Pipework and Condensing Plant. *Scale*, 1 to 500.

a = Live steam pipes. *b* = Boiler house. *c* = Wet air pump with electric drive. *d* = Surface condenser. *e* = Wet air pump. *f* = Drains from air pump. *g* = Workshop. *h* = Outlet pipe. *i* = Outlet of cooling water for oil and bearings. *j* = Pump for cooling water for bearings. *k* = Exhaust steam pipe for condenser safety valve. *l* = Exhaust air outlet for wet air pump. *m* = Inlet channel. *n* = Rotary pump with electric drive for condenser cooling water. *o* = Pump well.

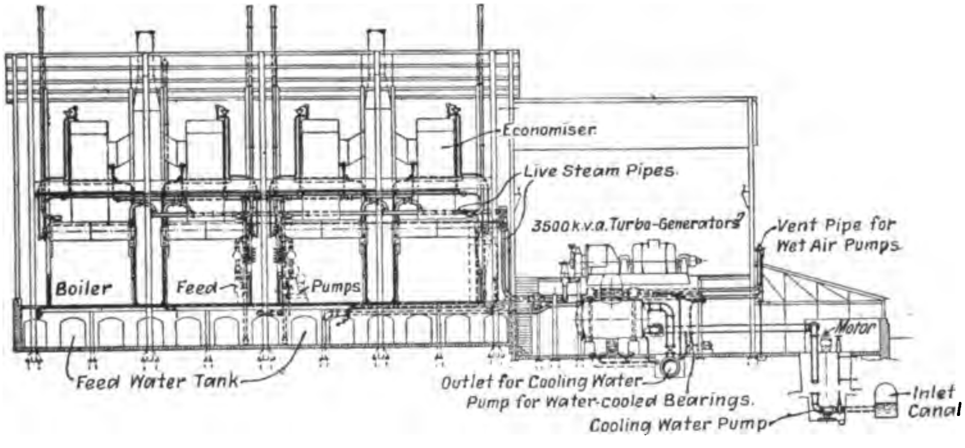
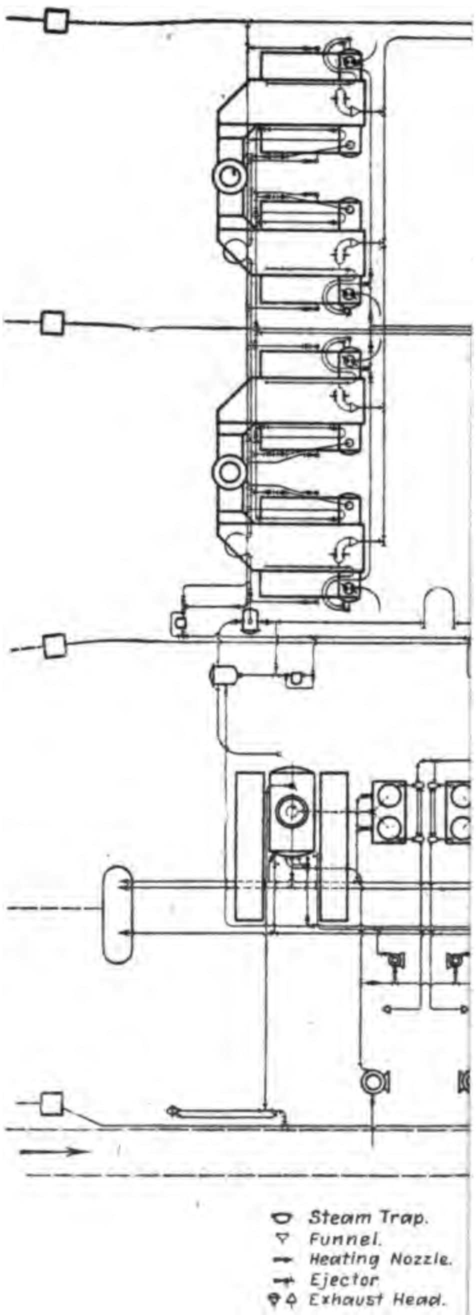


Fig. 113.—Simmerpan Power Station. Longitudinal Section showing Pipework and Condensing Plant. *Scale*, 1 to 500.

As already mentioned, the Brakpan and Simmerpan stations are connected to one another by two 40,000-volt transmission lines,



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each of which is carried on a separate row of masts. Both rows of masts also carry over the greater part of the distance one or two sets of wires for the 10,000-volt distributing circuit, a large proportion of the energy being consumed in the immediate vicinity of the transmission line.

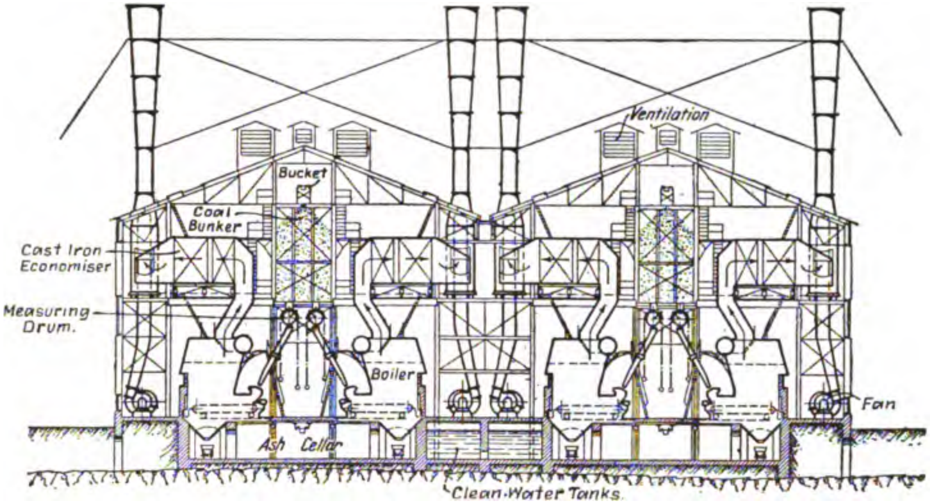

Fig. 114.—Simmerpan Power Station. Pipework in Boiler House.
Scale, 1 to 500.

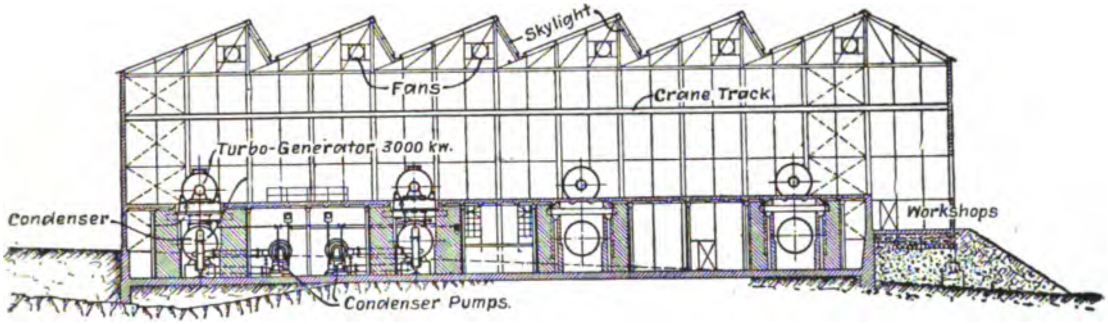

Fig. 115.—Simmerpan Power Station. Longitudinal Section through the Engine Room.

C. Hercules Substation.

The Hercules main switch and transformer station is situated half-way between the Brakpan and Simmerpan stations, the two

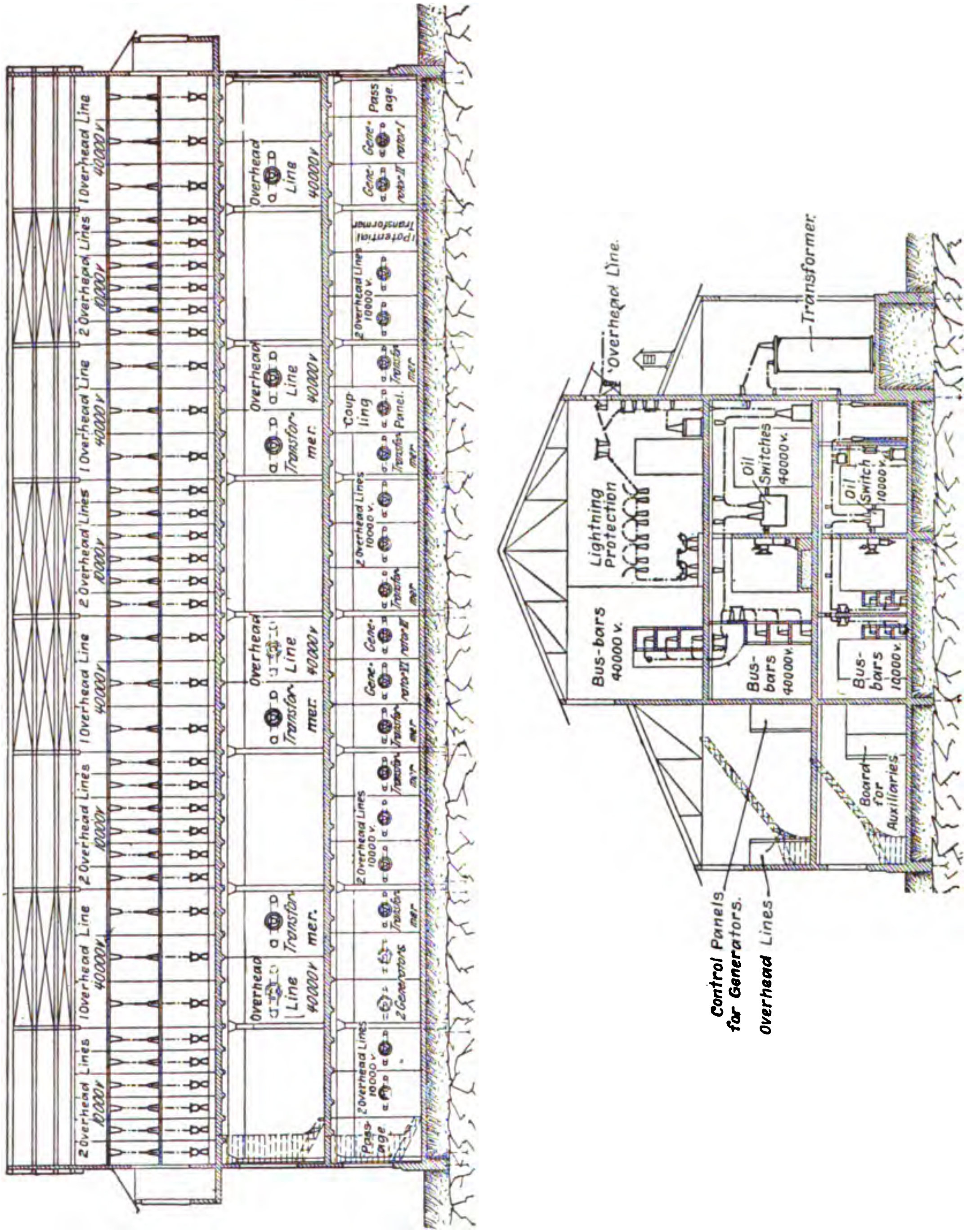

Fig. 116.—Simmerpan Power Station. Longitudinal and Cross Sections through the Switch House.

40,000-volt transmission lines passing right through the building (Fig. 117).

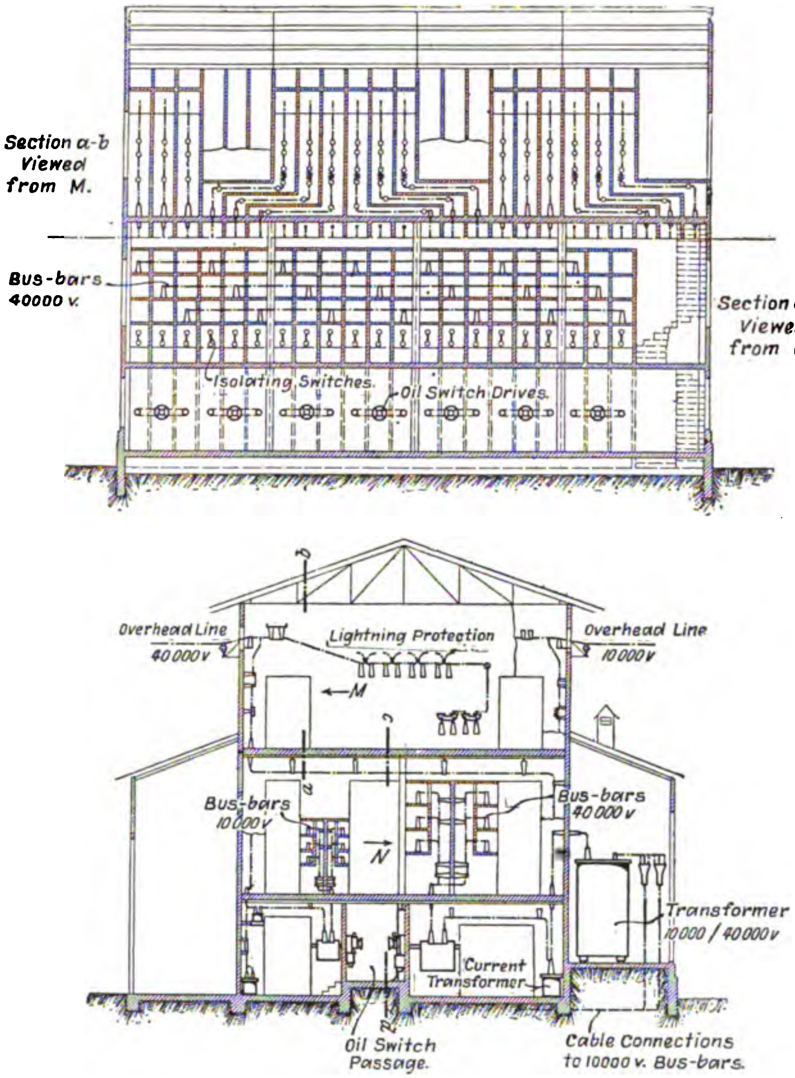

Fig. 117.—Hercules Substation. Cross and Longitudinal Sections.
***Scale,* 1 to 250.**

The pressure is here stepped down to 10,000 volts. As in the Brakpan and Simmerpan stations, local distributing networks are connected up to this station; they join the Simmerpan network on one side, and the Brakpan network on the other, so that energy can flow into the distributing network from two sides. The surrounding mines are supplied direct from the 10,000-volt network; the demand for power in this neighbourhood has, however, increased so rapidly in the last few years, that these two power stations are now no longer capable of meeting the demand in the eastern district, and a certain amount of energy must be obtained from the new works at Rosherville.

3. PREPARATORY WORK FOR FURTHER DEVELOPMENT.

a. General.

The municipality of Johannesburg, which had been taking a supply of energy from the Rand Central Electric Works, had in the meantime erected its own power station, with generators which were to be driven by gas engines. This station was, however, never put into commission, and the municipality was therefore obliged to extend the contracts for the supply of energy with the Rand Central Electricity Works, and those of a more recent date with the Victoria Falls Power Company. In view of the disputes which had arisen with the municipality, the contractors for the gas engine plant commissioned W. A. Harper, in the spring of 1908, to negotiate on their behalf.

In the course of his efforts to arrive at an understanding with the municipality, Harper put forward an entirely new scheme, involving the erection of a steam-driven power station, not only for the supply of Johannesburg, but also for the immediate neighbourhood. With this object he conducted negotiations with various mining companies concerned. Although the Victoria Falls Company was able to prevent an arrangement on these lines with the municipality of Johannesburg, Harper was successful in his negotiations with the mines, and was able to obtain a provisional contract for the supply of energy to the Eckstein group, the largest of the mining concerns.

Harper's contract with the Eckstein group is the most important contract of this kind that has ever been made with a single consumer.

In addition to guaranteeing a maximum consumption of 80,000,000 kw.-hours per annum, the Eckstein group engaged to take the entire power wanted at their mines under the terms of the contract; they further agreed to change over the existing steam plant to electric driving by the time new works could be started up.

According to the conditions existing at the time, one could assume with a fair degree of certainty that the consumption would be about twice the guaranteed value.

The contract also contained the following important conditions:—The supply was to commence on the 1st of January 1910, and the date of expiration was ten years later. About 40 per cent. of the output was to be supplied in the form of compressed air. The compressed air output was determined by exhaustive calculations, the conversion factor in particular for the kilowatt equivalent in air as a function of volume, pressure, and temperature being determined from the formula—

$$1 \text{ kw.} = \frac{1}{\eta} \frac{g}{1000} p_0 v_0 \ln \frac{p}{p_0}.$$

The constant $\frac{1}{\eta}$ in this formula was to be determined from efficiency tests to be carried out with the existing air compressors.

The price agreed upon for the supply of electricity was ·45d. per kw.-hour, and for compressed air ·67d. per kw.-hour. The prices were to be reduced in the event of lower railway freights for coal being obtained, and finally a certain share in the profits was to be allotted to the Eckstein group.

The fulfilment of the contract was based upon the assumption that Harper would be successful in forming a company to finance the scheme within a given time.

On his return to England Harper placed the matter before the A.E.G., who carefully examined the contracts and made their own estimates and comparative calculations in order to ascertain whether sufficient revenue could be obtained under the conditions agreed upon.

The result was unfavourable : the short duration of the contract, and extremely onerous conditions with regard to penalties in particular, made an acceptance of the terms impossible. The subsequent negotiations for improving the contract between the author and the principals of the Eckstein group in London were successful, inasmuch as some of the severest conditions were removed. At the same time it was found possible to agree to a contract period of twenty years, and to increase the maximum guarantee from 80 to 100 million kw.-hours per annum.

The modified contract was then signed in the autumn of 1908 by Lord Winchester, the President of the Victoria Falls Power Company, after he had been successful in securing the large extra capital the company required for the new undertaking.

The capital, which amounted to £1,800,000, was divided into debentures and shares in equal proportions.[1] The debentures were again subscribed in Germany, the Deutsche Bank participating on this occasion, with the result that a share of the plant was manufactured by the Siemens Schuckertwerke.

As the idea of developing the water power of the Victoria Falls had in the meantime been abandoned, because the Government, at the instigation of coal owners, had prohibited the importation of electrical energy into the Transvaal, the title of the company was altered to Victoria Falls and Transvaal Power Company, Ltd. The Rand Mines Power Supply Company was formed as a subsidiary company, in compliance with the terms of the contract with the Eckstein group. This step was essential on account of the group's participation in the revenue and to limit other legal rights relating to the assets of the new undertaking.

A new construction contract was made with the A.E.G. for the extensions, which included the erection of new power stations, the supply of seven steam turbines with a capacity 12,000 k.v.a. each, and ten air compressors for 4,000 H.P. each, also overhead transmission

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[1] The capital was increased in 1910 by £130,000 preference shares, in 1911 by £162,000 preference shares and £1,299,500 debentures, and in the beginning of 1912 by £500,000 debentures.

lines for 40,000 and 10,000 volts, a cable network for 20,000 volts, and an extensive network of air pipes for a pressure of 130 lbs. per square inch.

In addition to Arthur Wright and W. A. Harper, the author was requested to act as consulting engineer to the company and was entrusted with the engineering part of the work, whilst Wright and Harper undertook the certification of surveys and invoices and the work of inspecting and testing the whole of the plant before dispatch and after erection to ensure compliance with guarantees.

No details were available for the preparation of designs, nor had the site of the power station been selected or the nature of distribution of energy been made. For going into all these points the author travelled to South Africa in the company of Lord Winchester, who proposed to form the Rand Mines Supply Company. This was in the spring of 1909. The author's assistant engineer, R. Tröger, was already engaged with preliminary work on the spot.

The power demand of the Eckstein group had in the meantime risen appreciably in consequence of their having absorbed two new mining companies, the Modderfontein Gold Mining Coompany and the Bantjes Consolidated Mines. The total demand was eventually assessed at 320 million kw.-hours; to this amount had to be added the very considerable consumption of the Goldfields and Albu groups, which had since agreed to take a supply: it was therefore necessary to reckon with a consumption of about 500 million kw.-hours.

The coal and water supply, the determination of load factor, and the question of wayleaves demanded very careful attention for so huge an undertaking, the success of which depended entirely on how these matters were handled from the commencement. It seems, therefore, desirable to discuss these points somewhat more closely.

b. COAL SUPPLY ON THE RAND.

Coal is found to some extent on the Rand itself in the neighbourhood of Brakpan and Springs; it is here close to the surface and has a low calorific value, but when mixed with better grades of coal, it can be fired successfully on chain grates. It is interesting to note that in some places the coal deposits are on a higher level than the gold reef; coal and gold ore can then be raised in the same shaft.

The most important coal beds of the Transvaal are situated in the Witbank-Middelburg district, about eighty miles to the east of Johannesburg. The coal is found in numerous seams to a depth of 300 ft., the thickness of the seams reaching 23 ft. in places. The coal is good throughout, its calorific value being 11,600 to 12,700 B.Th.U.

The Heidelberg district and the large coal fields near Vereeniging on the Vaal river are also available for the supply of coal to the Rand; a large number of borings have shown that the seams in the latter district are very thick and extensive and are comparatively close to the surface.

With regard to the geological formation it should be remarked that the coal beds are for the greater part flat deposits, not very deep under the surface. The mines are scattered and in no way connected with one another; the quality of the coal varies considerably. It is thus impossible to gain any idea from the seams of one coal field as to the quality of the other deposits in the neighbourhood. Numerous abandoned shafts give evidence of unsuccessful mining operations.

The quality of the coal depends to a great extent on its subsequent treatment; all shale must be carefully removed by hand on sorting belts, a process which naturally increases the ultimate price appreciably, as even in the best mines up to 10 per cent. waste rock is raised with the coal.

The coal, as a rule, contains little gas; no experience of its suitability for mechanical stokers was available before the erection of the Victoria Falls Power Company's plants, because the boilers in the older works had been fired by hand by blacks or Chinamen. It was of course considered an advantage to introduce mechanical stoking wherever possible, and extensive experiments with different grades of coal were made before the system and size of the grate was finally decided upon. In the tests carried out in conjunction with Babcock & Wilcox, Ltd., it was found that the better grades of coal burnt satisfactorily on chain grates with a suitable spacing of links, and that coal containing little gas required mixing with a more gaseous quality; a slight increase in the size of the grate was also necessary for the Vereeniging coal in order to obtain the same steam output from the boilers.

Notwithstanding the many impurities it contains, the cost of mining the coal is very small; the low depth at which it is found, cheap native labour, chiefly, however, the great thickness of seams, which make all constructional work unnecessary, keep the mining costs very low. The cost of raising the coal is only 2s. to 4s. per ton, including the interest on the invested capital.

When mining the coal, substantial pillars are left standing. The volume of these reaches 40 per cent. of the entire seam; after the rest of the coal has been removed, about half the coal of these pillars can be mined, but in such case the roof must be allowed to fall.

Coal-cutting machines are much in use. Their construction depends upon the nature of the mine; they are, as a rule, driven by compressed air. Artificial ventilation is not considered necessary. The gases of combustion resulting from the blasting operations are removed, as in the gold mines on the Rand, by allowing the compressed air piping to remain open for some time. There is no danger from fire damp or coal dust explosions, and unprotected lamps (stearine candles) can be used everywhere.

The qualities of coal on the market are known as cobbles, nuts, small coal, and dust. In former years the dust and part of the small coal was thrown to waste with the remaining refuse, and even now large heaps of this class of coal may be seen in the neighbourhood of mines. It has lost largely in calorific value through spontaneous ignition and exposure.

Credit is due to H. Spengel, the former manager of the Victoria Falls and Transvaal Power Company, for recognising the value of this waste coal for firing boilers. He was able to make contracts of long duration with a number of mines, in accordance with which this coal was delivered free at the mine at prices from 6d. to 1s. per ton. The company was thus able to cover its coal requirements for a number of years exclusively from dust and small coal, and it only became necessary to resort to more expensive coal with the prodigious growth of the plants.

The price for cobbles and nuts varies from 4s. to 7s. per ton. The exceedingly high costs for railway transport increase the price at boiler house considerably; the freight from Vereeniging to Johannesburg is about 6s., and from Wittbank about 7s. 6d. per ton, so that the high price on the Rand is chiefly due to freight charges.

The tariffs were adjustable according to transport prices, but were not affected by fluctuations in the coal market; it was therefore essential for the company to find some means of effectively preventing appreciable advances in prices by the formation of syndicates. It was sought to avoid this danger by making contracts of long duration and by taking a share interest in coal mines.

A further protection against the fluctuation of coal prices was found to be the position of the power stations. The main station at the Rosherville dam is supplied from two separate coal districts each about the same distance from the works, and quite independent of one another, so that fluctuations in the freight rates cannot be taken advantage of in the coal prices; the total interruption in the supply due to strikes or breakdowns in railway communications is also not likely for the same reason.

c. WATER SUPPLY ON THE RAND.

Although the annual rainfall in the Transvaal is normal (it averages 27·5 in. a year), the supply of water was nevertheless one of the most difficult problems from the outset, its significance having increased with the growth of industry on the Rand. The altitude (the Rand lies nearly 6,500 ft. above sea level), the fact that the rainfall is limited to the summer months, October to March, and the local conditions (rocky or hard soil with no forest land), are inimical to natural irrigation. Apart from the few large rivers, water is only found in the water-bearing strata of the dolomite formation between Johannesburg and Vereeniging.

Thus at an early date the Boers had recognised the necessity for storing up the rain water by the construction of artificial dams across the principal rain channels. These stores of water are, however, of small capacity, having been designed for personal requirements. Natural folds in the structure of the land or small valleys were closed by earth dams, in the construction of which the Boers have attained a remarkable proficiency.

The rapid industrial advance was accompanied by the adoption of more systematic methods, and a number of dams were built on the Rand, some of which enable large quantities of water to be stored.

The most important of these are the Simmerpan, with a drainage area of 7 sq. miles, an average surface area of 130 acres, and an average capacity of 440 million galls.; and the Rosherville basin, having approximately the same average capacity and a surface area of 110 acres. The drainage area of this basin, which was originally 7·7 sq. miles, was later extended to 12·7 sq. miles by the construction of canals. Allowing an average loss of water of 16 per cent. through drainage, and an evaporation of approximately 5 ft. per year, these figures being in accordance with actual experience, it has been found that the quantity of water available annually in Simmerpan is 286 million galls., and 660 million galls. in Rosherville. The average rainfall was taken at 27·5 in.

In order to secure an additional source of water, a company, consisting of the parties immediately interested, was formed. Pumping stations and pipe lines were erected to bring the water from the dolomite formations to the south of the Rand to the Rand itself. This installation can only be used for industrial purposes in cases of emergency, however, as the cost of pumping 100 galls. is about 1·46d., when a total quantity of 220,000 galls. is pumped daily.

It is obvious that in selecting the site for the power station particular attention had to be devoted to the water supply; on the other hand, considerable opposition on the part of the different companies would have been encountered if the existing dams, which had been built exclusively for mining purposes, had been used for a large power station. The attitude taken up by the mining companies in this connection was so firm that for a long time the advisability of transferring the site of the power station to the extreme south of the Rand was seriously considered, as the water-bearing dolomite formation of this locality offered a favourable opportunity for the construction of cooling ponds.

After a further careful examination of the water conditions the fact was finally established that, even allowing for a considerable increase in the gold output, the quantity of water in the Rosherville pan was sufficient to cover the requirements of a large power station in addition to the supply for the mines. It was shown by calculations that when the basin was used as a cooling pond the latent heat in the quantity of water lost annually by evaporation (it amounts on the average to 154 million galls. per year) could be effectively utilised; it could also be proved with a fair degree of certainty that the steam consumption, and therefore the water consumption of the existing steam engines at mines, was approximately three times that of a large modern power station.

According to these calculations the saving of water due to the introduction of the electric drive for mining work was from $2\frac{1}{4}$ to 3 galls. per kw.-hour which would thus be available for any extensions to the mining plants, and would enable the quantity of ore worked to be increased by 50 per cent. with the same water consumption.

Negotiations conducted by the author with Reyersbach, the manager of the Eckstein group, finally led to an agreement to the effect that the water in the Rosherville pan should be used for the purposes of a large electric power station free of charge, on the condition that the Eckstein mines, which up to then had pumped out not more than 450 million galls. annually, should in future be allowed to take 600 million galls. It was also stipulated that the temperature of the water should not exceed 75° F. at the point at which it is pumped for the use of the mines.

Notwithstanding this restriction, the plans for a power station at

Rosherville were found to possess many advantages over other schemes, as investigations had shown that the demands made could be fulfilled under normal working conditions. In the very remote possibility of scarcity of water a supply could be obtained from the pumping plant of the above-mentioned company, without causing the average water costs to reach an excessive sum. The situation of Rosherville in the centre of the supply area, the satisfactory conditions for a regular coal supply, and another point of importance for installations abroad, namely, the low building costs in the vicinity of a large town (Johannesburg), increased the value of the agreement arrived at.

d. LOAD FACTOR AND POWER OF MINING PLANT.

Having settled on the site for the power station, the next step to take was to ascertain the power and load factor of plant used at the mines. The only basis to work upon were statistics of ore raised, but some statistical data relating to the power required for different work at a mine and the auxiliary plant were available. At the time of the author's visit a law had come into force prohibiting the importation of Chinese labour, and decreeing the gradual substitution of the latter by local labour; further measures had been proposed for the prevention of double shifts on underground work. The influence which such a radical change in the system of working would have upon the output and load factor had, therefore, to be considered from the outset.

The results obtained are classified in the following tables, the figures in Tables 1 and 2 being the final values in percentages of the consumption at the mines, while the figures in Tables 3 and 4 relate to an average hourly load of 100 kw. at the substation bus-bars; the tables are based upon the assumption that only one substation (transformer plant) is provided for each mine.

Tables 1 *to* 4.—*Output of the Main Generating Stations and Substations based upon the Power required by the Mines in kilowatt-hours, working with Single and Double Shifts.*

No. of Mines to each Substation:—1. No. of Mines to each Generating Station: n = approximately 20.

TABLE 1.—FINAL VALUES WITH A SINGLE SHIFT.

No.		Electric Drive.				Compressed Air.	Total.
		A. Stamps, Ball Mills, Fans, Pumps.	B. Winding Machines, Locomotives.	C. Lighting, Auxiliary Service.	D. Total Electric Drive, A, B, C.	E. Rock Drills, Auxiliary Machinery, Underground Ventilation.	F. D and E.
		Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
1	Proportion of each drive to total consumption at each mine	47	10	3	60	40	100
2	Load factor at each mine	96	30	35	66·1	40	52·3
3	Losses in the substation at the maximum load	3	3	3	3	...	1·5
4	Losses in network at the maximum load	10	10	10	10	5	7·5
5	Diversity factor for approximately twenty substations	100	70	80	87	80	83·5

TABLE 2.—FINAL VALUES WITH A DOUBLE SHIFT.

No.		Electric Drive.				Compressed Air.	Total.
		A. Stamps, Ball Mills, Fans, Pumps.	B. Winding Machines, Locomotives.	C. Lighting, Auxiliary Service.	D. Total Electric Drive, A, B, C.	E. Rock Drills, Auxiliary Machinery, Underground Ventilation.	F. D and E.
		Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
6	Proportion of each drive to total consumption at each mine	46	11	4	61	39	100
7	Load factor at each mine	96	36	40	69	60	65·1
8	Losses in the substation at the maximum load	3	3	3	3	...	1·7
9	Losses in network at the maximum load	10	10	10	10	5	7·9
10	Diversity factor for approximately twenty substations	100	65	80	85	85	85

TABLE 3.—VALUES FOR A SINGLE SHIFT, BASED UPON AN AVERAGE HOURLY CONSUMPTION OF 100 KW.-HOURS, AT FEEDER BUS-BARS OF THE SUBSTATION.

No.		Electric Drive.				Compressed Air.	Total.
		A. Stamps, Ball Mills, Fans, Pumps.	B. Winding Machines, Loco-motives.	C. Lighting, Auxiliary Service.	D. Total Electric Drive, A, B, C.	E. Rock Drills, Auxiliary Machinery, Underground Ventilation.	F. D and E.
		Kw.-Hrs.	Kw.-Hrs.	Kw.-Hrs.	Kw.-Hrs.	Kw.-Hrs.	Kw.-Hrs.
		Substation.					
11	Average consumption per hour at feeder bus-bars (No. 1) -	47	10	3	60	40	100
12	Peak load at feeder bus-bars (No. 2) - - - - -	49	33·5	8·6	90·9	100	190·9
13	Peak load at incoming feeder bus-bars (No. 3) - - -	50·5	34·3	8·9	93·7	100	193·7
		Network.					
14	Losses at peak load - - -	5·1	3·4	0·9	9·4	5	14·4
		Main Generating Station.					
15	Peak load, neglecting the diversity factor ($n=20$, Nos. 14 and 5) - - - - - -	55·6	37·7	9·8	103·1	105	208·1
16	Peak load, allowing for the diversity factor ($n=20$, Nos. 14 and 5) - - - - - -	55·6	26·5	7·8	89·9	84	173·9
17	Load factor, based upon the average hourly consumption (Nos. 11 and 16) - - -	Per Cent. 84·5	Per Cent. 37·8	Per Cent. 38·5	Per Cent. 67	Per Cent. 47·6	Per Cent. 57·5

Under normal working conditions the energy required by the mines is practically proportional to the quantity of ore crushed, or when based on gold output, it is inversely proportional to the amount of gold contained in the ore. In sinking shafts and carrying out preliminary work at new mines the forms of service classified under "A" do not ordinarily come into question, but the particulars for other classes of work are sufficient for determining this consumption after taking the values for ore as referring to rock. A very reliable figure, obtained from a number of the leading mining companies for the total energy required under normal working conditions for ore crushed, is from 35 to 42 kw.-hours per ton.

As the Eckstein mines all work with rich ores, an average value

TABLE 4.—VALUES FOR A DOUBLE SHIFT, BASED UPON AN AVERAGE HOURLY CONSUMPTION OF 100 KW.-HOURS AT THE SUBSTATION FEEDER BUS-BARS.

No.		Electric Drive.				Compressed Air.	Total.
		A. Stamps, Ball Mills, Fans, Pumps.	B. Winding Machines, Locomotives.	C. Lighting, Auxiliary Service.	D. Total Electric Drive, A, B, C.	E. Rock Drills, Auxiliary Machinery, Underground Ventilation.	F. D and E.
		Kw.-Hrs.	Kw.-Hrs.	Kw.-Hrs.	Kw.-Hrs.	Kw.-Hrs.	Kw.-Hrs.
	Substation.						
18	Average hourly consumption at the feeder bus-bars (No. 6) -	46	11	4	61	39	100
19	Peak load at feeder bus-bars (No. 7) - - - - -	48	30·6	10	88·6	65	153·6
20	Peak load at incoming feeder bus-bars (No. 8) - - -	49·4	31·5	10·3	91·2	65	156·2
	Network.						
21	Losses at peak load (No. 9) -	4·9	3·2	1·0	9·1	3·3	12·4
	Main Generating Station.						
22	Peak load, neglecting the diversity factor ($n = 1$, Nos. 20, 5, 21) - - - - - -	54·3	34·7	11·3	100·3	68·3	168·6
23	Peak load, allowingfor the diversity factor ($n = 20$, Nos. 22 and 10) - - - -	54·3	22·5	9·1	85·9	58·1	144
24	Load factor, based on an average hourly consumption (Nos. 18 and 23) - - - -	Per Cent. 85	Per Cent. 49	Per Cent. 44	Per Cent. 71	Per Cent. 67	Per Cent 69·5

for a single working shift of 37 kw.-hours per ton was taken in this case. With a double shift the forms of service given under "B" and "C" work less economically, although the additional consumption barely exceeds 5 per cent. of the total. A supply of 39 kw-.hours per ton was therefore allowed for double shifts.

Very careful statistics are kept on the mines in connection with the quantity of ore crushed. Bearing in mind the extent of ore deposits verified by numerous borings, these statistics helped to arrive at reliable consumption figures for the next few years.

In 1910 the quantity of ore crushed by the mines that were to take a supply of power was approximately 5·5 million tons; three

TABLE 5.—SUMMARY OF RESULTS.

No.		First Lay-out, $5\cdot5 \times 10^6$ tons per Annum. Working Shifts. Single.	First Lay-out, $5\cdot5 \times 10^6$ tons per Annum. Working Shifts. Double.	Second Lay-out, $7\cdot5 \times 10^6$ tons per Annum. Working Shifts. Single.	Second Lay-out, $7\cdot5 \times 10^6$ tons per Annum. Working Shifts. Double.
	Transformers in Substations.				
1	Peak load - - - - - kw.	22,000	22,500	30,000	30,600
2	,, ,, - - - - - k.v.a.	30,000	30,900	40,900	42,000
3	Including 50 per cent. reserve - k.v.a.	45,000	46,300	61,200	63,000
	Main Generating Station.				
4	Electric drives, maximum output kw.	21,000	21,000	28,600	28,600
5	Electric drives, maximum output k.v.a.	29,000	29,000	39,500	39,500
6	Including 40 per cent. reserve kw.	29,500	29,500	40,000	40,000
7	,, ,, ,, k.v.a.	40,500	40,500	55,000	55,000
8	Compressed air drives, maximum output - - - - - kw.	19,600	14,400	26,700	19,600
9	Including 25 per cent. reserve - ,,	24,500	18,000	33,400	24,500
10	Total maximum output - - ,,	40,600	35,400	55,300	48,200
11	Including reserve - - - ,,	54,000	47,500	73,400	64,500

mines were still engaged in sinking operations. It is intended to raise the annual output of these mines to 7·5 million tons.

The size of the substations and main generating station can be estimated from these figures. For the sake of simplicity it is assumed that the compressed air plant is entirely separated from the electrical plant. It should be mentioned, with regard to the question of shifts, that up to the year 1910 the mines were working on double shifts throughout; since then a number of mines have changed over to single shifts. In order to form an idea of the probable development of the demand for power, it is necessary to consider not only the increase in the quantity of ore raised, but also the probable effect of alterations in the system of working. This can be done best by considering extreme cases, namely that for single shifts on all mines and that for double shifts.

I.—First Lay-out for 5·5 Million Tons of Ore per Annum.

a. Single Shift.

$5\cdot5 \times 10^6$ tons mined per annum $= \frac{5\cdot5 \times 10^6}{8760} = 630$ tons per hour.

The hourly consumption is thus $= 630 \times 37 = 23,300$ kw.-hours.

1. Transformer load in substations (L_{Tr}), from Table 3, No. 13, D:—

$L_{Tr} = \frac{23,300}{100} \times 93\cdot7$ - - - - - = 22,000 kw.

At 73 per cent. power factor - - - = 30,000 k.v.a. (approx.).

Including 50 per cent. reserve - - - = 45,000 „

2. Main generating station, electric plant (L_{el}), from Table 3, No. 16, D:—

$L_{el} = \frac{23,300}{100} \times 89\cdot9$ - - - - - = 21,000 kw.

At 73 per cent. power factor - - - = 29,000 k.v.a.

Including 40 per cent. reserve - - - = 29,500 kw.

Or - - - - - - - = 40,500 k.v.a.

3. Main generating station, compressed air plant (L_{Dr}), from Table 3, No. 16, E:—

$L_{Dr} = \frac{23,300}{100} \times 84$ - - - - - - = 19,600 kw.

Including 25 per cent. reserve - - - = 24,500 „

4. Total output of main generating station ($L = L_{el} + L_{Dr}$):—

Without reserve - - - - - L = 40,600 „

Including reserve - - - - - L = 54,000 „

b. Double Shift.

With 630 tons of ore mined per annum, an hourly consumption is obtained of $630 \times 39 = 24,600$ kw.-hours.

1. Transformer load in substations (L_{Tr}), from Table 4, No. 20, D:—

$L_{Tr} = \frac{24,600}{100} \times 91\cdot2$ - - - - - = 22,500 kw.

At 73 per cent. power factor - - - = 30,900 k.v.a.

Including 50 per cent. reserve - - - = 46,300 „

2. Main generating station, electric plant (L_{el}), from Table 4, No. 23, D:—

$L_{el} = \frac{24,600}{100} \times 85\cdot9$ - - - - - = 21,000 kw.

At 73 per cent. power factor - - - = 29,000 k.v.a.

Including 40 per cent. reserve - - - = 29,500 kw.

Or - - - - - - - = 40,500 k.v.a.

3. **Main generating station, compressed air plant (L_{D_r}), from Table 4, No. 23, E:—**

$L_{D_r} = \frac{24,600}{100} \times 58{\cdot}1$ - - - - $= 14,400$ kw.
Including 25 per cent. reserve - - - $= 18,000$ „

4. **Total output of the main generating station ($L = L_{el} + L_{D_r}$):—**

Without reserve - - - - - $L = 35,400$ „
Including reserve - - - - - $= 47,500$ „

II.—Second Lay-out for 7·5 Million Tons of Ore per Annum.

All values under I. are increased in the ratio of $\frac{7{\cdot}5}{5{\cdot}5} = 1{\cdot}36$.

Quantity mined per hour - - - - - = 860 tons.
Hourly consumption with a single shift - - = 31,700 kw.-hours.
„ „ „ double „ - - = 33,500 „

The main generating station was built accordingly for the following total capacity:—

7 Turbo-generators, each 10,000 kw. - - = 70,000 kw.
4 Steam compressors, each 3,000 kw. - - = 12,000 „
Total - - - - - 82,000 kw.

As already stated above, some of the compressors are driven electrically, namely, six compressors taking 3,000 kw. each = 18,000 kw. This load has to be supplied by the above seven turbo-generators, in addition to the losses of the electric drive, which amount to about 10 per cent.

The total energy for compressors is 30,000 kw., which shows, therefore, that the compressor plant would be large enough for the second lay-out with a double shift. The change-over to single shifts raised the peak load for compressed air supply rapidly; moreover, this form of energy is very popular, and the company received a large number of applications for a compressed air supply in consequence. Further steam turbine-driven compressors with a total capacity of 28,000 kw. were therefore ordered from the A.E.G. Of these machines, those ordered last are to have a capacity of 10,000 H.P. each; they will thus be 2½ times larger than any other compressor built hitherto.

4. SECOND SECTION—ROSHERVILLE POWER STATION.

D. Rosherville Power Station.

(a) *Position.*

The works are situated on the east side of the Rosherville dam (see plan, Figs. 118 and 119), in the immediate neighbourhood of the industrial railway which stretches from the main line southwards over the whole of the Rand, and is used exclusively for the freight traffic of the gold mines.

(b) *Boilers and Coal Conveying Plant.*

In these works, also, the boilers are installed in a number of boiler houses (Figs. 120, 122, 123), containing two to four boilers with a capacity of 33,000 lbs. per hour each, which is sufficient for two 12,000 kw. turbo-generators. The first lay-out included three boiler houses at the present moment there are four.

Outside each boiler house there is a coal store extending in the longitudinal axis of the boiler house, unlike the arrangement at Simmerpan station. The storage capacity is 24,800 cub. ft., the yard is 160 ft. long, and is traversed by tracks of rails carried on iron trestles (see Figs. 124, 125, 126). As in the Märkische Electricity Works, the coal conveyors run in passages underneath the yard, and discharge the coal into hoppers placed in a row above the boilers. Owing to the small capacity of the hoppers they could be suspended with the conveyor track from the ironwork of the roof (Figs. 122, 123) without necessitating any columns to support the roof from the floor. The boilers are of the same type as those in the Märkische Electricity Works (see pp. 77 to 83), the only difference being the absence of the second upper drums, which are here replaced by steam separators in the main steam piping (see plan of pipework, Fig. 127).

(c) *Water Supply.*

The provision of an adequate water supply was attended by special difficulties, as fluctuations in the level of the pan at Rosherville up to 23 ft. have to be allowed for. It was at first intended to proceed in

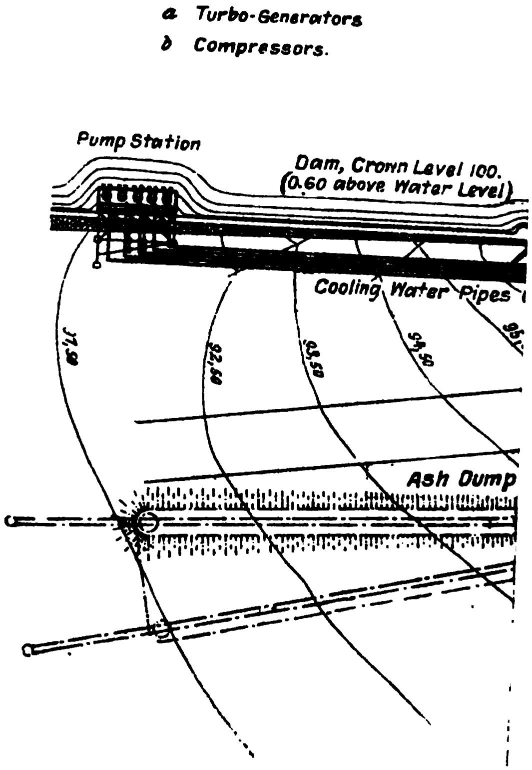

a Turbo-Generators
b Compressors.
Pump Station
Dam, Crown Level 100.
(0.60 above Water Level)
Cooling Water Pipes
92,50
93,50
94,50
Ash Dump

Fig. 119.—Ra

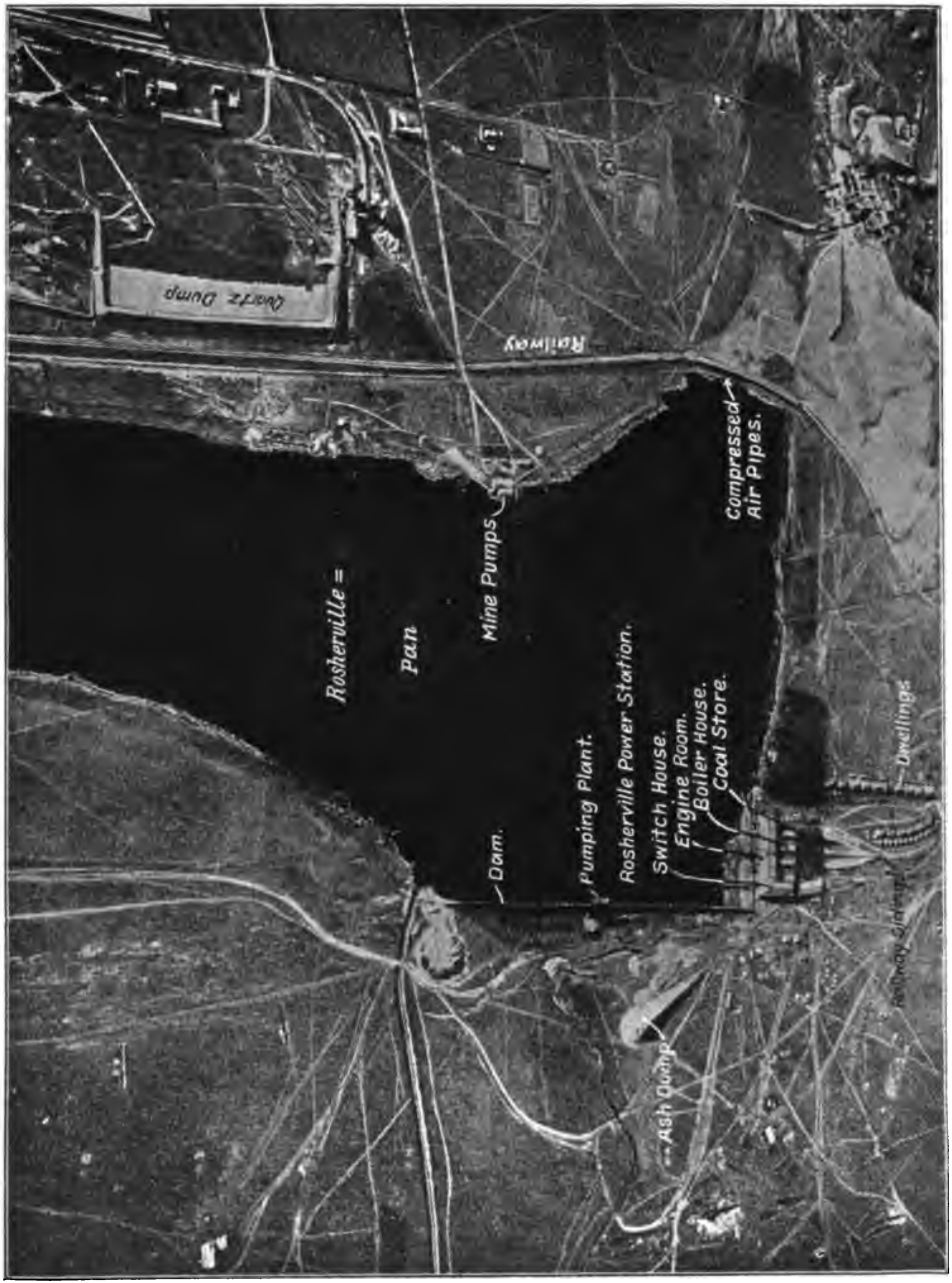


Fig. 118.—Rosherville Power Station viewed from a Balloon.

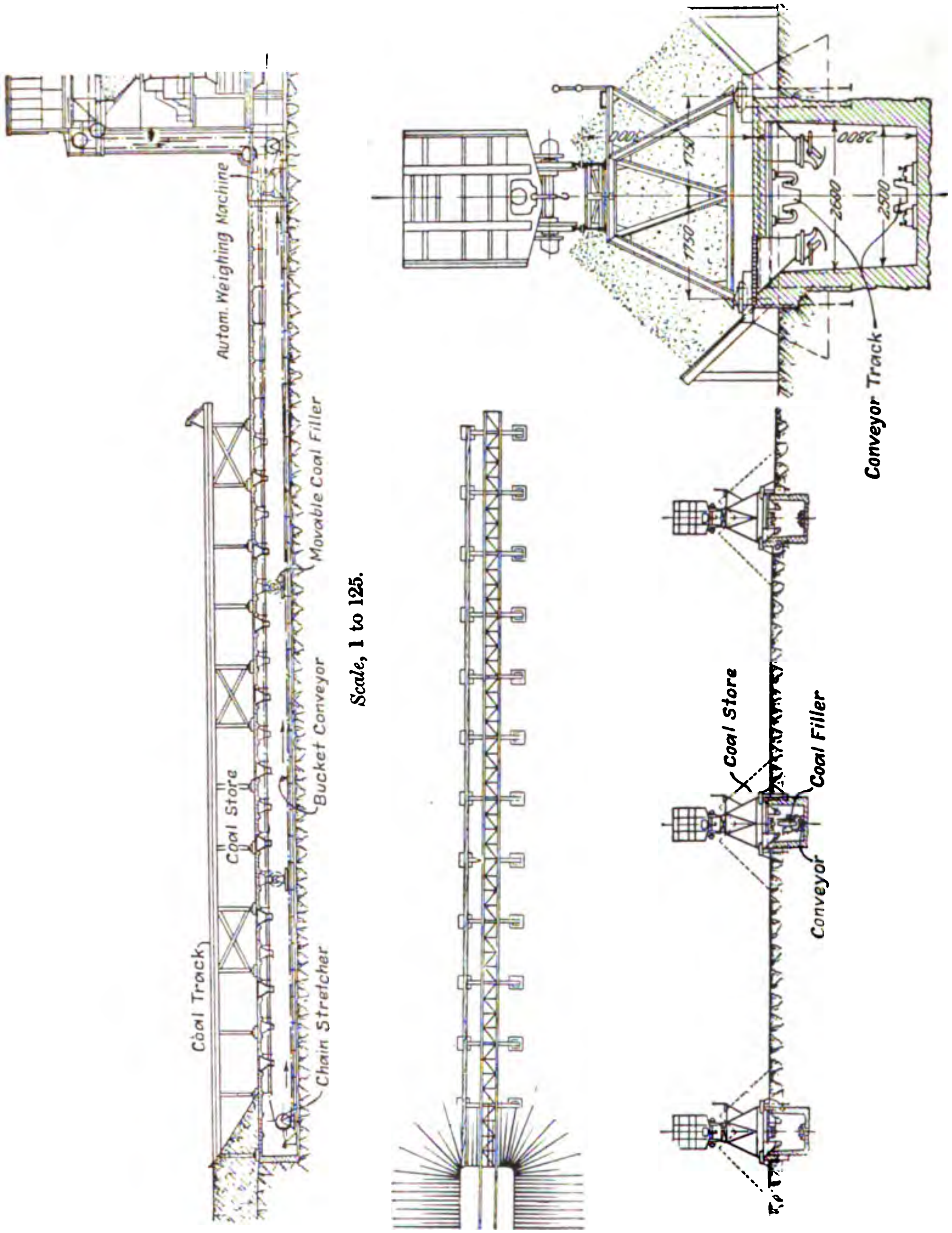


Fig. 124.—Rosherville Power Station. Plan and Section through the Coal Yard and Coal Conveying Plant. *Scales*, 1 to 500 and 1 to 125. (Dimensions in metres.)

the same manner as at Simmerpan by constructing a channel, the inlet of which could be deepened as the water level receded. This

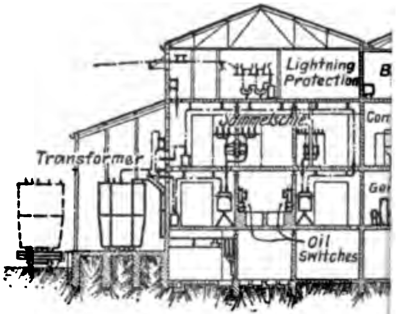


Fig. 121.—Rosher

method was, however, not adopted, as the very large quantity of water, 44,000,000 galls., made the construction of a final connection between the channel and the pan impossible after the plant was once in operation, and might have caused serious interruptions. The slope of the bank is very flat at this point, so that the subsequent work at lower levels would have had to be carried out for a distance of nearly 1,000 ft. into the pan.

The next solution to the problem, in which the water was to be drawn through pipes sunk into this pan, was rejected as not being sufficiently reliable. It would have been very expensive, as wide and deep shafts were required for the pumping plant in order not to exceed the maximum permissible lift at the lowest water level. It should be mentioned here that the theoretical lift is only 26 ft. owing to the altitude of the power station, so that after allowing for the pressure losses in the 1,000 ft. of suction piping it was not possible to count upon a lift of more than 16 ft. Another reason for abandoning this idea was that no guarantee could be obtained for completion within the allotted time, a point of special importance in view of the obligation to

Fig. 125.—Rosherville Power Station. View of the first Coal Conveyor Track, Boiler House, and Switch House. The latter is partially covered with corrugated iron ; the first part of the Boiler Plant in the background is in course of erection.

have a supply of energy ready by a given date under heavy penalties for delay.

According to a third scheme, vertical shafts were to be sunk close to the power station; from the bottom of these shafts tunnels were to be driven to the deepest part of the pan. This plan was undoubtedly cheaper to carry out, as men skilled in this class of work could be had on the spot. Unfortunately the rock near the site was very much decayed and intersected with water-bearing layers. Owing to the danger of an influx of water, completion of the work in time could not be relied upon. It was therefore necessary to fall back on a construction which could be carried out above ground.

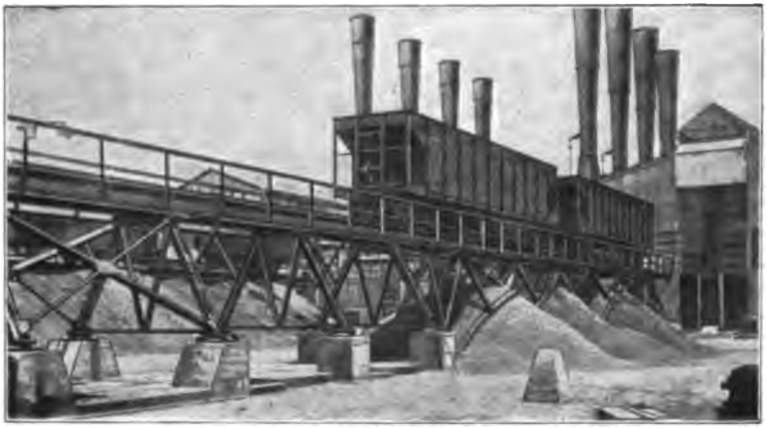


Fig. 126.—Rosherville Power Station. Coal Conveyor Track and two Railway Trucks for Automatic Discharge. Coal Yard underneath and Hoppers for the Bucket Conveyor.

The pan is formed by a dam 1,800 ft. in length, and as high as the pan is deep. The plan was to withdraw the water from the deepest point along the dam and deliver it to the power station through pipes. There was a certain risk in breaking through the dam here, wherefore it was decided to break through at a higher point, allowing a comparatively small quantity of water to run to waste in order to lower the pan level below the pump works. Syphon pipes were to be built into the dam, and the pumping plant was to be erected near the base of the dam, where the permissible suction lift would not be exceeded. This plan was worked out in all its details, but eventually was not sanctioned by the Eckstein Company, who would not consent to the dam being touched under any circumstances, because it was not considered strong enough. A construction was insisted on which put no strain whatever on the dam.

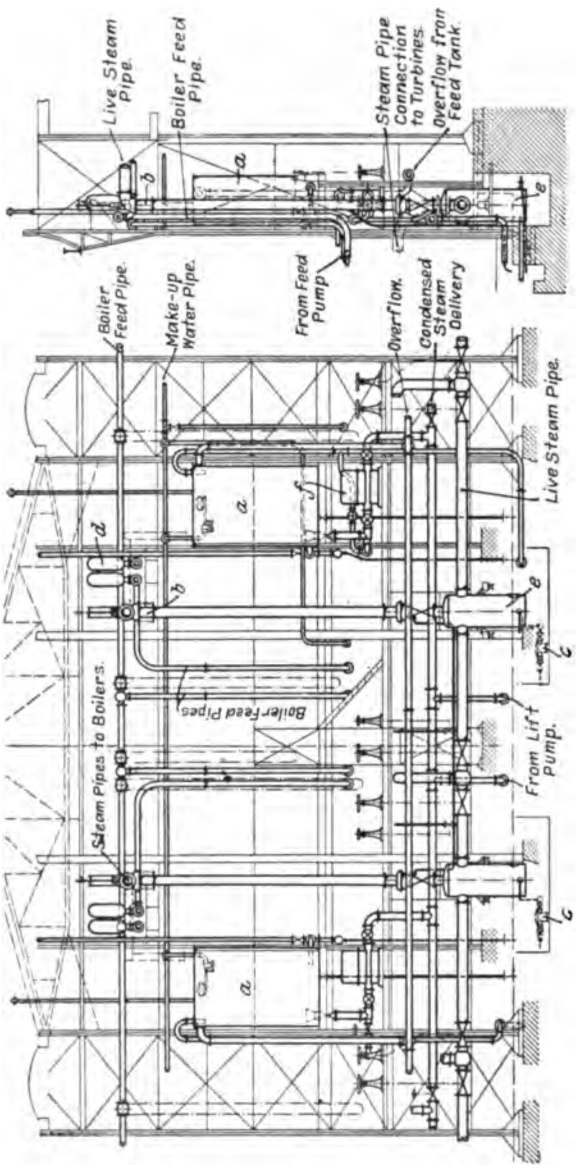


Fig. 127.—Rosherville Power Station. Pipework in Boiler House along the Wall of the Engine Room. The arrangement of Pipes in the three other Boiler Houses is practically the same. *Scale*, 1 to 500.

a = Feed tank for condensed steam. *b* = Compensator. *c* = Steam trap. *d* = Air chamber. *e* = Water separator. *f* = Water meter.

After having investigated all these schemes there was nothing to do but to erect the pump station in the pan itself close to the deepest part of the dam (Figs. 118 and 119). In order to secure a firm foundation for the machinery five caissons were sunk in the water, each of which contains a vertical rotary pump driven by a three-phase motor (Fig. 128). The caissons are constructed of boiler plate with a suitable iron framework over the top above water level, the whole of the plant being enclosed in a building. To ensure accurate alignment the bottom of each caisson is provided with three feet, with screw spindles for adjustment from above. After the caissons had been placed in position (Figs. 129, 130, 131) they were filled with hydraulic cement up to the level of the pump foundations, and the water above the cement was pumped out. No difficulties were encountered, and the plant is a success in every respect. The five pressure pipes (Fig. 132) pass from the caissons over the top of the dam without protection; they are secured partly to iron girders and partly to concrete supports, and run along the outside of the dam to the power station.

It was impracticable to feed the condensers direct from the pumps, as numerous branches and valves were required to ensure correct distribution of the water and sufficient reliability in operation. It was therefore preferred to construct a fairly shallow channel along the engine room from which the rotary pump of each condenser could draw its water. The arrangement offered the possibility of connecting the channel direct with the pan; a supply of water could then be obtained when the pan level was high enough without having to keep the pumping station running (Figs. 133, 134).

The outlet channel for the water from the condensers runs parallel to the inlet channel. Both channels have a comparatively large capacity to enable the condenser service to be maintained by the steam pumps alone at a reduced vacuum, should the electrical pumps break down. For this purpose there is a connection between the inlet and outlet channels, which opens automatically at a certain difference of water level due to a reduced supply from the pump station on the dam.

Special importance was attached to convenient supervision of the auxiliary pumps in the basement of the engine room. The pumps for one generating set are erected in the space between the condenser and the boiler house wall, and can be inspected through the opening in the floor of the engine room.

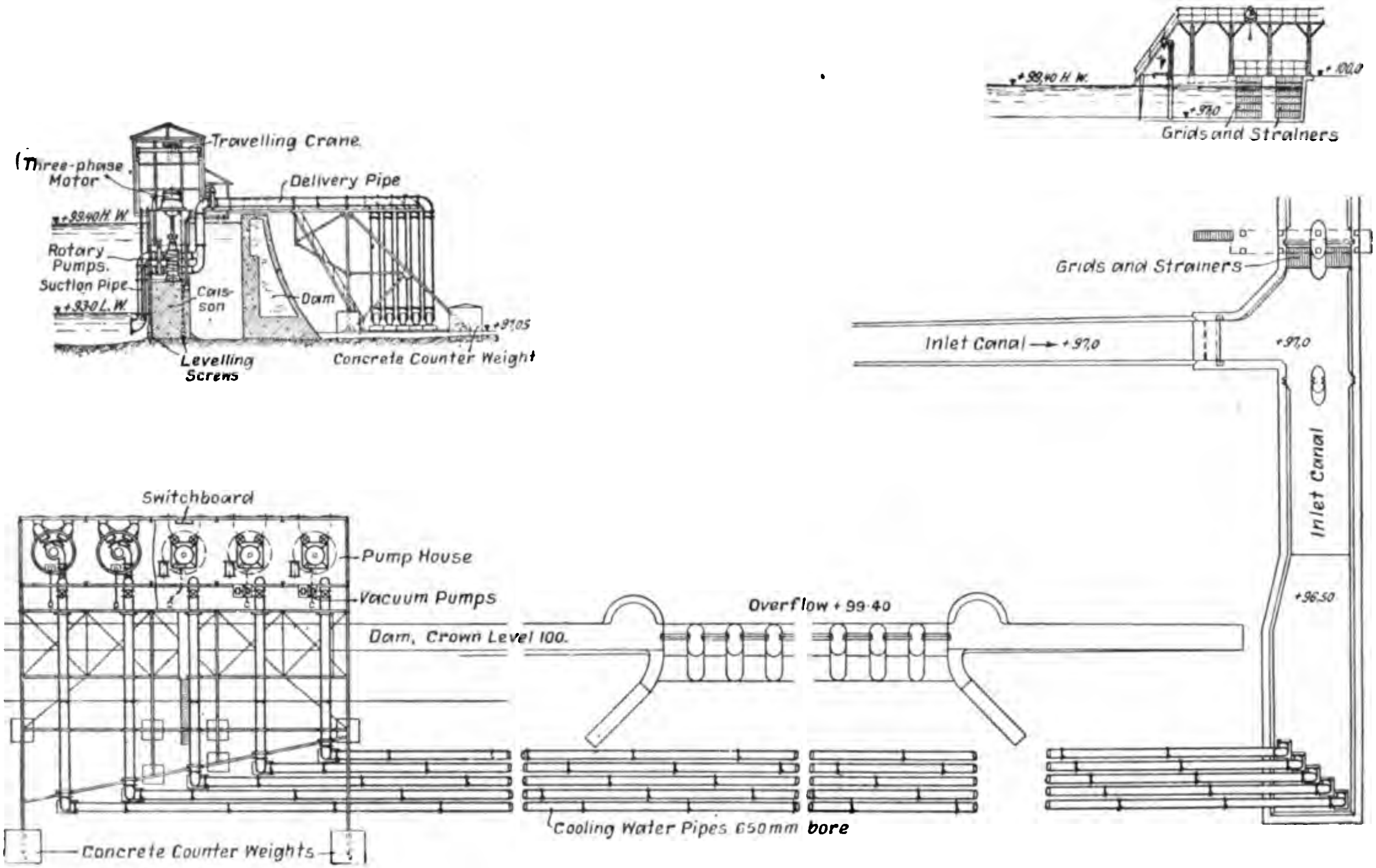


Fig. 128.—Rosherville Power Station. Plan and Section of Pumping Plant and Inlet Channel for Circulating Water. *Scale*, 1 to 700. (Dimensions in metres.)

Fig. 129.—Rosherville Power Station Pumping Plant. To the right of the Dam, lowering a Caisson from a Raft; to the left of the Dam, Iron Framework for supporting the Caissons and Delivery Pipes.

Fig. 130.—Rosherville Power Station Pumping Plant. Caisson in position, erection of the upper Framework; opening in the foreground for the Vertical Pump Motor.

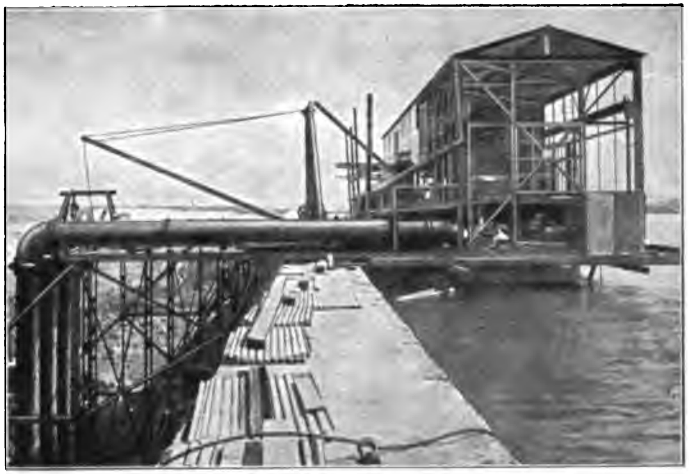


Fig. 131.—Rosherville Power Station Pumping Plant. Pump House in course of erection, with a portion of the Delivery Pipes in position. In erecting the plant the Dam was not made use of at any point, thus complying with the stipulation made by the Mining Companies.

Fig. 132.—Rosherville Power Station Pumping Plant. Laying of the five Delivery Pipes, 25 in. in diameter, from the Pumping Plant to the Inlet Channel.

(*d*) *Engine Room.*

The engine room (Figs. 120, 121, 123) contains five turbo-generators each with a capacity of 12,000 k.v.a., and six turbo-compressors for 4,000 H.P. each (Figs. 135 and 138). The pressure is 5,000 volts,

Fig. 133.—Rosherville Power Station. Excavating the Inlet Channel; Sandy Upper Soil with a Substratum of Rock.

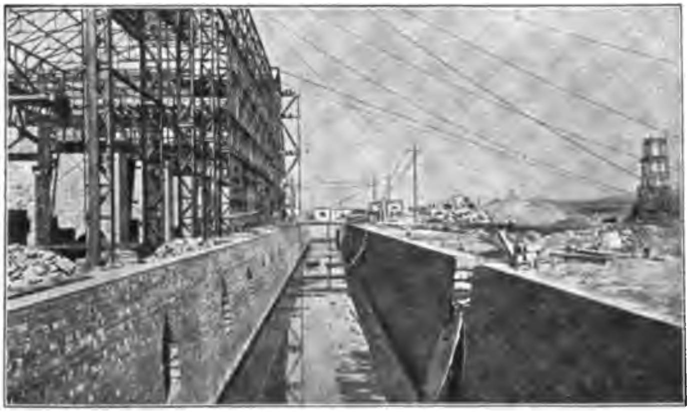


Fig. 134.—Rosherville Power Station. Masonry Work for the Inlet Channel. On the left, openings for the Suction Pipes; on the right, Flap balanced by Counterweight which allows the Water to flow back from the Canal automatically at Low Water Level; above, Iron Framework for the Machine House before the Corrugated Iron Covering was placed on it.

Fig. 135.—Rosherville Power Station. Engine Room with Travelling Crane. Preliminary Work for the Erection of Turbines.

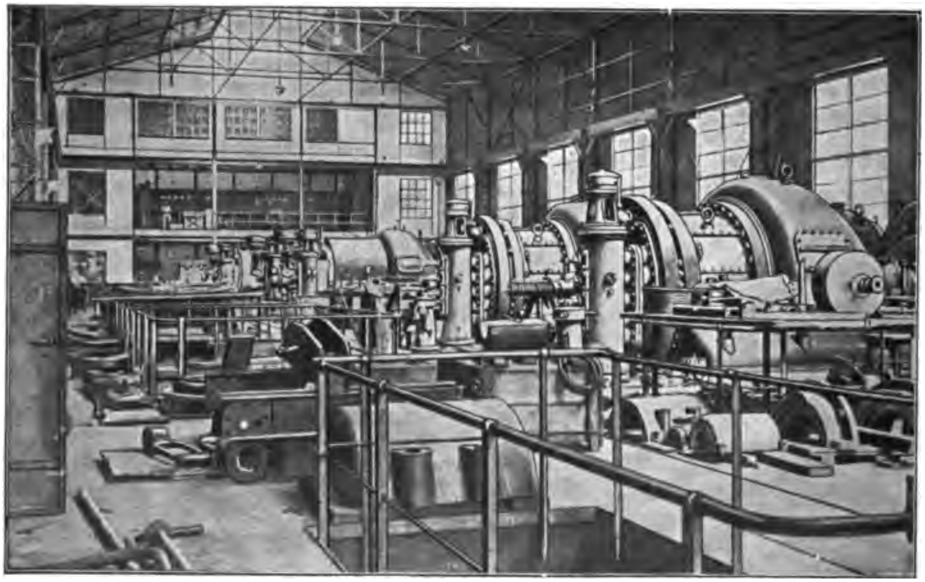


Fig. 136.—Rosherville Power Station. Interior of the Engine Room. Five Turbo-Generators completely erected and partly in commission. In the background, Control Room for Switchgear and Switch House.

suitable for bar winding; the speed is 1,000 revs. per min. The auxiliary turbines exhaust into the second stage of the main turbines, whereby the steam consumption of this plant is improved. The exhaust steam from the turbine-driven feed pumps is used for heating the feed water, the temperature of which is thereby raised to 100°-120° F. (Fig. 127). The air for cooling the generators is filtered before entering the machines, an arrangement which is indispensable owing to the frequent dust storms in winter. The warm air escapes from the engine room through passages which are made as short as possible to avoid unnecessary heating of the engine room (view of the engine room and switch house, Fig. 139).

Fig. 137.—Rosherville Power Station. View of the first Lay-out complete : 5 Generators, 4 Compressors.

In place of piston water meters, which require very careful handling, recording water meters on the Venturi principle are used in the feed pipe. This is the first power station where this has been done. They have given excellent results on account of their reliability and simplicity. It is not necessary to have a by-pass, as the nozzle contains no complicated constructional parts and can easily be inspected. The recording device is connected to the nozzle by small tubes, and is installed in the engine room so that it can be kept under careful control. The meters are also provided with an indicator which enables the attendant to ascertain the actual water consumption at any moment.

(*e*) *Switch House.*

The switch house is at right angles to the engine room and adjoins the south end of the latter (Figs. 119 and 120); the control board is situated in a room that opens on to the engine room, so that the switchboard attendant can see the machine plant; in other respects the switchgear is entirely separated from the engine room.

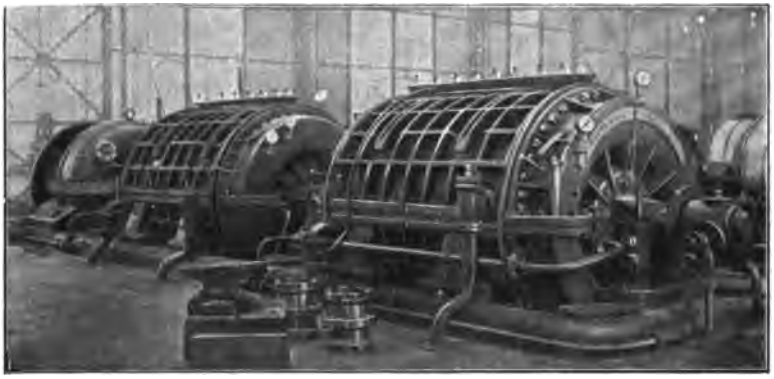
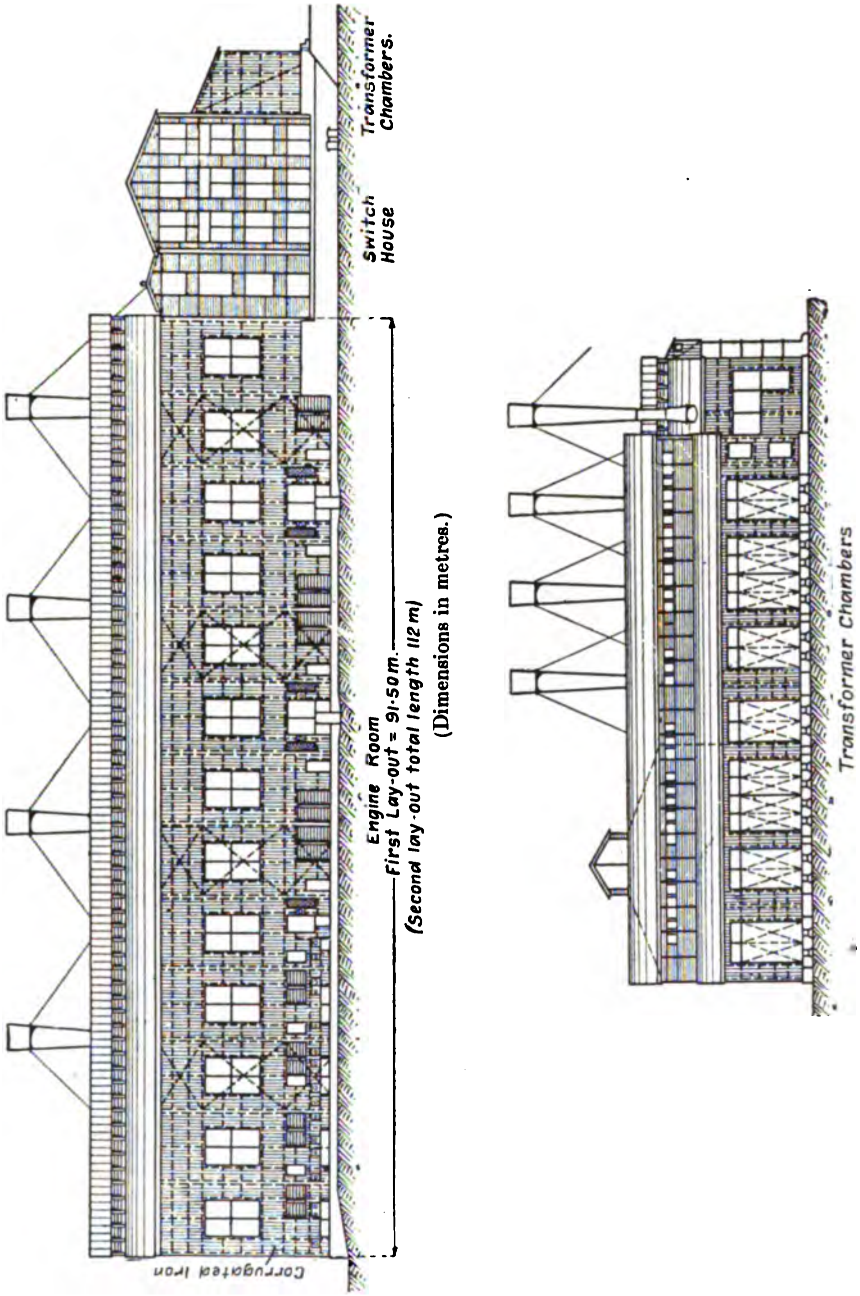


Fig. 138.—Rosherville Power Station. Compressor No. 5.

Apart from the control panels and switchgear, the building contains the battery and converters as at Simmerpan; the transformers are placed in an attached building (Fig. 140). Each generator has its own three-phase transformer with a capacity of 12,500 k.v.a., which is among the largest constructed up to the present time. The generator pressure is stepped up from 5,000 to 20,000 or 40,000 volts; the secondary windings can be switched over from one voltage to the other. Contrary to the Brakpan and Simmerpan stations, the current from the Rosherville station is distributed through a 20,000-volt cable network, while the pressure of the overhead feeders is 40,000 volts as in the older stations.

Two double sets of bus-bars for 20,000 volts were therefore necessary (see diagram of connections, Fig. 141). Under normal con-



(Dimensions in metres.)

Fig. 139.—Rosherville Power Station. View of the Engine Room and Switch House. *Scale*, 1 to 750.

ditions some of the generators and transformers work direct on to the 20,000-volt bus-bars, while the remainder are connected up to the 40,000-volt bus-bars; both sets of bus-bars can be coupled up through two 4,000 k.v.a. transformers for 40,000 and 20,000 volts. The transformers are changed over from 20,000 to 40,000 volts, or *vice versa*, very simply with isolating switches, so that in case of an emergency the supply to one or the other side can be augmented quickly. The dimensions of the switch house are somewhat unusual: it is 200 ft. long, owing to the large number of 20,000 and 40,000 volt outgoing transmission lines required for distributing the energy. At the present moment there are five 20,000-volt cables and eight 40,000-volt transmission lines. There are also two 500-volt feeders for the auxiliary service and for lighting, besides 2,000-volt feeders for the pumping station, as the pump motors could not be wound for 5,000 volts; the motors for a number of large cooling water pumps for the compressor plant, described further on, were also connected up to these feeders.

The arrangements here for ensuring a constant supply for auxiliary machinery are similar to those in Simmerpan station. In the event of the three-phase supply failing, the direct current machine for charging the battery is run as a motor, and the synchronous motor coupled to it is converted into a generator, which supplies current to the auxiliary plant until the normal three-phase supply is in order again; the auxiliary transformers are here cut off from the bus-bars automatically.

(*f*) *Compressor Plant.*

Apart from the three-phase generators, Rosherville power station contains six steam-driven compressors, each taking 3,000 kw., and running at a speed of 3,000 revs. per min. (Figs. 120 and 121).

Each compressor consists of the steam turbine and two cylinders all on one shaft; the condensers are arranged similarly to those of the turbo-generators. The air from the compressors is blown at a pressure of 130 lbs. per sq. in. into collector pipes, which enter the

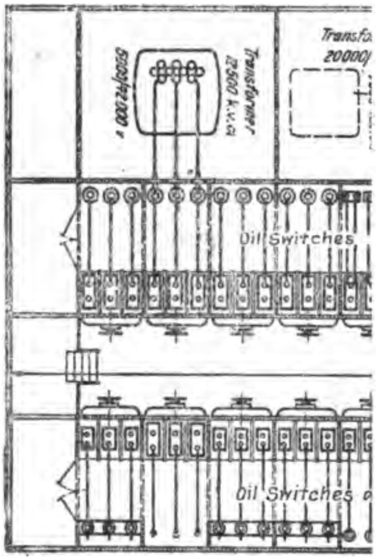


Fig. 140.—Rosherville Power
Section through the Sw
Scale 1 to 27
(Dimensions in m

current motor generators, 330/500 k.v.a., for charging the battery and supplying the auxiliary machinery and pumping plant in an emergency.

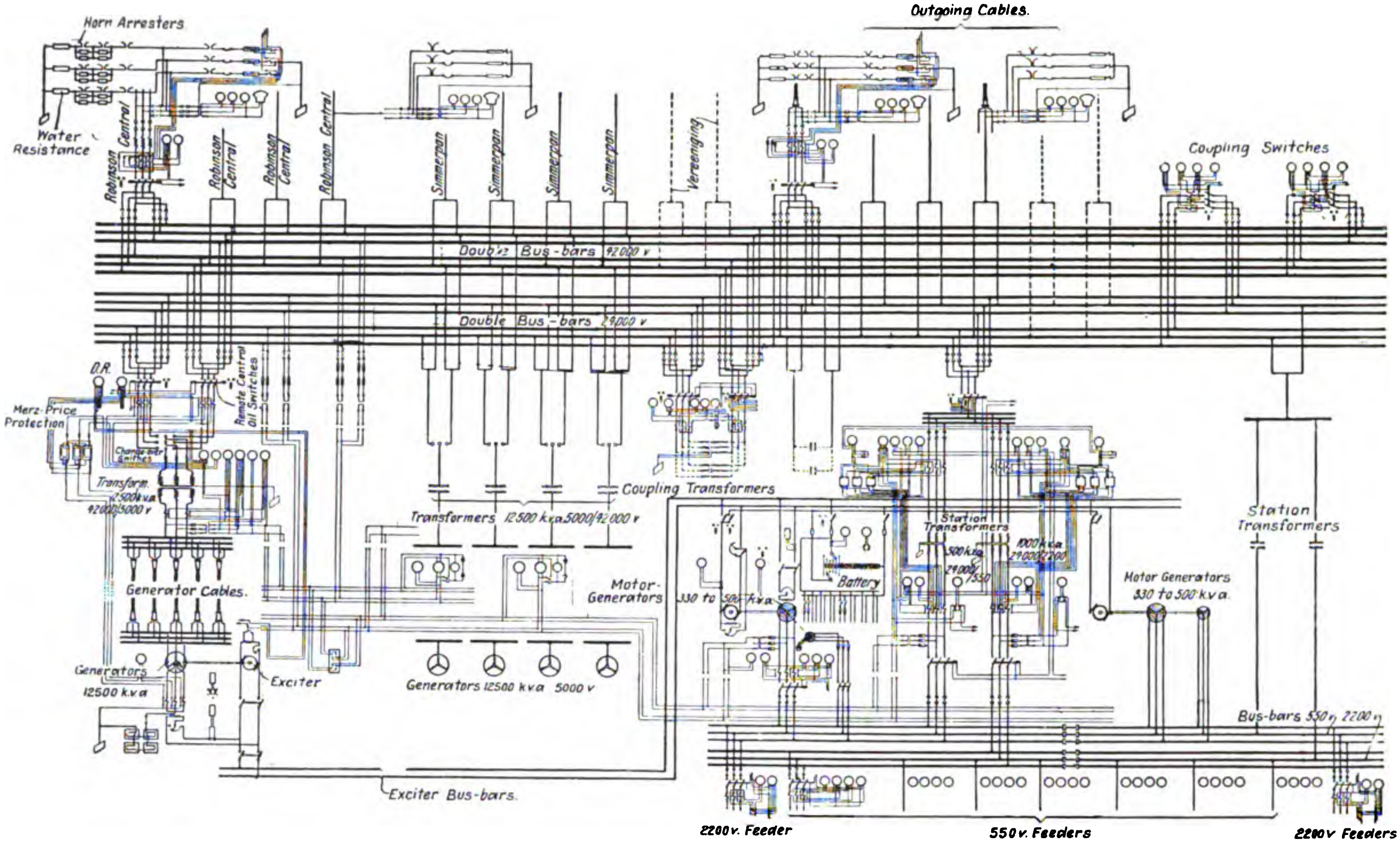


Fig. 141.—Rosherville Power Station. Diagram of Connections.

Five Generators, 12,500 k.v.a., 5,000 volts direct coupled exciters; energy transformed in five transformers of the same capacity to 42,000 or 24,000 volts; the transformers can be changed over to double bus-bars for 24,000 and 42,000 volts. The 42,000 and 24,000 double bus-bars are linked by two coupling transformers, 4,000 k.v.a. each. Four outgoing transmission lines for 42,000 volts to Robinson Central Station, four similar lines to Simmerpan. Six 24,000-volt cables for the distribution network. Two transformers for auxiliary service, 500 k.v.a., 24,000/550 volts each. Two transformers for the pumping plant, 1,000 k.v.a., 24,000/2,200 volts each. Two reserve panels. Seven feeders, 550 volts, for the auxiliary service (fans in boiler houses, etc.). Two feeders, 2,200 volts, for the pumping plant. Battery for excitation, 220 volts, 1,150 amps. Two three-phase direct current motor generators, 330/500 k.v.a., for charging the battery and supplying the auxiliary machinery and pumping plant in an emergency.

main valve chamber at the north-west end of the engine room; here the distributing pipes are branched off.

E. Robinson Central Station.

(a) *Central.*

The works (see plan, Fig. 142) are situated at a distance of only five miles to the west of Rosherville, and are stationed without a source of energy of its own. The installed capacity is 50,000 kw.; both the 20,000-volt cable network for local consumption and the compressed air system are supplied from here. The energy comes partly from Rosherville through four 40,000-volt overhead lines, and partly from Vereeniging through three 80,000-volt overhead lines. The energy is transformed down to 20,000 volts for electrical distribution, and to 5,000 volts for the motors driving air compressors (Figs. 143 to 146).

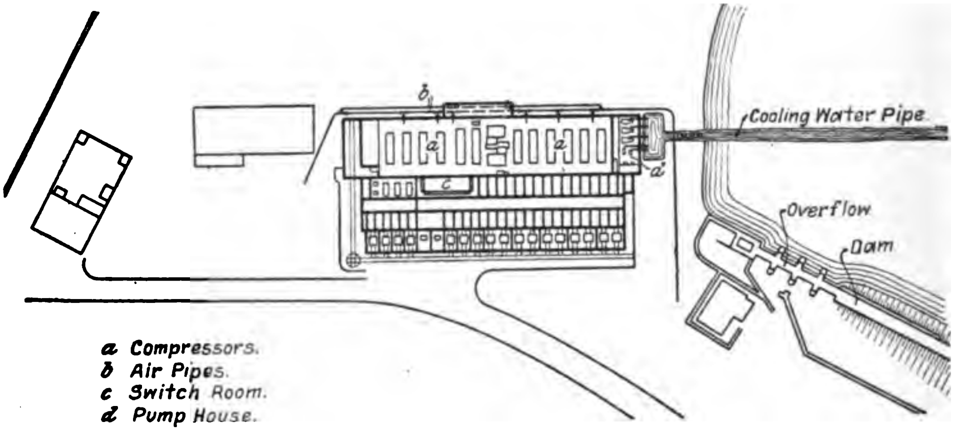


Fig. 142.—Robinson Central Station. Plan.

The large capacity of this station may be somewhat surprising in view of the proximity of Rosherville. This locality was, however, necessary, owing to compressed air requirements, and to the fact that the 20,000-volt network cannot transmit sufficient energy. With stations further apart the dimensions of the air pipes would also have

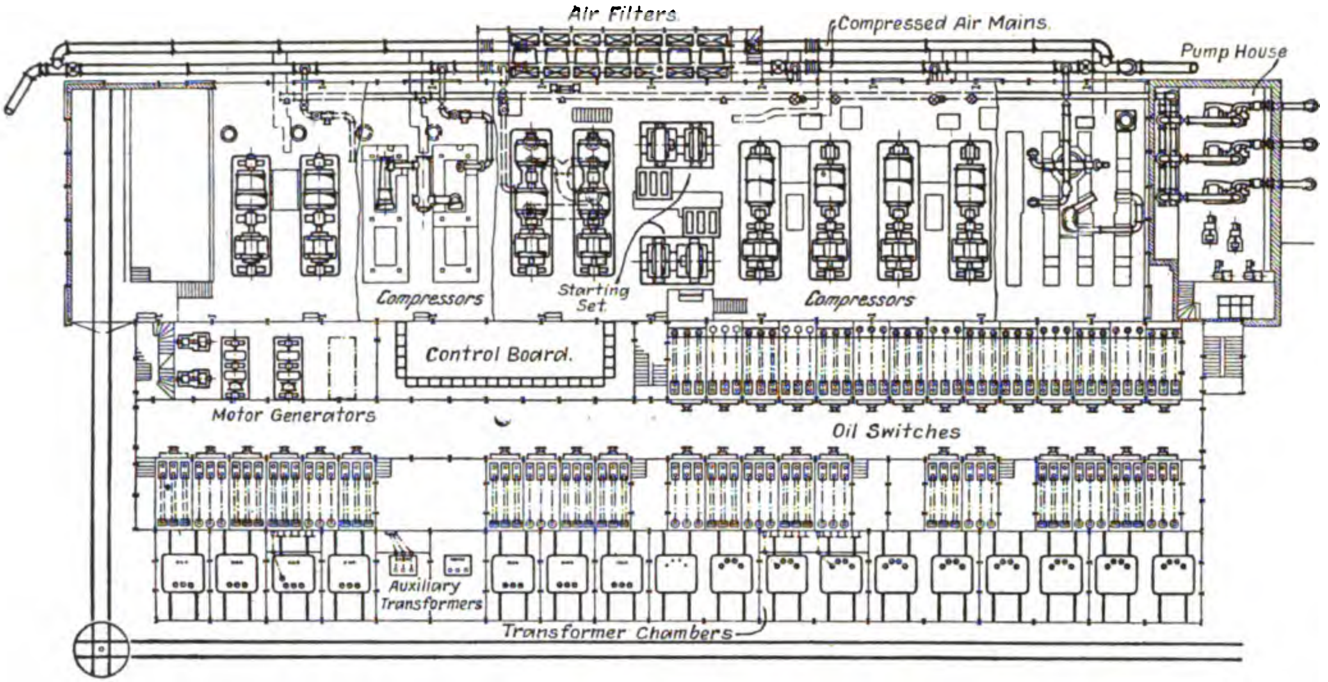


Fig. 143.—Robinson Central Station. Plan of the Switch House and Engine Room.

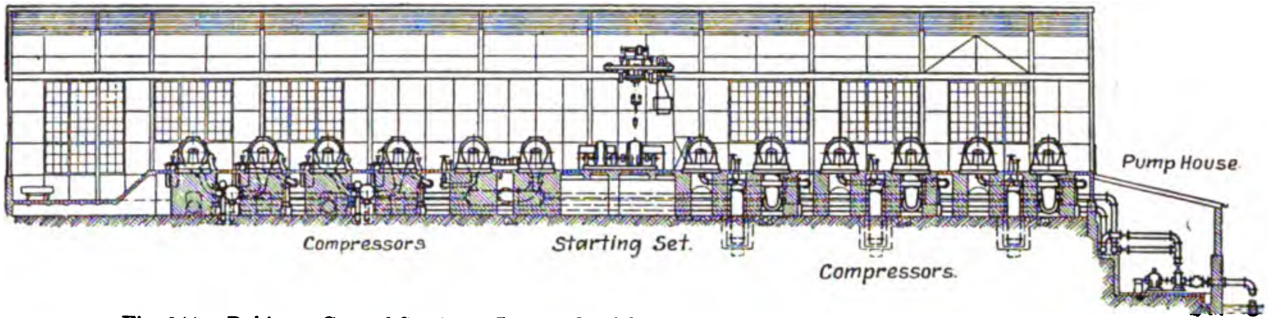


Fig. 144.—Robinson Central Station. Longitudinal Section through Engine Room and Pump House.

become inconveniently large. Careful comparative calculations made for various sites showed the superiority of the locality selected. A lake close at hand, the Robinson pan, could be utilised for providing the comparatively large quantity of cooling water required for the six 4,000 H.P. compressors erected here.

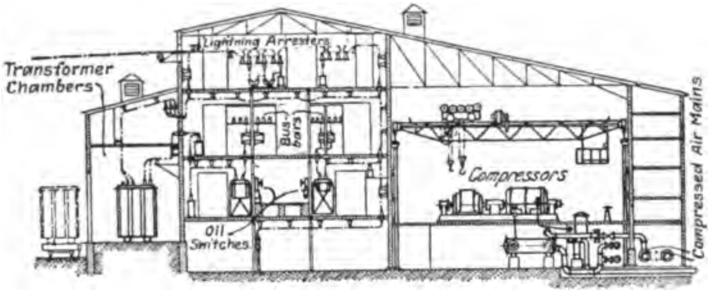


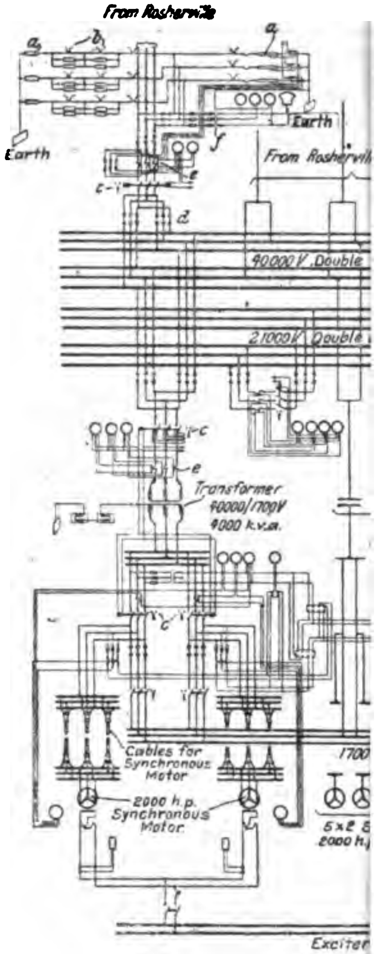
Fig. 145.—Robinson Central Station. Section through the Switch House and Engine Room.

The extensive switch house is similar to that in Rosherville, and therefore need not be described further (Figs. 147 and 148).

Fig. 146.—Robinson Central Station. Engine Room. Iron Framework completed ready for covering in ; on the left, Transformer Cells half finished.

(b) *Compressor Plant.*

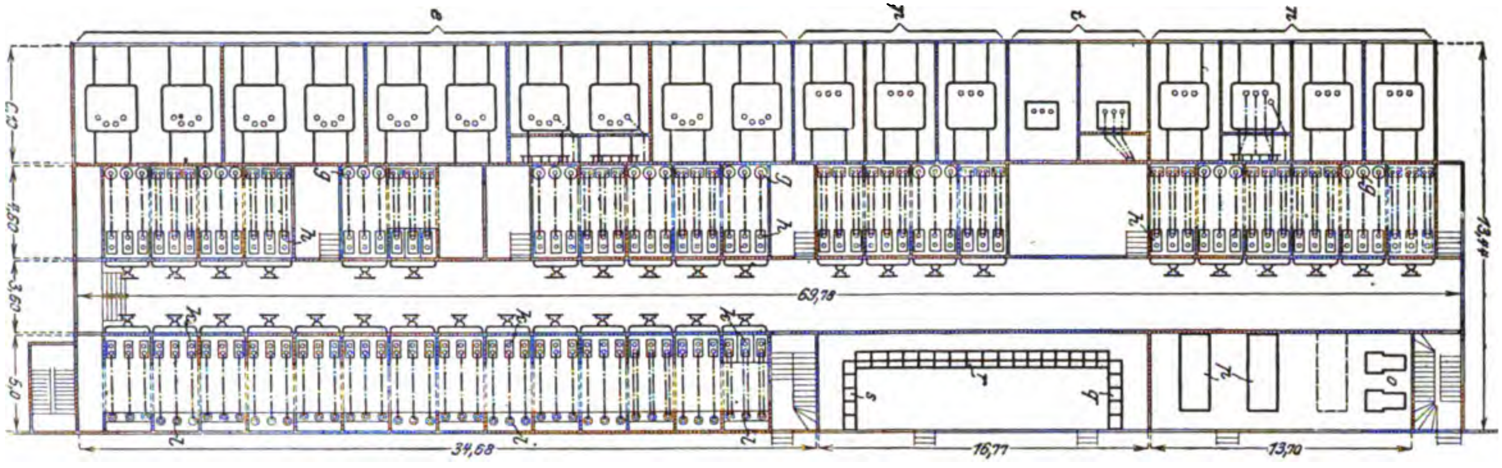
The air compressors are constructed in two parts, each with a 2,000 H.P. synchronous motor, and two cylinders on the same shaft. Although an induction motor would have been very much simpler to



a. Resistances,

b. Horn lightning

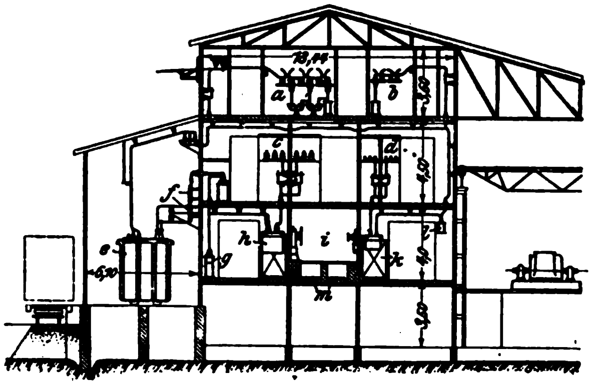
Four transmission lines
(80,000 volts) from Vereenigi
motors for air compressors,
in 3×2 transformers, 9.000
20,000-volt feeders. One c
bus-bars by two coupling t
feeders for auxiliary service
for excitation, 110 volts, 5
three-phase generator, 17,00



(Dimensions in metres.)

Fig. 147.—Robinson Central Station. Plan and Section through the Switch House.

a. Lightning arresters, 40,000 volts.
b. ,, ,, 21,000 ,,
c. Bus-bars, 40,000 volts.
d. ,, 21,000 ,,
e. Transformers, 4,000 k.v.a., 40,000/21.000 volts.
f. Choking coils.
g. Current transformers, 40,000 volts.
h. Oil switches, 40,000 volts.
i. Operating corridor.
k. Oil switches, 21,000 volts.
l. Current transformers, 21,000 volts.
m. Control cables.
n. Transformers, 4,000 k.v.a., 40,000/1,700 volts.
o. Boosters.
p. Converters.
q. Switchboard for 20,000-volt cables.
r. Main control switchboard.
s. Switchboard for 40,000-volt transmission lines.
t. Transformers, 500 k.v.a., 21,000/550 volts.

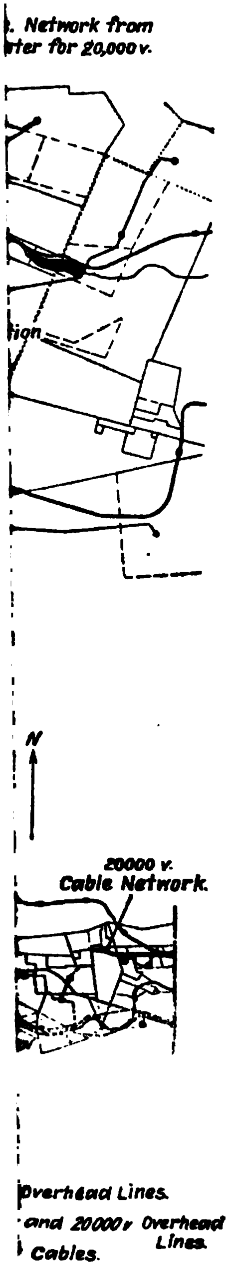


install, synchronous motors were selected with the object of improving the power factor of the entire network. The motors were therefore made large enough to work at full load, with a leading power factor of 85 per cent. When starting up the compressors run light and the suction pipe is closed. A special starting set, consisting of an induction motor and a generator, are used for starting up the air compressor motors (see diagram of connections, Fig. 148). The generator was designed with a number of poles to give rather more than fifty periods per second when the induction motor runs at full speed. Before putting an air compressor motor into commission, the generator of the starting set is coupled electrically to the motor whilst both are at a standstill and fully excited; the motor generator is then run up slowly, the synchronous compressor motor following.

When the synchronous speed of 3,000 revs. per min. is reached, and paralleled with the mains in the usual way, the generator of the starting set is switched off again. The same process is repeated with the second compressor motor; no difficulties have resulted from this method of working. The disadvantages of this indirect method of starting are counterbalanced by the improvement in the power factor obtained through the synchronous motors. The value of this advantage is fairly considerable, because the power factor of the induction motors on the Rand is generally low. The output required for starting up one half of a compressor in this manner is between 400 and 600 kw.

Fig. 149.—Robinson Central Station. Double Pipe Mains for Compressors outside the Building. Centralised Filter Plant for all Compressors visible in the Centre.

It is important that the air forced into the pipes should be as pure as possible, and filters of a good design are therefore essential. In Rosherville each compressor has its own filter; in Robinson


. Network from
ter for 20,000 v.
tion
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Overhead Lines.
and 20000 v Overhead Lines.
Cables.

ce page 229.

Central, however, a common filter installation is provided in the middle of one side of the engine room (Fig. 143). The air is drawn in high above the ground in order to keep it as free from dust as possible. The engine room basement is divided into two parts by a longitudinal partition; one part is the suction chamber for all compressors and for the synchronous motors. The warm air from the latter is exhausted into the other part of the basement. The advantage of this arrangement lies in the avoidance of all passages. The basement is subdivided by doors, so as not to interrupt air filtration during building operations.

The compressed air is delivered into a double system of collecting pipes, with valves, along the outside of the engine room. A branch pipe is used when the air is supplied from Rosherville only (Figs. 143, 145, and 149). The cooling water required for cooling the compressors is drawn from the Robinson pan by a special pumping plant erected at one end of the engine room (Figs. 143 and 144). The water is passed through coke filters made in two parts, so that one half can be inspected without interrupting the working of the other.

F. Distribution Network.

The form of the distributing network had to be adapted to the geographical position of the reef, which stretches in a comparatively straight line from east to west; consequently the network is never very wide (Fig. 150). Arrangements had to be made from the outset for interconnecting the stations, and for a possible supply of energy from Vereeniging. The transmission of large amounts of energy from one station to another had to be taken into consideration. The 40,000-volt overhead lines are therefore in a sense double bus-bars which extend over the whole of the Rand. The energy not required for local consumption is fed into these bus-bars from the various power stations, and the distributing stations take their supply from here. The source of energy can thus be arranged practically according to the demand in the neighbourhood of the stations at Brakpan, Hercules, Simmerpan, Rosherville, Robinson, Bantjes (Fig. 151), and Vereeniging stations.

A single feeder is carried to the extreme west of the Rand, to Luipaardsvlei; it is employed for the present as a distributing cable. The copper section of conductors is naturally greatest in the centre of the area of supply where the density of consumption reaches a maximum. The exact figures are 2·232 sq. in. in four separate sets of conductors of 3 × ·186 sq. in. each, carried on two rows of masts; for the conductors passing from east to west two lines, each 3 × ·1085 sq. in., are found sufficient for the present.

The distributing conductors are connected up to all these power stations and switch stations, and transmit at a pressure of 20,000 volts on the west side of Simmerpan, and 10,000 volts on the east side of this station. They consist of underground cables in the centre of the supply area. It was not possible to install overhead lines here owing to the great number of buildings; in all other districts overhead lines are installed. The feeders are all double mains; the distributing lines, however, are ring mains; in both cases the Merz-Price Protective System[1] has been adopted with great success, and has been found particularly advantageous for ring mains, which had to be subdivided

Fig. 151.—Bantjes Station (similar to Hercules Station). Main switch station for 40,000 and 20,000 volts, with transformer cells; in the background, masts for two 40,000-volt three-phase circuits with brackets for carrying three guard wires

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[1] See *E.T.Z.*, 1908, pp. 316, 329, and 361.

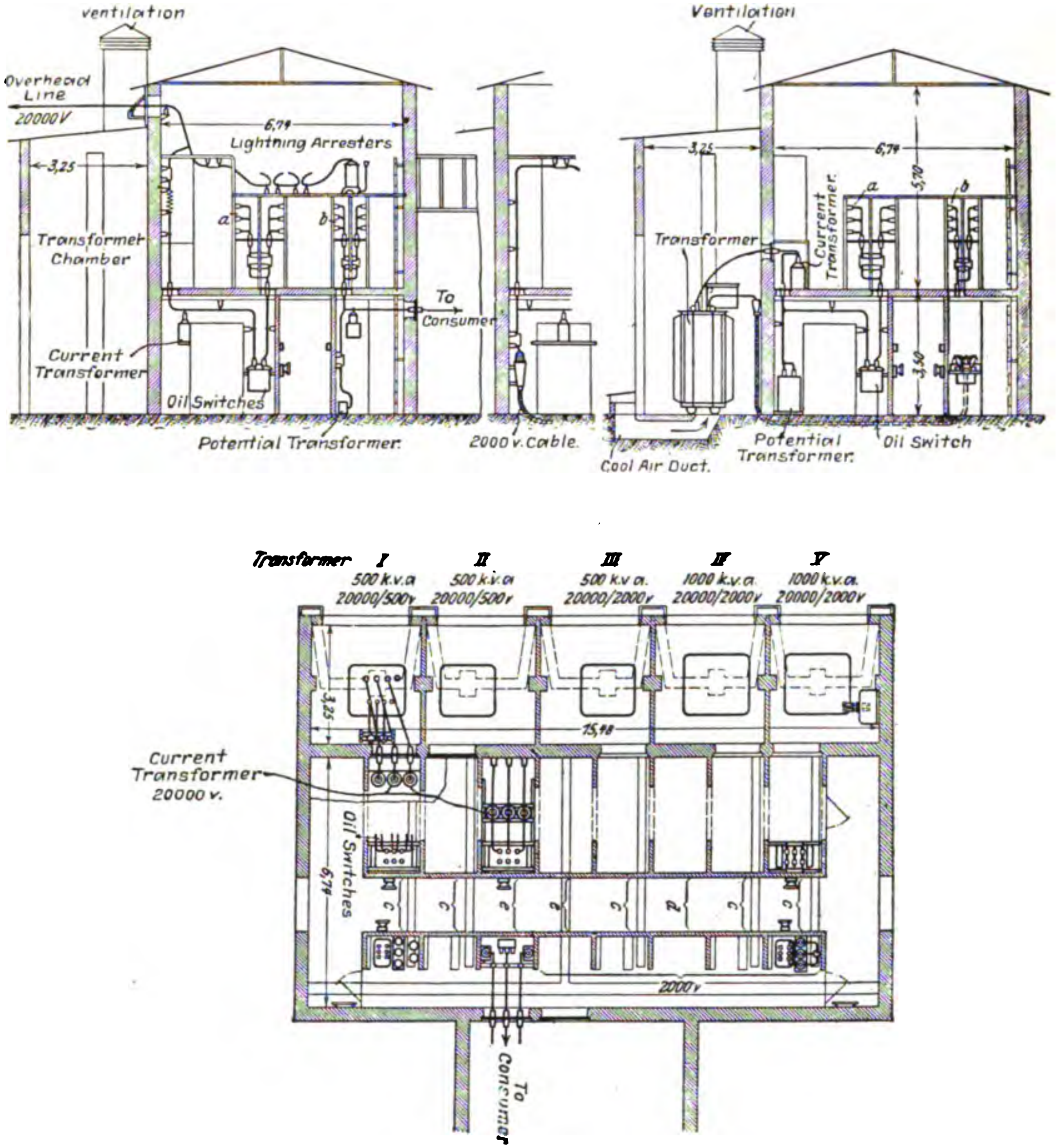


Fig. 152.—Standard Substation for Supplying Mines.

a = double bus-bars, 20,000 volts. *b* = double bus-bars, 2,000 and 500 volts. *c* = transformer. *d* = overhead transmission line. *e* = cables.

Section on the left: arrangements for connecting up to 20,000-volt transmission line. Section in the centre: arrangements for connecting up to 20,000-volt cable network. Plan: method of joining up the switch house to the mine—its general equipment is determined by the mine.

very much in order to secure a high degree of reliability in operation, and to make full use of the copper in the conductors. The standard cable section is ·155 sq. in. throughout, and the one three-phase cable is capable of transmitting 8,000 k.v.a.

The rapid rise in consumption in the Eastern Supply Area close to Brakpan makes it appear desirable to change the distribution pressure from 10,000 to 20,000 volts; all new substations are already equipped with plant for the higher pressure, and the incoming lines are insulated for 20,000 volts, so that within a short time only two pressures, 40,000 and 20,000 volts, will be in use, with the exception of the transmission from Vereeniging, which takes place at 80,000 volts.

G. Substations.

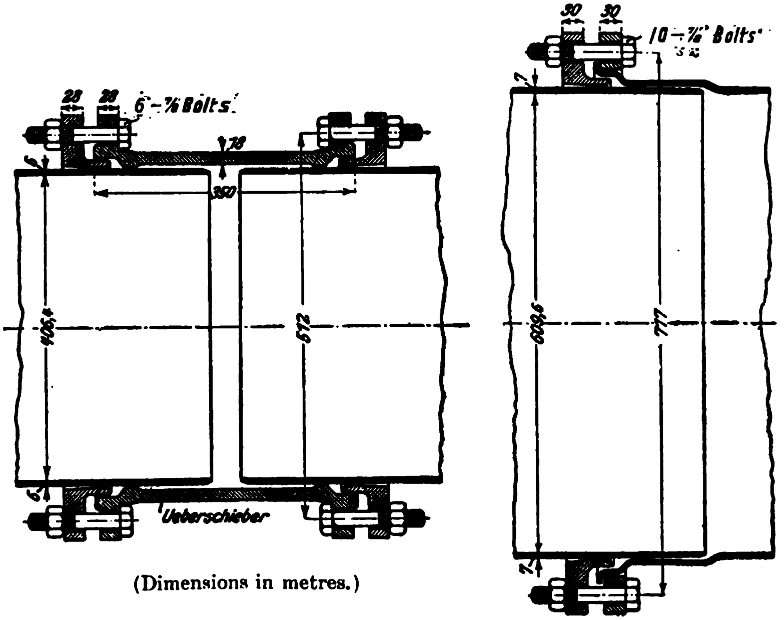
Standardisation is the essential feature of plant in substations. The main considerations which dictated this policy are the large number of substations (about sixty have been erected up to now), the interchange of plant without loss of time, and facilities in operation and supervision.

The substations had to satisfy the following requirements: the primary pressure is either 20,000 volts or 10,000 volts; the demand varies from 1,000 to 8,000 k.v.a., the secondary voltage is in some cases 2,000 and in others 500 volts; both voltages must, however, be supplied from the same station, as they are both required simultaneously on practically all the mines (large machines are connected to the 2,000-volt supply, small motors above ground are connected to the 500-volt supply). As the working conditions on the mines are constantly undergoing a change, all the substations had to allow for extensions, both on the 500-volt and 2,000-volt side. This made provision necessary for incoming and outgoing cables and overhead lines.

In order to meet these requirements the standard substation was built in the form of the letter T (Fig. 152); the conductors enter the station at the top end. In this part of the building are the transformer cells, arranged in two groups, according to secondary pressure; the bus-bars for 500 and 2,000 volts are run parallel. The centre contains the consumers' meters. The connections are taken from these meters out of the building into the adjoining switch house of the consumer. The latter's distribution gear is thus entirely separate from the company's substation. The 500-volt side and the 2,000-volt side of consumers' substations can be extended as desired.

H. Compressed Air Plant.

Out of a total of 320 million kw.-hours required by the Eckstein group, about 40 per cent. were to be supplied in the form of compressed air at a pressure of 130 lbs. per sq. in. According to the predetermined load factor, this quantity of air, together with the specified addition of 25 per cent. for spare plant, represents a machine output of approximately 50,000 H.P. The maximum distance over which the compressed air has to be transmitted is about 18 miles. When considering that no compressed air plant of anything like the same capacity had ever been constructed—the largest plant at the



(Dimensions in metres.)

Fig. 153.—Compressed Air Pipe. On the right: Standard Pipe Joint; on the left: Sleeve for connecting Smooth Pipe Ends (the latter is used when pipes have to be interchanged).

present time being that in Paris: it has an output of 8,000 H.P.; the largest reciprocating compressor has an output of 1,500 H.P.—one will realise the nature of the enterprise, with which were involved stringent guarantees both for performance and early completion. The whole plant had to be designed entirely from the beginning, and an erection period of one and a half years was therefore extremely short. The construction of rotary compressors was still in the development stages, and satisfactory results had only been obtained with small outputs; air pipe systems for such pressures as those now contemplated had never been constructed before. The development of the design of joints in the pipes alone (Fig. 153) occupied more than three months, as the Paris models proved entirely inadequate for the conditions in South Africa. The joint had to fulfil the following conditions:—

Fig. 154.—Compressed Air Plant. Laying 24-in. Pipe above ground on Masonry Pillars (marshy ground).

Fig. 155.—Compressed Air Plant. 24-in. Pipe; method of fixing the Pipe above ground on a straight section.

1. It must allow expansion and contraction, as the pipes are subjected to considerable temperature variations.

2. It must easily be taken apart and renewed when a new pipe is inserted.

3. It must allow a deviation of 5° to 10° from the straight line, so that the pipe line can follow any rise or fall in the ground.

4. It must remain perfectly airtight under these conditions (24 in. max. pipe diameter, 130 lbs. pressure).

5. The installation costs must be moderate, no machining of pipe ends being possible.

When it is considered that no measuring apparatus was available for integrating the complicated function based upon volume, temperature, and pressure (reading in kw.-hours), automatically, that air meters until then were only constructed for medium pressures, and that this apparatus had to be redesigned entirely, it will be possible to gauge the difficulty even of this part of the task.

Fig. 156.—Compressed Air Plant. Method of fixing the Pipes above the ground. Fixed point.

Fig. 157.—Compressed Air Plant. Anchor for a 30-in. bend above ground. The illustration shows how the pillar has given way owing to the inadequate foundation.

A measuring apparatus was required to meter a total output of more than 100 million kw.-hours per annum with great accuracy, because the value of this power amounted to more than £250,000; an error of 1 per cent. thus makes a difference of £2,500, which explains the importance of accurate air measurement.

The fundamental principles to be applied to the installation of the compressed air network agreed with those of the electric cable network in some respects. As all the Eckstein mines required compressed air in addition to electric energy, the compressed air pipes and electric cables could very often be laid in the same trenches (Figs. 154 to 158).

The pipework permanently connects the plant in Rosherville and in Robinson central station (Fig. 150); if one of the stations is shut down, the air supply can be maintained by the other one. Valve chambers are built into the system (Fig. 159), which enable a section of the pipes to be cut out in the case of a fault.

Fig. 158.—Compressed Air Plant. 22-in. Pipe washed out of the Trench as the result of heavy rains.

The pipes are generally placed underground; they are run above the ground on cement pillars only for crossing valleys and marshy land. At such places they are protected against the excessive heat of the sun by a corrugated iron covering (Fig. 160). The pipes are made up of lengths of 25 ft., and vary from 9 in. to 24 in. in diameter. The packing used for the joints consists of sectional rings of high quality rubber. It was guaranteed that the maximum leakage loss would not exceed 2 per cent.; the actual losses in practice were found to be less than 0·5 per cent.

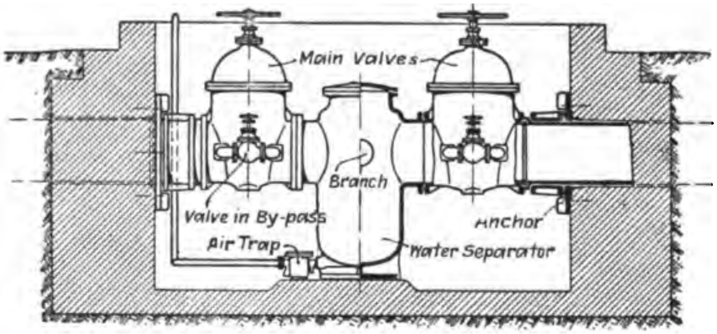


Fig. 159.—Compressed Air Plant. Valve Chamber with Branch Pipe and Drainage.

The size of pipes was calculated in accordance with the maximum permissible speed for the movement of air.

The general principles followed in the design of the pipe system were low capital cost and a certain minimum air pressure, with a full supply at the point of consumption. Having agreed on this minimum, which would of course apply to all consumers, however distant, it was found that a branched system of pipes could be dimensioned along new lines, which led to definite reduced pressures at each junction of pipes in the system. With the knowledge of the drop in pressure up to each junction it was then a simple matter to determine the size of the pipes. One is accustomed to calculations of this kind for electric conductors, but for an air supply system nothing of the kind had been done before. The calculations were made by R. Troeger, after the author had decided on the method of procedure.

Fig. 160.—Compressed Air Plant. Compressed Air Pipe Line above ground, and covered with welded corrugated iron as a protection against the heat of the sun.

The air consumption of each consumer is measured in kw.-hours, determined on an isothermal basis. A special compressed air meter is installed at each mine (Fig. 161), which automatically records the supply. The construction of this apparatus presented considerable difficulty, in view of the appreciable fluctuations in temperature and pressure.

As meters for measuring the air volume on the gas meter principle, in which the integrating mechanism is influenced by pressure and temperature, would have attained abnormal dimensions and a very intricate design, it was finally decided to employ a nozzle on the Venturi principle, and a recording device controlled by fluctuations in pressure and temperature (the latter only approximately). The spring of the gauge for pressure differences, and the thermometer spring influenced by temperature, each move a logarithmic cam, the movements are added up by gear wheels, and the sum is transmitted to an anti-logarithmic cam, so that the integrating mechanism records the product of both movements. The meters were developed and constructed by Messrs G. Kent, London, and were found to be very satisfactory.

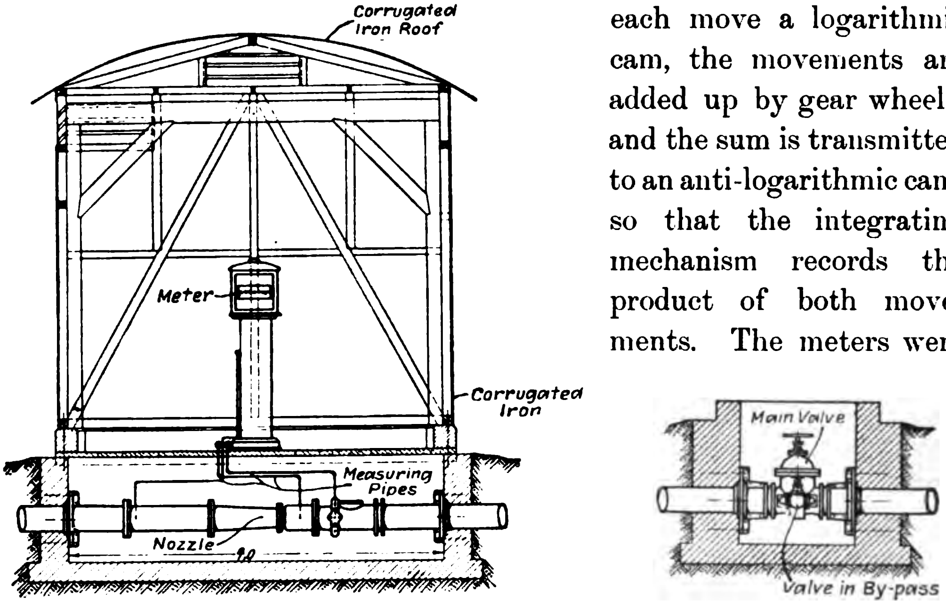


Fig. 161.—Compressed Air Plant. Section of an Air Meter House.

5. PREPARATORY WORK FOR FURTHER DEVELOPMENT.

a. General.

The limited cooling capacity of the Rosherville pan, which suffices for plant of not more than 50,000 to 60,000 kw., and the high charges for coal transport, induced the Victoria Falls and

Transvaal Power Company to make a contract with the Vereeniging Estates for the right to erect a power station in the centre of the extensive coal district on the Vaal river. A previous contract with the Vereeniging Estates, made by Wilson Fox at the time the company was formed, but supplemented later, secured the right of obtaining coal at prime cost, plus an extra sum of 1s. 1d. per ton, together with the right to examine production costs.

Serious objections were at first raised by the gold mines, who doubted whether energy could safely be transmitted through 30 miles of overhead transmission lines under South African atmospherical conditions. The objections were overcome by the promise that the output of plant off the reef should not exceed a given fraction of the total output. In the event of the transmission lines failing, the whole supply was to be covered by the plant on the Rand. The company was, however, permitted to increase the external source of energy on proving in practice that the system of overhead transmission was satisfactory.

The preliminary work, including the purchase of land, borings, locality of site, and questions of water supply, was settled in 1909, whilst the author was on the spot; the commencement of building operations was, however, delayed by negotiations with the authorities in connection with the necessary wayleaves.

b. WAYLEAVES.

The legal conditions for the transmission of energy on the Rand by means of overhead lines and underground cables were exceedingly simple. As the land in this district consists almost exclusively of mining claims, the rights of property of mine owners are restricted by legislation to the minerals underground, while the land itself is at the mine's disposal only as far as it is required for working the ore. The authorities are therefore free to grant permission to a third party to use the land for transmission lines. When the company took over the Rand Central Electric Works, it also acquired the concessions granted to that company. It was therefore protected against opposition on the part of the mines, provided that their buildings were not interfered with, a condition which could easily be fulfilled.

The conditions were, however, different for the lines from Vereeniging; the conductors had to be taken over private property for practically the whole distance, and difficulties arose similar to those we are accustomed to encounter in Europe.

The question as to whether the consent of local authorities for the erection of transmission lines was necessary, in addition to the private permission of land owners, was open to dispute, as Transvaal legislation had not hitherto dealt with this matter. In order to avoid the danger of placing itself in a false position legally, the company decided, nevertheless, to apply for the official consent, as the concession of the Rand Central Electric Works did not extend to this territory. The immediate result of this step was violent opposition by a number of the coal mines who feared serious loss of business with the company.

The Government was obliged to appoint a special Power Commission to go into the matter, under the chairmanship of Sir Thomas Price, the President of the Railways. The proceedings of the Commission lasted several months, during which time witnesses of both parties were examined publicly. Both Lord Winchester and the author were consulted repeatedly with regard to European conditions, and were requested to make a confidential declaration concerning existing or proposed legal measures bearing upon the subject. The very exhaustive report which was then handed to the Government naturally occupied considerable time in its preparation, so that one and a half years elapsed before the required permission for the erection of the transmission lines was given to the company. The principal condition imposed was that energy should be supplied on the same terms to all parties concerned, and particularly to local authorities. A special tariff prepared by the author was accepted.

On receipt of the wayleaves the erection of Vereeniging power station was immediately begun; it was put into commission recently with an output of approximately 70,000 H.P.

The question of utilising the power of the Victoria Falls on the Zambesi has not been raised again since, as the opposition of the coal owners would have been very much fiercer against this scheme than it was in the case of the transmission from Vereeniging. In the latter scheme it was merely a question of a scarcely noticeable transference

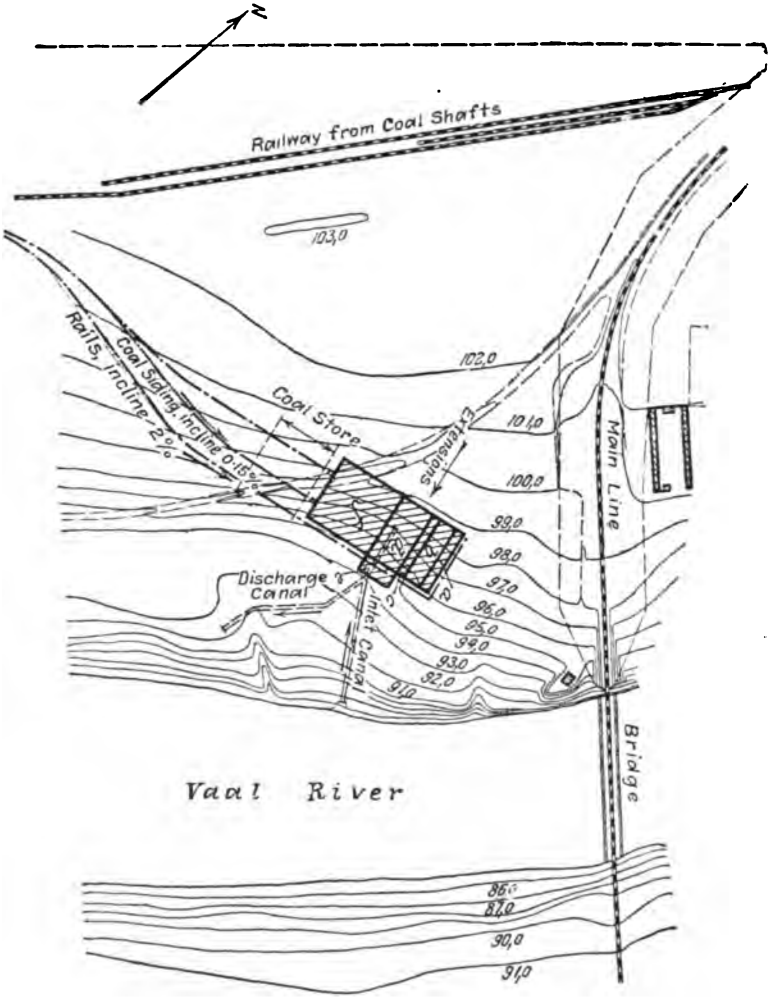


Fig. 162.—Vereeniging Power Station. Plan. *Scale*, 1 to 5,000. (Dimensions in metres.)
a = Transformer cells. *b* = Switch house. *c* = Operating switchboard.
d = Engine room. *e* = Workshop. *f* = Boiler house.

of the coal output from certain coal mines to others; the transmission of large quantities of energy from Rhodesia, on the other hand, would have dealt a severe blow to the coal industry. It should be stated

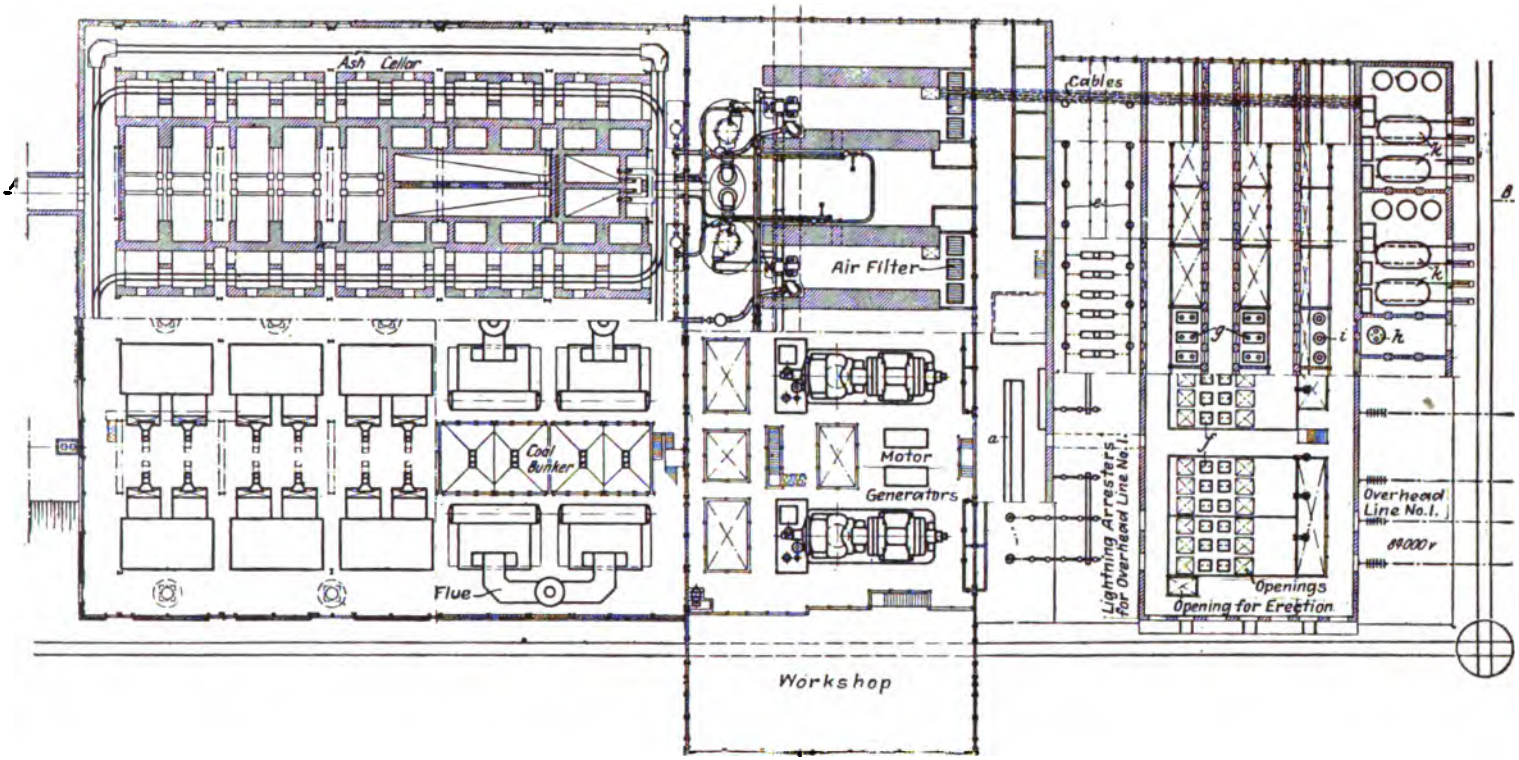


Fig. 163.—Vereeniging Power Station. Plan of Boiler House, Engine Room, and Switch House.

a = Operating switchboard. b = Automatic switch and regulator room. c = Battery room. d = Passage. e = 84,000-volt bus-bars. f = Resistances. g = Oil switches. h = Choking coil. i = Current transformers. k = Transformers.

here that no appreciable economic advantages can be expected from this long distance power transmission as long as the coal prices in the Transvaal remain on their present level.

6. THIRD SECTION—VEREENIGING POWER STATION.

a. Engine Room, Boiler Houses, Coal Conveying Plant.

The power station (see plan, Fig. 162) now contains four turbo-generators, two of which are for outputs of 12,000 k.v.a., the other two having outputs of 18,000 k.v.a. Two further sets with outputs of 16,000 k.v.a. each are on order; they will, however, be erected in Simmerpan power station.

Steam is produced in two boiler houses (Figs. 163, 164, 166), each containing ten boilers with a water-touched heating surface of 5,920 sq. ft.; the boiler plant is constructed in a similar manner to the plant in Rosherville. The coal conveyor plant is also constructed on the same principles. Arrangements had to be made here for storing a larger quantity of coal, because only one set of rails was available. The quantity of coal stored outside the boiler house could be augmented by increasing the height of discharge (raising the railway line) (Figs. 164, 167); moreover, contrary to general principles, large coal bunkers were installed in the boiler house itself, as it is proposed to bring the coal from the mines by means of a ropeway at a later date. This point had to be taken into consideration when designing the boiler house, and space for the future ropeway was there allowed beside the bucket conveyor. The boiler house bunkers are large enough to hold sufficient coal for operating the power station from Saturday midday to Monday morning, during which time the coal mines are generally closed (Figs. 164, 166).

The arrangement of the engine room (Figs. 163, 164, 165) is also similar to that at Rosherville. The only important departure is in the cooling water supply, the provision for which was extremely difficult

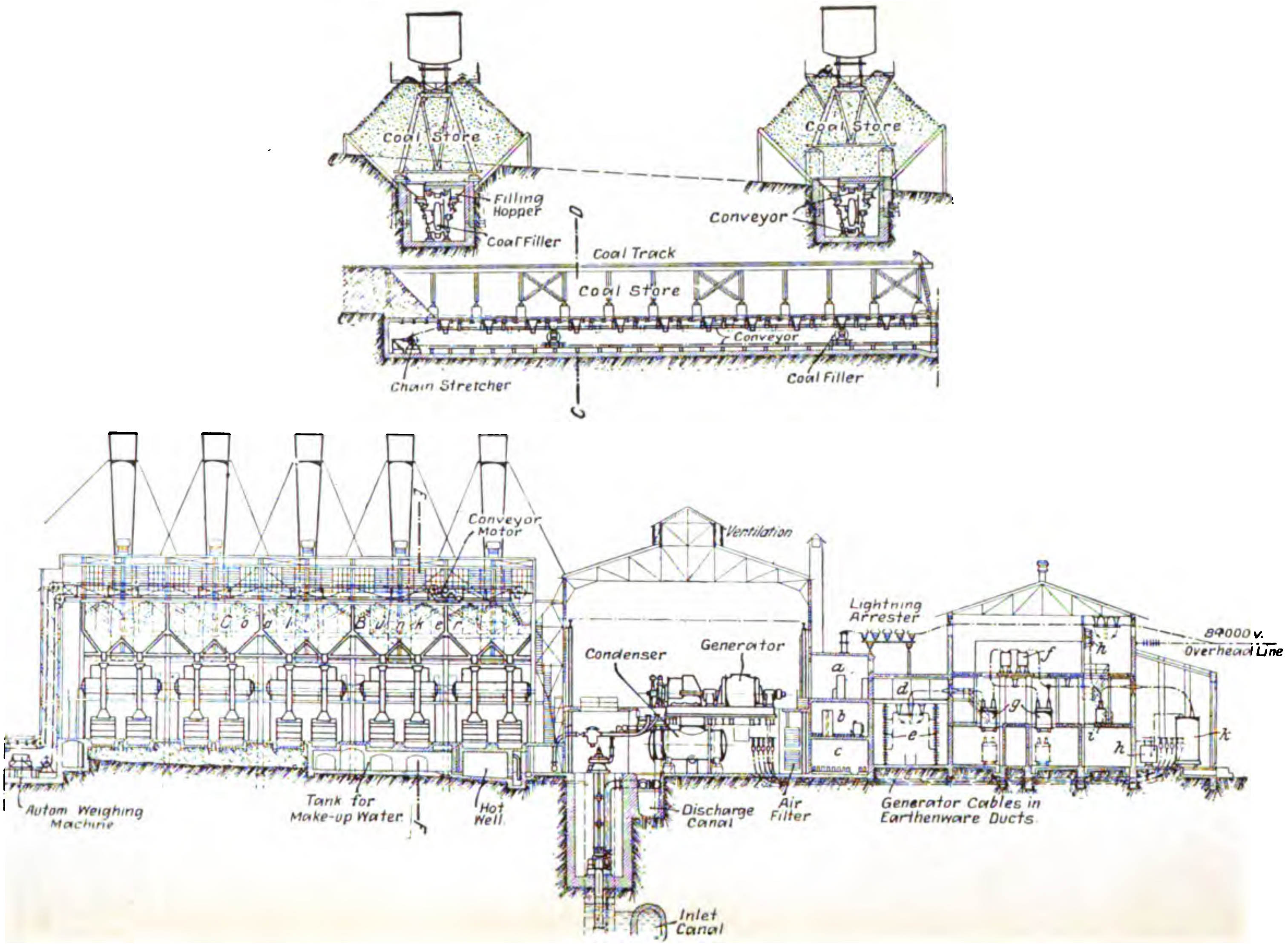


Fig. 164.—Vereeniging Power Station. Section through Coal Conveyor Plant. Boiler House, Engine Room, and Switch House.

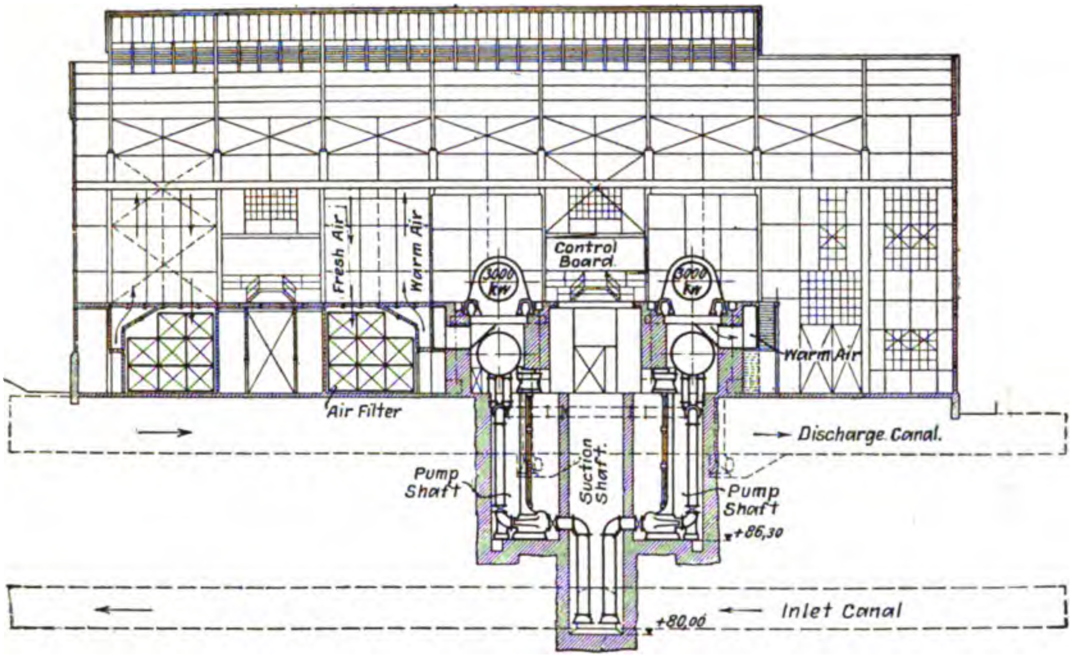


Fig. 165.—Vereeniging Power Station. Longitudinal Section through Engine Room. *Scale*, 1 to 500.

here. The difference in the water level of the Vaal river sometimes reaches 30 ft.; these fluctuations occur very suddenly, as the rainfalls are discharged into the rivers much more rapidly than is the case in most European rivers, owing to the absence of forests. The water supply had to be arranged to be able to follow these sudden changes in the lift.

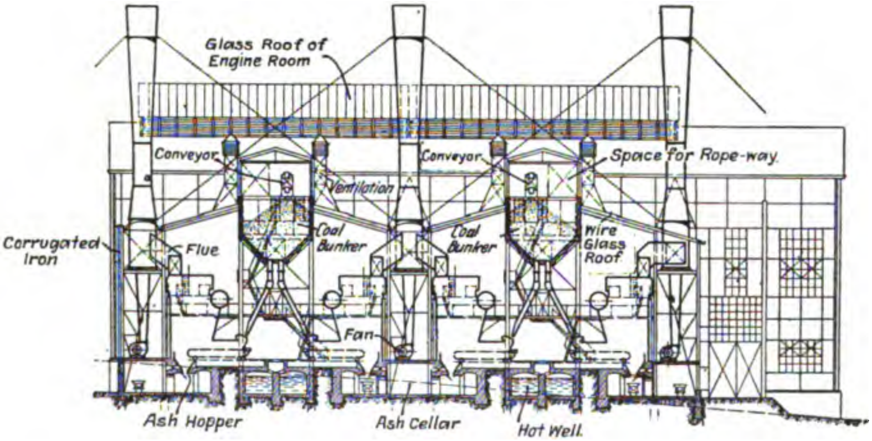


Fig. 166.—Vereeniging Power Station. Section through Boiler Houses. *Scale*, 1 to 600.

After various schemes had been worked out, it was finally decided to drive an inlet channel from the deepest part of the river to a point underneath the engine room, and to erect the pumps in shafts connected with the tunnel by pipes and valves. The constructional costs were considerable (Figs. 164, 165). Each set of two pumps draw their water from a common suction shaft with fine strainers. A coarse screen is provided at the mouth of the tunnel, where the water enters from the river (Figs. 168, 169). The pump shafts are so deep that even at the lowest water level the permissible suction lift is not exceeded; they are placed immediately in front of the turbine foundations, so that the arrangement of pipes is quite simple. The circulating water pumps have vertical shafts, and they are driven by vertical turbines in the engine room basement (Fig. 170). The water leaves the condensers through pipes which discharge into an open channel ending in the river below the intake (view of building, Fig. 171; view from the Vaal river, Fig. 172).

Fig. 167.—Vereeniging Power Station. Coal Store below the Railway; Pockets in the floor for filling the Bucket Conveyor.

b. SWITCH HOUSE.

The switch house (Fig. 173), contrary to that at Rosherville, lies parallel to the engine room, an arrangement which has its particular advantages in this case on account of the cables between the generators and the switch house, which consist of five and eight separate cables each with a section of 3 × ·325 sq. in. The switch house is entirely

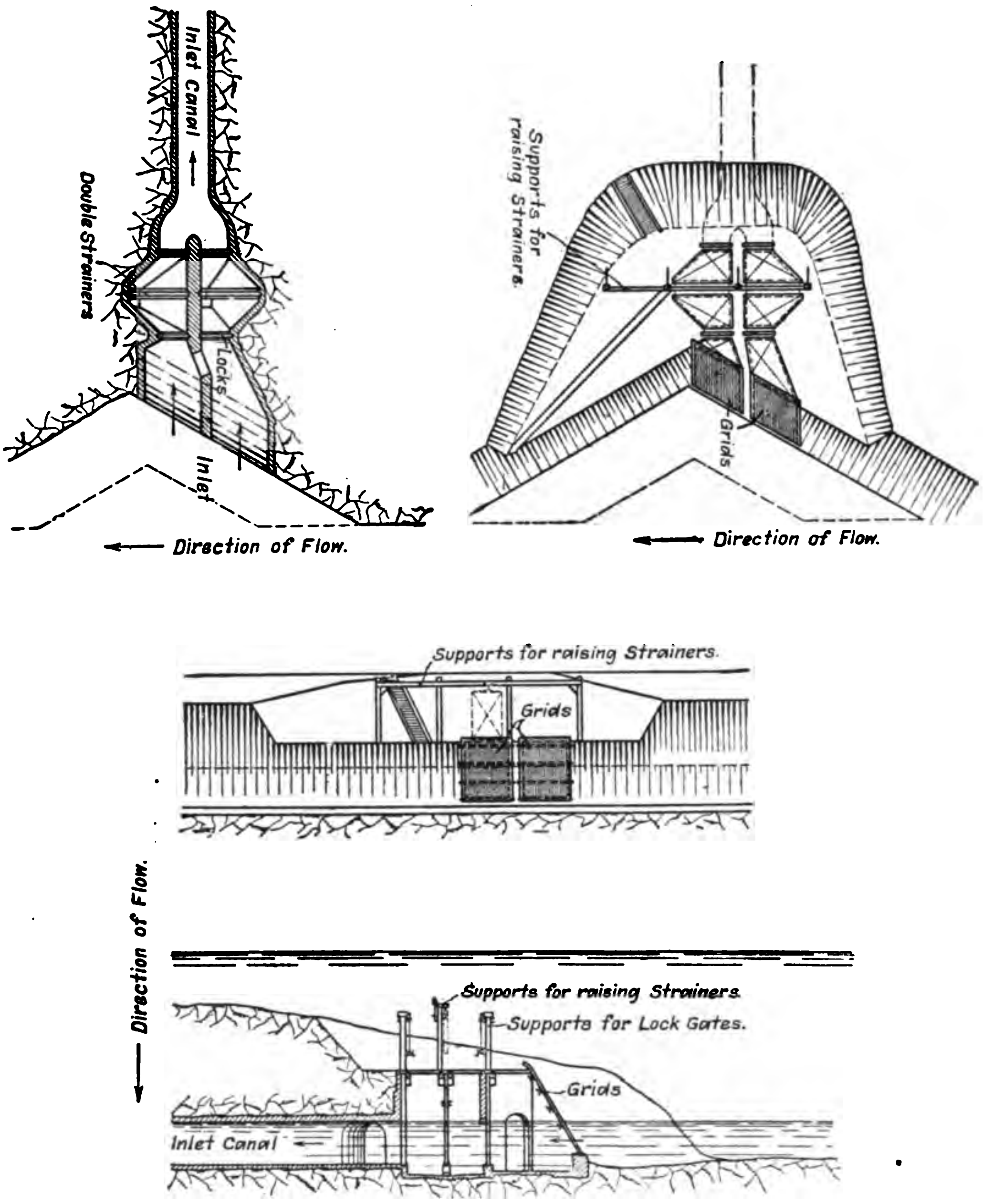


Fig. 168.—Vereeniging Power Station. Plan and Section of the Intake for the Condenser Cooling Water. *Scale*, 1 to 500.

separated from the engine room. The space between the switch house and engine room is utilised for the control board, the battery, the regulators, and other auxiliary apparatus.

For transmission to the Rand the pressure is raised to 84,000 volts. The transformers are again erected in special cells along the wall of the switch house; at present there are six transformers, namely, two with a capacity of 12,500 k.v.a., and four with a capacity of 9,000 k.v.a.

The construction of the bus-bars differs from what is customary; they are placed in a special room, and are attached to the centre of a chain of suspension insulators stretched between the ceiling and the floor. This is an arrangement which is not only electrically very safe, but is also very strong mechanically, as the stresses in the bus-bars in the case of short circuits occur only in the direction of the insulator chain. Isolating switches are mounted on the ceiling, and enable the transformers and transmission lines to be switched over from one set of bus-bars to the other.

Fig. 169.—Vereeniging Power Station. Inlet Channel under Construction.

The very heavy currents which have to be broken by the switches in the event of short circuits in the transmission lines made it appear advisable to adopt the principle of switching in steps. Two oil switches are therefore connected up in series; one of them is bridged over by a non-inductive resistance. When switching in or out, the series resistance is first closed or opened, after which the other switch is operated; the resistances are so dimensioned that approximately the same switch capacity is allotted to each switch. If it is found by experience that two steps are insufficient, a third switch with resistances can be connected up in the space which is provided for this

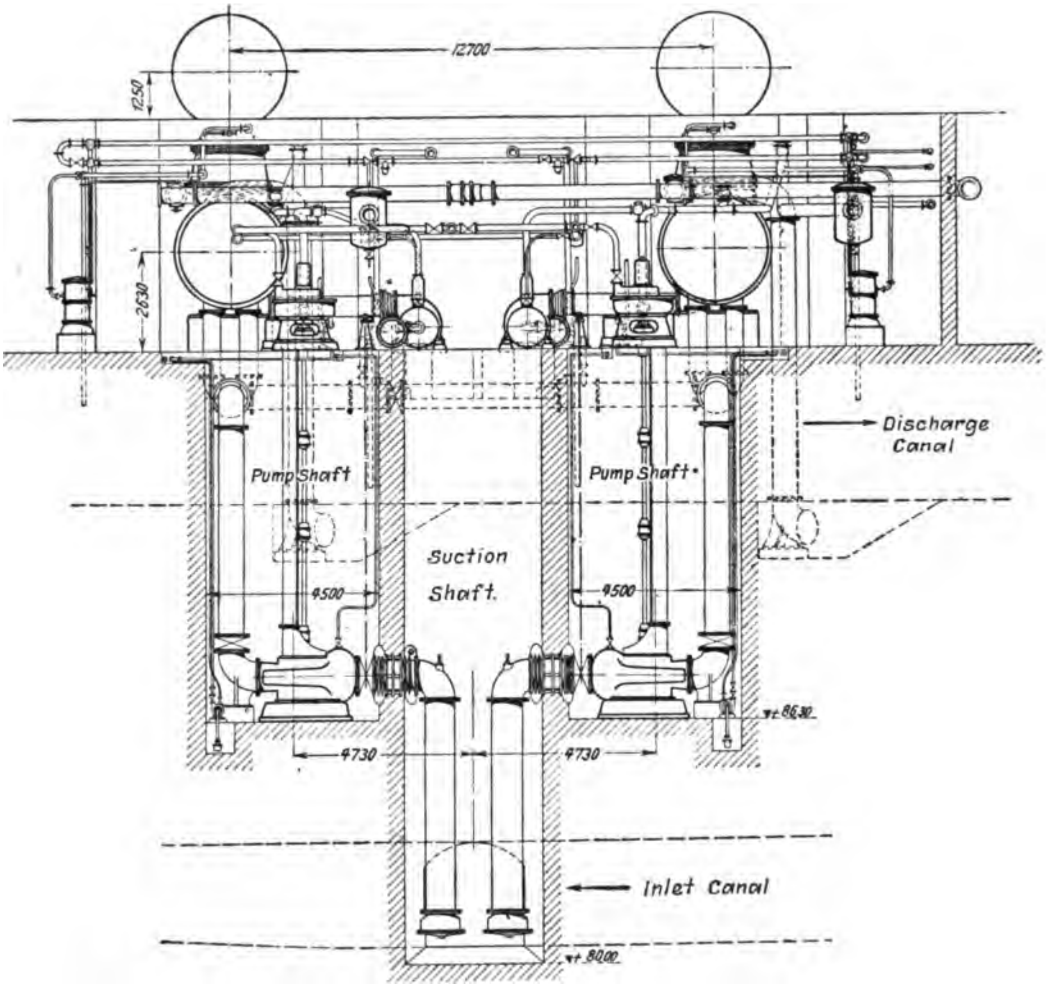


Fig. 170.—Vereeniging Power Station. Section through the Pumping Shafts and Suction Shaft. *Scale*, 1 to 200. (Dimensions in metres.)

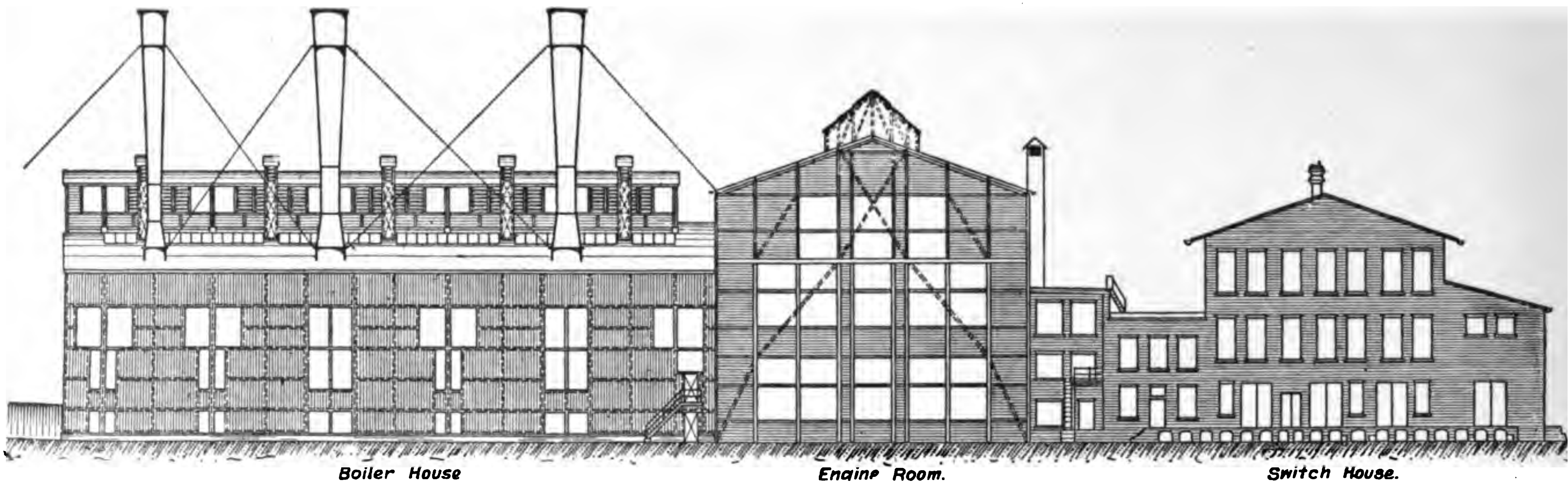


Fig. 171.—Vereeniging Power Station. View of the Buildings. *Scale*, 1 to 500.

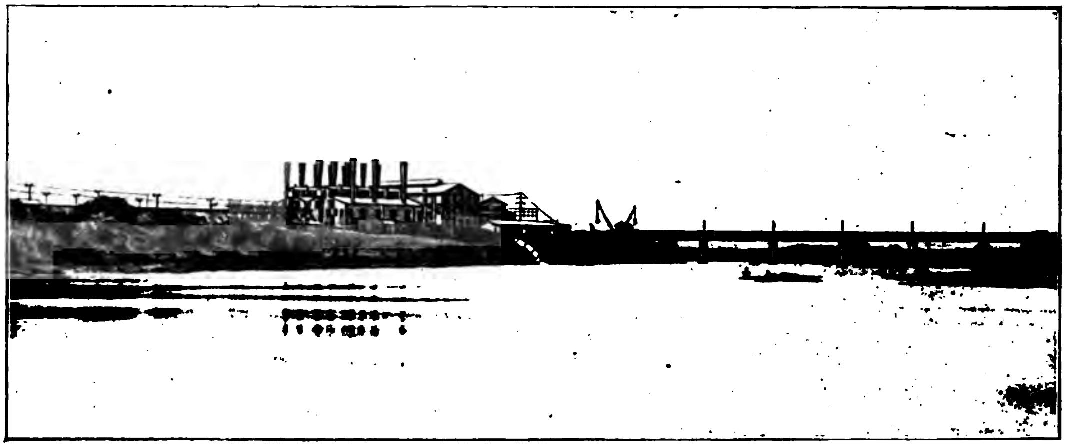


Fig. 172.—Vereeniging Power Station. General View from the Vaal River.

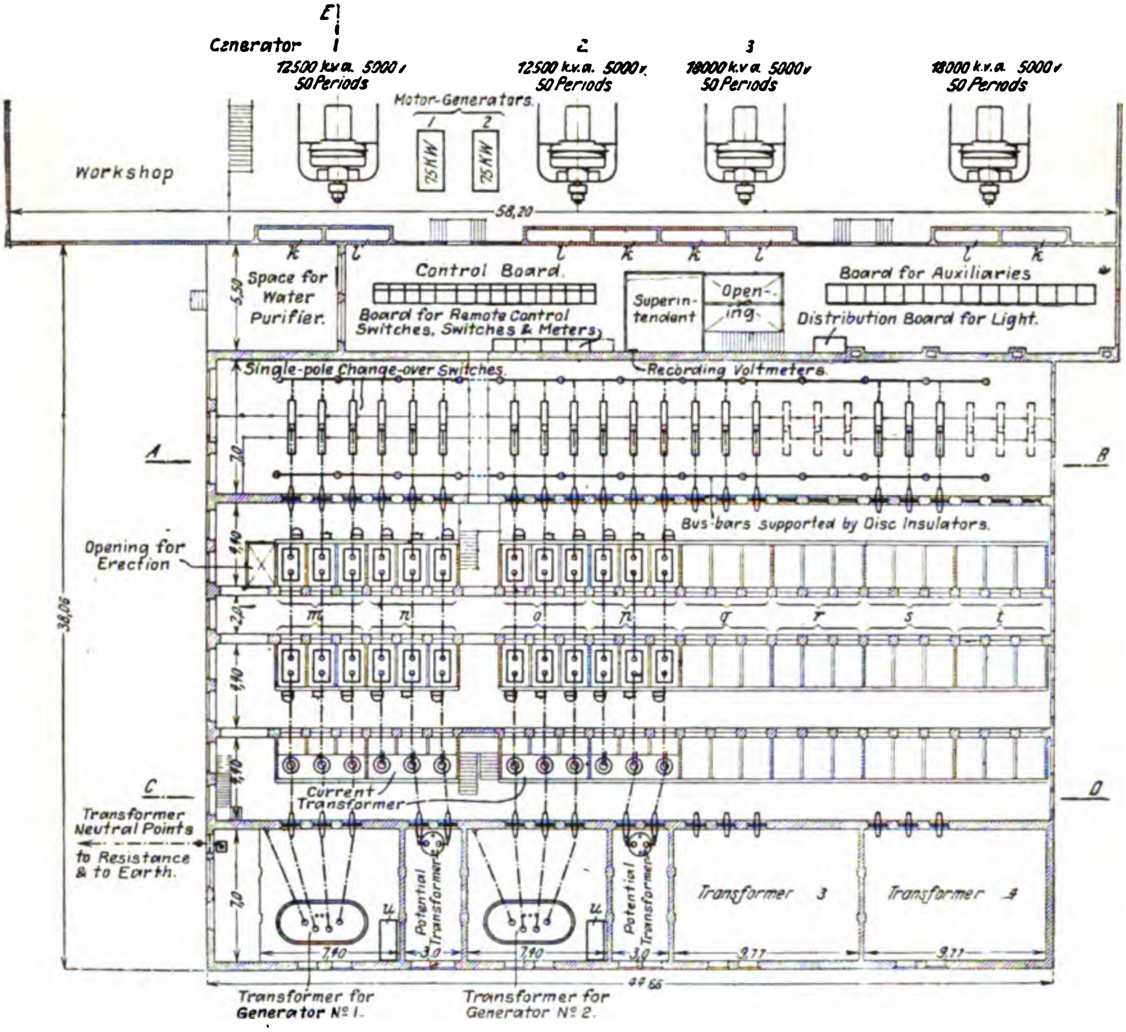


Fig. 173.—Vereeniging Power Station. Plan and Section of Switch House. *Scale*, 1 to 400. (Dimensions in metres.)

a = Operating switchboard.
b = Room for d.c. machines, automatic switches, and regulators.
c = Horn lightning arresters.
d = Isolating switches.
e = Double bus-bars with suspension insulators for 84,000 volts.
f = Room for lowering oil tanks.
g = Remote control oil switches.
h = Choking coils.
i = Water-cooled transformers.

k = Exhaust air.
l = Fresh air.
m = Generator, 1.
n = Transmission line, 1.
o = Generator, 2.
p = Transmission line, 2.
q = Generator, 3.
r = Transmission line, 3.
s = Generator, 4.
t = Transmission line, 4.
u = Oil tanks.

Two remote control oil switches each.

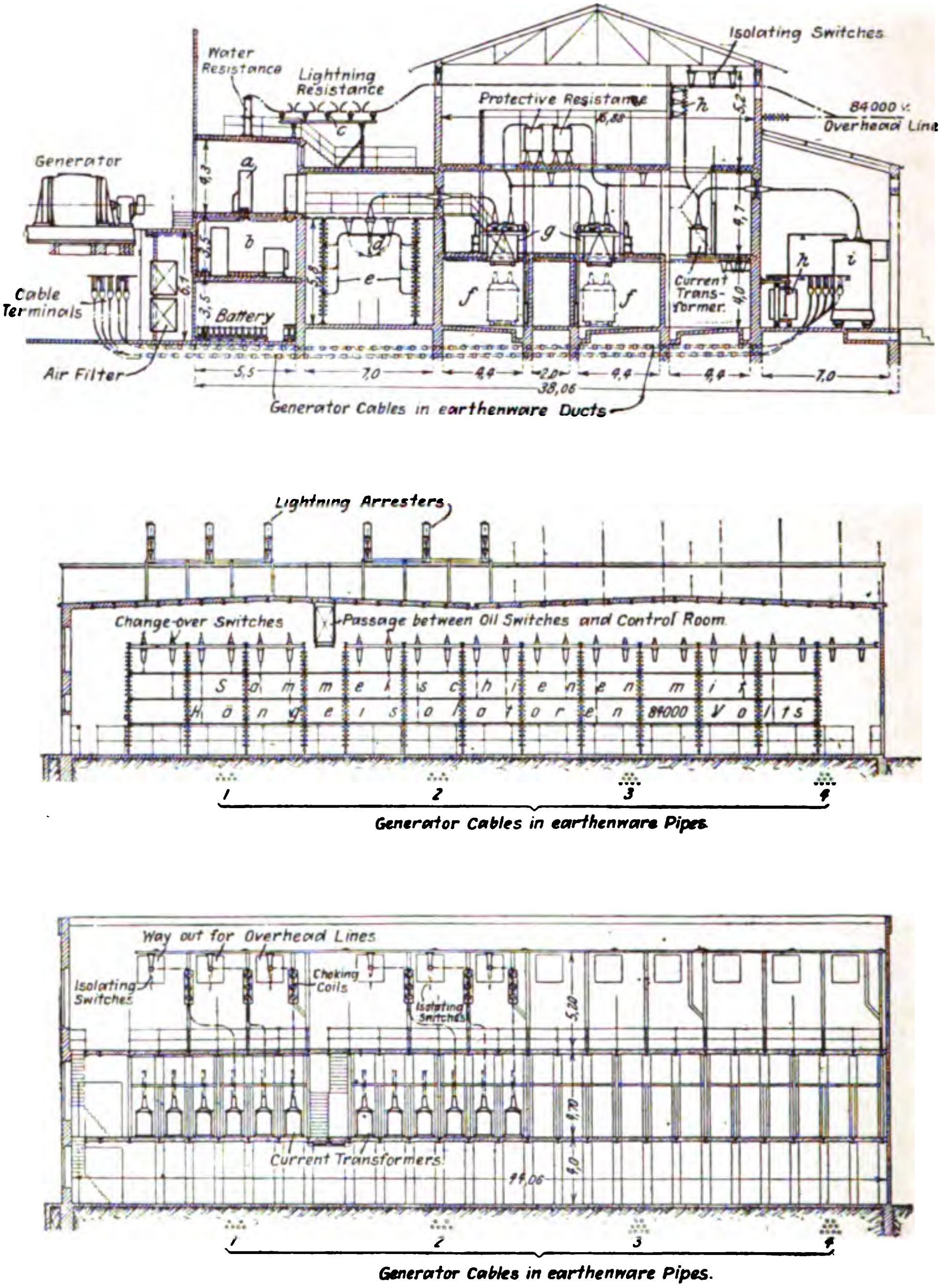


Fig. 173A.—Vereeniging Power Station. (Dimensions in metres.)

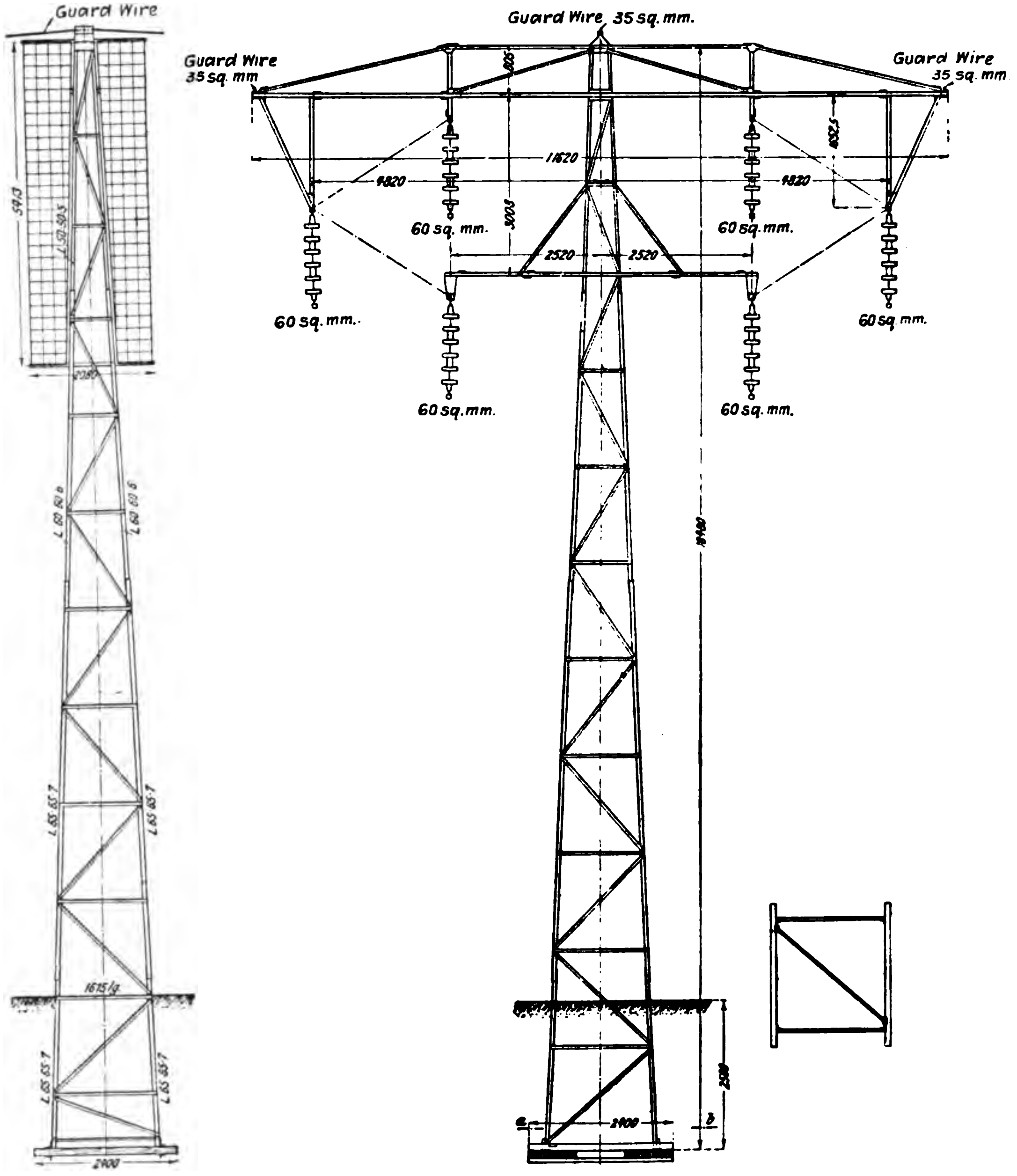


Fig. 174.—Vereeniging Power Station. Intermediate Mast for Two Circuits, 80,000 volts.
Scale, 1 to 120. (Dimensions in metres)
a = Guard netting for the workmen.

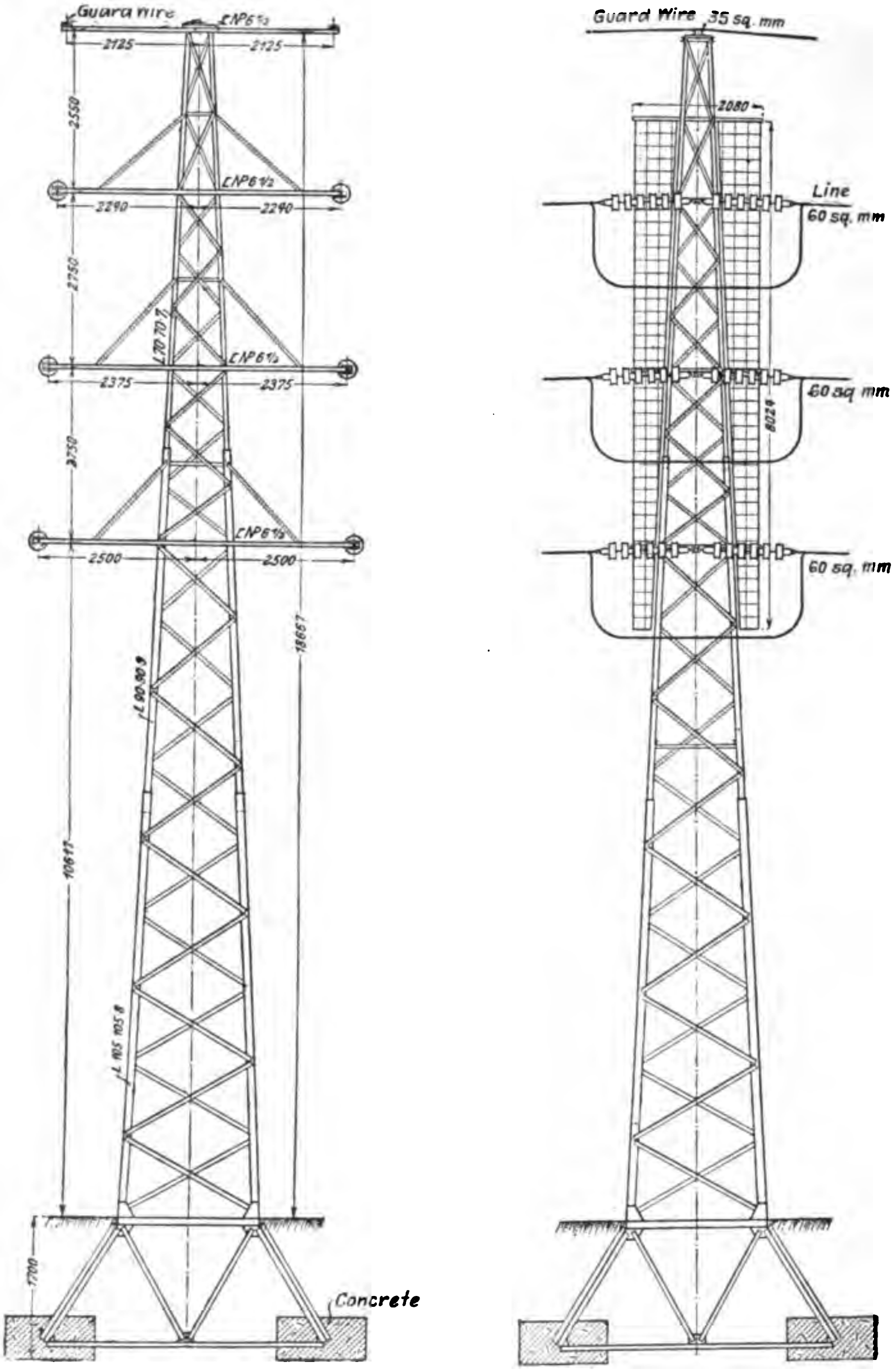


Fig. 175.—Vereeniging Power Station. Anchor Mast for Two Circuits, 80,000 volts; the Conductors are transposed at Anchor Towers. *Scale*, 1 to 120. (Dimensions in metres.) *a* = Guard for the workmen.

purpose. The switches can be lowered by means of a winch to the floor beneath. In order to simplify the amount of labour, the oil cases are connected to pipes leading to pumping plant at one end of the installation; a reservoir and an oil drying plant have also been placed here. Similarly to the oil switches, the transformer cells and transformer tanks are connected to this plant through pipes, so that all oil tanks can be filled and emptied quickly (see also Figs. 37 and 37A).

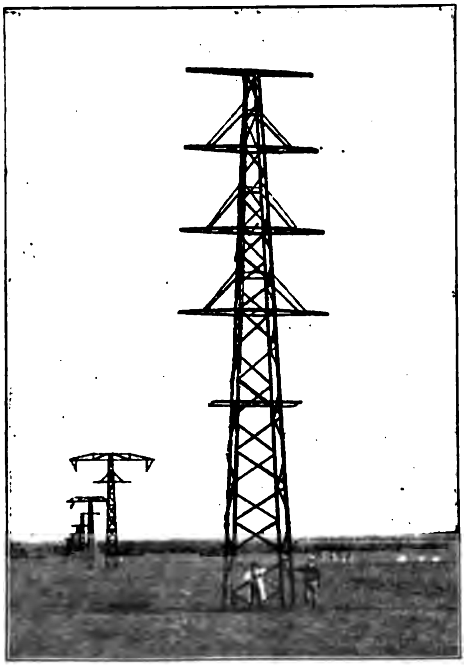


Fig. 176.—Vereeniging Power Station. Anchor Mast.

Fig. 177.—Vereeniging Power Station. Experiments carried out on an 80,000-volt intermediate mast in order to find out how the masts withstand breakage of a conductor in the neighbourhood of an anchor mast. The cross shows the length which the conductor has slipped through the suspension clip.

c. TRANSMISSION LINES TO THE RAND.

The energy generated at Vereeniging is transmitted to the Rand through four circuits with ·093 sq. in. conductors, carried on two rows of masts with two circuits each (Figs. 174 to 180); all lines terminate at Robinson Central. The conductors are fixed to link insulators of the

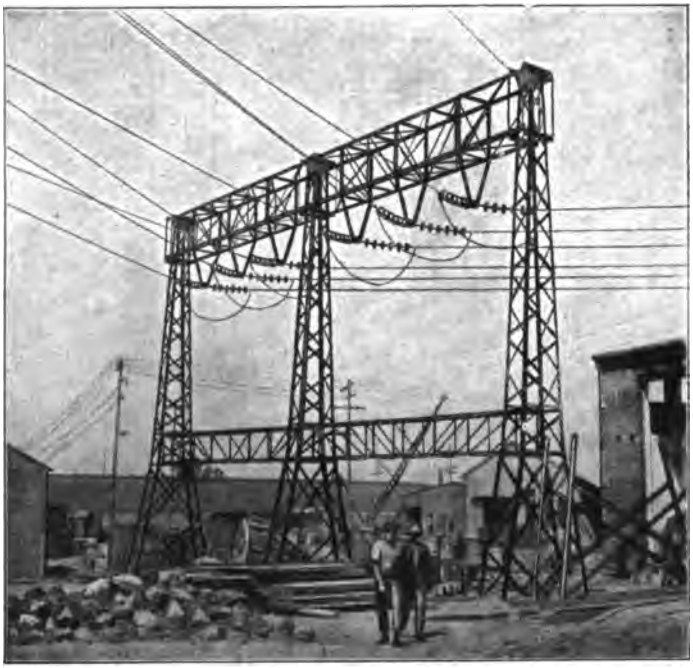


Fig. 178.—Vereeniging Power Station. Anchor Masts for 80,000-Volt Conductors at the point where the latter enter the Switch House.

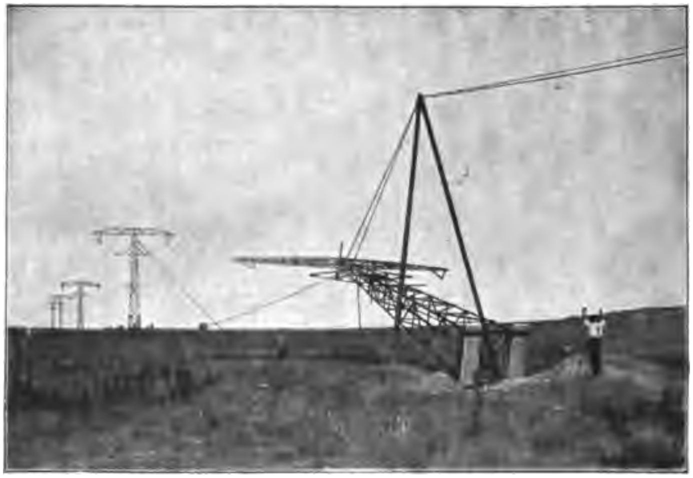


Fig. 179.—Vereeniging Power Station. Erecting an Intermediate Mast.

Hewlett type, and are supported every half to one mile by anchor masts on which the three conductors are transposed. The pressure is stepped down on the Rand in three-phase transformers (each with three sets of windings), the secondary side being constructed with separate 40,000 and 20,000 volt windings, so that apart from the transmission of energy, they also serve to balance the load in the 40,000 and 20,000 volt network on the Rand. This arrangement distributes the load between the two networks as desired, a result that could only have been attained otherwise by using special voltage regulators. A further beneficial effect is the simplified operation and improved load control of Rosherville power station. Whereas formerly the output of generators feeding either the 40,000 volt or 20,000 volt network had to be adjusted according to consumption, and special transformers were required for balancing the load on these networks, the present arrangement gives greater freedom, because any shortage in the power supplied from Rosherville for either of the two networks is made up automatically from Vereeniging.

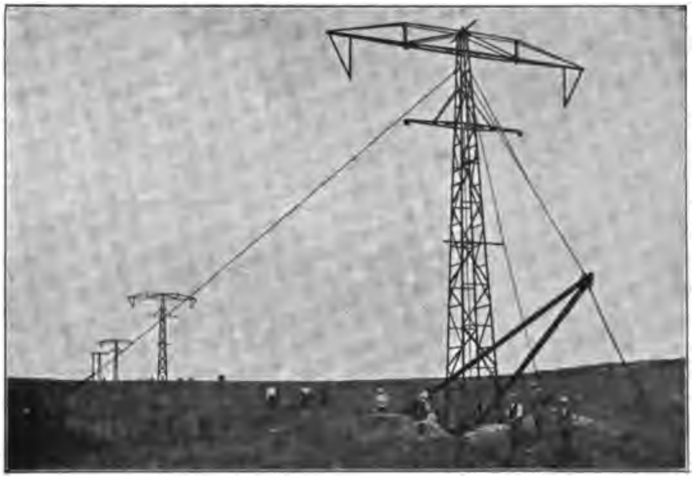


Fig. 180.—Vereeniging Power Station. Intermediate Mast Erected. Cross Bar underneath for carrying two Telephone Circuits.

7. SUMMARY.

In the preliminary scheme of 1905 the boilers are placed at right angles to the engine room, and artificial draught and iron chimneys are introduced. The economisers, however, are designed for use with several boilers, an arrangement resulting in long iron flues and a branch passage as a by-pass round the economiser. Fans for producing the necessary draught are placed in the flues direct. The coal conveying plant consists of a vertical hoist and a belt conveyor; it is still composed of a number of independent operations. The coal bunkers are situated above the boilers. They are of large capacity, and will hold the entire supply of coal; moreover, they are suspended from the ironwork, which is not practical. The switch house and transformer chambers immediately adjoin the engine room, the transformers being inside the switch house.

In *Brakpan station* we already find an economiser for each boiler; the flues become short in consequence, and instead of direct draught, an indirect draught with separate chimneys is adopted. The coal bunkers over the boilers can accommodate the entire coal supply inside the boiler house. The coal is here measured by a drum built into each shoot. The boilers are still fed by reciprocating pumps. The switch house is entirely separate from the engine room, as are also the oil switch chambers from the bus-bar rooms. The transformers are erected in the switch house, but in special chambers.

Simmerpan Station.—The boiler house is designed similarly to that at Brakpan, as it was built practically at the same time. These works show a progressive development only inasmuch as the greater part of the coal supply is not stored in bunkers over the boilers, but outside the boiler house in special bunkers. The coal is conveyed uninterruptedly by bucket conveyors. The arrangements for measuring coal for boiler feeding, and for driving condenser pumps is the same as in Brakpan station. The condenser pumps are driven electrically in both stations.

Rosherville Station.—There are no large coal bunkers in the boiler house, but small coal hoppers are suspended from the ironwork of the roof; they hold coal for a few hours' supply. The coal is stored outside the boiler house; the coal bunkers are arranged along the longitudinal axis of the boiler houses; the coal is conveyed into the boiler houses uninterruptedly by a very simple system. In place of cast-iron economisers, separate wrought-iron economisers are mounted on top of each boiler. There are no flues, but a large number of short chimneys. The switch house is in a special building, which is so close to the engine room that the control panels, etc., can be placed in the connecting gangway. In the switch house the oil switches, bus-bars, and lightning arresters are each placed on a different floor, and are entirely separate from one another. The transformers are erected in chambers attached to the switch house. The coal is weighed by automatic coal weighing machines (one for each boiler house). The boilers are fed by turbine-driven rotary pumps. The condenser pumps are driven by steam turbines.

Vereeniging Station.—The coal storage arrangements are similar to those in Rosherville. The small coal bunkers in the boiler house are sufficient for one day's supply. This comparatively large capacity was necessary on account of the ropeway to be constructed later. Apart from the switchgear installation, which is designed for a much higher voltage, the arrangement of the switch house parallel to the engine room (advantage: short connecting cables), and the provision of feed water meters on the Venturi principle, this station is in other respects very similar to Rosherville station.

The total capacity of generators in commission amounts to 288,000 H.P., the compressed air plant alone having an output of 78,000 H.P.; the transformer capacity is 473,000 k.v.a.

Thanks to the able management of the undertaking by the Marquess of Winchester and Mr A. E. Hadley in London, and Major the Hon. W. L. Bagot and Mr Bernard Price in South Africa, the economic results achieved are quite satisfactory. The development is very favourable, and the difficulties that were encountered at first, due to a somewhat too rapid advance in consumption, have been overcome. The future can therefore be faced with confidence.

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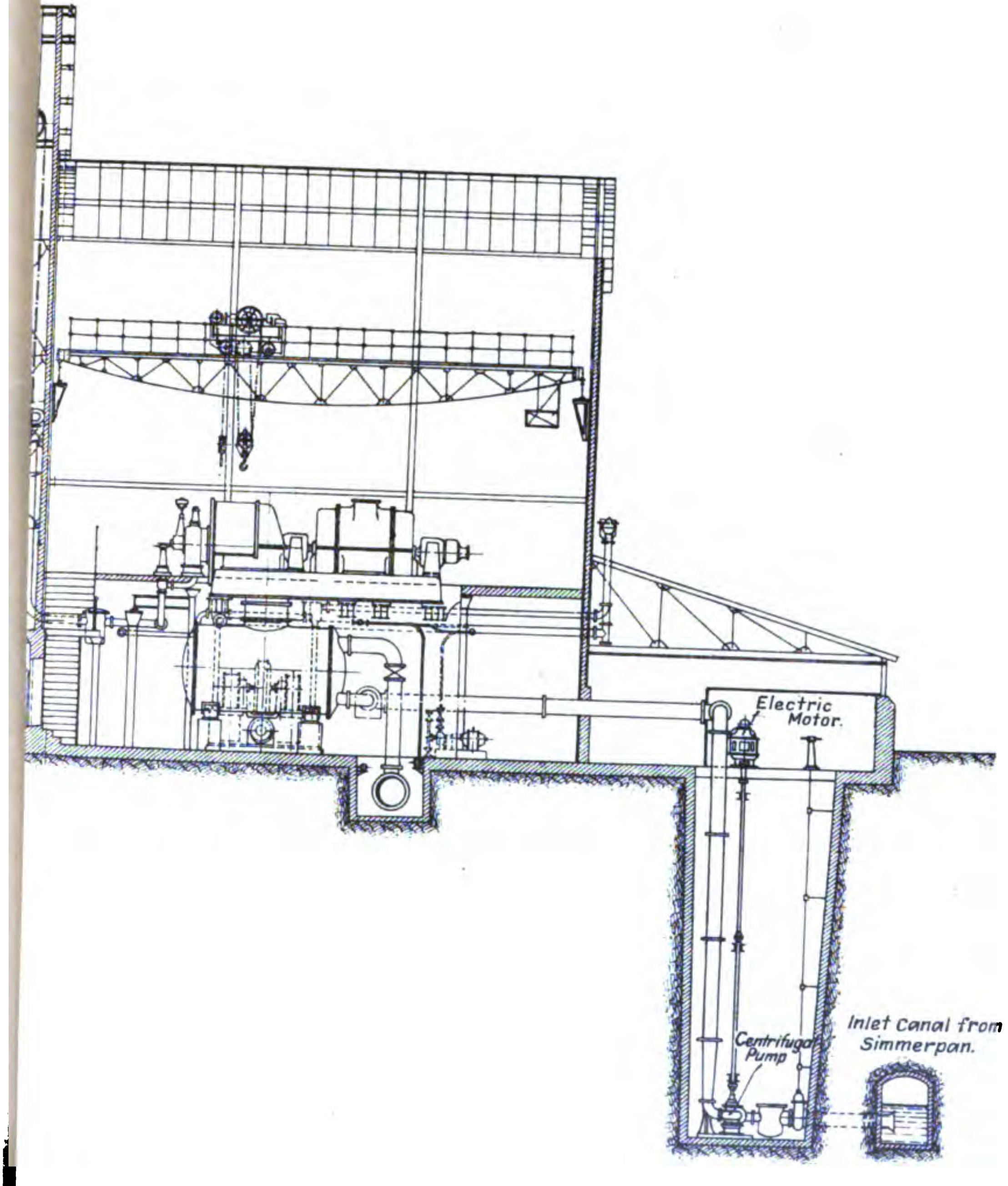

Electric Motor.
Centrifugal Pump
Inlet Canal from Simmerpan.

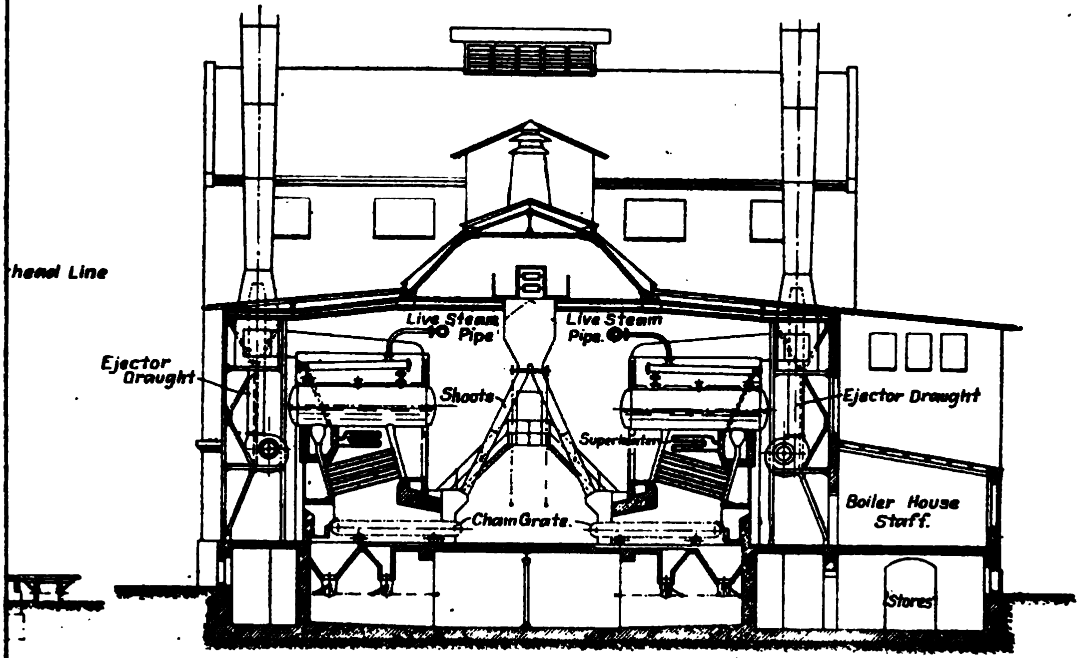
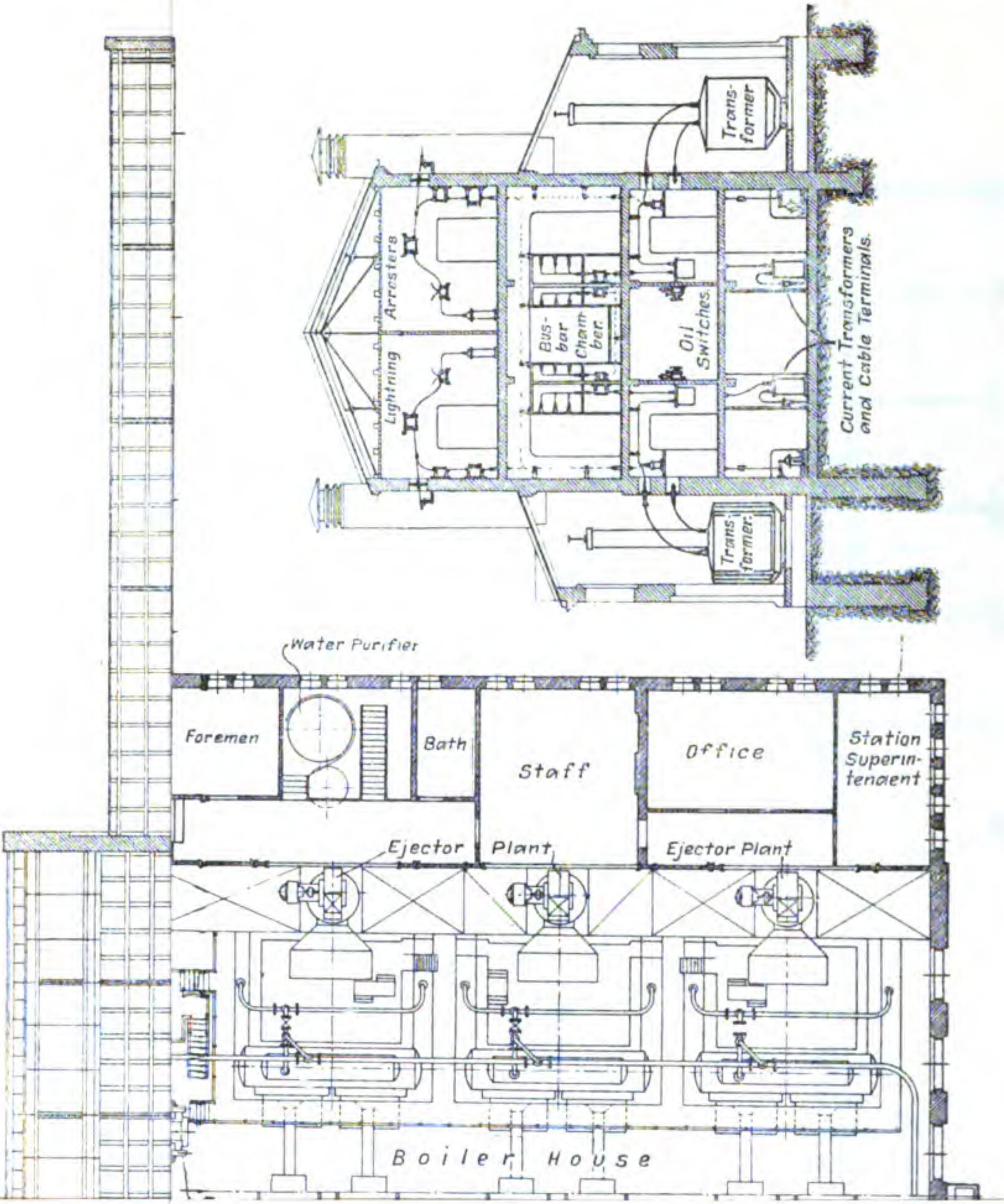

head Line
Live Steam Pipe
Live Steam Pipe.
Ejector Draught
Shoots
Ejector Draught
Superheater
Boiler House Staff.
Chain Grate.
Stores

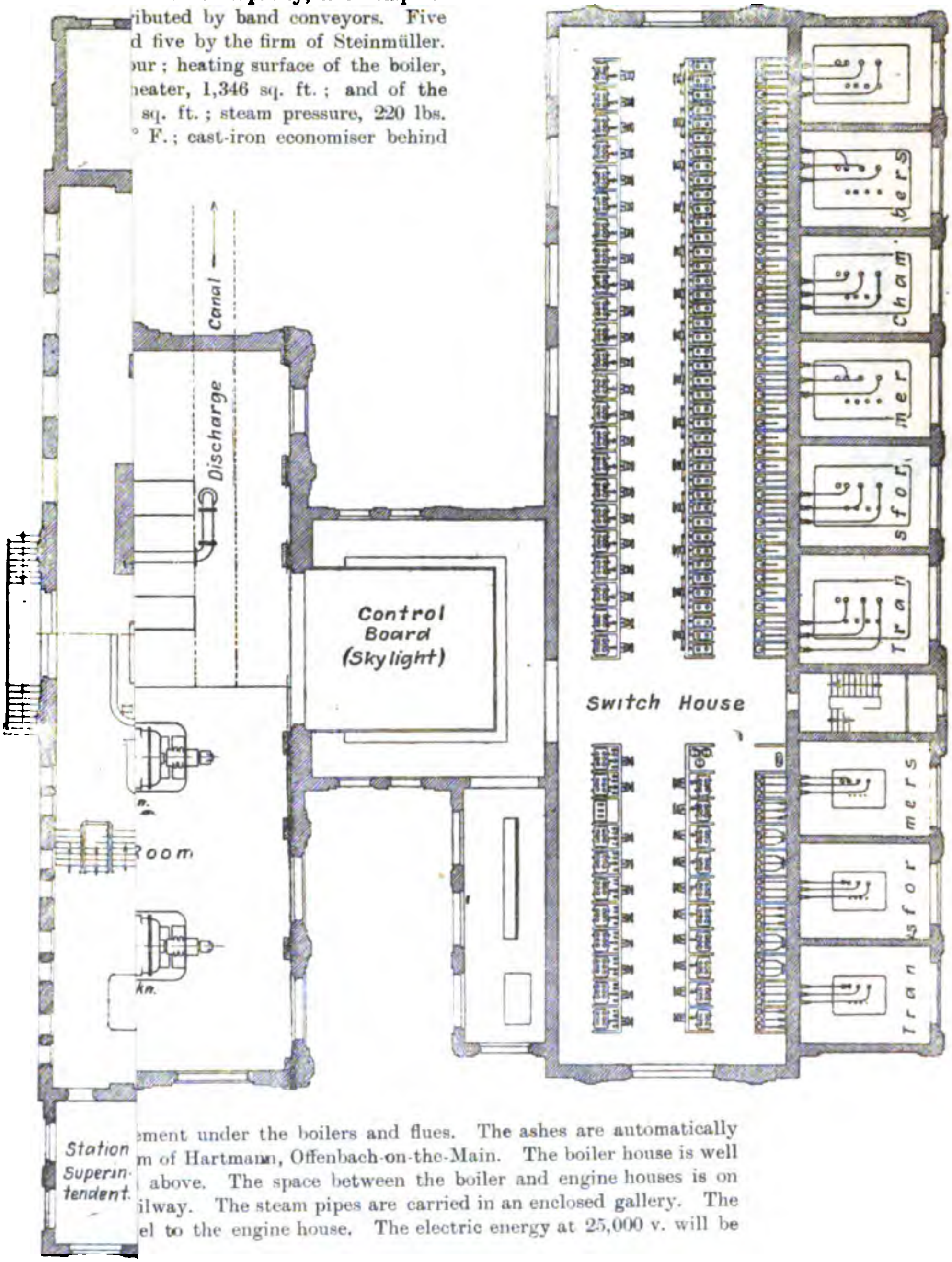
Plate IV.


Lightning Arresters
Bus-bar Chamber
Oil Switches
Transformer
Transformer
Current Transformers and Cable Terminals
Water Purifier
Foremen
Bath
Staff
Office
Station Superintendent
Ejector Plant
Ejector Plant
Boiler House

Works. Ground Plan.

PLATE V.

d three of 8,000 kw. each. Fuel,
Bunker capacity, five compart-
ibuted by band conveyors. Five
d five by the firm of Steinmüller.
ur ; heating surface of the boiler,
eater, 1,346 sq. ft. ; and of the
sq. ft. ; steam pressure, 220 lbs.
° F. ; cast-iron economiser behind



ment under the boilers and flues. The ashes are automatically
m of Hartmann, Offenbach-on-the-Main. The boiler house is well
above. The space between the boiler and engine houses is on
ilway. The steam pipes are carried in an enclosed gallery. The
el to the engine house. The electric energy at 25,000 v. will be

PLATE VI.

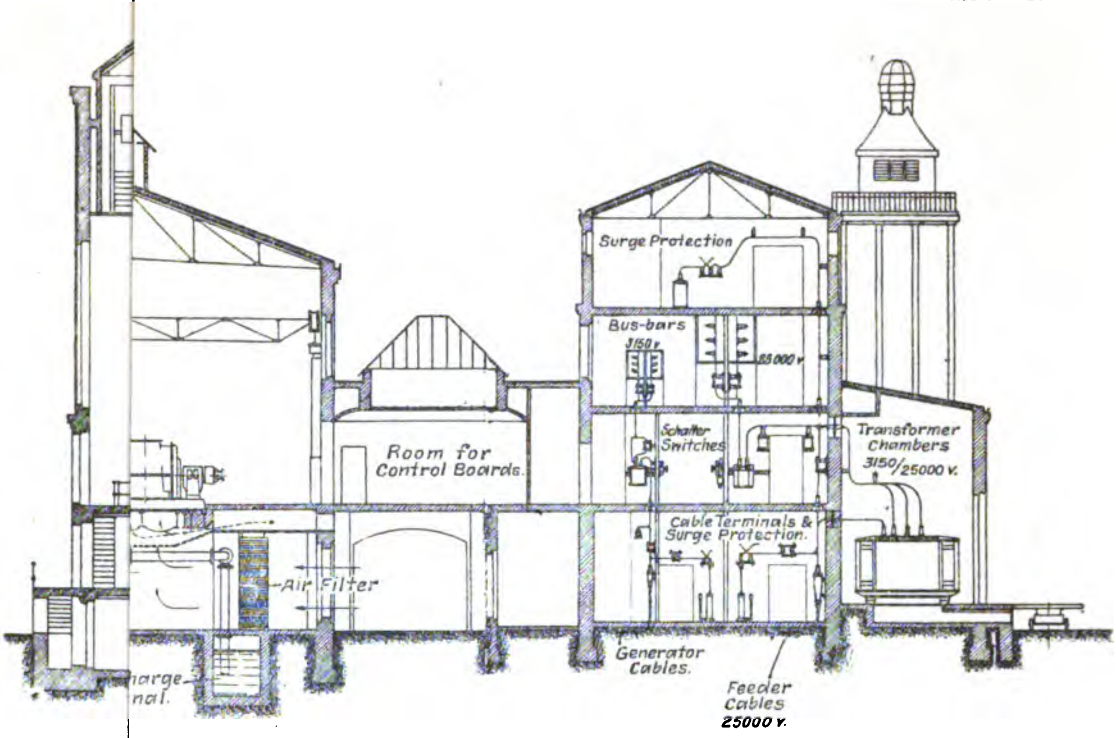


Fig. 41.—Fortuna Electric Supply Works.

Sections through boiler house, engine house, and switch house.

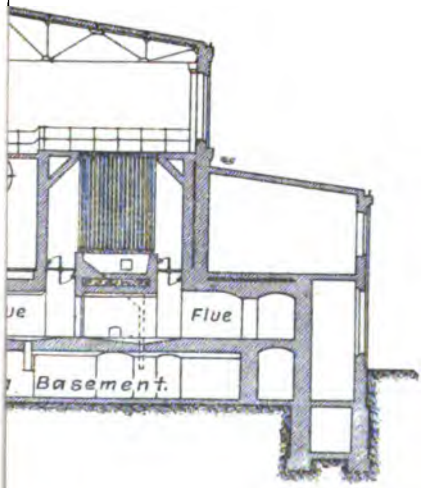


PLATE VII.