GROVES AND THORP'S

CHEMICAL TECHNOLOGY

OR

CHEMISTRY

APPLIED TO ARTS AND MANUFACTURES

VOL. IV.

ELECTRIC LIGHTING AND PHOTOMETRY

CHEMICAL TECHNOLOGY

OR

CHEMISTRY IN ITS APPLICATIONS TO ARTS AND MANUFACTURES

WITH WHICH IS INCORPORATED

RICHARDSON AND WATTS' CHEMICAL TECHNOLOGY

VOL. IV.

EDITED BY

W. J. DIBDIN, F.I.C., F.C.S., &c.

ELECTRIC LIGHTING

BY

A. G. COOKE, M.A., A.M.I.E.E.
HEAD OF THE ELECTRICAL ENGINEERING AND PHYSICS DEPARTMENT
OF THE BATTERSEA POLYTECHNIC

PHOTOMETRY

BY

W. J. DIBDIN, F.I.C., F.C.S., &c.
FORMERLY CHEMIST AND SUPERINTENDING GAS EXAMINER TO
THE METROPOLITAN BOARD OF WORKS AND THE
LONDON COUNTY COUNCIL (1882-1897)

PHILADELPHIA
P. BLAKISTON'S SON & CO.
1012 WALNUT STREET
1903

PREFACE.

Some apology is perhaps necessary for the attempt to compress into the space of some two hundred and seventy pages a mass of information covering the whole subject of Electric Lighting. The aim has been to put together a connected, and, as far as possible, complete and scientific account of the whole subject in such a manner as it is hoped may be useful to specialists in one or more branches of work connected with electrical industry who may wish for a *résumé* of all the various systems, machinery, lamps, &c., in use for the supply of electric lighting; more especially to Architects, Civil and Mechanical Engineers, and scientific workers, to whom a general knowledge of the subject is of professional value. To such readers the completeness of their general view is of the highest value, though it may not be the detailed knowledge of the actual worker in one branch, since they will wish to know the reasons, not merely the bare facts, of certain data and limitations which, originating in the achievements of a collateral industry, may apply to their own professional work.

It is hoped that the work may be read with facility by any one who has an elementary knowledge of Electricity and Magnetism, or even that knowledge which every educated person will acquire by observation without further instruction and reading. Efforts have been made to avoid gaps in the logical continuity of the argument; and to simplify formulæ by a reduction to the minimum of all minor corrections necessary to professional exactness. In short, the aim is a readable treatise, as well as a work of reference. Details which are likely to be ephemeral only appear as examples; and the examples of manufacture chosen for description, or theory of design, are not necessarily those believed to be the most recent or the best, but such as are thought serviceable for expounding the principles and methods of manufacture and working.

The section relating to photometry has been carefully compiled with a view to the full description of existing and proposed standard methods of determining the visional intensity of artificial illumination, and particularly with a view to showing the necessity for an International Agreement as to a standard of light. The experience which has been gained during the past two decades by the investigations carried out in England, France, Germany, and America has succeeded in the production of various methods, many of which are practical and reliable; but the danger underlying this work is that in the struggle to produce an acceptable proposition, the initial value of the "standard of light" may be unconsciously lowered. For this reason it is desirable that a "standard of reference" should be agreed upon by the respective governments. The molten platinum standard of M. Violle has been recommended for that purpose, although it is objected to as an instrument for daily use. The question of public lighting is one of so much commercial importance that it is most desirable that a common agreement should be arrived at in regard to the valuation of the light sold and paid for. In consequence of the introduction of the arc light, and that produced by the Welsbach Mantle system, the *quality* of the light requires as much or even more consideration than its *quantity*. That is to say, that it is by no means certain that the photometrical equivalents as ordinarily understood are parallel with the commercial or eyesight equivalent. For instance, the light of x candles produced by the arc light may be the only description of light suited for a particular purpose; no multiple of x candles produced by, say, ordinary gas flames, being capable of taking its place. The value of a given light must be in relation to the object for which it is employed, and not according to some arbitrary standard having a spectroscopic character totally unsuited for many special purposes. Whilst this point of view is one that must not be lost sight of, it is nevertheless undoubtedly desirable that some basis of general agreement should be arrived at. Doubtless the most reliable standard would be one in which the respective portions of the spectrum were as nearly as possible comparable in their relative intensity to sunlight, and that the photometrical ratio of each of the major divisions of the coloured spectra should be agreed upon and tabulated for general reference. This is in fact the lines upon which Abney, Nichols and others have worked, but, unfortunately, their researches have not yet reached the stage when the commercial world becomes aware of their importance.

In order to make the work complete, from the point of view of the "gas photometrist," the valuable "notification of the Metropolitan Gas Referees" has been added in the form of an appendix, as it describes the recognised methods for the estimation of the impurities in coal gas, viz., sulphur, ammonia and sulphuretted hydrogen. Although not strictly coming under the head of photometry, yet it is so clearly associated with it from the point of view of the Gas Works Manager that the subject cannot be overlooked with advantage.

CONTENTS.

ILLUSTRATIONS.

PLATES.

CHEMICAL TECHNOLOGY.

ELECTRIC LIGHTING.

CHAPTER I.

Introduction.

In attempting to arrange a programme which may serve as a logical basis for the discussion of the numerous different systems whereby electric currents are used for the purposes of lighting, it is found that they may all be grouped under three or four distinct headings. In each of these groups a distinct class of machinery is required for the generation of the electric currents, a distinct arrangement of conducting wires for their distribution, and each group of systems has its own peculiar advantages according to the purpose for which the lighting is required, whether public or private, and according to the distance to which transmission from the centre of generation has to be made. No system can be pronounced intrinsically better than another, although for some special purpose the question as to the best system for that particular purpose may need most detailed consideration before being finally adopted.

To explain the fundamental cause for the variation of these systems, it is necessary to consider this fundamental difference that distinguishes lighting by means of electric currents from other systems of illumination discussed in this series. Whereas the consumption of fuel is the primary source of all means of illumination (except in the case where wind or water-power is employed), in other methods of illumination than that by means of electric currents the fuel is obtained and reduced to a more or less portable form, and distributed in this form to the various centres of illumination where its combustion produces not only light but also heat. The discussion of other means of illumination therefore concerns itself mainly with the chemical preparation of the fuel in a form suitable to distribution and combustion at various distributed centres. Now it is most important to distinguish electricity, or the electric current, from the fuel. Neither does the quantity or magnitude of the electric current necessarily bear any relation to the amount of illumination obtainable by its means, nor do the variations of the systems of electric lighting arise from variations in the physical composition of electricity. The combustion of the fuel, if fuel be used as the source of the electric current, takes place at a single centre, whilst the illumination is only produced at a number of small centres distributed over a surrounding area. The fuel may be similar in nature—coal, oil, etc.—to that employed and distributed for direct production of illumination; but the heat-energy produced is transformed, first into mechanical energy, then into the form of energy associated with electric currents, and thus transmitted to distant points. In the latter form energy, instead of fuel in material form, is distributed to the various centres, where once more it is transformed into heat, and the distributed centres become sources of combined heat and luminous radiation exactly analogous to those where similar radiation is obtained directly by the combustion of the fuel. The function fulfilled by the electric current is therefore simply that of transmission or distribution of energy. The term *power*, meaning the rate of production and utilisation of energy, is more convenient in this connection, as the conception of an electric current is generally freed from that of quantity of electricity, or the electric fluid.

It will be seen at once that the three extra transformations of the power which must be effected in supplying "electric" lighting must necessarily, as in all physical transformations except to the lowest form of energy—that of heat—be attended by waste; and this waste must, in order to compete effectively with other systems, be compensated for by certain advantages. The advantages possessed by electric lighting may be summarised as follows:

Firstly. A greater freedom in the choice of fuels, utilising cheaper or unreduced material, and their more efficient combustion at larger centres; and sometimes the utilisation of equivalent "free" sources of mechanical power from wind or water.

Secondly. The more convenient and inexpensive distribution by the electric conductor.

Thirdly. The more efficient production of luminous radiation with less attendant heat.

Understanding, then, that the electric current is only the distributing medium, it will be seen that the question of distribution must be dealt with most carefully, and explanation of the various systems of distribution in logical sequence should be the programme to be followed in arranging a work on the subject of electric lighting. This course will be adopted, and for each system or group of systems the suitable machinery for the generation of the electric current, or, as it is better expressed, the transformation of power from the mechanical into the electric form, must be explained and illustrated. To make the explanation intelligible, whilst giving a sketch of the design and principles of working of this machinery, a brief summary of the science of electro-magnetism must be inserted. It will then be possible to give, in addition to illustrations and dimensions of some of the principal types now in use for various purposes, the calculations that must be made for one special example, and some estimate of the degree of efficiency and accurate regulation possible. Although necessarily less detailed and practical than specialised treatises on the design of electro-magnetic machinery, a brief treatise on the principles involved may be useful to those more concerned with the selection and arrangement of the systems to which they are applicable.

Were it necessary in this treatise to arrange the subjects discussed, as are the Propositions of Euclid or the successive chapters in an Elementary Science Text-book, in the order in which knowledge must be acquired by a student, it would probably be advisable to commence with the explanation of the various types of lamps, incandescent, arc, etc., since upon the manner in which electric power is transformed to luminous radiation depends very largely the form in which it must be generated and distributed. It will be necessary to assume a general knowledge if the question of distribution is to be dealt with immediately, or to anticipate the details which will be given subsequently in the chapters concerning electric lamps and measuring instruments. This arrangement has been adopted after due consideration as the most lucid and convenient order for most readers.

We have emphasised the fact that the electric current is by no means analogous to the fuel which is distributed for other means of illumination. That which is truly analogous to fuel, in the sense of bearing a quantitative relation to the fuel consumed in its production, we term electric *energy;* but since this physical quantity is not capable of being stored, except in minute quantities, in the medium in which electric phenomena are produced, passing directly from and to other forms of energy, we shall have to deal more frequently with the term electric *power*, indicating the rate at which energy is transferred. It will be assumed that the reader is acquainted with the elementary theory of electricity and magnetism, and familiar with the expression of the power conveyed by electric current, as in the case of all natural phenomena with which energy or power can be associated, by the product of two factors, the measures of the electromotive force and the current. It is possible, as will be shown, to transform mechanical power, the primary product of the consumption of fuel, into the power associated with and transmitted by an electric current, the magnitude of which and the magnitude of the electromotive force producing it are quite independent; each of these magnitudes, moreover, may be what we will, provided the product of their measures does not exceed an amount proportional to the number of horse-power absorbed in their production. Utilising the commonly accepted units and notation, if E be the number of volts, C the number of ampères in an electric circuit, then $E \times C$ is the measure of the electric power in watts, and the minimum horse-power necessary to produce it is $\frac{E \times C}{746}$. The rate of fuel consumption, and the heat and light radiation obtainable also bearing definite relations to the same product, save in so far as losses must inevitably attend the transformation of the one form of energy into the other. Throughout the succeeding chapters the discussion of these relations, and the way in which the losses may be minimised, will form the principal theme.

The multiplex systems of electrical distribution for lighting and power purposes arise chiefly from this freedom of choice in the magnitudes of the electromotive force and the electric current necessary for the transference of a given amount of power. We have to consider the possibility, or at least the convenience, of any relative magnitude for the conditions attending—

(1) *Generation*, or, more correctly, transformation of power from the mechanical forms or directly from fuel.

(2) *Transmission* to greater or less distances.

(3) *Subdivision*, with accurate regulation, to the various lamps or centres of illumination.

(4) *Utilisation*, or transformation of the power into light.

With regard to *Generation*, there is little difficulty in modifying the relations between the magnitudes of the two factors of electric power at pleasure without serious variation in efficiency of the operation; but this choice gives rise to extreme variations in the design of the machinery for the purpose.

On the other hand, the question of *Transmission* to a distance necessitates a reduction of the current factor, the reduction being the more imperative as distance over which the power is to be transmitted is increased. Unless the current factor be decreased, and the electromotive force factor be correspondingly increased, to a far greater extent than that most suitable for utilisation with the present form of lamps, and to an extent which renders special precaution necessary to render the systems free from danger to life and property, transmission and distribution must be confined within a very limited area in the neighbourhood of the centre of generation. It will be seen at once that small currents require correspondingly small conductors for their transmission. The extra insulation demanded by an increase in the electromotive force will be shown to be a far less serious matter than the cost of large copper conductors, so that the initial expenditure of a system designed to transmit a small current at high electromotive force will be comparatively small. Moreover, the power wasted in heating the conductors will, even with a proportionate reduction of the sectional area of the conductors as the current is decreased, bear a reduced ratio to the total power transmitted, so that a higher working efficiency can be maintained. The distance of transmission is therefore the paramount consideration determining the relative magnitudes of the power factors, and excessive distances generally give rise to complicated systems to retain the advantages, and remove the difficulties attending the use of high electromotive forces.

The appropriate *Subdivision* of the power associated with an electric current among the numerous centres of illumination may be effected by the subdivision of either or both the power factors. The most convenient is the subdivision of the current factor, effected by connecting the lamps "in parallel," that is to say, as separate circuits between two transmitting conductors. Such a system may be likened to the distribution of water for the supply of a residential district, the lamps corresponding to the taps whereby the water escapes, and one of the conductors, with its radiating branches, to the complete system of water mains. To complete the analogy, however, it is necessary to suppose a collection of the water by a system of return mains, similar to the distributing system, whereby all the water is returned to the source and redistributed without loss. The circulation of the blood in the arteries of the body and return by the veins would form, in some respects, a more apposite analogy.

The parallel system will be considered first in detail, and its limitations explained. It will be seen that, although eminently suitable for interior lighting with incandescent lamps, the electromotive force factor will be limited by the exigencies of lamp construction and considerations of safety to life and property, and therefore the distance of transmission will also be confined within very reduced limits. A considerable extension of this limit is obtained by a simultaneous subdivision of the electromotive force factor of the power, and as the complications involved do not materially affect the design of the generating machinery suitable to the simple parallel system, the various "multiple-wire" systems, as they are termed, will be explained in the same section.

Turning next to the other extreme, we have the subdivision of the electromotive force factor, or "series" system, in which the same current is used for all the lamps. This system will require in general a totally distinct type of generating machinery, and is specially adapted to public or street lighting with arc lamps. It will, moreover, be suitable to other special conditions, which will be described in the chapter devoted to this system.

For longer distances than are attainable with the multiple wire systems, and for incandescent lighting of the interior of buildings, the various "transformer" systems are introduced in order to combine the advantages of the parallel system with the economy in capital and working expenses introduced by the employment of high electromotive forces and small currents. The numerous modifications of these systems can be grouped under two headings, according as continuous or alternating currents are employed.

Having thus drawn up a programme of the work to be done in explaining the various systems of distribution of power for electric lighting, each system or group of systems will be studied in detail, the general description being followed by a study of the design of the machinery appropriate to each. A digression from the programme will be found necessary to explain the theory of electromagnetism with the notation which it is preferred to adopt in applying it to the design of machinery; this will be introduced before dealing with the machinery suitable to the parallel, or "low tension" systems of transmission. Sufficient has been indicated in this chapter, in very general words, as to the function which the electric current fulfils, as the mere connecting link between the source of power and the points at which power is converted into luminous radiation.

We have stated that the mere magnitude of the current, as measured by the galvanometer or other similar instrument, is not necessarily proportional to the power transmitted, or to the luminous radiation which is produced. Instead of fuel being distributed to various points, as in the case of gas and oil, the electric current may be compared with a current of water employed for hydraulic transmission of power, or to the speed of shafting or ropes for similar purposes. To these it is exactly analogous in requiring another factor to be known, the electromotive force corresponding with the pressure of the water, the torque of the shafting or the tension of the rope, before the magnitude of the power transmitted is known. As the design of the pipe conveying the water, and of the shaft or rope, is modified greatly by the relative value of the two factors of the mechanical power transmitted, so is that of the electric conductor. The sectional area of the conductor depends mainly on the magnitude of the electric current, as the sectional area of a pipe depends on the magnitude of a water current; but in both cases there is considerable modification according to the distance to be transmitted. The necessary insulation of the conductor depends mainly on the electromotive force, just as the thickness and tensile strength of the metal pipe depend on the pressure of the water within it. As a treatise on Hydraulic Transmission of Power would first deal with the theory of the flow of water and then of the size and strength of pipes to convey it, so, assuming a general knowledge of the theory of electric currents and electromotive force, the technical details of conductors for electric lighting may be generally discussed in the succeeding chapter before proceeding to their selection and arrangement under the different systems. The actual calculations of size of conductor and insulation will of course be postponed but the physical qualities of the various materials, employed for all systems alike, should form our initial study. Anticipation of some details and terminology will be inevitably necessary, but will be avoided as far as possible.

CHAPTER II.

Conductors.

We may commence with the following table, showing the specific resistance of various metals when pure and tested at a temperature of 15° Centigrade.

	Specific resistance in microhms.
Silver (annealed)	1.488
Copper (annealed)	1.580
Copper (hard drawn)	1.616
Gold	2.036
Aluminium	2.881
Zinc	5.866
Platinum	8.957
Iron	9.611
Tin	13.070
Lead	19.420
German Silver	20.710
Platinoid	32.907
Mercury	94.070

This table will show that copper is only rivalled in electrical conductivity by the valuable metals, and the only possible competitors for electric transmission of power are aluminium and iron. The latter may be used with economy under some exceptional circumstances, particularly for return mains, in cases where little or no insulation is required, and leakage current will do no harm. In mines, for example, there is often a quantity of iron cable which has served its purpose for haulage, etc., and which may be used. The iron or steel plates of ships, iron water pipes, etc., have been employed to carry the return current; but the practice is reprehensible since electrolytic action commonly ensues. Since the sectional area of an iron conductor would require to be seven times that of a copper main, and the weight five times, to give the same resistance, the cost of the carriage being correspondingly greater, the cost of the copper main itself will probably be the smaller, and the greatly increased cost of insulation would altogether prohibit the use of iron under ordinary circumstances.

Aluminium has recently replaced copper very extensively for electric transmission in America, more especially for power transmission and electric traction. Compared with copper conductors of equal sectional area the conductivity of aluminium is about 0.6; compared with conductors of equal weight, the ratio of conductivity is nearly 2. As the price of aluminium is now but little more than twice that of copper, and likely to be further reduced if the demand were increased by utilisation for electric conductors, the substitution of aluminium for many purposes in connection with electric lighting seems very probable. The two greatest objections are the difficulties of soldering and the increased cost of insulation. For overhead bare-wires aluminium appears specially suitable, as the tensile strength of wire may be made very great as compared with the weight. The degree to which aluminium is subject to corrosion under atmospheric influences is now being made a subject of careful experiment, and the result will largely determine its future value.

The conductivity of copper is greatly reduced by the presence of even the smallest amount of impurity; some specimens of copper wire, or that which is commercially so-called, giving a conductivity no greater than that of iron. The conductivity of different samples of copper is usually expressed in terms of the conductivity of "pure copper" in the hard drawn form as determined by Dr. Matthiesson, who found that there was no appreciable difference between the conductivities of silver and copper in the form of hard drawn wire, but by annealing the conductivity of copper was raised 2.3 per cent., and that of silver as much as 9 per cent. Annealed copper was too soft, however, for practical use, and he preferred to take the conductivity of pure hard drawn copper as the standard, which he determined as 1.634 microhms, or .000001652 B.A. units of resistance at 0° Centigrade. Specimens are sometimes reported as having a conductivity of 101 or 102 per cent., this meaning either that a purer specimen than that tested by Matthiesson is obtained, or more frequently that it is tested in a somewhat softer condition. It is commonly specified that the specific conductivity of the copper used for electric light conductors should be of at least 98 per cent. conductivity, and this seems to be easily attainable.

The resistance of all metals increases with the temperature, and this increase must be taken into account when dealing with conductors for electric power distribution. Matthiesson found that the conductivity of iron was diminished by 39.2 per cent., and that of nearly all other metals by 29.3 per cent., when raised from 0° to 100° Centigrade; whilst German silver loses only 3.1 of its conductivity between the same limits of temperature. The rate of increase of resistance is not quite uniform, being more rapid at higher temperatures. Matthiesson found that the conductivity at t° C. could be represented with sufficient accuracy in the form

$$A - B.t + C.t^2;$$

but it will be more convenient to adopt an expression for the resistance, instead of the conductivity, that of copper being given by Ayrton (a deduction from Matthiesson's results) as

$$r(1 + .003824\,t + .00000126\,t^2),$$

r being the resistance at 0° C.

Dr. Siemens adopted for the resistance an expression of the form

$$aT^{\frac{1}{2}} + bT + c,$$

where T represented the temperature in Centigrade degrees reckoned from the absolute zero, that is from 275° C., giving for copper, a formula correct through a very wide range,

$$.026577\,T^{\frac{1}{2}} + .0031443\,T - .22751.$$

At 20° C. the rate of increase is in the proportion of ·003874 of the resistance (at zero temperature) for every degree of rise, and for such variations as will be permitted in electric light conductors we may consider this rate uniform, and adopt the usual term "temperature coefficient" for this fraction.

The temperature coefficients of most other pure metals differ but slightly from that of copper; iron, however, gives a greater variation (.0048), whilst alloys have a much smaller temperature coefficient (German silver .00044; platinoid .00025). For this reason, as well as their high specific resistance, these and other alloys are useful for the construction of standard resistances: whilst the rapid increase of the resistance of iron with the temperature renders it the more valuable as a material for regulating resistances in series with constant potential arc lamps, or similar purposes where the object is to restrain a dangerous excess of current.

The resistance of a mile of pure hard drawn copper conductor of one square inch section at 0° C. may be taken as .042 ohm, and at 15° C. as .04458 ohm. With a current of 1000 ampères flowing in this cable, the difference of potential between its extremities (at 15° C.) will be 44.58 volts, or a difference of one volt for every 39.48 yards. The same difference of potential must exist with conductors of any section and length if the current density, 1000 ampères per square inch, be retained; and when the current density is altered the difference of potential must be altered in the same proportion. For rough estimates of the fall of potential along conductors, it is convenient to make this easily remembered result the basis of calculation, taking 2.5 volts as the fall (when 1000 ampères on the square inch is the current density) for every 100 yards, adding one-hundredth of a volt for every degree Cent. in the same distance when the rise in temperature is considerable, and correcting for any alteration of the current density from this standard amount. It will be seen later that such estimates are of great value, and constantly recurring in dealing with the various systems of electric lighting, the approximate result given by the rule being of sufficient accuracy for all practical purposes.

The sectional area of electric light conductors to carry given currents will in most cases be determined by the question of the highest permissible fall of potential along them, the consequent waste of power and difficulties placed in the way of uniform regulation necessitating a smaller current density than that which will be allowed by considerations of safety. These determinations are considered in their appropriate places for the different systems of distribution; but in some cases, generally those of distribution within a very limited distance, it becomes necessary to see that the current density in the conductors does not, even when satisfying the conditions of efficiency and regulation, exceed the limits determined by safety. These limits are determined by codes of rules laid down by the Board of Trade, chiefly for street mains, &c., and by Fire Insurance Companies for house wiring.

The Board of Trade regulation with respect to the sectional area of conductors are as follows (Rules 4 and 5, issued Feb. 1896):

"4. *Maximum Current to Conductors.*—The maximum working current in any conductor shall not be sufficient to raise the temperature of the conductor or any part thereof to such an extent as to materially alter the physical condition or specific resistance of the insulating covering, if any, or in any case to raise such temperature to a greater extent than 30° Fahr. (16.6° Cent.): the cross sectional area and conductivity at joints must be sufficient to prevent local heating, and the joints must be protected against corrosion.

"5. *Minimum Size of Conductors.*—The sectional area of the conductor in any electric line laid or erected in any street after the date of these regulations shall not be less than the area of a circle of one-tenth of an inch diameter, and where the conductor is formed of a strand of wires each separate wire shall be at least as large as No. 20 standard wire gauge."

The former regulation will lead us to a discussion concerning the rise in temperature likely to occur with various current densities, sizes of conductors, and types of conduit. The latter regulation is introduced to remove or minimise the danger of fracture of strands of the conductor, or injury to the insulation, when subjected to the necessary bending and other rough usage of drawing-in systems.

For internal wiring, the rules adopted by most of the British Fire Offices fix the limit of the rise in temperature at 18° Fahr. (10° Cent.). Whilst, corresponding with the Rule 5 above mentioned which determines the minimum size of wire to be used, even with the smallest currents, on account of mechanical strength to bear the necessary handling, and to permit slight corrosion without dangerous reduction of the sectional area, it is specified by the Phœnix Fire Office Rules that "All conductors of a larger sectional area than No. 16 S.W.G. should be composed of strands.

No conductor of less size than No. 18 S.W.G. should be used except in fittings, and in fittings no conductor should be less than No. 20 S.W.G." Other rules raise the limit for unstranded conductors to No. 14 S.W.G.

The limiting rise in temperature of 18° Fahr. (10° Cent.) is founded on the estimate that double the current density would raise the temperature to the limit which is considered dangerous. As it is elsewhere specified for india-rubber insulation that it should not soften at a temperature below 160° Fahr., this may be considered the dangerous limit. Now doubling the current density in the conductors would raise the temperature by an increment four times that of the normal current, or 72° Fahr. (40° Cent.) instead of 18° Fahr. (10° Cent.), so that the dangerous temperature would only be reached with a doubled current if the temperature of the surroundings were 88° Fahr., a fair estimate of the maximum likely to occur, without artificial heating, in the climate of Great Britain.

Now the predetermination of the rise of temperature in conductors with different current densities cannot be effected with any exactness, as much will depend on the thickness and heat conductivity of the insulating material, of the casing or conduits in which the conductors are laid, etc.; nor is it an easy matter to measure it when the conductors are laid. Under similar conditions we may find a law of variation connecting the sectional area, current density, and limiting temperature attained, by assuming that the rate of dissipation of heat varies as the surface of the conductors, and the rise in temperature above the surrounding objects at a little distance from the wire: a law which may reasonably be expected to hold good for small variations in temperature when the conductor is surrounded by material of much lower heat conductivity than the conductor itself, or is radiated from the bare surface of an uninsulated conductor. The constants of the variation may then be determined experimentally for any given conditions.

The rate of heat generation is proportional to C^2R, or $\frac{C^2}{d^2}$ for a given length of the conductor, d being the diameter. The rate of heat dissipation may be taken as proportional to the rise in temperature, T, multiplied by the surface, or by the diameter, d, for a given length; therefore since

$$\frac{C^2}{d^2} \propto d.T$$

it will follow that

$$C \propto d.^{\frac{3}{2}}T.^{\frac{1}{2}} \text{ and } T \propto \frac{C^2}{d^3}$$

The current corresponding to a given rise in temperature therefore varies as d , and the *current density* as $d^{-\frac{1}{2}}$; or, in terms of the sectional area A, as $A^{\frac{3}{4}}$ and $A^{-\frac{1}{4}}$ respectively.

Exhaustive experimental investigations have been made independently by Preece, Forbes, and Kenelly to determine the rise in temperature in conductors. For bare, round, solid wires, having a tarnished surface from which the heat escapes solely by radiation, Preece gave the following formulæ for the total current C, and the current density D, which gave a rise in temperature of T degrees Centrigrade,

$$C = 182.76\, A^{\frac{3}{4}}T^{\frac{1}{2}}$$

$$D = 182.76\, A_{-\frac{1}{4}}T^{\frac{1}{2}}.$$

But the results will be considerably modified with a bright surface, from which the radiation would be slower, and the current giving the same rise in temperature much less. On the other hand, a slight current of air would reduce the temperature, or allow a larger current to be used; and a stranded wire, having a larger surface for the same sectional area would also allow of a larger current. In the latter case, taking as an approximation

$$D = 200\ A^{-\frac{1}{4}}T^{\frac{1}{2}},$$

we may estimate that, for a bare cable of one square inch sectional area, a current density of 632 ampères per square inch would raise the temperature 18° Fahr., and for the same rise in temperature 160 ampères could be carried on a cable of 0.16 square inch section, or with a current density of 1000 ampères per square inch.

More valuable results, at least for our purpose, were given by Kenelly in 1889, from experiments carried out by the Edison Electric Light Co. with insulated conductors enclosed in wooden mouldings, as in the common practice of internal wiring. Under these conditions, Kenelly gave the following formula for the current which would raise the temperature of a conductor 10.4° Cent.

$$C = 560\ d^{\frac{3}{2}},\ d \text{ being the diameter in inches,}$$

or

$$C = 138\ d^{\frac{3}{2}},\ d \text{ being the diameter in centimetres;}$$

or, inverting these results, the required diameter is given in inches and centimetres by

$$d = .0147\ C^{\frac{2}{3}} \text{ and } .0374\ C^{\frac{2}{3}} \text{ respectively.}$$

To compare the former result, using that in which the inch is used as the unit of length, with those of Preece, we may reduce it to

$$C = .668\ A^{\frac{3}{4}} \text{ for a rise of } 10.4° \text{ Cent.};$$

or generally

$$C = 208\ A^{\frac{3}{4}}T^{\frac{1}{2}}$$

$$D = 208\ A^{-\frac{1}{4}}T^{\frac{1}{2}}.$$

From this it will appear that the heat is removed more quickly by conduction than by radiation from the tarnished metal surface, at least with the insulating substances used (impregnated cotton). The effect of insulating suspended wires, especially if the external surface is blackened, is to increase the rate of radiation, the larger surface for radiation more than compensating for the resistance of material to the conduction of heat. For Kenelly's complete report, which dealt also with insulated and uninsulated wires suspended in the interior of a room and in the open air, we may refer to the "Electrician," Dec. 13 and 20, 1889.

As the pre determination of the rise in temperature of conductors is subject to considerable uncertainty, it is far better to specify the current density that may be employed with various currents. It is evident from the experimental results given above that the formulæ for the current and current density

$$C = 600\ A^{\frac{3}{4}} \text{ and } D = 600\ A^{\frac{1}{4}}$$

will, for stranded conductors, give a rise in temperature of less than 18° Fahr. under any practical conditions; therefore we might take as the law for minimum current density

$$D = \frac{5000}{\sqrt[3]{C}},$$

which would allow a current density of 500 ampères per square inch for a conductor carrying 1000 ampères; 1000 ampères per square inch for a conductor carrying 108 ampères; 1500 ampères per square inch for a conductor carrying 37 ampères; 2000 ampères per square inch for a conductor carrying 15 ampères.

The regulations issued by the Phœnix Fire Office allow a current density of 1000 ampères per square inch for a conductor carrying 100 ampères or less, merely specifying that the current density should be less with a larger conductor. More recent regulations issued by the Liverpool and London and Globe Insurance Co. specify more exactly as follows:

For incandescent lamps only: 1500 ampères per square inch of sectional area for currents up to 10 ampères. 1000 ampères per square inch of sectional area for currents from 10 to 100 ampères. 800 ampères per square inch of sectional area for currents over 100 ampères. For arc lamps, motors, heating appliances, etc.: 1000 ampères per square inch of sectional area for currents up to 50 ampères. 800 ampères per square inch of sectional area for currents over 50 ampères.

The lower current density allowed for the conductors carrying the current for arc lamps, etc., is necessitated by the greater liability of the current to exceed the normal amount. The following table of suggested sizes of conductors is also issued with these rules:

Size.		For Incandescent Lamps only.		For other Purposes.
S.W.G.	Area (solid) square in.	No. of 60 Watt. 100 Volt Lamps.	Current in Ampères.	Current in Ampères.
18	.0018	4	2.7	1.8
61/38	.0018	4	2.7	1.8
3/22	.0019	4	2.8	1.9
7/25	.0022	5	3.3	2.2
3/20	.0031	8	4.6	3.1
16	.0032	8	4.8	3.2
7/23	.0032	8	4.8	3.2
108/38	.0032	8	4.8	3.2
7/22	.0044	11	6.6	4.4
7/21½	.0050	12	7.5	5.0
14	.0050	12	7.5	5.0
7/20½	.0061	15	9.1	6.1
7/20	.0072	17	10.0	7.2
7/18	.0128	21	12.8	12.8
19/20	.0198	33	19.8	19.8
7/16	.0229	38	22.9	22.9
19/18	.0349	58	34.9	34.9
7/14	.0356	59	35.6	35.6
19/17	.0479	80	47.9	47.9
19/16	.0624	104	62.9	50.0
19/15	.0789	131	78.9	63.1
19/14	.0973	162	97.3	77.8

Insulation.

The insulation resistance of a cable, L centimetres in length, of circular section, the internal and external diameters of the insulating covering being d and D respectively, will be given by the formula,

$$R = \frac{\sigma \log \frac{D}{d}}{2\pi L}$$

σ being the specific resistance, or that of a cubic centimetre from one face to the opposite. For the substances used as insulators, the value of σ when expressed in megohms will be exceedingly great, and it is convenient to adopt the unit of specific insulation resistance suggested by Preece, that of 10^{24} c.g.s. units, or 10^{18} ohms or 10^{9} megohms per cubic centimetre. In terms of this unit, the specific resistance of substances frequently employed is given by the following table:

Insulating Material.	Specific Resistance in Preece Units.	Temperature of Test Degrees Centigrade.
Dry air	infinity	—
Paraffin	34	46
Ebonite	28	46
Flint glass	20	20
India-rubber (Siemens' special) .	16.17	15
" " (untreated) . . .	10.9	24
" " (ozokerited) . . .	6.6	15
" " (vulcanised) . . .	1.5	15
Shellac	9.0	28
Gutter-percha	0.45	24
Vulcanised bitumen (Callender E.L. cable)	0.45	15
Glass (ordinary)	0.09	20
Mica	0.048	20
Paper (parchment)	.00003	—
" (cardboard)	.000005	—
" (ordinary)	.000003	—

The above list is collected from the results obtained by numerous experimentalists. The specific resistance of insulating materials generally decreases with the temperature, although at moderate temperatures a preliminary rise is observed with some. In specifying the insulation resistance required for conductors, it is necessary to specify also the temperature at which the test should be taken, 75° Fahr. being customary. The test of insulation should be taken after a minute's electrification at the maximum potential it is proposed to use, when possible, or at least 100 volts. The insulation will appear to improve after a short time of electrification, owing to the cessation of the current supplying the statical charge communicated to the dielectric, and the opposing E.M.F. of electrolysis, which seems always to accompany the passage of the current. When intended to be impervious to moisture, as the insulation for all conductors for electric lighting should be except for flexible connection and the like, it should be tested after 24 hours immersion in water.

The attainment of exceedingly high insulation resistance is not, at least with moderate electromotive forces, of paramount importance in the conductors for electric lighting. Where the E.M.F. does not exceed that used for parallel distribution for arc or incandescent lamp, the thinnest paper insulation, if perfectly dry and mechanically sound, would be sufficient, the corresponding leakage current, distributed over the whole system of conductors, would not be sufficient to do any harm by its electrolytic or other action, and the waste of power would be wholly insignificant. The requirements of the insulating covering, which are of more importance, are as follows:

(1) It must be of sufficient flexibility, mechanical strength, and thickness to withstand the rough usage to which it may be subjected during laying, and subsequently.

(2) It must be impervious to moisture, and not affected, appreciably, in specific resistance, etc., by such temperatures as that to which it may unavoidably be subjected. For ordinary internal wiring 160° Fahr. is specified by insurance rules, at which temperature the insulation should not be softened so that the conductor may be displaced, and it should not be easily inflammable.

(3) It should not tend to corrode the conductor.

(4) For high tension conductors, it should be of sufficient thickness to prevent the passage of a disruptive spark, even if the E.M.F. be raised considerably above the normal amount; to ensure this, it should be tested before use with double the maximum E.M.F.

(5) The cost of the material should be as low as possible consistent with the previous conditions.

Now india-rubber not only comes highest in the specific insulation list of all flexible and tenacious substances, but approximates to the above conditions more closely than any other; therefore it is adopted for the larger proportion of underground street conductors, and almost exclusively for indoor wiring. Vulcanised rubber, although much inferior in specific insulation to pure, is preferred on account of the more important conditions of mechanical strength, durability, etc. In order to satisfy the third condition above, a thin inner coating of pure rubber should separate the vulcanised rubber from the copper, and the latter should be carefully tinned, otherwise the copper is liable to corrosion by the sulphur used in the vulcanisation. In order to render the insulation impervious to moisture an outer covering of waterproof tape is supplied, and for further mechanical protection a braiding of tarred flax.

For low tension work, that is, for use with electromotive forces not exceeding 250 volts, the thickness of the insulation need not be greater than that which will ensure continuity throughout, and will resist the stress produced by bending the conductor, etc. As the latter will be greater with larger conductors, a greater thickness of insulation will be required or better quality of rubber, and the insulation test, which makes the same demand, and tests the continuity of the covering, remains the best means of specifying the extent of insulation required. The Phœnix Fire Office regulations insist that the insulation of the conductor before laying should exceed 250 megohms per mile when intended for dry places, and 600 megohms per mile when intended for damp places; other regulations specify 300 megohms throughout. The corresponding thickness of vulcanised rubber is very small, and is generally greatly exceeded by that supplied by manufacturers, as the addition to the cost of the copper conductor is relatively unimportant. Some further standard of mechanical strength and durability of rubber insulation, whereby it may be satisfactorily tested, is much needed. Some engineers require that specimens of the cable should not show any apparent injury to the insulation after the straining consequent upon bending it round a drum to a curvature greatly in excess of that to which it is likely to be bent in all succeeding manipulation.

Electrical faults, however, frequently develop as a consequence of straining in the insulation only after a long time, in some cases within the writer's experience after months or years of regular use, undisturbed by further manipulation. A very excessive mechanical strain has therefore to be exerted if a satisfactory test made immediately is to be trusted.

For high tension work, that is, for use with electromotive forces exceeding 500 volts if continuous, and 250 volts if alternating, the Board of Trade regulations insist on a continuous covering of insulating material having a thickness of not less than one-tenth part of an inch; and in cases where the extreme difference of potential in the circuit exceeds 2000 volts, the thickness of insulating material must not be less in inches or parts of an inch than the number obtained by dividing the number expressing the number of volts by 20,000. It is also specified that no conductor should (except with written consent) be used for the transmission of more than 300,000 watts (or 50,000 for aerial lines), so that with 2000 volts the limiting current is 150 ampères. With conductors of the size suitable for currents less than this, the minimum thickness permitted, if of high grade rubber, the insulation resistance should exceed 5000 megohms per mile, and this is commonly specified as the standard for high tension work.

To justify the Board of Trade regulation as to minimum thickness, the following experiments as to the electric strength of air and india-rubber made by Siemens may be referred to. Measurements of the "striking distance" of disruptive sparks were taken with various electromotive forces, obtained from an alternating current transformer, the "virtual E.M.F." being measured with an electrostatic voltmeter. In air, between flat discs, the striking distances were as follows:

E.M.F.	Millimetres.	Inches.
2,000	0.67	.0264
4,000	1.59	.063
6,000	2.53	.100
8,000	3.60	.142
10,000	4.80	.189
12,000	6.46	.254
15,000	10.23	.395

It must be observed that the maximum E.M.F., which most probably determines the striking distance, would be about the virtual measure multiplied by $\sqrt{2}$, but as the most common use of high pressure supply will be with alternating E.M.F., the customary method of virtual measurement will be for our purpose the most valuable. The striking distance between sharp points will be but little greater, if at all, for the same E.M.F. Between a steel point and disc (the former a sharpened cone with an angle of 60°) Siemens found for 2000 vertical volts the striking distance was 0.4 millimetres (or less than between the discs); with 8000 volts 4.08 millimetres (or somewhat greater); and for higher E.M.F. the distances of sparking were about the same as above.

To test the electric strength of india-rubber the following tests were made of the E.M.F. required to puncture the insulating covering of cables, and india-rubber sheets of various thicknesses.

	Thickness in Millimetres.	E.M.F. of Disruptive Spark.
40 inches of 880 H. wire . .	3.5	21,500
10 yards of experimental core .	3.8	20,000
1½ " " " . .	2.5	16,000
1 yard concentric cable . . .	3.5	28,000
India-rubber sheet. . . .	.5	7,000
" "	1.0	10,500
Experimental core	10.0	38,000

Thus india-rubber seems capable of withstanding nearly three times the electric pressure of a similar thickness of air.

It would appear, therefore, that with a thickness of india-rubber of one-tenth of an inch, or 2.5 millimetres, the E.M.F. producing a disruptive spark would be about 16,000 virtual volts alternating, or 24,000 with continuous E.M.F., and across a corresponding air gap 6000 or 9000. The Board of Trade Regulations may therefore be taken to give a safety factor of eight with 2000 virtual volts alternating E.M.F. With extra-high tension the safety factor is less, 10,000 volts (⅕ inch thickness of insulation) apparently giving a safety factor of about five, but there is then much less danger of mechanical injury.

When an installation for the interior lighting of a building is complete, a minimum insulation resistance for the whole system is demanded by fire insurance offices, and generally by the supply company to whose system the installation is to be connected, if not supplied by a separate generating plant. The value of this insulation test is by no means a satisfactory criterion of the safety of the installation, only serving as a partial safeguard against very defective workmanship, and of little value as a proof of durability and improbability of failure. Although the test can hardly be omitted, it should not be substituted for thorough inspection of the work. With conductors insulated to at least 300 megohms per mile, the leakage current must be infinitesimally small with a moderate E.M.F., but it will be impossible to prevent a much larger leakage from the fittings where the conductors are bare, and some degree of dampness on the surface of the porcelain or other insulators will greatly lower the insulation of the whole installation, and cause it to be a very variable quantity. As the fittings are therefore the main source of leakage, it would appear to be the more justifiable requirement that the minimum insulation resistance permitted should be in inverse proportion to the number of lamps employed, irrespective of size, which should not affect greatly the insulation attainable for the corresponding fittings. This should make the test as satisfactory a criterion of the quality of the work as it is capable of being. Other regulations, however, define the minimum insulation resistance as inversely proportional to the total current to be used in the installation, thus making the maximum leakage current proportional to the whole current.

The Phœnix Fire Office Regulations specify as the minimum insulation resistance between the whole installation and earth, and between the conductors, for continuous currents with an E.M F. not greater than 220 volts, as half a megohm for installations of 25 lights, and a smaller insulation resistance in proportion for a larger number of lights. For alternating currents the insulation resistance must be double that given by this definition. The Regulations adopted by most other Fire Offices specify that the leakage from the conductors to earth over the whole installation, or between the conductors, should not exceed the twenty-thousandth part of the working current even under the most unfavourable conditions. Under dry conditions double the insulation resistance is insisted on. With 100-volt lamps of 16 c.p., taking .64 ampère each, the working current would be 16 ampères, and the leakage thus permitted between the conductors under unfavourable conditions 1/1250 ampère, corresponding to an insulation resistance of 125,000 ohms, or only a quarter of that required by the Phœnix Regulation. The standard required by many supply companies is much higher than those of insurance offices, that of the London Electric Supply Corporation alternating current being,

for less than 25 lamps . . .	2 megohms.
for from 25 to 50 „ . . .	1.25 „
for from 50 to 100 „ . . .	.75 „
for upwards of 100 „ . . .	.5 „

The Regulations recommended by the Institute of Electrical Engineers as to the insulation resistance of complete installations is as follows:

> "The insulation resistance in megohms of the whole of any installation either to earth, or from any supply conductor to any return conductor when all branches are switched on, but the lamps, motors, &c., removed, must in no case be less than that given by dividing the electromotive force in volts by the number of lamps; thus, if the electromotive force be 100 volts and the number of lamps be 50, then 100/50 = 2, that is, the resistance must be 2 megohms. Tests should be made of the electromotive force intended to be used, but in no case less than 100 volts."

This regulation seems somewhat severe, in view of the fact that high insulation is not a perfect criterion of the quality of the workmanship; for whilst it may easily be satisfied with very moderate care in wiring buildings where plaster, brickwork, etc., are thoroughly dry, and where the fittings need be few and may be placed in dry unexposed positions, there are many conditions, such as in new buildings, public halls, etc., where the best of workmanship, with the types of porcelain fittings approved by experience for safety, may give much lower insulation. When the fittings are supported on dry woodwork, a higher insulation may be secured thereby, which is obviously no proof of diminished risk of fire. A relaxation of the regulation in special cases is most reasonable, and due recognition of the value of an insulation test, with its limitations is needed.

Seeking for the possible causes of fire that may arise from Electric Light installations, we may class them as follows:

(1) Those which may arise from the lamps themselves, when placed near inflammable material and improperly protected. There is little or no danger to be anticipated from small incandescent lamps, even in the event of fracture, but the larger sizes and arc lamps need to be placed at a considerable distance from woodwork, etc.

(2) Those which may arise from overheating of the conductors.

(3) Those which may arise from the leakage current through imperfect insulation.

At present we have only to deal with the two latter, since the first will be discussed in the chapter on Incandescent Lamps. With conductors of sufficient sectional area, as already determined, and sufficiently protected by fuses against undue increase of the current, there still remains a possibility of local heating owing to increased resistance at one point. This may occur with loose contacts in the fittings, imperfect conductivity at the joints, or corrosion of the conductor reducing the sectional area. Corrosion is especially serious with conductors of small sectional area, but is not likely to occur except after the breakdown of the insulation, when the leakage current may by electrolytic action produce very rapid corrosion. Small conductors are also liable to injury, or even fracture, in handling, and, although continuity is maintained in the circuit, considerable heating will ensue at that point. The local heating may be sufficient to ignite the insulation, or the casing or other inflammable material in the neighbourhood, and in the presence of any inflammable gas the danger will be extreme.

Defective insulation may be caused through insufficient mechanical protection of the conductors, and consequent abrasion, chemical decomposition, or decay of the insulating material. The greatest danger of this occurring is in the hidden portions of the work, where the conductors pass through walls and under flooring, and are subject to the attacks of vermin, acid liberated from moist plaster, etc., and where maintenance of continuity in the wood casing, earthenware or metal tubes, or other mechanical protection, may easily be shirked by careless workmen. The insulation of joints with pure rubber, as in common practice, is seldom up to the standard of the rest of the insulation in durability. Moisture and dirt in the fittings is a no less common cause of low insulation. Now a "fault" or complete break-down of insulation at one point of a circuit will not cause leakage of the current provided the remainder of the system is highly insulated throughout, and is therefore less dangerous in a transformer system which is made up of many independent circuits. Two points of weak insulation, especially if on different branches of a parallel system, may, however, cause considerable leakage, which may become the immediate cause of a fire by the carbonisation of damp woodwork, converting it into conducting material, and finally igniting. Wood casing, most commonly adopted on account of convenience, cheapness, and appearance, whilst perfectly satisfactory when dry, may become, when wet and in the presence of leakage currents, a source of danger instead of safety.

The system of wood casing has the great advantage over any other method of mechanically protecting the conductors that it lends itself easily to decorative effects, and therefore encourages the placing of the conductors on the surface of walls and ceilings where they are easily accessible, and always under some supervision. It should be used only in dry situations, and the wood well seasoned and well varnished. In passing through walls it is recommended, and generally insisted on, that the conductors between which considerable difference of potential exists should be carried in separate tubes of stoneware, or other incombustible material, set in cement. The possibility of percolation of water through these, and so saturating the wood casing, must also be duly guarded against.

The Insulated Tube system employs iron pipes with an inner coating of a special paper, prepared with an insulating material, and rendered fire and water proof. The paper lining is made smaller than the iron tube, and after being placed inside it, is expanded to it by pneumatic pressure. It is made in ten-foot lengths, and elbows and bends are supplied for making joints. The lengths are joined by insulating couplings. These tubes are built into the walls, and the insulated conductors drawn in subsequently. The advantages claimed over the use of ordinary iron pipes are: Firstly, additional insulation which can receive no mechanical injury; secondly, the conductors can be drawn in or out without fear of abrasion of the insulation by burrs on the metal; thirdly, a short circuit between the conductors in the pipe is not accompanied by an "earth," and the fireproof qualities of the inner covering prevents injury to the pipe, as shown by the following test: A length of bare iron pipe and another of insulating tubing were taken, and two insulated wires run through both, under exactly the same conditions. These wires were short-circuited, with the result that a hole was blown in the iron pipe, whilst the insulated iron pipe stood the test perfectly. A 150-ampère fuse was arranged in the circuit employed for this experiment.

The principal objection to the Insulated Tube system is unquestionably its expense, which must compare unfavourably *as to first cost* with wooden casing.

The use of concentric conductors for internal wiring presents many advantages, but has not been widely favoured owing to the demand of supply companies that both conductors should be highly insulated. For private installations with a separate power supply no system could be more safe. The central conductor is highly insulated from the outer, which is made up of finer wires, forming a complete metallic sheath. If the outer conductor be maintained at the same potential as the earth at one point, for example let the corresponding dynamo terminal be connected to earth, the maximum potential at any point will be that of the fall of potential along the main, and the thinnest insulation will prevent any appreciable leakage. The outer conductor may, in fact, be earthed throughout its whole length without any risk of fire, and if the fall of potential along it does not exceed 1½ volts no appreciable electrolytic action will ensue. It has sometimes been the practice to reduce the fall along the outer main by making the conductor of greater section than the central conductor, so that the fall of potential may be almost entirely due to the former, and to leave the outer conductor uninsulated, but this is less satisfactory than the use of a thin insulating covering which also protects the copper from corrosion. The only possible leakage with the full potential of the circuit is between the inner and outer conductors, and the only possible break-down is a short circuit resulting in the blowing of a fuse. The lead covered concentric conductors occupy much less space than any system of separate conductors, and may be buried in plaster, etc., without fear of injury. The chief objection is the difficulty of making satisfactory joints for branch circuits, but with suitably designed junction boxes the difficulty may be got over, and by the complete elimination of joints, which are always the weakest points of a system, a much safer result can be obtained. It has been suggested that concentric conductors might be employed with advantage for the branches of a three-wire system, the outer conductor being always connected to the middle main, which is to be earthed at some point, and the central conductor to one or other of the outside mains.

Fusible "Cut-outs."

Having settled the maximum current which it is desirable to allow to pass through any main or branch conductor, the next point is to arrange some automatic device or "cut-out" by which the current can be prevented from increasing much beyond this limit. There are two classes of automatic cut-outs in use, namely—those depending on the magnetic effects, and those which depend on the heating effects of the current. The former consist of electromagnets through the coils of which the current passes, and when the current exceeds the strength for which the instrument is adjusted, the electromagnet pulls over an armature and breaks the circuit. The connection is in general restored by returning the armature by hand. These are not much used for protecting cables, as they have neither the certainty of action nor simplicity of the fusible cut-out. They are invaluable for the protection of secondary batteries, and several examples will be treated under that heading.

The latter class of cut-outs consists of a short length of thin wire, generally of a material that fuses at a low temperature, which will melt and break the circuit when the current rises to 50 or 100 per cent. above that which the conductor is intended to carry. These short wires are termed "fuses."

It must be noted that fuses are intended to protect the cables and connections in a system, and are as a rule incompetent to protect incandescent lamps from injury. Incandescent lamps will not bear an excess current of more than 10 or 15 per cent. for long, and will speedily be destroyed if an excess of 25 per cent. were reached. Even if the fuses were made so light as to melt with this small excess of current, which would involve their remaining when all the lamps were burning at a temperature near melting-point, they would be no protection whatever when only a few of the lamps were alight. The kind of danger against which a fuse can provide a safeguard is an accidental short circuit between the flow and return leads such as is very likely to occur in a fitting, or between twin wires, during the removal and replacement of some kinds of lamp, or in the carrying out of any repairs or additions to the circuit, should such work have to be performed while the current is flowing. The conditions to be secured for a good fuse are as follows:

(1) That it should melt with the desired excess of current. This excess is frequently specified as 50 per cent., but there is much to be said in favour of allowing a wider margin. From the nature of the events which call for the action of the fuse, it will be seen that little harm is likely to be done by strengthening the fuse, so that it melts with a 100 per cent. excess. Exact calculation is not possible with regard to fusible wire, as so much depends on the soundness of the contacts, and the conduction of heat from the wire. Great inconvenience is produced by the frequent melting of fuses in which too small a margin is allowed.

(2) A sufficient length of break. One inch is generally considered ample on low tension circuits, up to 100 volts, and it is a safe rule to increase the length in proportion to the electromotive force, so that in 2000-volt circuits a break of nearly two feet should be allowed. It is convenient also to vary the length with the current, less than an inch being necessary for small currents, such as that of a 16 c.p. lamp. Three or four inches break is advisable for main fuses (from 50 ampères upwards).

(3) The avoidance of unnecessary resistance. This is of no great importance if the fuses are short and the number small, the additional resistance being insignificant.

(4) The fuse should melt suddenly in case of a short circuit. To obtain this there should be as little metal as possible in the fuse. Several strands of fine wire will carry more current than a large wire of the same sectional area, owing to the greater proportionate area for radiation, and therefore for a fuse of the same capacity much less metal need be used. This gives an additional advantage that the molten metal is not so likely to cause damage.

(5) The fuse should be sufficiently protected from mechanical injury, and from the possibility of the melted wire setting fire to combustible material.

Fuses to carry small currents are commonly made of lead, or tin, or an alloy of both metals. The resistance of tin is more than eight times, of lead than twelve times that of pure copper, and of alloys of lead and tin still greater. Moreover, the melting-point of lead is 612° F., of tin 442 °F., and of alloys of the two still lower. Fuse wire melting with currents of from one ampère can therefore be constructed of these metals of sufficient cross-section to be roughly handled.

For currents of over fifteen ampères, the use of fine wires of high conductivity are much to be preferred. For small currents, copper wire would need to be so fine that most careful handling would be necessary, and contacts could not be depended on. But with large currents the quantity of metal in lead or tin fuses would have to be very great; they have therefore considerable capacity for heat, and melt too slowly when there is a rush of current due to a short current. Moreover, being always warm with the current, they are liable to deteriorate, and need to be replaced periodically. Thin copper wires carrying the same current will, on the other hand, melt nearly instantaneously with a large current. The resistance rising rapidly with the temperature will cause the change from a cool state to melting-point to be very abrupt.

Copper wire of No. 30 S.W.G. preferably tinned to prevent oxidisation when exposed to high temperatures, will melt when exposed to free radiation in still air with about fourteen ampères. In short lengths the free conduction to the terminals of the fuse will cause it to bear a much larger current, but to compensate for this the radiation in a closed box is much reduced. One or more strands of this size of copper wire makes an effective fuse, and the quantity of metal is only about one-tenth of the corresponding tin or lead fuse. The currents with which wires of different materials and sectional areas fuse have been very carefully determined by Mr. W. H. Preece, but the results must be considerably modified as above when the wire is of short length and enclosed in a fuse box. In the course of his investigations, he showed experimentally that, when the wire was not very fine, the current required to raise a wire of given material, and of diameter d, to a given temperature varied as $d^{\frac{3}{2}}$. We have seen that for a small increase of temperature T, it is reasonable to expect that the current will vary as $d^{\frac{3}{2}}\ T^{\frac{1}{2}}$, but this law would clearly not hold for high temperatures, because the rate of cooling is no longer proportional to the excess of temperature above that of the surrounding air. For the same material and the same temperature, the law of cooling does not enter the calculation, and we may write $C = ad^{\frac{3}{2}}$, the constant factor a to be determined by experiment, which is the relation found by Mr. Preece. The most important case is when the temperature is the fusing-point of the particular metal, and the values of a for the fusing-point are given by Mr. Preece as follows:—

Material.	a (d given in inches).	a' (d given in Centimetres).
Copper	10,244	2530
Aluminium	7,585	1873
Platinum	5,172	1277
German silver	5,230	1292
Platinoid	4,750	1173
Iron	3,148	777.4
Tin	1,642	405.5
Alloy (lead 2, tin 1)	1,318	325.5
Lead	1,379	340.6

It should be noticed that, for wires of the same diameter, but of different materials, the currents which produce fusion are proportional to the corresponding values of a or a'. The currents which will produce the same rise of temperature in different wires are not in any way deducible from the values of a or a'.

As an example to find the current which will fuse a copper wire of No. 18 S.W.G.

$$C = 10244\ (.048)^{\frac{3}{2}} = 107.73,$$

so that the fusing current is just under 108 ampères.

Mr. Preece's experiments were carried out with wires 6 inches in length. In fine wires, the length, if over the minimum of one inch, will not affect materially the magnitude of the fusing current. With thick wires, however, a considerable modification would have to be made, were it not for the fact that it is convenient to use a longer fuse for large currents. A fuse generally will melt near the centre with a moderate excess of current, showing the effect of heat conduction in cooling the ends of the wire. Care must be taken to ensure good contact at the terminals, for it is a most common event for fuses to melt through the additional heating of a bad contact. Specially constructed fuses, having the ends of the wire soldered to flat contact pieces, are a great convenience, and ensure certainty of action.

Much valuable space might be occupied by a description of the many forms of fuses and fuse boxes designed for safety and convenience, but the whole subject of electrical fittings is too extensive to be included in such a work as this. It may be noted, however, that much convenience arises from the commendable practice of concentrating all the switch and fuse fittings for a floor or section of a building at one accessible point, and the use of a well-designed switchboard to unite them all. This not only enables higher insulation to be obtained, but allows facile inspection of the work at all times. The fuses may be labelled so as to be found immediately, and, moreover, there can be adequate protection without porcelain covers for each fuse, which, in the screw design lately universal, invariably broke after being removed or replaced several times. With this system of small switchboards, joints on branch circuits may be almost, if not entirely avoided. It is generally insisted on by fire insurance companies that fuses should be inserted in each main at points where the main decreases in size and upon each branch conductor. But it is possible to take too many precautions as to safety and needlessly multiply the number of fuses. It must not be forgotten that these safety devices only guard against certain contingencies, and cannot replace the necessity of good workmanship which is the true safeguard. Single-pole fuses upon the minor branches are quite sufficient, provided they be all placed upon branches of the same main; for a large current can only arise from a short circuit, or two faults upon branches from different mains, in which case there is always a fuse to break the circuit. Light single-pole fuses are necessary in every ceiling rose from which a flexible connection to a pendant lamp is taken, and this should generally be upon the opposite branch conductor to that of the fuse which protects the group to which the lamp belongs.

Street Mains.

The first experiments in Electric Power distribution were made with overhead wires, either bare and supported by insulators, after the manner of telegraph wires, or with continuous rubber insulation. This method is only retained in towns under severe restrictions, and except for certain systems of electric traction is practically superseded by the use of underground mains. The various systems of underground distribution are commonly classed under two headings: (1) The "fixed" systems, under which the conductors when once buried are inaccessible for inspection, renewal, addition, or connections, except by re-excavation, which, when the mains are, as is most usual, laid under the pavement of the footpaths, is generally an expensive matter. These systems include those using lead covered or armoured cables, and others such as the Callender "Solid Bitumen" System, where the cables are laid in troughs and additional insulation to that of the cables secured by a filling of solidifying bitumen, run in in a fluid state. (2) The "drawing-in" systems, under which the cables can be more or less conveniently replaced or supplemented without re-excavation.

The latter systems present many advantages, which render them preferable except in special cases, though as a rule they are more expensive at first than the former. A lead or armoured cable can be laid in a very narrow trench, and can be bent with great ease so as to avoid the network of gas, water or other pipes which is to be found under the pavement of cities. Therefore much expense is saved in the excavation and laying of the cables, and the lead covering or iron armouring is less expensive than any known form of conduit.

The most common form of drawing-in system is that in which cables, generally with vulcanised rubber insulation, are drawn into cast-iron pipes previously laid under the pavement. For smaller branch-connections, and where many bends are necessary, it is often cheaper to use wrought-iron pipes. When many conductors have to be carried in the same street, and on the same side of it, it is of great advantage to have several conduits for the sake of drawing-in cables without injury, and when both high and low tension mains are used separate conduits are insisted upon by the Board of Trade. The go-and-return mains must however always lie in the same conduit, or the influence of any change in the current may be felt in neighbouring telephone circuits.

Now, although for a single conduit the ordinary cast-iron pipe, with lead or cement socket joints, can scarcely be improved upon for cheapness and efficiency, the use of multiple conduits has given rise to several methods of construction which are often cheaper and more compact. The "Johnston" system employs iron castings in the shape of double, triple, or multiple troughs, the conduits being of nearly square section, made in lengths of five feet. These are covered continuously by flat covers of the same length, but jointed together alternately with the joints of the troughs. The method of coupling is somewhat intricate, and performed as the conduits are being laid. Continuous joints are made between the troughs and covers with putty, but it cannot be expected that they should be perfectly watertight, nor is this at all necessary when under street pavement, and well-insulated cables used. A great convenience in the system lies in the fact that access can easily be had to the cables at any point, by simply uncoupling and lifting a five-foot cover.

Doulton and Co. have recently introduced a very cheap system of multiple conduits made of earthenware, three-foot lengths being cemented together. This system may be made quite watertight, but the conduits are of somewhat large external section, which may be at times an inconvenience.

The Callender Company construct conduits of bitumen which afford additional insulation in themselves to that of the cables. There are two different systems, one a drawing-in system much used with either rubber or bitumen insulated cables for low tension distribution; but for high tension work the additional insulation of the bitumen could not be considered of any value unless the fixed system is employed.

The fixed system employs initially a trough of cast iron or sound timber supplied in six-foot lengths. As soon as the troughs are placed in position and connected in lengths a small quantity of refined bitumen, in a molten state, is run in, and before setting, spacing bridges of bituminised wood are placed in it, at intervals of 18 inches. The insulated cables are then paid into position, and held in place by these bridges, so that they are clear of the sides and bottom of the trough, and of each other. More bitumen is carefully run in, so that all the space remaining around the cables and between them and the sides is filled solid by it to within half an inch of the top of the trough, and, on its setting, the main is finished off by a covering of Portland cement concrete, about 1 inch thick. In alternating current work, strong cast iron lids are substituted for this concrete. All the bitumen employed is genuine natural Trinidad bitumen, free from admixture of gas-tar or pitch.

For the drawing-in system two modifications are used. In the *Callender Webber* system the conduit is formed by cases or blocks of bituminous concrete made in lengths of 6 feet, and pierced by varying numbers of ways. The standard sizes of these cases are for 2, 3, 4, or 6 of such ways, of either $1\frac{1}{2}$, 2, $2\frac{1}{2}$, or 3 inches in diameter.

The bitumen concrete is composed of natural bitumen, sand, and wood fibre, specially treated. The resulting material is tough and strong, with great power of resistance to crushing, breaking, and tensile strains. It is impervious to water, is not affected by the gas or acids found in the ground, and is a non-conductor of electricity. It does not expand or contract. It is capable of withstanding the weights of heavy traffic. It can be made in any shape, and the cases can, by suitable treatment, be bent on the job. This type of conduit can be easily and rapidly constructed.

The best method of jointing the cases is by bringing them together, placing specially made iron mandrils in each of the ways, running in bituminous concrete between the two, and ramming home by jointing tools. This quickly sets, and the mandrils are withdrawn, leaving a perfect joint as strong as the main itself. Mandrils and jointing tools are supplied with the cases when required.

The ways are quite smooth throughout their entire length, and there is no projection likely to damage the cable whilst being drawn in, especially where mandrils are used in making joints. The cables can be removed at any time, as they do not adhere to the surface of the ways.

The Callender Raworth system combines the great mechanical strength of the solid bitumen system with the facilities for extension of the Callender Webber. It consists of a conduit of cast-iron troughs having flanges suitable for joining the pieces into continuous length. When laid in the trenches, melted bitumen is run in, and spacing bridges are fixed at short intervals. Tubes of specially made paper impregnated with bituminous compound are placed in position, resting on the inverted arcs of the bridges; these tubes are jointed together by sleeve-pieces, and are then completely surrounded by bitumen. The conduit is completed by a cast-iron lid, having flanges fitting over the main trough. A series of ways is thus formed having great mechanical strength and possessing considerable insulating properties, and into these ways the insulated cables are drawn in.

At various points throughout any system of conduits it is necessary that access may be had to the conductors for connections, testing, and generally for drawing in or out. For this purpose the arrangements are manifold, and the generic term "box" is commonly used for any accessible portion of the conduits. Sometimes these boxes are breaks in the line of conduits, built in with brickwork or concrete with a removable iron lid; sometimes specially constructed of iron continuous with the conduits. Where the insulation of the cable is continuous, the boxes need not be made watertight, and the bottom of the box is left open if upon gravel or other porous soil, so that the box and conduits may thus be drained.

Other boxes are made absolutely watertight, the cables entering through glands, and attached to bare terminals resting upon insulators. These bare terminals afford a means of disconnecting rapidly any section for testing, and interconnecting an elaborate network without joints. For better insulation they may be filled with insulating oil or paraffin wax. The design and arrangement of the boxes must vary very greatly with local conditions, and are generally left to the choice of the consulting engineer rather than made an integral part of any of the various conduit systems. The different kinds of boxes may be classed as follows:—(1) *Draw boxes*, inserted about every hundred yards, and at all points where sudden changes in direction of the conduit occurs. The most important quality requisite is that the length of the boxes should be sufficient that the cables may be drawn in or out without great bending, and of sufficient volume that a small amount of "slack" may be left in each box for convenience in connecting, etc. (2) *Service boxes*, small boxes inserted at every party wall for house connections, not necessarily with a removable cover upon the surface of the pavement, as access without a few cubic feet of excavation is not generally requisite. In many systems these boxes are mere "handholes," giving access to the cables by lifting a small cover or trap-door in the conduit. It is important to note that all branch connections should be made by V-joints, and not simply T-joints, so that the joint may be pulled back into the conduit for a few feet in one uniform direction (say towards the generating station). By systematic working in this way the amount of slack necessary in the mains for conveniently making the joints may be much reduced, it being possible to draw the mains backwards and forwards for a short distance in the conduit. House connections are made from the service boxes by armoured cables, or cables drawing through wrought-iron pipes. (3) *Junction* or *network* boxes, for detachable connections made by bare terminals upon insulators. These are of great convenience for testing, separation and rearrangement of circuits, insertion of fuses, etc. In the very elaborate and extensive systems of supply from a central station these junction boxes are now considered a primary necessity. With a never-ceasing supply, day and night, alteration and additions can only be safely made by disconnecting a section in which the jointer may work. Wherever possible the main conductors should be "looped," that every point may be reached by more than one route, and any section temporarily cut out at junction boxes without breaking continuity to more distant points.

To replace vulcanised rubber various less expensive insulating materials are used, of which a few will now be described.

The Callender Company use bitumen, for cables as well as conduits, prepared in two different ways, claiming a greater durability for this mineral substance than for rubber, at least when exposed to damp. The specific insulation is however much lower, necessitating an extra thickness, but even thus the expense is much less than in rubber for equal insulation resistance. The vulcanised bitumen cables are covered with a solid sheath of bitumen, vulcanised and put on under heavy pressure at one operation. It is then taped and compounded, served with jute yarn or heavy tapes, and then braided with hemp yarn, and passed through a bath of asphalte compound, thus providing sufficient mechanical protection to stand the inevitable rough usage whilst being handled on the streets. In other cables bituminised fibre is used, and a solid drawn lead tube put on under great hydraulic pressure. Such a cable may be laid directly in the earth, but when thus used it is preferably protected by a serving of compounded yarn, over which a steel armouring is placed, consisting of two wide tapes or ribbons of mild steel wound spirally one over the other, and finally protected by a double serving of jute yarn, well impregnated with preservative compound.

Nearly all the large low tension systems in London and the provinces have been carried out for the most part with the use of bare copper strip carried on underground insulators for the street mains. This method is no doubt the cheapest possible when the conductors need to be exceedingly large, but in its extensive application two great difficulties have arisen. Firstly, in London and all the large cities of England, there already exists beneath the streets a wonderful maze of gas-pipes, water-pipes, and often telegraph, telephone, and pneumatic tube conduits, so that there is considerable difficulty in finding sufficient space for the large "culverts" required for the bare copper systems. In traversing the congested parts it is therefore frequently necessary to abandon the culvert, and lay armoured cables, or iron or bitumen conduits. The effect is to produce a patchwork of many different systems. Secondly, a number of explosions have recently occurred in connection with these systems, which, although not unknown with the insulated cable systems, are much more difficult to prevent in the large culverts. These have probably been due almost entirely to the leakage of gas through the earth from neighbouring gas mains, and could have been prevented by some effective system of ventilation, but it is certain that the danger is greater in the presence of bare conductors with possible electrolytic action upon damp insulators.

In the *Crompton* system, now abandoned in favour of insulated cables, bare copper strip is carried beneath the surface of the footway in culverts with concrete walls, supported at intervals by glass or porcelain insulators, and maintained under great tension so as to be carried over considerable spans without much sagging between the insulating supports. It is employed by several of the principal West London and Provincial Low-tension Supply Companies, most of them working on the three-wire system of distribution. Three mains are therefore commonly required, but in many parts of the system one or two pairs of *feeder* mains have to be carried, so that five or seven-wire culverts are rendered necessary. In the latter cases the feeder mains are usually carried on the side supports, the distribution mains in the middle.

The minimum excavation in the footway for a three-wire culvert is about 2 ft. 5 in. broad by 1 ft. 10 in. deep; for a five-wire culvert the breadth is 3 ft. 2 in. The walls and floor of the culvert are then built of concrete, six inches thick, leaving an interior channel 17 inches (or 26 inches) wide by 13½ inches deep. The roof of the culvert consists of York flagstones throughout, except that at every alternate party wall, or about every 15 yards, a removable iron cover is placed, at which points the interior is thus rendered easily accessible, and house connections may be made. Under these covers are placed the insulating supports. The culverts are bridged across by stout oak baulks (4 by 3 inches) built into the concrete walls, and upon these are mounted the glass or porcelain insulators. Glass insulators were at first employed for this system, but porcelain insulators carrying a gun-metal fork, in which the copper strip is placed, seem to be preferred. The glass insulators were five inches in height, shaped with five deep grooves in their sides, and painted with hot copal varnish to prevent the creeping of damp, which is the chief cause of low insulation in bare copper systems.

The copper strip is supplied in considerable lengths, having a section of 1 inch by ¼ inch. The requisite number of these strips to give sufficient sectional area for each main are drawn into the culvert, and piled one upon the other in the forks or grooves of the insulators; into which they fit easily with their greater breadth placed horizontally. A tension has now to be applied to the strip so as to reduce the sag to not more than 2½ inches. For this purpose "straining girders" are built into the concrete walls at convenient distances, not more than a hundred yards apart, and at all places where bends in the culvert are necessary. These straining girders consist either of two heavy oak baulks, the one above the other, or of a single cast-iron girder. A gun-metal bridge piece spans vertically between the two oak baulks, or the upper and lower divisions of the cast-iron girder, and presses against them through very strong insulating blocks in such a way as to throw upon them the tensional stress which is to be applied to the strip. This tension is applied by a hydraulic jack, or for short lengths simply by a crowbar lever, and the gun-metal grip screwed down to hold the strip. Two such straining girders are placed a few feet apart, tensional stress applied to the strip in each direction, and the projecting strips clamped together by a gun-metal grip-box.

Occasionally, where the culvert system has to be departed from, on account of the paucity of space available, cast-iron casing of the section illustrated is adopted with insulated cables. The branch connections for house service, etc., are also made with insulated cable by means of specially designed attachments.

The *Kennedy* system, also used by the Westminster Supply Company, is similar to the Crompton save that the necessity of applying tension is done away with by placing insulators every six feet. The culverts are made much shallower (7½ inches internally), and hollow earthenware insulators rest on the bottom of the culverts. As access to each insulator cannot be had when there are so many, special provision has to be made for keeping the strip in the insulator grooves when drawing in. The difficulty is admirably met by the use of a trolley, which can be drawn through the conduit with the copper strip attached. The trolley spans the conduit just under the roof, and runs with wheels supported upon shelves made in the concrete walls when building.

A third variation of the bare copper system is used by the St. James' and Pall Mall Company. This district is unique, an enormous number of lamps being supplied within a very small distance from the generating station, and the load-factor, as may be expected in "Club-land," the highest in the world. Cast-iron culverts, 11 by 7 inches, are used, the troughs being supplied in lengths of three or six feet, and covered continuously with iron lids. The insulators are in the form of porcelain bridges, and the strip, which is of section 2 inches by $\frac{1}{10}$ inch, resting edgeways in the insulators, can be carried across spans between them as great as in the Crompton system without similar tension of the conductors. The district is conveniently supplied by one large ring of mains, fed by six sets of feeder mains at convenient points, with minor branches. The three-wire system is used, the largest conductors consisting of 8 strips, giving a sectional area of 1.6 square inches, the middle wire being one half the sectional area of the other two.

Brooks' system of oil insulation has been used for several years for Electric Lighting mains, more especially in high-tension distribution, with great success. The cables are drawn into iron pipes, and consist of stranded copper conductors covered with raw jute, hemp strand, and braiding, several conductors being generally combined in one cable. The cables thus covered are first heated to about 300° Fahr. in a tank of insulating oil, generally a thick, very viscous compound made of the waste products of rosin oil, which impregnates the fibrous covering, driving out all moisture, and renders the insulation extremely high. The iron pipes are carefully laid so that there may be little or no leakage, and are filled with the same oil, a tank being connected to the conduits and filled to a level above the highest point of the system, so that the oil is under some pressure. Similar systems of insulating cables with fibre impregnated with oil have been largely used for telegraph and telephone communication, but it is also excellently adapted for high tension distribution of power, on account of the valuable property that the fluid insulation is *self-remedied* after the passage of an arc between the cables, or to the pipes, caused by abnormal raising of the electromotive force. Connections are made when the mains are laid by lead-covered cables with junction boxes and connection boxes, the cables entering the pipes through glands, but subsequent access to the mains themselves can only be had after drawing off the oil. On account, therefore, of the comparative inaccessibility of the conductors for branch connection, it is best suited for high tension distribution to sub-stations, with a parallel low-tension network upon some more accessible system.

Further details as to the main conductors and conduits adapted to certain special systems of transmission will be given in conjunction with those systems. The present chapter has included a fairly wide summary of those generally applicable, or at least applicable to the interior wiring or low-tension street distribution, which invariably is the final stage in all systems, except the series system of distribution for public lighting with arc lamps.

Electrical Testing.

The methods of testing the conductivity and insulation of electric light mains, and conductors used in machinery for generation and distribution, will be found in the numerous laboratory text-books covering the subject, and it is only intended here to touch on certain modifications of the methods there described which commend themselves to practical engineers. The aim of the laboratory experimentalist is to produce results of the highest degree of accuracy, with the minimum use of artificial standards for comparison, the time involved in calculations and allowance for errors being of little consequence. The practical engineer demands methods which shall be of sufficient accuracy, but would prefer such as may be rendered direct reading and effected rapidly by unskilled assistants, after the standards and connections have been verified by an expert. For these purposes the Wheatstone Bridge and allied methods, though scientifically perfect with due corrections for certain errors due to connections, etc., are of little value except for the primary calibrations. The engineer, also, lays the greatest on the importance, real or imaginary, of approximating in test conditions to something of the actual conditions of working. The testing of resistance, which is part of the everyday work of the Electric Light engineer, commonly lies at the extreme ends of the scale of magnitude: either the minute resistance of short thick copper conductors, and joints on the same, or high insulation resistance. It is important that the former should be measured by methods involving large currents through the conductors, and the latter with high electromotive forces.

The development to high perfection of the moving-coil or d'Arsonval type of galvanometer has placed in the hands of the engineer an instrument highly convenient for arranging direct reading tests. It has the following advantages over the older form of moving needle galvanometers: constancy of calibration and freedom from external influences; low internal resistance, combined with sensibility; uniformity of scale attainable for large angles of deflection; a complete dead-beatness of action. With reflecting types a constant per readable division of scale of the order of magnitude of one hundreth of a micro-ampère is readily obtainable, with internal resistance of only one hundred ohms; with portable pointer types a constant of about a micro ampère with similar resistance, but uniformity of scaled, can only be depended upon when the fixed magnet is specially designed for the purpose, at the expense of sensibility.

The method of procedure which will commend itself to practical engineers will be to primarily construct four or more resistances, by means of which the same galvanometer may be arranged to read *directly* as ampèremeter and voltmeter of widely varying calibration :

(a) A thick manganin strip with intermediate terminals for galvanometer connections, such that the reading may be directly in ampères.

(b) A fine wire shunt, giving similarly readings directly in micro-ampères (or hundreths of a micro-ampère).

(c) A fine wire coil of the highest possible resistance, such that by

FIG. 1.

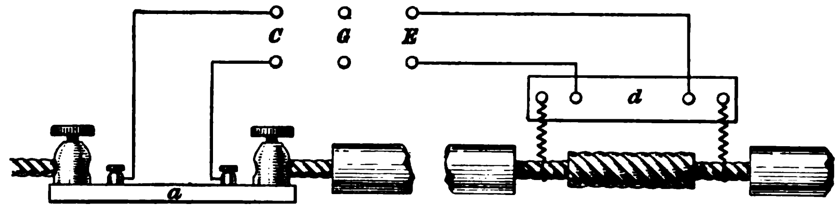


Diagram of connections for conductivity test (a joint).
(C G E, two-pole change-over switch for galvanometer, to read ampères or microvolts.)

FIG. 2.

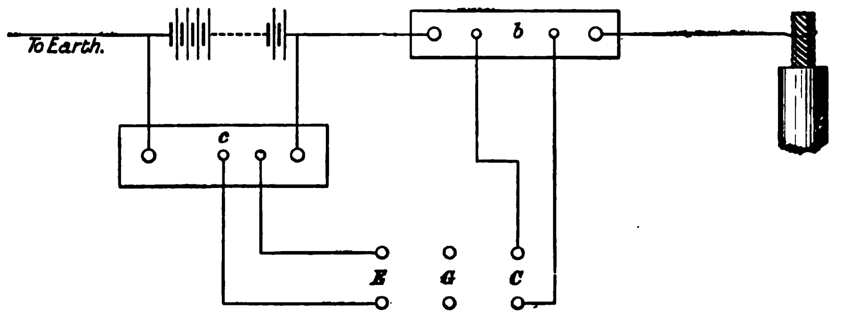


Diagram of connections for insulation resistance.
(E G C, two-pole change-over switch for galvanometer, to read volts or micro-ampères.)

bridging a portion with the galvanometer direct reading in volts may be obtained.

(d) A more moderate resistance, reducing the calibration similarly to microvolts.

The calibration of these resistances is simply effected and easily verified. Once constructed, the measurement of conductivity and insulation resistances is simply a matter of connecting and taking the ratio of pairs of readings, the current and electromotive force or difference of potential, and may be left in the hands of an unskilled assistant. It may be noted that any moderate variation of the constant of the galvanometer will not affect the measurement of the resistance, as the ratio of the two readings remains unaltered, and the methods are free from all errors due to resistances of contact, " Peltier " effects, etc. The exact current and electromotive force employed are separately observed and recorded.

The accompanying diagrams (Figs. 1 and 2) illustrate the methods applied to testing the conductivity of a joint and the insulation of a cable. A large current is supplied by a dynamo or accumulator in the former test, and a high electromotive force by a battery of small cells in the latter; a two-pole two-way switch for connecting the galvanometer to the two resistances used in succession.

A direct-reading ohmmeter, giving the ratio of electromotive force to current, is sometimes used, with a small generator to supply the current or electromotive force. This may also be adapted to high or low measurements, but the method neither ensures the certainty or accuracy of separate readings, nor are the exact conditions of the test specified.

CHAPTER III.

Parallel Distribution.

The Parallel System of distribution of electric power has been compared in the Introduction to the supply of water for a town, with this important modification, that a collection return of the water to the source of supply by an exactly similar or "parallel" system of water mains is arranged for. The lamps are compared to taps permitting small currents of water to pass from the supply to the return main, thus subdividing the main outflow of water from the source according to the section of the opening through the various taps.

The ordinary conditions of water supply, in which the escaping water is not again collected, but allowed to flow into a drain or is removed in some similar way, and new water collected from an unpolluted source, may be compared with a parallel system employing an "earth-return," not unknown in the early days of Electric Lighting, but now considered impracticable and dangerous. The only difference will then be that the water supply of the world may be considered as an inexhaustible reservoir, whereas the electrical capacity of the earth must, for the storage of electricity to supply lighting, be considered practically infinitesimal.

The analogy might be further extended. The flow through any tap is proportional to the sectional area of the opening and to the head of the water at that point on the distributing main; if a charge be made for the water, according to the sectional area of the tap or feed-pipe leading into a house, an equal head of water throughout the system ought to be insisted on, but owing to varying heights of the points of supply, and the reduction of head by friction of the water current in the mains, considerable variation is unavoidable. This question, of comparatively little importance in water supply as compared with that of the purity of the water, is of vital importance in the analogous case of the supply of power by electric currents. For it is the electromotive force or difference of potential between the mains at various points of the system that the accurate subdivision and regulation of the light depends. As the friction of the water in the pipes causes a loss of head at distant points varying with the current flow, so the resistance of the electric conductors causes a fall or reduction of electromotive force at distant points likewise varying with the electric current, and therefore subject to considerable variations as the demand for light alters during the day or night.

Incandescent lamps are almost invariably supplied from a parallel system of electric conductors. This system may be directly connected to a generator, or supplied as a branch from some system of transformation such as will be described later. In either case the lamps require to be so constructed that, in accordance with Ohm's law, the resistance of the filament allows a current to pass through suitable to its surface for radiation of heat and light, when an appropriate difference of potential for which they are designed is maintained between their terminals. The light radiated varies very greatly in reply to comparatively small variations of the current, and a slight excess of current will speedily destroy the filament, so that it is requisite that the variation of electromotive force from that specified should never be more than a small percentage. We have therefore to arrange that a constant electromotive force, or difference of potential, should exist at any point on the parallel system at all times, and, as further regulation save that at points of generation or transformation of electric power seems at present impracticable, the only solution is that of uniform and constant electromotive force at all points throughout the system.

We have already observed that the possibilities of commercial efficiency in any system of distribution depend on making the electromotive force great in order that the current representing a given output of electric power may be correspondingly small. The magnitude of the electromotive force permissible is limited by two considerations. Firstly, that of safety, both to persons and property. The rules of the Board of Trade permit the use of the electric current for lighting of the interior of buildings subject to the restriction that the maximum difference of potential between any two conductors, or between any conductor and earth, shall in no case exceed 250 volts, except with the "express approval" of the Board of Trade. (Rules issued February 1896.) With such pressure an accidental shock can scarcely inflict any serious personal injury, and with reasonable precautions the danger of fire is undeniably less than with any other means of illumination.

Secondly, the magnitude of the electromotive force is limited still further by the demands of lamp construction. The most convenient sizes of lamp for the lighting of the small rooms of dwelling-houses are those of from 8 to 16 candle-power, that is to say the equivalent of the common gas jet, or perhaps somewhat greater. Incandescent lamps of the small size cannot yet be constructed satisfactorily to suit an electromotive force of more than about 120 volts on account of the necessary fineness of the filament. For the lighting of ships, and smaller land installations, where the maximum distance of distribution is so small that the efficiency may be kept high and the cost of mains low without serious difficulty, it has been considered convenient, in order that lamps of low candle-power may be used, to work with electromotive forces of 50 to 70 volts. The more common practice in larger installations, and the secondary circuits of transformer systems (to which the discussions of this chapter apply as well as to those directly supplied from a dynamo), is the use of 100 volts. In others a slight advance on this, to 110 or 115 volts is preferred, partly on account of the additional efficiency, but also with a view to convenience in supplying arc lamps from the same system. Arc lamps requiring 45 to 50 volts and a current of 10 ampères may conveniently be placed two in series between constant potential mains, but for satisfactory regulation a resistance of from one to two ohms must be placed in series with them, rendering necessary an additional 10 to 20 volts.

Quite recently incandescent lamps of from 16 candle-power have been manufactured with two filaments in series contained in the same bulb, each giving 8 candle-power, and thus single lamps of 16 candle-power adapted for an electromotive force of 200 volts can be obtained. Their use has not yet been extensive owing to the present arrangement of the circuits for 100 volts, and the methods hitherto adopted for the direct use of higher electromotive forces has required the partial combination of a series with the parallel arrangement of lamps, in the form of the multiple wire systems to be presently described.

It is still questionable whether any advantage can be gained by employing lamps suited to high electromotive force beyond that at present in common use. The increased fineness of the carbon filament causes greater fragility and a shorter "life," rendering a lower efficiency, or more watts per candle-power, necessary. In short, the question of efficiency in distribution is simply that of the relative lengths and sectional areas of the incandescent lamp filaments and the conducting wires leading to them. By simultaneously reducing the sectional areas of both the same efficiency may be obtained with a lower initial expenditure in the installation, but with a greater annual expenditure in lamp renewals. As the latter expenditure naturally falls on the consumer, and the former mainly on a public Supply Company, the latter having the power of choice are inclined to choose an electromotive force exceeding the golden mean which would give the best results. The two interests are, however, ultimately, if not immediately, identical, and there will be no great difficulty in modifying present systems to suit the electromotive force ultimately found to be most convenient. The improvement in the manufacture of lamps is likely to cause a higher electromotive force to be demanded; but, on the other hand, the value of small lamps in more convenient positions deserves more recognition than it has received in the past, and may encourage a reduction in the electromotive force supplied.

The distribution of electric power by the parallel system, using 100 to 110 volt lamps, is a sufficiently simple matter when the distance between the furthest lamp and the generator is not greater than two or three hundred yards. The points which require attention are:

(1) To reduce as far as possible the waste of power due to resistance in the mains.

(2) To maintain the electromotive force between the terminals of each lamp, as nearly constant as possible, whatever number of lamps may be burning.

The two conditions are intimately associated, but the second is frequently more difficult to secure than the first. If all the lamps be at nearly the same distance from the dynamo, and supplied by the same mains, it is very easy so to vary the difference of potential between the dynamo terminals that a constant difference of potential shall be obtained at the end of the mains, whatever be the output of current. This may be secured in various ways. The dynamo may be "compounded" in such a way that the electromotive force between its terminals is raised by an amount CR, where C is the current and R the resistance of the pair of mains to the lamps, above the electromotive force at no load, which will secure the desired effect. Or a pair of "pilot" wires may be brought back from the extremities of the mains, which, when connected with a voltmeter in the dynamo room, will indicate to an attendant the electromotive force between the terminals of the lamp, and thus guide the hand regulation, effected very simply by a rheostatic resistance in series with the coils of a shunt-wound dynamo. This method of regulation is adopted in many low-tension central stations, but the regulation might, if desired, be made automatic by causing an electromagnet to vary either the cut-off of the engine and thus the speed of the dynamo, or adjust the rheostatic resistance in the same way as the attendant would.

When the lamps have to be supplied from the mains throughout the greater part of their lengths these methods are not sufficient, as, unless the mains are unlimited as to size, it is impossible to maintain a constant potential at more than one point whatever the current in the main may be; the lamps nearer to the dynamo than this point will have a higher, and those from it a lower, electromotive force, the variation increasing with the number of lamps.

The difficulty may be grappled with, if not overcome, by subdividing the mains into a number of pairs of conductors, each supplying a group of lamps. The current density in the conductors supplying the lamps which are near the generator may be kept high, and that in the conductors supplying the most distant lamps as low as possible, so that as nearly as possible a uniform fall of electromotive force may be secured in the mains throughout the whole system. In this case, if the lamps in use at any moment are distributed over the system with a moderate degree of uniformity, a properly compounded dynamo may be made to keep the electromotive force very nearly constant for all the lamps. The objection to this system is that the highest degree of efficiency possible is not secured.

A better method, commonly adopted, is to approximate to uniformity by the following device. Let us assume that the maximum variation in electromotive force permissible is e, so that, E being the correct electromotive force for which the lamps are designed, we can allow a variation from $E-\frac{1}{2}e$ to $E+\frac{1}{2}e$. Six volts is about the greatest that should be allowed on a normal hundred-volt circuit. As then the variation is between 97 and 103 volts, and these represent the extreme limits of variation, which will only be reached by the extreme lamps, and that only for short periods of time in actual practice, it will not be excessive in large private installations, although perhaps somewhat unfair in public supply to a number of different consumers. The Board of Trade rules for public supply only allow a variation of four per cent. at any consumer's terminals from the declared constant pressure. In this case there will be an additional fall along the conductors within the building to be allowed for.

Suppose, now, the dynamo be so regulated or compounded that the electromotive force at no load is E, and when all the lamps are burning is $E+\frac{1}{2}e$ at the nearest lamp, the intermediate mains may be of such size that a fall of pressure e is allowed between the nearest and furthest lamp. The size of the main is frequently made proportional to the maximum current it is intended to carry, so that the fall in pressure is proportional to the distance throughout the whole system. There are, however, advantages in decreasing the current density as the mains become smaller and the more distant points of the area of distribution are approached, so that, without adding greatly to the weight of copper used, the electromotive force may be more uniform throughout.

If we are prepared to submit to the inconvenience of supplying lamps adapted to different electromotive forces for different parts of the system, we may, by a suitable choice of lamps, reduce the variation allowed by one-half. By obtaining lamps for the positions nearest the dynamo adapted to an electromotive force of $E+\frac{1}{4}e$, for the furthest of $E-\frac{1}{4}e$, and a graduated standard throughout, the maximum variation from the standard electromotive force will only be $\frac{1}{4}e$, provided the regulation of the dynamo is perfect.

As a simple example, suppose we have to supply 400 sixty-watt (or nearly sixteen-candle power lamps), each requiring 0.6 ampères at 100 volts, uniformly distributed along the mains, that the branches to the most distant lamps are 300 yards from the dynamo, and suppose, for the sake of simplicity, that the area of the cross-section of the mains is such as to maintain uniform current density throughout. The total length of main is 600 yards, so that a maximum loss of 6 volts corresponds with a loss of one volt per hundred yards, or a current density of 400 ampères per square inch. Then the sectional area of the mains at the dynamo end will be 0.6 square inch, corresponding to about 61/11; its average sectional area about 0.3 square inch, or rather less than 37/12; and the cost of the cable with the standard insulation resistance of 600 megohms per mile will be about £200, or at the rate of 10s. per lamp.

Returning to the question of the efficiency of distribution, assistance in the choice of the size of mains to attain the highest commercial efficiency is given by an economic law propounded by Sir William Thompson (Lord Kelvin). Setting aside the question of regulation, if the cost of the conductor may be taken as proportional to its sectional area (which is nearly, but not quite, the case), the most economical arrangement is secured when the annual interest on the cost and depreciation of the conductor is equal to the cost of the power annually wasted by it. In estimating this, of course the cost of laying the conductor must be left out of consideration, except such small portion as may be proportional to the weight or sectional area. Let us apply this to the case considered above. When all the lamps are burning the loss of power in the mains is 240 × 3 = 720 watts, the *average* drop in electromotive force being 3 volts. When half the lamps are in action, the loss is only one quarter of this, and so on. The average loss will be proportional to the square root of the mean square of the number of lamps running at all hours throughout the year, and this will largely depend on the purpose for which the building is designed. The average time of using the lamps in a provincial town is about 700 hours per annum, but in a city club the average may be twice as great. If the installation considered is a building devoted to the latter purpose, we may reasonably estimate the power lost in the mains as 720,000 watt hours, or 720 units, the calculation being analogous to that used in the chapter on alternating currents. Taking interest at 5 per cent. and depreciation at 10 per cent. on £200 we have £30 per annum, so that the size of mains chosen will be the most economical if 720 units cost £30, which is at the rate of tenpence per unit. This is several times greater than the probable cost of power, so that in this case we are certainly limited rather by considerations of effective regulation than by commercial efficiency, otherwise it would pay to use lighter conductors and waste more power.

If a lower electromotive force than 100 volts were used, the current would have to be increased in the inverse ratio of the electromotive force, in order that the same power might be supplied, and if the limit of percentage variation chosen is to be maintained, the loss in electromotive force must be reduced in proportion to the decrease of the standard electromotive force. The resistance of the conductor must therefore vary directly, and the sectional area inversely, as the square of the standard electromotive force chosen. Hence if 50 volts had been chosen as the standard in the above installation the mains must have been of four times the size. The cost would have been four times as great; the current 480 ampères instead of 240; the difference of electromotive force between the extreme lamps 3 volts instead of 6; and the waste of power would then be the same. On the other hand, if we could use 200 volts as the standard electromotive force (and it will be shown shortly how this is possible with certain qualified conditions with the use of incandescent lamps adapted to an electromotive force of 100 volts), the current would be reduced to one half of that with 100 volts; and the weight of copper to one quarter for the same loss of power in the mains, twice as much fall in potential only representing the same percentage loss, and thus 12 volts being permissible instead of 6.

Network and Feeder Mains.

We have so far dealt with the problem of efficient distribution on the supposition that the power is supplied by mains proceeding directly from the generator to groups of lamps, or by branch circuits from a larger pair of mains. When the lighting is distributed over an area such as that dealt with in central station supply, where the mains have to be laid in streets running in various directions, and branches are taken off at various points into the buildings, the system of conductors generally becomes very elaborate, being advantageously connected together so as to form a network of complete loops, the positive and negative mains (and branches therefrom) being, of course, kept separate throughout, and only connected through the lamps. The current may then proceed to or from any lamp by many different routes, and the calculation of the drop in pressure to any lamp is a complicated matter. Such a network is generally connected to the generator by what are called "feeder mains," to which it is intended that no lamps on branch conductors should be connected, but which carry the current direct to convenient points on the network, preferably to those near which there is a heavy demand. The current density in these feeder mains may be much greater than in the network, being only limited by considerations of safety and efficiency; for the loss of electromotive force in them can be easily compensated for, and thus the potential difference between the mains at the various points of connection maintained uniform. To secure this compensation the large conductors intended for feeder mains are frequently constructed so as to include two pilot wires among the strands of the conductor, insulated from the other strands, and connected to a voltmeter (of the electrostatic, or of the extremely high resistance type) in the generating station. Where bare copper strip is used separate pilot wires must be carried back in the culverts. This voltmeter will give information to the attendant or "switchman" as to the potential difference at the extremity of the feeder. If, owing to a heavy demand in the region of the network near the point of connection, this potential difference is lowered, this pair of feeder mains may, when several dynamos are used, be connected to one having higher electromotive force, or one or more secondary cells may be added to raise the potential difference of that pair of mains alone. The cells used for this purpose may be charged by periodically shifting them to feeders where lower electromotive forces are required, and at the same time reversing their connections. If the network be carefully arranged, and the current density fairly low, approximate uniformity of potential difference is maintained throughout the system if it be kept uniform at the points of connection of the feeders. The feeder mains will generally form radiating branches, interconnected by a network of conductors in the cross streets. There is scope for ingenuity in arranging this network so as to maintain uniformity of electromotive force under all conditions. For example, in a street crossing between the routes of two pairs of feeder mains, the supply mains in them may be taken the positive from one pair of feeder mains, and the negative from the other only. In this case the current from any lamp in the street must necessarily pass the whole length of the street on one main or the other, and if it be arranged that the current density is uniform throughout, and likely to remain approximately so with the varying demand, uniformity in potential difference between the terminals of all lamps will be secured. This device will, however, not produce the highest efficiency possible, especially if the heavier demand is at the extremities of the street. As long as the current is fairly constant in magnitude, varying only as lamps are switched on or off, no appreciable inductive effect should result in neighbouring telephone circuits; but if it should happen that uses of the current other than for lighting cause rapid though minute variations the method described above could not be tolerated.

For the interior wiring of buildings in which the supply of power is obtained from a central station, either as a branch from the street mains, or the secondary circuit of a transforming system, it will be impossible to further compensate for the fall of potential in the interior conductors, except so far as may be effected by increasing the electromotive force over the whole system by one or two volts at the time of maximum demand, and thus giving an average compensation for the fall in the premises of the various consumers. It is necessary to stipulate, for the protection of consumers and the reputation of supply companies, that firms contracting for the wiring should allow for sufficient sizes of conductors that the maximum fall to the furthest lamp should not exceed a certain amount when all the lamps in the installation are in use. For this two volts is generally specified, and the use of a maximum current density of 1000 ampères per square inch throughout will then allow a distance of transmission of forty yards, sufficient for most buildings. For a few isolated lamps in attics, etc., there would of course be no objection to allowing a greater fall of electromotive force. Adopting a uniform current density, the requisite sizes of the leads are easily found from tables supplied by the manufacturers of the cables.

Multiple-Wire Systems.

When the area of distribution extends to distances of more than about a quarter of a mile from the generating station, the devices detailed above will be insufficient to grapple with the difficulties of maintaining simultaneously high efficiency, commercial economy, and uniform potential with the simple parallel system as long as small incandescent lamps cannot be satisfactorily constructed to suit electromotive forces greater than 120 volts. We are still well within the limiting electromotive force made advisable by considerations of safety, and it would therefore be permissible to make use of electromotive forces of upwards of 200 volts, placing lamps suited to 100 volts or more in pairs, connected in series, between the mains, and thus enable us to supply to four times the distance with the same loss of power and variation from uniformity.

This system would be attended with the inconvenience that two lamps must always burn simultaneously, or an equivalent dissipative resistance be inserted in place of one of them. The three-wire system, invented by Dr. John Hopkinson, enables us to avoid this difficulty with large installations, and renders direct supply of electrical power at 200 volts satisfactory to distances at least of upwards of half a mile.

Similar generating plant is employed, the requisite 200 volts being obtained most conveniently by placing two dynamos, each giving 100 volts, in series; sometimes one dynamo having three terminals and a double armature is used to fulfil the same conditions. It is necessary of course that the dynamos should be able to exceed this minimum voltage by 10 per cent. at times of heavy load to allow for the fall of E.M.F. permitted in the mains, being either compounded or hand regulated to maintain the requisite electromotive force in the network.

A third main is taken from the intermediate terminal, and lamps are connected throughout the whole system between the branches from this main and the extreme mains, thus being supplied with the requisite hundred volts. The system is thus like two combined parallel systems with a common main. If the two systems were completely separate they would be like two circuits of a simple parallel system; but the common main, which is the positive main of one system and the negative of the other, carries to or from the generating station only the *difference* of the currents in the two extreme mains, and thus if the two sections of the combined system be carefully arranged that the number of lamps, or rather the power required in each is as nearly as possible the same at full load, and likely to remain approximately the same at different hours of the day or night, the third main need only be very small, and will, in fact, only be used to any extent in carrying the current from a group of lamps in one section to a group in the other. The same current supplies the power for both sections of the system, and is therefore only one half as great as it would be in a two-wire or simple parallel system; and with the same current density in the extreme mains the percentage fall of potential is only half as great, provided the lamps are so arranged that the current traverses very short distances in the intermediate wire, and the corresponding fall can be neglected.

The maintenance of uniformity depends largely on the equality of the demand in the two sections, and is therefore only applicable to extensive systems, where equal *averages* can be depended on. To save great expenditure of copper in the third wire, it is to be recommended that the two sections be combined as closely as possible, branches from all three mains being taken into every building, and the sections as nearly equalised as possible in each. The calculation of the necessary size of the third wire is often an intricate matter. It has been suggested that lamps should be always connected permanently to branches from the intermediate wire, and that it be arranged by means of a two-way switch that the same lamp could be placed on either section. The lamp would always be brightest when placed in the section which contained the fewest lamps, so that equality might be maintained by the natural disposition of a consumer to obtain the better light.

The system of feeder mains and other devices to secure uniformity of electromotive force previously described are equally applicable to the three-wire system. Owing to the cost of the third wire, and additional possibilities of variation in electromotive force due to the switching on or off of groups of lamps, the full theoretical increase in efficiency of this system, that of four times that of the two-wire, is not secured, so that the limit of the economical distance of distribution has been put at between a half and three-quarters of a mile with 100-volt, or one mile with 200-volt lamps.

The power is correctly measured in watts in this system if ampère meters be placed on the external mains, and the sum of their readings be multiplied by 100, or the measure of the electromotive in volts in either section.

For large areas of distribution we may maintain a direct supply for 100-volt lamps without transformation by the use of four or five wire systems, with electromotive forces of 300 and 400 volts. These systems are only extensions of the three-wire principle, having three or four separate sections with intermediate mains to carry the current from lamp to lamp.

Multiple-wire systems will extend the limit of the economical area to distances of a mile to a mile and a half. Further combination of the series principle with the parallel is not permissible for interior lighting, although permissible, with proper precautions, for street lighting. Moreover, with the five-wire system, it is not permissible to take branches from all the mains into the same building, in accordance with the law insisting on a limiting difference of potential of 250 volts; and it is necessary that the middle wire should be "earthed," preferably at the generating station, in order that the potential of the extreme mains should not exceed the required limit.

In these somewhat complicated systems there is considerable difficulty in maintaining approximate equality in the demand in all the sections at all times, and so preserving uniformity in the potential differences without the necessity of large intermediate mains. To compensate for this inequality a machine called the "potential equaliser" has been used with considerable success at Paris and other places. This consists of several dynamo armatures rigidly coupled, or built on the same shaft, each of which is connected across an adjacent pair of mains. These armatures are identical in design, and rotate in magnetic fields of exactly equal intensity. They are of as low resistance as it is possible to construct them, consistent with the generation of the requisite E.M.F. in each to oppose that of the circuits to which they are connected.

If the E.M.F. in each of the sections of the supply system (between adjacent mains) is the same, all the armatures will be motor-driven with very small currents, sufficient power being absorbed to overcome the friction, each giving an E.M.F. equal to that of the section to which it is connected. If the E.M.F. in any section rises, owing to the reduction of the number of lamps in it, a larger current will pass through the corresponding armature of the equaliser, tending to increase the speed. The E.M.F. in the other armatures will then rise, increasing that in the corresponding sections, which had begun to fall owing to the larger current required in them. In other words, the armatures connected to the sections which have a reduced number of lamps become motors driving the remaining armatures, which act as generators. A secondary battery may be made to fulfil the same function as the equaliser, but requires much greater space and more attention. One or the other of these methods for equalisation requires to be adopted when the supply is carried to a great distance, whether by the three-wire or the more elaborate multiple-wire systems.

CHAPTER IV.

Electromagnetism.

The term "dynamo," taken in its most general signification, denotes a machine for the conversion of Power from the mechanical to the electrical form. In other words it is a machine by means of which the uncreatable and indestructible physical quantity which we know as "power," and measure as the product of its two factors of velocity and mechanical force, is transferred to the medium in which electrical phenomena are reproduced, and measured by its two factors of electric current and electromotive force.

Dynamos vary very widely in design according to the relative magnitudes, and other conditions, of the two factors, electric current and electromotive force, whose product represents the power when in the electric form. These conditions are determined by the system of distribution which it is intended to employ for the electric power. We shall have to consider the design of classes of dynamo suited to each system which is described in these pages; and, with the limited space at our disposal, we must confine ourselves very rigidly to such parts of the theory as will have a direct bearing on the efficiency and practical working of the system in question. It will be advisable to give a summary description, limited in scope, but complete as far as it goes, which shall neither intrench on the province of the Scientific Text-book, nor the Technical Hand-book of the Dynamo Designer, appealing rather to the user than the builder of machinery.

A dynamo consists essentially of two parts. Firstly, a magnetic field, produced by permanent magnets or electromagnets; and secondly, an electric circuit, in which an electromotive force and an electric current are produced by its motion relatively to the magnetic field in which it is placed, and which is continuous with an external circuit through which the power is distributed. The latter part of the dynamo is termed the armature.

Electromotive force in the armature is produced either by the motion of the armature in the magnetic field; or by the motion of the magnetic field in which the armature remains stationary; or by the variation of the intensity or arrangement of the magnetic field in the neighbourhood of the armature by the motion of masses of iron. A rotary motion is alone suitable to the ordinary practice of engineering, though a reciprocating motion might conceivably offer some advantages, and has, in fact, been used with good effect for the generation of electromotive forces for certain purposes

FIG. 3.

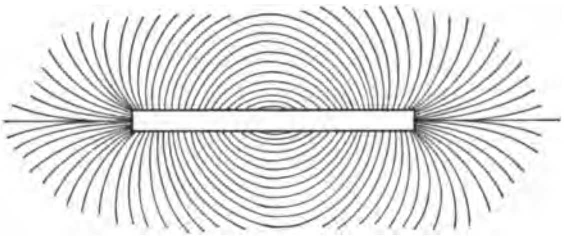
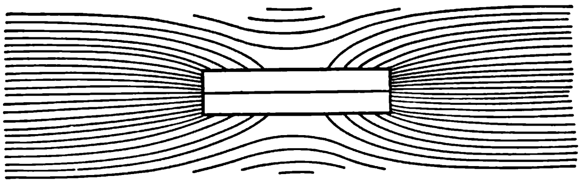


FIG. 4.



outside the scope of this article. For the production of continuous currents the motion of the armature is almost exclusively employed, but for alternating currents each of the other methods present numerous advantages.

Confining ourselves at first to the description of the magnetic field of a dynamo, the theory of which is for the most part the same for all classes of dynamos, we will assume that the reader is fairly well acquainted with the nature of permanent magnets, and with the representation of the magnetic field in its neighbourhood by the graphical method of drawing "lines of force." All elementary text-books deal at some length with the theory of lines of force, as produced by permanent magnets and by coils of wire carrying electric currents, and with the methods of tracing them by scattered iron filings or by a compass-needle; it would serve no good purpose to fill these pages with one more repetition of the same story. It will be sufficient to indicate summarily a few points to be especially remembered, and take up the theory at the point where it is generally left by the text-book on Elementary Magnetism so as to apply the results specially to the magnetic field of the dynamo.

Two typical examples of magnetic fields traced by lines of force are given in the accompanying illustrations. Fig. 3 represents the magnetic field produced by a permanent steel bar magnet in its immediate neighbourhood. Fig. 4 represents a uniform magnetic field (in which the lines are parallel and the magnetic force constant at all points) distorted by the presence of a bar of iron, which is converted into a magnet by being placed in the field. In all cases the lines begin and end in iron or stretch beyond the field represented. Points on the iron towards which the lines of force seem to converge are termed poles; areas of the surface of the iron where streams of lines enter are said to have distributed polarity.

The following facts should be carefully noted:—

(1) Lines of forces due to magnets begin and end at the surface of the iron at points of opposite polarity, "north" and "south." They are no longer traceable within the iron by the methods described. An apparent exception of lines passing away from the limits of the diagram is obviously explained by supposing that they proceed to the magnetic poles of the earth.

(2) Lines of force due to electric currents in wires form closed loops passing round one or more wires.

(3) The magnetic force at any point of the field is in a direction tangential to a line of force passing through that point. All the mechanical forces of attraction and repulsion between magnets or coils in the magnetic field may be at once determined by supposing a tension to exist along the lines of force, and an outward pressure or thrust at right angles to the lines.

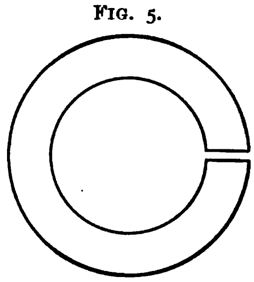
(4) The relative intensity of the magnetic force in different parts of the field is accurately indicated by the relative density of the lines of force in that part, provided that the lines be drawn without discontinuity, and with even distribution wherever the force is uniform. Just in proportion to the spreading out or drawing together of the lines, when conceived drawn in space and not on a flat surface as shown in the illustrations, the magnetic force is correspondingly weaker or stronger.

(5) The magnetic force at any point, *external to iron* or other magnetisable substance, may be represented quantitatively, just as it is direction, by the density or *number of lines of force per square centimetre*. By this we understand that lines are supposed drawn in the direction of the magnetic force at the rate of one per square centimetre when the magnetic force is of unit strength, and more in proportion where the force is greater. The observation (4) made above, which may be mathematically demonstrated, shows that it is possible with continuous lines so to represent the magnetic force at all points of the field. This *number* is a measure of the Magnetic Force, and may be fractional; for the earth's magnetic field in the neighbourhood of London it is somewhat less than one-half. The graphic representation of the field by lines drawn on paper, or imagined drawn in space, has suggested the unit, one "line of force per square centimetre," and some students are inclined to confuse the measurement and the graphic representation so as to find a difficulty in the expression half a line per square centimetre, or to conceive spaces existing between the lines drawn, in which no magnetic force acts. The more thoughtful are well satisfied with a term for the unit which indicates direction as well as magnitude. Faraday's original term, the "unit tube of force," avoids the suggested confusion, and a shorter term, "Gauss," has been suggested for the name of the unit of Magnetic Force, but it is seldom adopted. For the definition of the unit on the centimetre-gram-second system we may refer to scientific works, as the engineer is generally satisfied for his magnetic measurement with secondary standards, and to work with formulæ which we shall give later without mathematical proof.

The part of the magnetic theory which is generally least understood, and frequently misunderstood, is the continuation of the magnetic field into the interior of a piece of magnetised iron. We can suppose the system of lines of force to be continued, though untraceable, into the interior from a pole, or distributed polarity, of one kind, and to emerge at another pole, or distributed polarity, of the other kind. As in any piece of iron the total north and south polarity are equal, we shall find as many lines emerging as entering when the field is correctly mapped out externally to the iron, and so may imagine the continuity to exist through the interior. Lines of force will thus in all cases, with magnets as well as coils of wire carrying electric currents, form closed loops. But it is all-important to notice that in the interior of the iron these continued lines can no longer represent the Magnetic Force. For, when passing from the exterior to the interior of iron, the Magnetic Force due to the polarity is immediately reversed, but the density, or number of lines of force per square centimetre, is not correspondingly reduced, but as a rule rather increased.

We must here make a distinction between the number of lines of force (supposed continued from the external field) which is called the *Magnetic Induction* (and universally denoted by the letter B), and the calculable Magnetic Force due to all poles, both of the piece of iron itself and external magnets, and to coils of wire carrying currents. The measure of the Magnetic Force is denoted by the letter H, and while in non-magnetisable material H = B always, in the interior of iron H is generally very much less than B. Consider, for example, a permanent magnet of the form of an incomplete ring, Fig. 5, a short air-gap intervening between the two poles. The magnetic field between the two poles will be very strong, and lines of force of very great density must be supposed drawn across the gap to represent the field. If these lines be continued into the iron the density will be the same, if not greater, within the iron right round the ring; but the Magnetic Force due to the poles will in reality be very small on the other side of the ring, as the two poles, being close together, will almost neutralise one another. Further, a moment's consideration will show that the Magnetic Force in the iron throughout the whole ring is in the opposite direction to that expressed by continuing the lines of the gap round the ring. Therefore neither in magnitude nor in direction can the continued lines represent the Magnetic Force within the iron. In all magnets the Magnetic Force *due to its own poles* is in opposition to the Magnetic Induction.

FIG. 5.



Iron ring with air-gap.

If we wish to explain the physical meaning of Magnetic Induction within any piece of magnetised iron we may suppose a small cavity made at any point in the shape of a flat disc, having its axis in the direction of the lines of force. If the thickness of this disc is very small in comparison with its diameter, we may suppose the lines of force to pass across it as we have supposed them to pass in the previous example of the ring with small gap, maintaining the same density as in the adjacent iron. The Magnetic Force measured in this disc-shaped gap will be the Magnetic Induction, and will be that produced by all external poles and coils in the neighbourhood combined with the distributed polarity over the flat surfaces of the disc-shaped gap. The latter will generally be much the larger term, so that the Magnetic Induction will be immensely greater than the Magnetic Force, which only includes the former term—the calculable forces of poles and coils in the neighbourhood. If the cavity be of the shape of a long, thin tunnel along the lines of foree, the inner polarity at the ends of the tunnel will be insignificant in effect, and the Magnetic Force in the interior will be correctly measured in such a cavity.

When an unmagnetised piece of iron is placed in a magnetic field, it becomes of itself a magnet. It may or may not have magnetic poles of its own. If it has not, as in the case of a complete iron ring magnetised by the current flowing through a solenoid coil wound upon it, the Magnetic Force, or *Magnetising* Force as it may now be called, is unaltered, and is simply that given by the coil alone. But the iron is strongly magnetised, the strength depending upon the quality of the iron and the strength of the *Magnetising Force.* The effect of this magnetism of the iron could be recognised by the extra strength of the magnetic field in a short air-gap, made by splitting the ring at one point, but the poles thus formed would inevitably weaken the Magnetising Force in the iron of the ring; supposing this weakening allowed for, we see that the Magnetic Force in the gap, which is that above defined as the *Magnetic Induction*, is different from the Magnetising Force due to the coil alone, and may be looked upon as a combined field due to the magnetisation of the iron added to the original field of the coil.

It is possible, however, to recognise and measure the Magnetic Induction without forming an air-gap, and thus modifying the Magnetising Force. Any change in the Magnetic Induction produces electromotive force in another coil wound round the ring during the change, and proportional to the rate of change; this gives an indirect method of measurement which saves calculation of the weakening, or demagnetising force, of the poles formed by splitting the iron ring. The details of this measurement are to be found in any text-book for the electrical laboratory, and reference may be made to the Standard Text-book by Prof. Ewing on "Magnetic Induction in Iron and other Metals." We shall confine ourselves to the statement of the general results, and their application to the iron magnets of electro-magnetic machinery.

The Magnetising Force at the centre of a flat coil, as used in the tangent galvonometer, is deduced at once from the definition of the unit of current and may be written

$$H = \frac{2n\pi C}{10r},$$

where n is the number of turns; C the current in ampères; r the radius of the coil in centimetres. The calculation for other shapes of coil for the Magnetic Force at various points of the field speedily leads to complicated mathematics.

At a distance d from a straight wire of infinite extent the Magnetic Force is given by the formula

$$H = \frac{2C}{10d}.$$

This case is interesting from the fact that the lines of force forms circles round the wire carrying the current, at every point of which the Magnetic Force is the same. If we multiply the Magnetic Force by the length of a circular line of force, $2\pi d$, we get a quantity, $\frac{4\pi}{10}C$, which is independent of the distance from the wire, *i.e.*, the same for any line. This result is a particular case of a general theorem which is of incalculable value, and which we will assume without further proof. If we have any closed circuit whatever, and divide this circuit into a large number of minute lengths, multiply each length by the resolved value of H tangentially to the circuit, and add all the products, the total sum, when a sufficient number of parts is taken that H may be approximately constant throughout any part, is always

$$\frac{4\pi}{10}C,$$

[illegible] through the curve traced. This infinite [illegible] Integral of the Magnetic Force." The [illegible] its expression as $\int H ds$ round the [illegible] elementary dynamics will see that it is [illegible] unit pole carried by the Magnetic Force round [illegible]

[illegible] theorem, easily proved in the general case, lies in [illegible] an approximation of sufficient accuracy for [illegible] employed for electromagnets, giving us the [illegible] point in the interior. If the length be great in [illegible] of the solenoid, the Line Integral of the Magnetic [illegible] line of force from one end through the coil and [illegible] end by an external curve is approximately, Hl, [illegible] the solenoid. For in the internal part of the circuit [illegible] constant throughout; and in the external part, though the [illegible] longer, the value of H is so reduced by the spreading of [illegible] contribution to the Line Integral is but small. We shall [illegible]

$$Hl = \frac{4\pi}{10} nC,$$

[illegible] number of turns, or

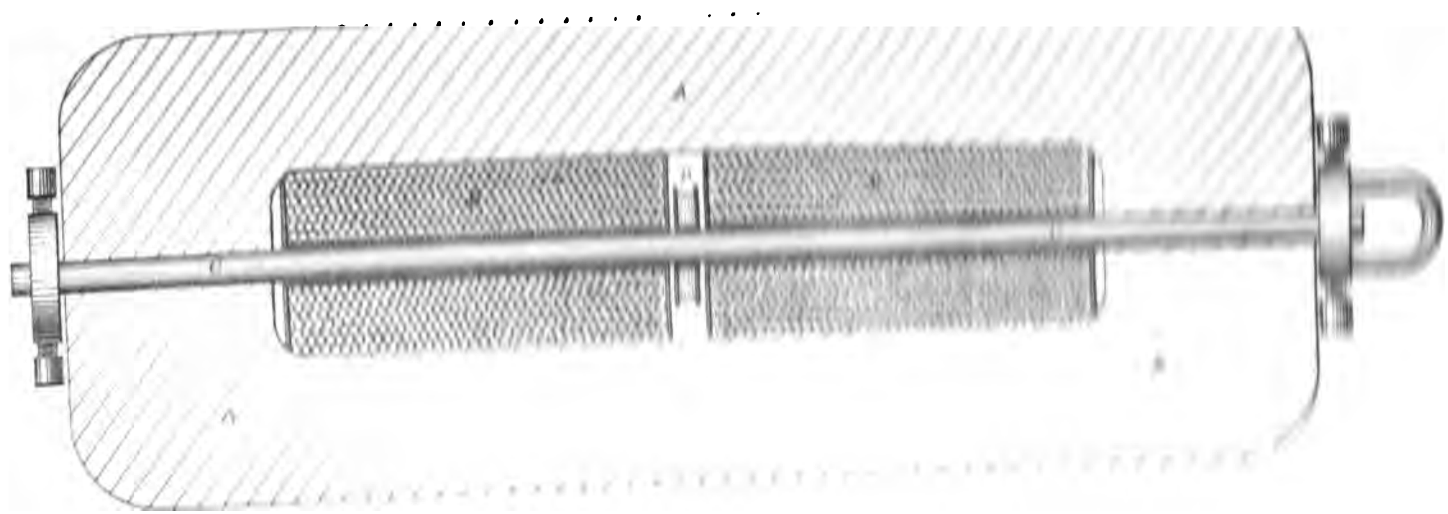
$$H = \frac{4\pi}{10} \cdot \frac{n}{l} \cdot C,$$

[illegible] depending on the *number of ampère-turns per centi-* [illegible] assuming the coil to be very long in comparison with its diameter.

[illegible] still more approximately true when applied to the interior of [illegible] on a ring of non-magnetic material so as to cover the ring with [illegible]

[illegible] complete ring of iron is used as the core of the ring solenoid, or [illegible] long wire is placed within the long solenoid, the Magnetic Force [illegible] (or unappreciably altered except near the ends of the wire), but [illegible] Induction is very much greater. This may be shown by [illegible] the current, which reverses both Magnetic Force and Induction, and produces an instantaneous current in a secondary coil, such as described above, when completed through a Ballistic Galvanometer. The amplitude of the "throw" of the ballistic galvanometer measures the change, in this case the double value of the reversed Magnetic Induction, and is many times greater than that produced in a similar arrangement with non-magnetic core, which is proportional to the Magnetic Force. The ratio of increase is called the "Permeability" of the iron, denoted by the Greek letter μ, so that $B = \mu H$. The Permeability thus measured is found to be independent of the shape, that is to say, the relative diameter and radius of the core ring, as long as the complete magnetic circuit is maintained, or as far as the approximations described will hold. In the case of the long soft iron wire, the error is inappreciable only if the length of the wire is over 400 diameters. To render the formula for H applicable to short bars of iron, Hopkinson adopted a device which is illustrated in Pl. I. The external magnetic circuit is completed by a heavy A yoke of soft wrought iron, into which the ends of the bar to be tested are carefully fitted. The contribution to the Line Integral of the dispersed magnetic field in the yoke is practically negligible, and with a small correction for the ends, the bar may be considered equivalent to a ring of length equal to the length of the bar C within the yoke. B is the Magnetising Solenoid; D the secondary coil in which

Plate I.



where C is the total flow of current through the curve traced. This infinite summation is termed the "Line Integral of the Magnetic Force." The mathematician will at once recognise its expression as $\int H ds$ round the curve; any one acquainted with elementary dynamics will see that it is really the work done upon a unit pole carried by the Magnetic Force round the closed curve.

The importance of this theorem, easily proved in the general case, lies in the fact that it will give us an approximation of sufficient accuracy for solenoid coils such as are employed for electromagnets, giving us the Magnetic Force at any point in the interior. If the length be great in proportion to the diameter of the solenoid, the Line Integral of the Magnetic Force following a line of force from one end through the coil and returning to the same end by an external curve is approximately, Hl, where l is the length of the solenoid. For in the internal part of the circuit H is practically constant throughout; and in the external part, though the circuit is slightly longer, the value of H is so reduced by the spreading of the field that its contribution to the Line Integral is but small. We shall have therefore

$$Hl = \frac{4\pi}{10} nC,$$

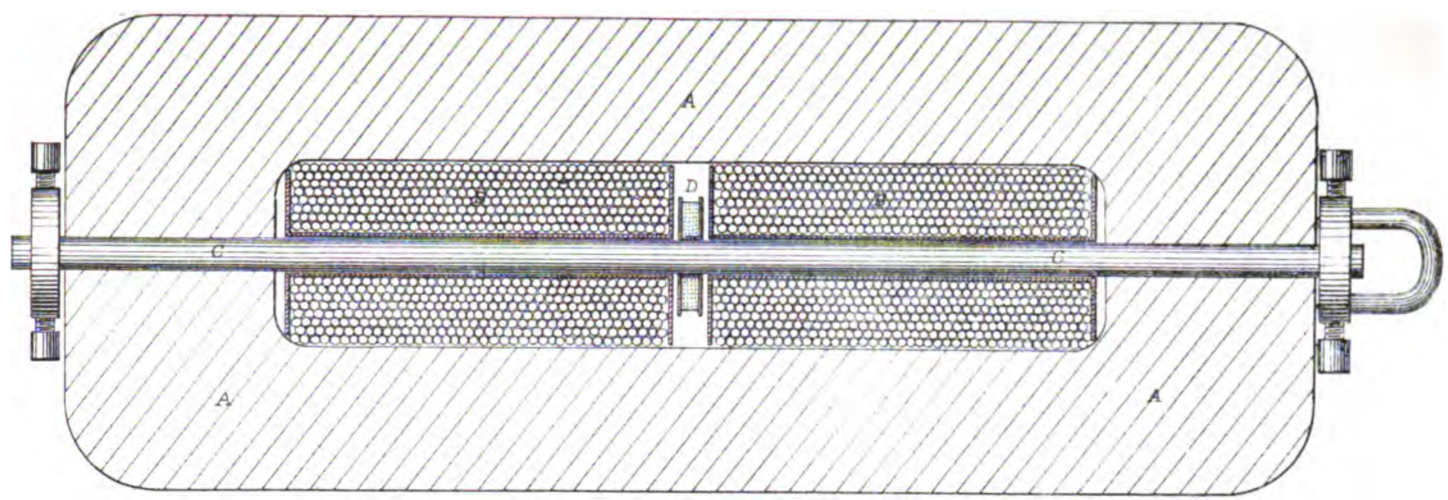
where n is the number of turns, or

$$H = \frac{4\pi}{10} \cdot \frac{n}{l} \cdot C,$$

the force therefore depending on the *number of ampère-turns per centimetre*, $\frac{n}{l}$, assuming the coil to be very long in comparison with its diameter. The formula is still more approximately true when applied to the interior of a coil wound on a ring of non-magnetic material so as to cover the ring with fair uniformity.

When a complete ring of iron is used as the core of the ring solenoid, or when a very long wire is placed within the long solenoid, the Magnetic Force is unaltered (or unappreciably altered except near the ends of the wire), but the Magnetic Induction is very much greater. This may be shown by reversal of the current, which reverses both Magnetic Force and Induction, and produces an instantaneous current in a secondary coil, such as described above, when completed through a Ballistic Galvanometer. The amplitude of the "throw" of the ballistic galvanometer measures the change, in this case the double value of the reversed Magnetic Induction, and is many times greater than that produced in a similar arrangement with non-magnetic core, which is proportional to the Magnetic Force. The ratio of increase is called the "Permeability" of the iron, denoted by the Greek letter μ, so that $B = \mu H$. The Permeability thus measured is found to be independent of the shape, that is to say, the relative diameter and radius of the core ring, as long as the complete magnetic circuit is maintained, or as far as the approximations described will hold. In the case of the long soft iron wire, the error is inappreciable only if the length of the wire is over 400 diameters. To render the formula for H applicable to short bars of iron, Hopkinson adopted a device which is illustrated in Pl. I. The external magnetic circuit is completed by a heavy A yoke of soft wrought iron, into which the ends of the bar to be tested are carefully fitted. The contribution to the Line Integral of the dispersed magnetic field in the yoke is practically negligible, and with a small correction for the ends, the bar may be considered equivalent to a ring of length equal to the length of the bar C within the yoke. B is the Magnetising Solenoid; D the secondary coil in which

Plate I.



West, Newman, lith.

the instantaneous currents produced by reversal measure the Magnetic Induction.

The Permeability of iron is not, however, a constant quantity, even for any given sample of iron. Tested by the reversal method just indicated it is found to increase at first with the Magnetising Force, so that the Magnetic Induction increases at a greater rate than the Magnetising Force. The Permeability reaches a maximum value, somewhat over 2000 for soft wrought iron, and subsequently decreases, the ultimate limit being probably unity. In very intense magnetic fields it appears, according to experiments detailed by Professor Ewing in his standard work, that the difference $B - H$, the excess field due to the magnetisation of the iron, advances to a final limit. In the purest iron this limit is the greatest and amounts to about 22,000.

If the magnetising coil could be removed, the magnetic condition of the iron remaining intact, the density of the lines of force would be $B - H$. The Magnetic Induction may, in fact, be considered as the total strength of two fields, the Magnetic Force added to the magnetic field created by the iron itself. At any point where the lines of force emerge from the iron the strength of the polarity per square centimetre in c.g.s. units may be shown to be $\frac{B - H}{4\pi}$, which is termed the Magnetisation and generally denoted by the symbol $\mathbf{I}$. For if these lines of force be allowed to spread out equally in all directions from the end of a long wire (so as to be unaffected by neighbouring poles) the density at a distance r from the end will be obtained by dividing the total number, $4\pi\mathbf{I}$ if the section of the iron be one square centimetre, by $4\pi r^2$ the area of the surface of the sphere. This gives $\frac{\mathbf{I}}{r^2}$, so that $\mathbf{I}$ is a measure of the polar strength per square centimetre. The maximum value of $\mathbf{I}$ for the purest samples of iron is about 1750.

We have so far been able to avoid consideration of the reactionary effect of the Magnetic Force due to polarity of the iron magnetised by employing the complete magnetic circuit of the ring or Hopkinson's Yoke, or the very long wire. In the dynamo the magnetic circuit in iron must unavoidably be broken for the insertion of the armature, and, however short the air-gap, a weakening of the Magnetic Force within the iron, and a strengthening in the air-gap between the poles must ensue.

Consider for a moment the case where the gap is extremely short compared with the section of the ring, so that the spreading of the lines of force on the edges of the gap may be of little consequence, and the Magnetic Induction may be taken as uniform throughout the whole circuit. In the air-gap the Magnetic Induction and Magnetic Force are equal, the latter being immensely increased by the proximity of the poles on either side. On entering the iron the Magnetic Force due to the poles is reversed, the attraction of the nearer being in opposition to the Magnetic Force of the coils; and on the whole the Magnetic Force is in the same direction as before, but inversely reduced so that, with the same Magnetic Induction as in the gap, the equation $B = \mu H$ still remains. Though it is hard to measure the reduced value of the Magnetic Force, it may be confidently assumed that the relation to the Magnetic Induction is the same as would be given by a test of the sample where the value of the Magnetic Force is given by the measurable effect of a coil carrying an electric current.

But although the Magnetic Force is increased in one part of the circuit and decreased in another, the Line Integral through the complete magnetic circle is unaltered, and equal to $\frac{4\pi}{10}nC$, as before. It is sufficient to observe that the Line Integral in any closed circuit is really the work done on a Unit Pole in traversing the circuit, and that it would be in defiance of the principle of the Conservation of Energy to suppose that fixed magnets could supply continuously energy to a moving pole, as would be the case if the Line Integral for a closed curve were in any way altered. Dividing the Line Integral into two parts, for the air-gap and iron ring respectively, calling the lengths l_1 and l_2, and the value of the Magnetic force H_1, H_2, that of B being the same throughout, we have

$$H_1 = B \qquad H_2 = \frac{B}{\mu},$$

and the Line Integral equation

$$H_1 l_1 + H_2 l_2 = \frac{4\pi}{10} nC$$

becomes

$$B\left\{l_1 + \frac{l_2}{\mu}\right\} = \frac{4\pi}{10} nC.$$

It will be noticed that, for a sample of wrought iron in which the permeability is 2000, an air-gap of $\frac{1}{2000}$ of the length of the ring core is sufficient to call for twice the strength of magnetising current in order to produce the same Magnetic Induction as was required for the complete iron ring.

The most general case, or at least the most complicated that is amenable to mathematical calculation, of a magnetic field is one in which the magnetic circuit consists of magnetic materials of various qualities and sectional area, broken here and there by air-gaps of various breadth. It must be assumed that the lines of force are kept very approximately within a prescribed area, where we can make an average estimate of the length traversed in the various materials. The magnetic circuit of the dynamo, for example, will include the "limbs" upon which the magnetising coils are wound, an iron ring and cylinder upon which the armature is wound, air-gaps, pole-pieces, and a "yoke" or bed-plate. It will generally happen that a certain amount of leakage, or wandering of the lines of force outside the prescribed area, will occur, and the method by which an approximate allowance is made for this leakage will be described later. Dealing at present with the ideal case, we may assume a certain total number of lines of force to traverse the whole magnetic circuit. This total number is a measure of the whole strength of the electromagnet; it is termed the "Flux of Magnetic Induction," and will be denoted here by the letter N.

In any part of the magnetic circuit where the sectional area, taken over a place perpendicular to the direction of the lines of force, is A square centimetres, we shall have

$$B = \frac{N}{A}.$$

If the lines of force may be considered to traverse with this density a length l of uniform section in a material of permeability μ, the contribution of this part of the magnetic circuit to the Line Integral will be given by

$$H.l = N.\frac{l}{A\mu}.$$

Supposing N to persist uniformly throughout the whole circuit we shall then have, on addition to the Line Integral for all parts,

$$N\left(\frac{l_1}{A_1\mu_1} + \frac{l_2}{A_2\mu_2} + \text{etc.}\right) = \frac{4\pi}{10} nC.$$

On the right hand side of the equation the quantity nC is supposed to represent the total number of ampère-turns in all coils wound round the magnetic circuit; the position and arrangement of such coils is of no moment, except in so far as it affects the leakage of the lines of force. The above equation gives a means of determining N from the known measurements and magnetic properties of the materials employed for the electromagnet for any number of ampère-turns in the magnetising coils. Unfortunately the variable value of the permeability according to the Magnetic Induction in the various parts complicates the problem. It will be shown that a graphic solution is possible; but this is not absolutely necessary to the dynamo designer, who will more frequently have to deal with the inverse problem, which is simpler, to determine the number of ampère-turns required to produce a given Flux of Magnetic Induction. Each part of the Line Integral may then be taken separately; the requisite Magnetic Force in each part of the circuit being determined from tests of samples of the materials used.

The equation giving the Flux of Magnetic Induction in a magnetic circuit affords a very striking and instructive analogy to Ohm's Law, giving the current in an electric circuit

$$C \times R = E.$$

Comparing the Flux with the electric current, the quantity $\frac{4\pi}{10}nC$ creating the magnetic field may be termed the *Magneto-motive force* in analogy to the term Electromotive force. The sum of the values $\frac{l}{A\mu}$ is exactly analogous to the summation of the resistance of the different parts of an electric circuit, if only the permeability be compared with the electric conductivity of materials employed. The summation of $\frac{l}{A\mu}$ might be termed the Magnetic Resistance of the circuit, but the single word *Reluctance* has been generally adopted to avoid confusion. The word is simply a convenience, and it will serve us well in general discussions concerning the magnetic circuit, but it must always be remembered that its value depends upon the intensity of magnetisation of the iron, and the true relation between the Magneto-motive Force and the Flux of Magnetic Induction can only be represented by a curve.

We have defined the permeability of a sample of iron as the ratio of the Magnetic Induction to the Magnetising Force producing it, noting that this ratio is not a constant quantity, but that it depends upon the intensity of the Magnetising Force. The permeability is also found to be modified by the previous magnetic history of the iron, that is to say, whether brought into its present state by an increase or a reduction of the Magnetising Force. In applying the formulæ already given to the magnetic circuit of a dynamo, it is sufficiently accurate to employ such a value for the permeability as is given by tests involving a reversal of magnetism, or magnetisation from an initially neutral state; for, with the constant vibration to which the field magnets of a dynamo is subject, the effect of previous condition is neutralised, and the state attained is very nearly that given by the reversing tests of the ballistic method.

For the sake of certain calculations with respect to the dynamo and other electro-magnetic machinery, it is necessary to state briefly the conditions which effect the relation between Magnetic Induction and Magnetising Force. On applying the Magnetising Force the permeability at first increases to a maximum and subsequently diminishes; on gradually removing the Magnetic Force the Magnetising Induction decreases very slowly, and on complete removal a certain proportion of the Magnetisation remains. This is termed the "Residual," generally expressed by a percentage of the maximum. It depends mainly upon the purity of iron, and is therefore greatest in wrought iron, least in cast iron, containing a large proportion of carbon and other impurities. The corresponding quality is termed "retentiveness" or "retentivity," but it must be carefully noted that this quality must be measured under conditions where there is no cause to remove the magnetism. The specimen must be of the complete ring form, as the slightest magnetic polarity causes a demagnetising force which very greatly reduces the residual magnetism in wrought iron. Mechanical vibration and eddy currents due to sudden decrease of the magnetism from the maximum have a similar effect.

The quality which may be called "permanentness" of a specimen, since it represents its suitability for the construction of permanent magnets, is quite different. This quality is best measured by the reversed Magnetising Force required to first reduce the specimen to a neutral state. The term "Coercive Force" applied to the measure of this Demagnetising force has generally been adopted.

On increasing the Magnetising Force in the reverse direction to that used for first magnetisation, the permeability at first assumes somewhat smaller values than it did in the first magnetisation from the neutral state. The difference gradually reduces till a little beyond the maximum value, when the iron is said to be "saturated," the difference is practically negligible.

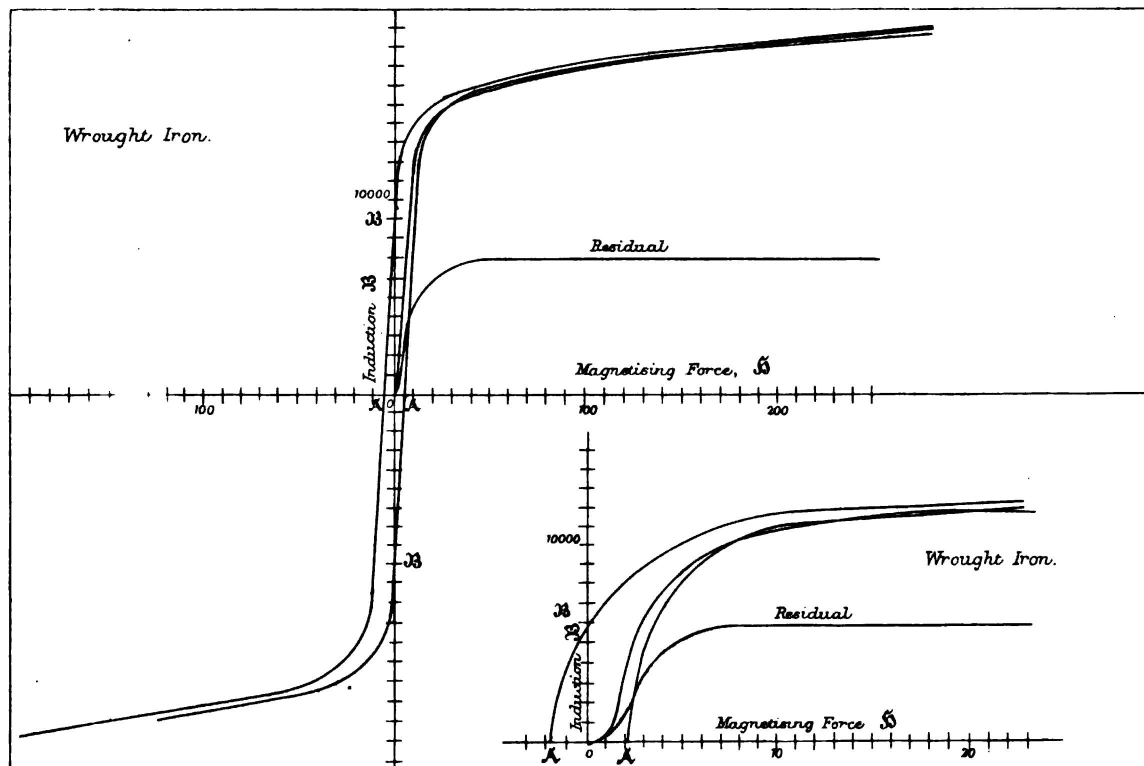
The following table will give a summary of the relative magnetic qualities of several classes of iron and steel, when the Magnetising Force has been raised to the high value of 240 c.g.s. units.

	Magnetic Induction. B.	Residual Magnetic Induction.	Coercive Force.
Wrought iron annealed	18,251	7,248	2.30
Grey cast iron	10,783	3,928	3.80
Malleable cast iron	12,408	7,479	8.80
Whitworth mild steel (annealed)	18,936	9,840	6.73
Whitworth mild steel (oil hardened)	18,796	11,040	11.00
Tungsten steel	14,480	6,818	51.20
Manganese steel	310	—	—

It will be seen from these results (due to Dr. John Hopkinson) that very great differences exist, especially in the coercive force. It is clear that the impurities of the carbon in grey cast iron considerably reduces both the saturation limit of the Magnetic Induction and the residual Magnetisation. The purer forms of steel, although of much less permeability with low Magnetising Forces, approach the same saturation limit as wrought iron, and the residual magnetism, when satisfactorily measured, is about the same. The coercive force of steel, however, is much greater than that of either wrought or cast iron, and is increased by hardening, and also by the addition of tungsten. On the other hand, alloys of steel with manganese tend to become almost entirely non-magnetic. One specimen, containing 12 per cent. of manganese and 1 per cent. of carbon, had a permeability of 1.3 to 1.5, varying very little with the strength of the field. An alloy of steel containing 25 per cent. of nickel, which is also a magnetic metal, had

' & E Hopkinson.

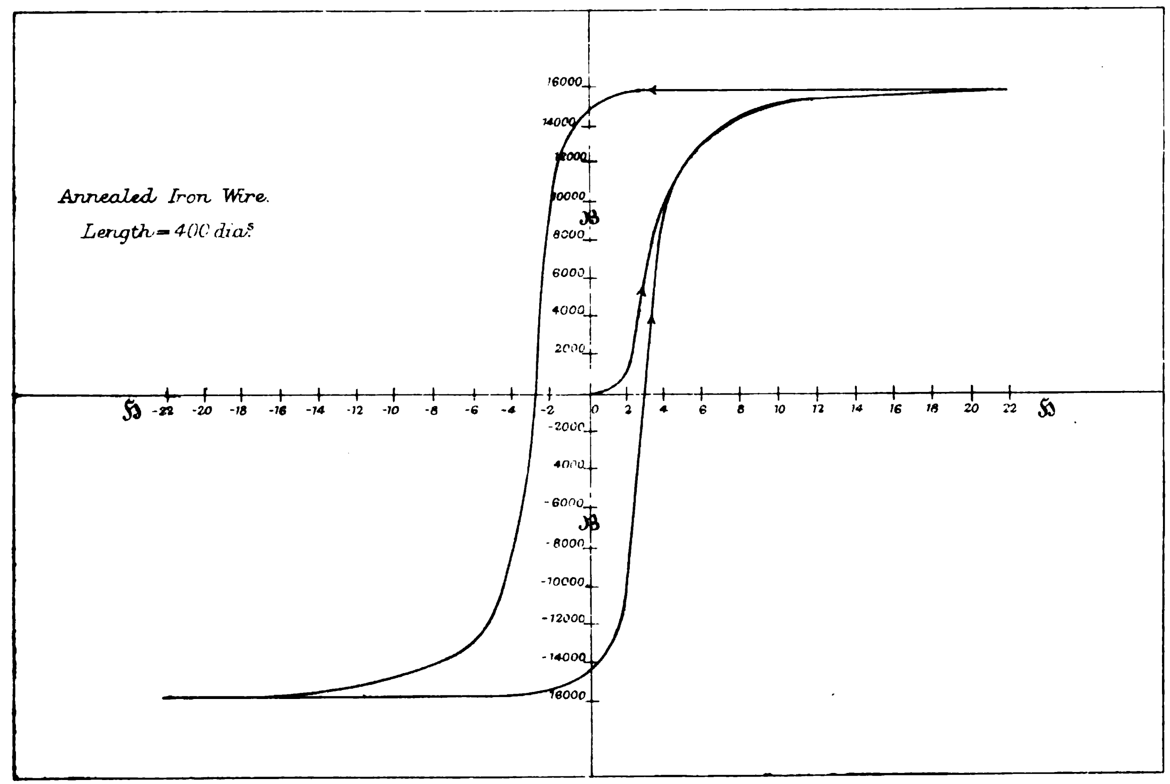
Plate II.



West, Newman, lith

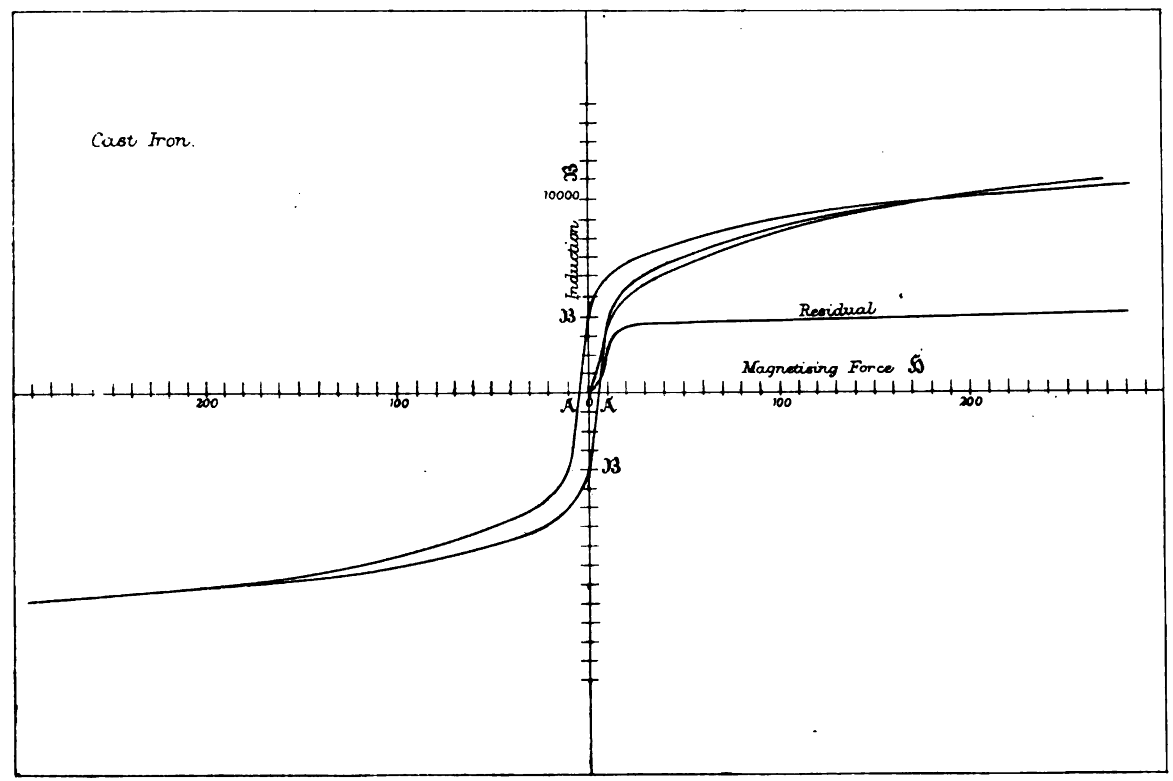
J. & E. Hopkinson.

Plate III.



West, Newman, lith.

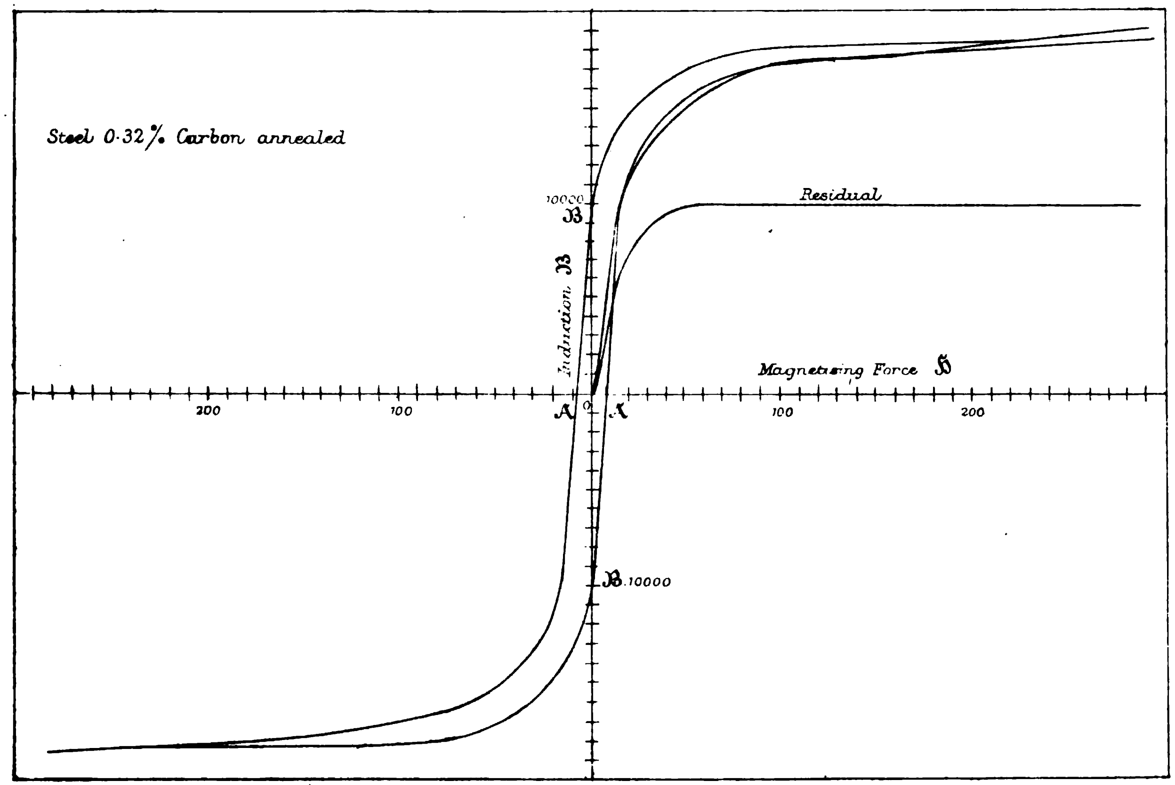
Plate IV.



West, Newman, lith

J. & E. Hopkinson.

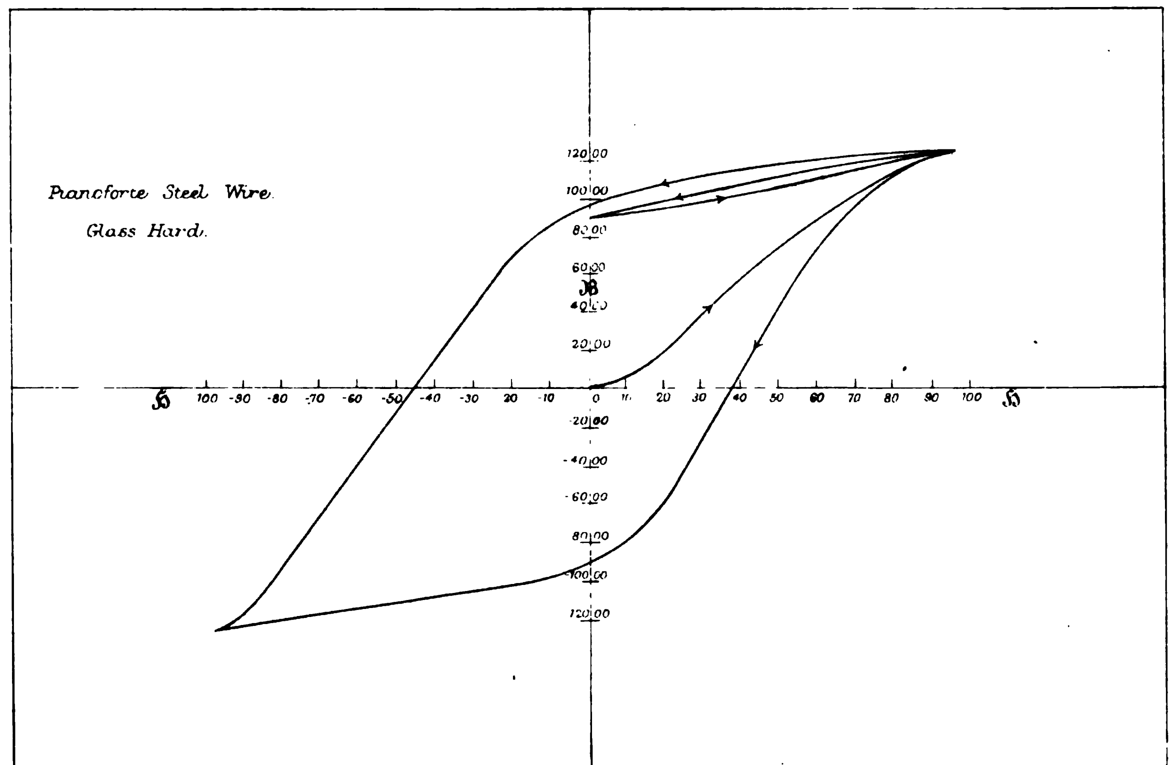
Plate V



West, Newman, lith.

J & E. Hopkinson.

Plate VII



West, Newman, lith.

magnetic properties similar to those of manganese steel, the permeability being constant and equal to 1.4. When cooled below freezing-point, however, this alloy became strongly magnetic, and remained so on returning to the ordinary temperature.

Plates II., III., IV., V., VI., VII., are the cyclic curves of Magnetic Induction given by Dr. Hopkinson for various specimens of iron and steel from which the measures of Retentiveness and Coercive Force were taken. The curves marked "residual," gives the amount of residual magnetism (by its ordinates) corresponding to a maximum Induction represented by the corresponding ordinates of the rising branch of the curve of Magnetic Induction.

A magnetised piece of iron possesses, in virtue of its magnetisation, a certain quantity of potential energy; this is shown by the fact that when the Magnetising Force is removed, the decrease in the Magnetisation can generate currents of electricity in surrounding conductors, these representing the expenditure of energy.

When a specimen is made to pass through a complete cycle of magnetisation, energy is alternately supplied to the system in magnetisation, and removed in demagnetisation. In accordance with the principle of conservation of energy, all the energy applied to the system must be capable of being subsequently traced, either still in the form of potential kinetic energy, or in the degenerated form of heat. Now, part of this energy supplied is removed from the iron and dissipated by currents in the magnetising coil or other conductors, but part goes to heat the iron itself by some process which cannot be explained until we know something of the nature of magnetism. At present we must consider this process as akin to some kind of molecular friction to which the name *Hysteresis* has been given.

The following investigation will show what is the excess of energy supplied to the iron over that removed from it during a complete cycle of magnetisation.

To avoid the mathematical difficulties of the general problem let us take the case of a uniform magnetic circuit of length l, and cross section σ, as we have it in an iron ring. On this ring, suppose a magnetising coil of n turns, the the current being C absolute units.

Then

$$H = \frac{4\pi n C}{l}$$

As the Magnetic Induction is increased, a back electromotive force is produced in the magnetising coil of $n\sigma\frac{dB}{dt}$ absolute units, requiring an expenditure of an additional power of $n\sigma\frac{dB}{dt}$. C to maintain the current. This represents the power delivered to the magnetic field. When the Magnetic Induction is decreasing, and $\frac{dB}{dt}$ of the opposite sign to C, power is being returned to the magnetising coil, an electromotive force being required from the generator to maintain the current, smaller by $n\sigma\frac{dB}{dt}$ than that determined by the resistance of the coil.

The total energy absorbed by the magnetic field is therefore

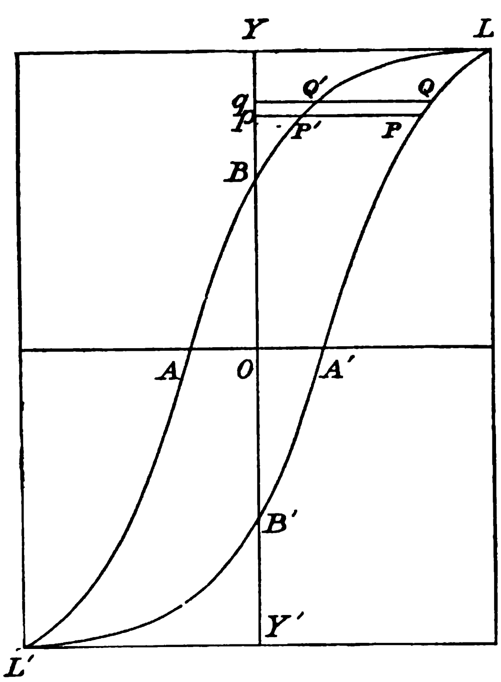
$$n\sigma\int C\frac{dB}{dt}dt = n\sigma\int CdB = \frac{1}{4\pi} . l.\sigma.\int HdB \text{ ergs.}$$

Now, $l.\sigma$ is the volume of the iron; and $\int$HdB, in a complete cycle, is the area of the Magnetic Induction curve. Thus we may write that the energy dissipated in a complete cycle, per cubic centimetre of iron, is

$\frac{1}{4\pi}$ × area of the *Magnetic Induction* curve.

The proof given above with the notation of the calculus might be rendered more simple and lucid by the substitution of a graphical construction as shown in Fig. 6. The closed curve *LBAL'B'A* represents a complete cycle of magnetic induction. The area *QPpq* may be shown to

FIG. 6.



Hysteresis Curve.

be proportional to the work done in increasing the Magnetic Induction from the valve *Op* to *Oq*, the coefficient $\frac{1}{4\pi}l\sigma$, as before shown, being necessary to give the measure of the work done in ergs. The energy returned in the process of demagnetisation through the same range is similarly represented by the area *P'Q'pq*, and the difference, the area *PQQ'P'*, represents the energy dissipated in Hysteresis. This area is an element of the closed curve, and the sum of all such elements, or the whole area of the closed curve, represents the energy dissipated in a complete cycle, the coefficient $\frac{1}{4\pi}$ giving the measure in ergs per cubic centimetre of iron.

The result obtained is equally applicable *at any point* of an irregularly magnetised mass of iron. For hysteresis exhibits itself in the heating of the iron, and the heat thus generated at any point of the iron can only depend on the magnetic qualities of the iron and the range of Magnetisation. The complete curves are exactly analogous to the indicator diagrams of engines, the area, multiplied by a certain constant, giving the energy that must be expended to produce the complete cycle of magnetisation.

The expenditure of energy depends on the variation between the values of the Magnetic Induction when the Magnetising Force is increasing or decreasing. If there is no iron in the field B = H, the Magnetic Induction is always single-valued in terms of the Magnetising Force, the curve is reduced to a straight line, and all the potential energy supplied to the field is returned.

When there is iron in the field the Magnetic Induction has two values for any given Magnetising Force, just as in the steam engine the pressure has two values for any given volume, and Hysteresis, or expenditure of energy takes place. It will be seen that in the different classes of iron and steel the Hysteresis depends mainly on two factors, namely, the limits of the Magnetic Induction (or Magnetisation), and the Coercive Force, for the curves, in all cases, are very similar in shape, and may be made approximately identical by choosing different scales for H. It will be observed, moreover, that the horizontal breadth of the curve is very approximately the same throughout, so that the area may be taken as that of a rectangle of the same height and breadth. Thus the Hysteresis is very nearly in ergs per cubic centimetre,

$$\frac{\text{Coercive Force} \times \text{Maximum Induction}}{\pi}$$

The multiplier 0.00971 (or rather less than $\frac{1}{100}$) reduces this to foot-pounds per ton of iron.

In passing through a complete cycle, in which the Magnetic Induction is carried above saturation point, the Hysteresis in different specimens will depend chiefly on the Coercive Force, and will be approximately proportional thereto. Dr. Hopkinson has conducted experiments on a number of standard specimens to determine the Hysteresis from the measured area of the curves It appears that in wrought iron the work done per cubic centimetre in producing a complete cycle of strong magnetism varies from 10,000 to 17,000 ergs; in carefully annealed wrought iron plates it should not exceed 13,000 ergs.

In one sample of soft grey cast-iron an expenditure of only 13,000 ergs was thus measured, but the usual qualities gave 30,000 to 40,000 ergs. Whitworth mild steel, well annealed, gave from 40,000 ergs; hardened, from 60,000 to 100,000 ergs; pianoforte steel wire gave 116,000 to 117,000; whilst a specimen of tungsten steel gave as much as 216,800. In these measurements the Magnetic Induction was raised to saturation, that is, to about B = 15,000. The importance of using the softest annealed iron in those portions of electro-magnetic machinery which are subject to constant reversals of magnetism is evident; a still more important question for investigation is the variation of the hysteresis-loss of energy with the magnitude of the maximum value of B, since this will greatly affect the design of such machinery.

The following table gives approximately the number of ergs dissipated per cubic centimetre per cycle in the magnetisation of very soft iron for maximum values of B given in the first column.

B.			Ergs per c.c. per cycle.
1,000	...	...	206
2,000	...	...	466
3,000	...	...	830
4,000	...	...	1,240
5,000	...	...	1,712
6,000	...	...	2,256

B.			Ergs per c.c. per cycle.
7,000	...	...	2,842
8.000	...	...	3,464
9,000	...	...	4,162
10,000	...	...	4,937
11,000	...	...	5,710
12,000	...	...	6,675
13,000	...	...	7,600
14,000	...	...	8,596
15,000	...	...	9,560
16,000	...	...	10,630
17,000	...	...	11,750
18,000	...	...	12,940
19,000	...	...	14,250
20,000	...	...	15,500

These measurements are exhibited graphically in Plate VIII., taken from the original paper of Dr. J. Hopkinson (*Phil. Trans.* 1885). It will be seen that the number of ergs dissipated increases with the maximum induction, but at a higher rate; for values of B between 2000 and 5000 the variation is almost exactly proportional to $B^{1.4}$; and for values of B between 5000 and 10,000 to $B^{1.5}$. Prof. Ewing gives, as the result of further investigations, the following approximations covering a wider range:

From B = 200 to 500	Hysteresis-loss varies as $B^{1.9}$
From B = 500 to 1000	" varies as $B^{1.68}$
From B = 1000 to 2000	" varies as $B^{1.55}$
From B = 2000 to 8000	" varies as $B^{1.475}$
From B = 8000 to 14,000	" varies as $B^{1.7}$.

Thus the rate of variation is that of a power of B which varies from 2 to 1.47 (or as above to 1.4) and back to 2.

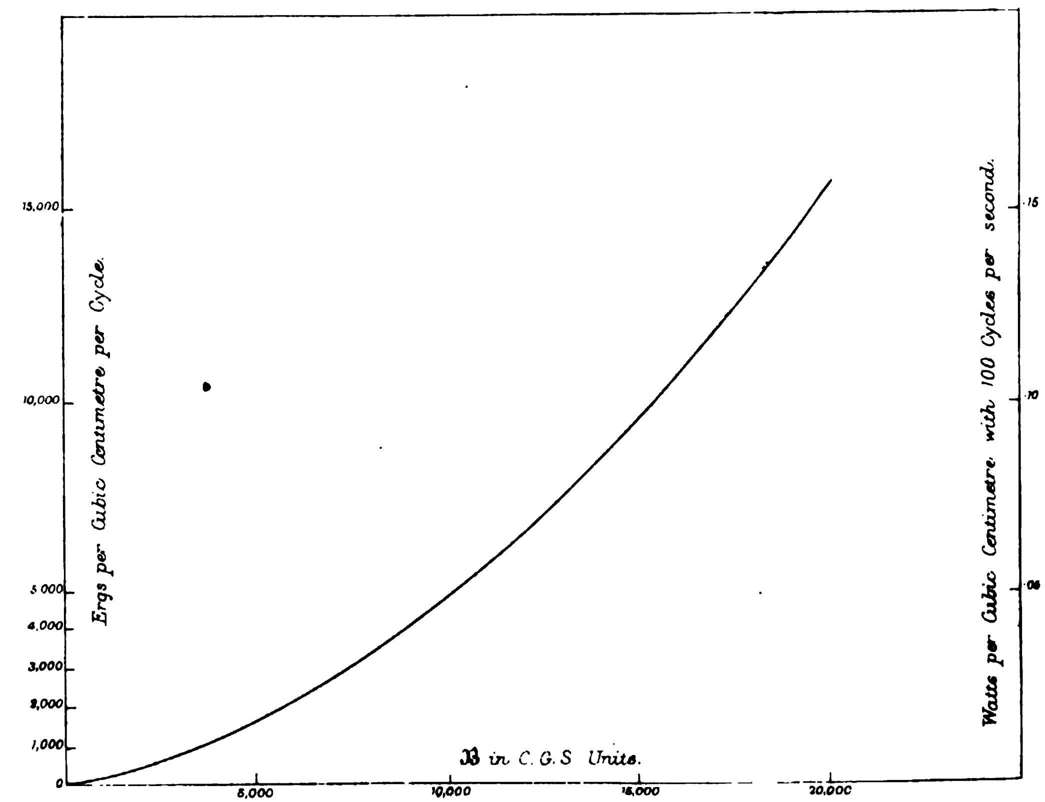
From B = 2000 to 8000 hysteresis-loss = ·01 $B^{1.475}$, and the nearest approximation throughout the whole range is given as .0034 $B^{1.6}$.

The measurement of the hysteresis-loss of energy in samples of soft iron is a matter of practical importance to builders of dynamos and transformers. The method involving the tracing of the Magnetic Induction curve is tedious. A direct reading instrument, shown in Fig. 7, giving fairly approximate readings, has been devised by Prof. Ewing. Specimens are prepared in the form of thin oblong strips of exact lengths, a number of which are clamped together, and pivoted so as to be free to turn about a vertical axis. A pointer is attached moving over a scale, and a slight adjustable weight keeps the specimens and pointer normally in a vertical position. A permanent horse-shoe magnet is placed so that in one position its magnetic circuit is completed through the specimen slips. This magnet supplies a Magnetising Force of fixed intensity, and can be rotated about the same axis so as to produce rapid reversals in Magnetic Induction through the bundle of specimens.

The result of Hysteresis will be to give the specimens a torque in the direction of the rotation of the magnet, which will produce a permanent deflection proportional to the expenditure of energy per cycle. For it is evident that to move a mass of iron in a fixed magnetic field so as to change the Magnetisation will require the application of that amount of power that is dissipated in Hysteresis; and in the same way in a rotating magnetic field it will require a certain amount of torque to keep the iron stationary, for in this case the iron still moves relatively to the magnetic field. The power dissipated in Hysteresis would be measured by the product of the torque multiplied by the relative speed of rotation (that is their measures

J & E Hopkinson.

Plate VIII.



West, Newman lith.

in certain units). Now the speed of rotation is proportional to the number of reversals of magnetisation in the specimens above mentioned; and therefore the torque, or the deflection of the pointer, is proportional to the Hysteresis-loss per cycle. It is also, within certain limits, found to be sufficiently independent of the number of specimens clamped together, and their thickness, on account of the variation of magnetic induction through the specimen, for little error to be thus introduced. The method is simply one of comparison with standard specimens, in which the Hysteresis-loss has been measured by exact methods, and only at a standard intensity of magnetisation. The Hysteresis-loss with different intensities of Magnetic

FIG. 7.

Induction can be calculated from that with the standard intensity, since the law of variation is similar in all cases.

It is in the heating of the iron that the energy dissipated in Hysteresis is to be traced, so that it would seem that the surest method of measurement would be through the raising of the temperature of the iron. But since the 10,000 ergs dissipated per cycle of strong magnetisation in soft iron only produce a rise in temperature of 0.000285° Centigrade, it will require a large number of reversals to produce a measurable change. And if these reversals are made with great rapidity another source of heating is involved, which is difficult to separate from that of Hysteresis. This is due to the eddy currents set up in the iron by the magnetic changes. We shall see, when studying the construction of dynamos and transformers, how these eddy currents are, to a large extent, eliminated by constructing the iron of thin plates or wires (technically called *lamination*) instead of a solid casting or forging. There does not appear to be any great variation in Hysteresis owing to the rapidity of the magnetic changes, at any rate with strong fields. The "time-lag" in magnetisation that has been observed seems to be mainly due to eddy currents. Further experiments are needed, but at present we must assume that the dissipation of power by Hysteresis is proportional to the rapidity of the magnetic reversals. On the other hand, if the eddy currents are proportional to the rate of changes in Magnetic Induction (as is the electromotive force producing them), the energy dissipated by them is proportional to the square of this rate of change, and, therefore, to the square of the number of reversals per second.

CHAPTER V.

The Closed-Coil Dynamo (General Theory).

ELECTROMOTIVE Force (E.M.F.) is produced in a turn of wire while the flux of magnetic induction through it is being increased or diminished, and the magnitude of the E.M.F. is proportional to the rate of increase or diminution. Measuring the flux, as explained above, by the number of unit tubes of Magnetic Induction, or lines of force, it is found that the E.M.F, is measured in c.g.s. units by the number of unit tubes, or lines of force, added to or subtracted to the total flux through the turn of wire per second. To obtain the practical unit of E.M.F., the volt, a rate of change of a hundred million, 10^8 lines of force per second is required. The E.M.F. will be produced in such a direction in the turn of wire as will cause a current to flow, whose electromagnetic effect opposes the change. In other words, taking the positive direction along a line of force to be that in which a north-seeking pole would be drawn, a decrease of the magnetic flux through the turn of wire will cause an E.M.F. tending to make a current flow through it round the lines of force in the direction of revolution of a right-handed screw advancing in the positive direction of the lines of force and *vice-versa*. This is commonly known as Lenz' Law, and will be shown directly to be a necessary consequence of the Law of the Conservation of Energy. It follows that a decrease of the flux of Magnetic Induction in one direction is equivalent to an increase when the lines of force are in the opposite direcion.

The E.M.F. may be calculated when the wire is wound in a coil of many turns by multiplying that in each turn by the number of turns, provided an identical flux of Magnetic Induction is included in all the turns. This is only equivalent to saying that, the various turns being in series, the E.M.F. produced in the whole coil is obtained by the addition of that in all the turns.

The simplest conceivable form of dynamo armature will consist of a flat coil, of one or more turns in the same or in parallel planes, rotating in a uniform magnetic field about any axis in the plane of winding. In such a coil, when rotating with uniform speed, the flux of Induction will reach a maximum twice in every revolution, but alternately in one direction and then in the other. The change must therefore be alternating in direction, reversing at every maximum value of the flux of Induction. The flux of Induction at any moment will be proportional to the sine of the angle of inclination of the plane of the coil to the direction of the lines of force, and therefore the rate of change, or the E.M.F. produced in the coil, will be proportional to the cosine of the same angle. It will follow that the greatest E.M.F. will be found when this angle is zero, that is to say, when the plane of the coil is parallel to the lines of force, and therefore when the flux of Induction through the coil is zero.

The circuit of the armature may be completed in the external circuit by sliding contacts, or brushes, touching two separate insulated brass rings on the axle to which the ends of the coils are attached. The E.M.F. thus produced would be what is known as an alternating E.M.F., reversing in direction every half-revolution. If, on the other hand, the extremities of the coil be connected respectively to two semi-circular segments of the same ring, insulated from one another, and the sliding contacts, or brushes, which lead to the external circuit make contacts one with each segment, and in such positions that the contacts interchange segments when the E.M.F. changes in direction (every half-revolution at the moments at which the magnetic flux through the coil reaches its maximum values), the E.M.F., though still alternating in the armature coil itself, becomes uniform in direction in the external circuit. The E.M.F. will still, however, be variable in magnitude, and is known as a *rectified oscillatory* or a *pulsating* E.M.F.

Considering for the moment only the case where the external circuit is free from self-inductance, let us say a bank of incandescent lamps, the current at any moment will be determined by the E.M.F. at that moment and the resistance of the whole circuit, and will follow exactly the same cycle of changes as the former. It will be zero at the moment of the interchange of the contacts on the divided ring, or commutator, but in any other position a current will be flowing which will react upon the magnetic field. For example, in any position where the flux through the coil is decreasing, the current in the coil will, according to Lenz' Law, tend to maintain the flux against the decrease, and the effect will be, not so much to create new lines of force, as to deflect or distort the neighbouring lines of the uniform field so that they pass through the coil, weakening the surrounding field in the same way as a piece of wrought iron would if placed in the field. The appearance of the lines of force would be as if they were dragged forward by the conductors of the armature, as threads when about to be cut with a blunt knife. This distortion of the field will give rise to a force reacting on the coil, of which the effect may be easily traced by supposing a tension along the lines of force, and a lateral pressure. In this case the force will act to oppose the motion of the coil towards the position of the zero flux, and it is easy to see that in all cases a force-resisting motion will result.

The resisting force has to be overcome by the driving force applied to the dynamo pulley. An alteration of the current by increase or reduction of the resistance of the external resistance would result in a corresponding alteration of the distortion, and therefore of the driving force, to maintain the speed. An alteration of the speed would produce a corresponding alteration of the E.M.F., and as the force, or torque on the pulley, would still be proportional solely to the current (being quite independent of the speed or E.M.F. except so far as they affect the current) the mechanical power required will be proportional to the product of the measures of the E.M.F. and the current, or to the number of watts.

Let the E.M.F. be altered in another way, by increasing the number of turns in the coil. The distortion produced by the same current will now be increased in proportion to the increased number of turns, that is, to the increased E.M.F., so that the mechanical power employed is still proportional to the number of watts, or the electrical power produced,

In Siemens "magneto-electric machine," which first appeared in 1856, we have the nearest approach to this ideal simple dynamo that is practically possible. The coil is wound on a shuttle-shaped piece of iron, and revolves in the cylindrical interspace between the poles of a permanent magnet. The coil is in fact wound in two deep horizontal grooves, on either side of a cylindrical core rotating about its axis, the conductors crossing at each end on one side or other of the shaft. Two collector rings, or a split ring, are mounted upon the shaft to give alternating or pulsating E.M.F. This was the first practical dynamo, or magneto-electric machine, for supplying continuous or alternating currents, but considerable modifications were necessary before the dynamo was available for the efficient conversion of considerable mechanical into electrical *power*.

The term "continuous current" is generally understood to mean one that is continuous or invariable, in magnitude as well as in direction, or rather, free from rapid periodic variations such as must inevitably be produced in an armature consisting of a single coil wound in one plane, or, as in Siemens' shuttle-wound armature, wound with many turns in parallel planes. To produce such an E.M.F. and current it is necessary that, though the numerous turns of wire with which it is wound may be each passing through different positions or phases of periodic change, the armature as a whole should exhibit uniform conditions in any position during its rotation, owing to its perfect symmetry in construction and winding about the axis of rotation. Such an arrangement is closely approximated to by what is known as the *closed-coil* armature.

On a cylindrical iron framework a *single coil* of many turns is wound, every turn of which is in a plane passing through the axis of rotation, and as far as possible in all such planes, so that the surface of the cylindrical core is covered uniformly with conductors lying on its surface parallel to the axis of rotation. In winding, the successive turns advance from plane to plane with as small changes of inclination as possible, till the plane of the first turn is again reached, after the plane of winding has made a complete revolution, and then the two ends of the conductor are joined together, forming a single *closed* or endless coil.

Fig. 8 illustrates the principle, a diagram showing one of the methods of winding the "closed" coil, known as "ring" winding. It represents a case in which the successive turns contain only somewhat less than half the total flux of Induction passing between the poles. Other types will be described later, but this is most convenient for illustrating the principle by diagram, as the separate windings do not cross one another, but form an endless spiral round a ring core. The arrangement of the lines of force are shown in Fig. 9.

In such a closed or endless coil the total E.M.F. will be *nil*, and no current will tend to flow round the complete circuit thus formed. For the total flux of Magnetic Induction through the coil is zero in all positions, the turn in any one plane being counter-wound to that reached after traversing half the winding from it. Or otherwise, observing that the successive turns exhibit at any moment similar conditions to those of any one turn in successive positions during a complete revolution, the change of the flux of Magnetic Induction produced in the closed coil, when it is so rotated that each turn passes to the position of that consecutive to it, is the same as the change in a single turn taken through a complete revolution, and therefore obviously zero.

In a uniform magnetic field, or when the armature is between two poles of a magnet, two of the turns, those most nearly including the maximum flux of Magnetic Induction at the moment, will themselves have zero E.M.F.; and since in rotation from the plane of one of these turns to that of the other the flux changes continuously from a maximum in one direction to a maximum in the other direction, the E.M.F. in all the turns at any moment between those in these two planes (half the turns of the closed coil) is in the same direction, thus creating a considerable difference of potential *between* the two turns, which in themselves have zero E.M.F. The remaining half of the closed coil is composed of an equal number of turns whose E.M.F. is in opposition to that of the turns of the former half, in the sense of continuity round the closed coil, but tends to create the same difference of potential between the turns of zero E.M.F. The closed coil, in fact, resembles two exactly similar batteries of cells, the turns corresponding to cells of different E.M.F. connected in series in each battery: the two batteries being then connected together by joining like poles, so that in the complete or closed circuit thus formed the E.M.F. of one battery is in opposition to that of the other. But if the terminals of an outside circuit were joined one to each of the connected poles of the batteries, the batteries would be connected in parallel with respect to the outside circuit. We should thus get only the same E.M.F. between the terminals that one

FIG. 8.

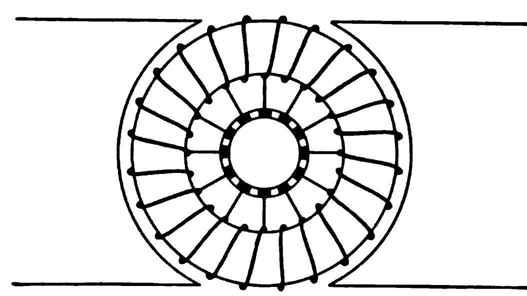
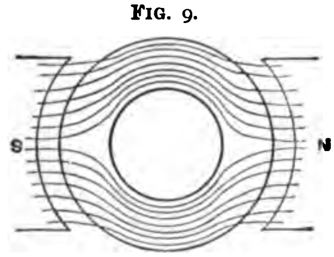


Diagram of Ring-Winding.

FIG. 9.



Lines of Force through Armature Core.

battery alone would give, but the internal resistance of the combination will be only one-half of that of a single battery.

In the closed-coil armature the points corresponding to the connected poles of the batteries are not fixed points on the coil, but hold fixed positions in space as the armature revolves, the highest and lowest points in the diagram. We require to make connections between the terminals of the external circuit and points on the closed coil in close proximity to the turns having at any moment maximum magnetic flux, or zero E.M.F., and to be perpetually altering these contacts as the armature rotates. The exact positions of these contacts are not of extreme importance, as the coils in the neighbourhood of the point of contact have very little E.M.F.; and the best positions in practice will not be always those indicated in this preliminary explanation, but will need to be modified when a current is flowing in the armature.

A method of making these contacts with sufficient correctness for all practical purposes and in such a way that they remain unchanged as the armature revolves, is to connect every turn, or, if they are very numerous, to make a sufficient number of branch connections from the closed coil at equal intervals, to a number of metal bars or strips, insulated from one another, but built up so as to form a cylinder rotating with the shaft. Sliding contacts, or brushes, pressing against the surface of this cylinder may thereby make contact with the required points, and by sliding from one bar to the next, change the points of contact with the closed coil with sufficient frequency to be never far from the points where the E.M.F. in the turns of the coil reverses, and thus to maintain a practically constant difference of potential between the terminals of the external circuit. Such an arrangement is known as the *commutator*.

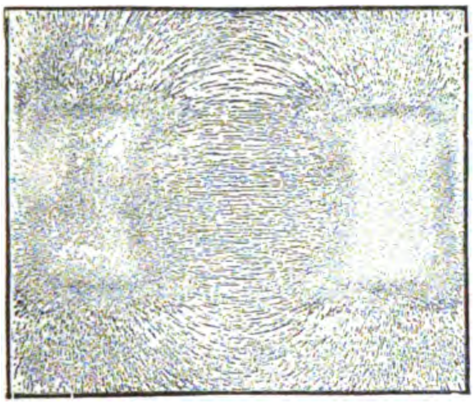
The value of using an iron core on which to wind the armature coil is that the lines of force prefer to follow a path as far as possible in iron, so that even with permanent field-magnets a much greater flux of Magnetic Induction passes through the armature owing to the concentration of the field; and when electro-magnets are used, the magnetic circuit is decreased greatly in resistance or reluctance, so that less Magnetising Force is required to obtain the requisite strength of field. The core or framework for a closed-coil armature must be cylindrical in shape, so that it may fill while revolving as nearly as possible the cylindrical interspace between the poles of the field-magnets. The cylinder is generally hollow, the shaft of the dynamo having to pass through the central space, and an air-space being advisable between the steel shaft and the iron core, in order that the former may not form part of the magnetic circuit. Moreover, since it is advisable to have a large periphery to the cylinder, and wide-embracing pole-pieces, in order that greater breadth and shorter length of gap (in which the necessary conductors are wound) may be obtained between the poles of the field magnets and the iron core, ample section of iron is given in the interior of the core when the internal diameter is from one-half to three-quarters of the external. The cross-section, therefore, of the armature, and the disposition of the lines of force in the neighbourhood, is for a two-pole dynamo similar to that shown in Fig. 9, the magnetic circuit dividing in the interior of the core into two branches as indicated.

The effect of the iron core in concentrating the field through the armature is well shown by Figs. 10 and 11, representing the disposition of the lines of force before and after the insertion of the core, as traced by the cohesion of iron filings along them.

The first known application of the principle of the closed-coil armature was in a model designed by Prof. Pacinotti, of Pisa, in 1864. The model was not, however, improved upon so as to become of practical utility, and quite independently, some seven years later, the same principle was re-invented by Gramme. Pacinotti's armature was wound on a simple iron ring, into which sixteen iron wedges were driven at equal intervals between the windings, so as to form projecting teeth, which coming successively opposite the pole pieces, enabled the air gap to be reduced to the minimum required for clearance. Gramme improved on this by building a ring-shaped core of iron wire, thereby avoiding the eddy currents which are produced in a solid conducting mass rotating in a magnetic field, but in omitting the teeth or projections his invention missed what most modern designers look upon as a great advantage.

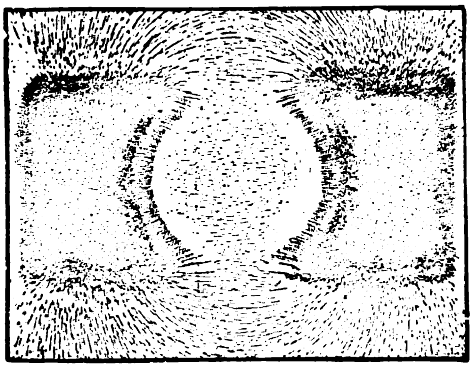
The modern armature-core is built up of ring-shaped stampings from plates of the softest charcoal iron, of from one-quarter to one-half of a millimetre in thickness. These rings or discs are electrically insulated from one another by thin sheets of paper, or a coating of varnish, and bolted together in a framework so as to form the required ring or cylinder (the former term being most appropriate when the diameter greatly exceeds the length, and the latter when the length exceeds the diameter). The driving is effected from the shaft by a gun-metal "spider," or some equivalent means. Observing that the eddy currents tend to flow, as in the armature coils, in planes perpendicular to the lines of force, it will be seen that the core built up of plates slightly insulated from one another, of sufficient thinness, will effectively eliminate this source of waste, while permitting better continuity in the paths of the lines of force through the iron than the iron-wire core of Gramme. By cutting deep grooves along the surface of the core, in which the conductors are afterwards laid, the air-gap may be

FIG. 10.



Lines of Force with Armature-core removed.

FIG. 11.



Lines of Force with Armature-core inserted.

reduced to the minimum requisite for clearance. This being the perfected method of utilising an advantage first realised in Pacinotti's model, such an armature-core is generally called a *Pacinotti core*, and the projections, or ridges, between the grooves, *Pacinotti teeth*. The advantages over smooth-cored armatures are reduced reluctance in the magnetic circuit, and superior mechanical strength, as the conductors cannot be displaced on the surface of the core by the shearing force to which they are subjected in driving. It is, in fact, exceedingly probable that very little shearing force on the conductors exists at all when Pacinotti armatures are employed; the magnetic lines of force confine themselves almost entirely to the iron teeth, avoiding the gaps in which the armature conductors lie, and the shearing force resisting the revolution of the armature acts upon the teeth and not on the conductors, thus relieving the insulation of the pressure that would otherwise exist. In large machines a further distinct advantage is gained by the lines of force avoiding the conductors, in that eddy currents are not produced in the large copper bars employed, which need not therefore be laminated, or built up of thin copper strip or wire. The objections to Pacinotti teeth are (1) An extra difficulty in obtaining high insulation between the conductors and the iron core in which they are sunk; (2) an increased distortion of the magnetic field by the current flowing in the armature, with attendant difficulties in preventing sparking at the commutator, the causes of which we shall deal with shortly; (3) the production of eddy currents, and consequent heating and waste of power in the poles of the field magnets, owing to the variation of the distribution of the lines of force as the teeth or ridges pass in front of them, unless certain precautions be taken as to the size and shape of the teeth.

The excessive effect of armature reaction in distorting the magnetic field and rendering sparkless commutation difficult that is found with Pacinotti cores, and will be presently described, caused the smooth core to be preferred by manufacturers until recent years. Now that effective means of compensating for or eliminating this effect have been devised, the intrinsic merit of the Pacinotti core is causing it rapidly to supersede the smooth core, which will in all probability be soon rendered obsolete, except for very small and cheap dynamos. Considerable choice still remains as to the shape of the teeth. Rectangular grooves and ridges are permissible only if the former be of small width, not greatly exceeding the actual clearance or distance of the outer surface of the teeth or ridges from the polar faces. It will be shown later that under these conditions the Magnetic Induction at the surfaces of the pole-faces will be practically uniform, and eddy currents will not be formed within the pole-faces as the armature revolves. This is a convenient type of core for large dynamo armatures, employing large bars or copper strips as conductors, fitting into grooves somewhat less than one centimetre in width, and allowing a reasonable clearance. Such armatures are very easily wound.

If larger teeth are preferred, so that many conductors may be carried along each groove, we must either build up the pole-faces of laminated iron to prevent eddy currents (a common device with alternators), or narrow the groove on the external surface of the core, forming T-shaped teeth or ridges. The conductors are then nearly enclosed in the iron, and a further advantage is gained in preventing the conductors from flying outwards by centrifugal force without the employment of bending wire, but the winding is more difficult and expensive. The narrow neck of the grooves is generally closed by a wooden plug. It is only a step further to completely enclose the conductors in iron, pushing them through tunnels just beneath the surface formed by stamping holes in the plates.

The armatures of Pacinotti and of Gramme were both ring-wound, that is, all the turns of the closed coil pass through as well as over the external surface of the ring-shaped core, as indicated in Fig. 8. Every turn in this method of winding successively includes, as a maximum, one-half of the total flux through the armature-core. Another method of winding is that in which every turn crosses at each end of the cylinder from one generating line on its surface to that diametrically opposite (or nearly so) so that the turn includes, as a maximum, the total magnetic flux. This method is known as *drum*-winding, and a partial diagram is given in Fig. 12. It is inadvisable to trace all the turns in the diagram, owing to the confusion through overlapping. The dotted line represents a complete turn round the cylinder, from A' to A, consisting of two surface conductors and a cross connection at the back of the cylinder. Another cross connection (in the middle of which the commutator connection is made) brings us to B', where the next turn begins in a plane slightly inclined to the preceding. The winding of the closed coil is only complete when the starting-points of the turns A' B' C', etc., as well as the returning points A, B, C, etc., symmetrically cover the periphery of the cylinder.

The ring-winding is obviously the best adapted to ring-shaped armatures, that is, those whose diameter is great in proportion to their length; for though the maximum magnetic flux through any turn is only one-half of that through a turn in drum-winding, and therefore its contribution to the E.M.F. of the dynamo only one-half, two turns passing through the ring will be less in length and resistance than one turn of drum-winding. On the other hand, when the length of the armature is to be great, drum-

FIG. 12.

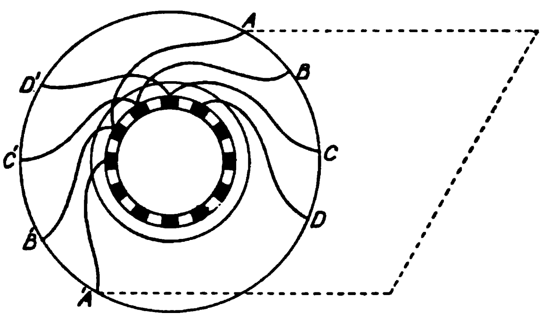


Diagram of Drum-winding.

winding is to be preferred in spite of many difficulties in its construction, and is generally adopted for dynamos of large size.

The difficulties of drum-winding arise from the crossing of the turns one over the other, and the complicated system of end connections necessitated. In the larger sizes of dynamo, where the number of turns is comparatively small, the surface conductors are bars of square section, or copper strip of moderate breadth, and the end connections of thin copper strip of considerable breadth, and by suitable systematic methods which will be briefly described later, the difficulties may be effectively coped with. A further objection to drum-winding, of less importance for large sizes, lies in the fact that conductors between which the greatest difference of potential occurs are brought into close proximity, and special care has to be taken with the insulation between them.

The E.M.F. of a dynamo with closed-coil armature may be calculated thus. Taking first the case of the two-pole ring-winding, and the total magnetic flux through the armature as N units, or lines of force, the total change in any turn during a half revolution, in which it passes from one brush contact to the other, is that of N lines, the maximum flux of $\frac{1}{2}$N being reversed. The time-average of the E.M.F. during this half revolution is $\frac{2N.v}{60}$ c.g.s. units, or $\frac{2N.v}{60 \times 10^8}$ volts, where v is the number of revolutions of the armature per minute (the customary measurement of the speed of machinery). The E.M.F. of the armature is obtained by multiplying this result by one-half the number of the turns, for this number in series forms one of the internal circuits from brush to brush; and since the turns are wound at equal angular intervals, we are justified in taking the time-average of the E.M.F. in one turn as the average of the E.M.F. in all the coils at any moment. Hence if the armature be wound with n turns in all, the formula giving the E.M.F. of the dynamo will be

$$E = \frac{N.n.v}{60 \times 10^8}.$$

The same formula, without modification, will be applicable to the drum-wound armature, provided we take n to denote the number of surface conductors. For in drum-winding there will be two of these for every turn, and thus the double magnetic flux through every turn will be allowed for.

Kapp has suggested as the unity of Magnetic Induction an Induction of 6000 c.g.s. lines per square inch, taking a square inch as equal to 6.4 square inches. This is equivalent to a Magnetic Induction, B, of 937.5 c.g.s. units.

This method of reckoning Magnetic Induction has the disadvantage of combining the inch and the centimetre as units of length and of applying a system of measurements based entirely on the centimetre to measurements made in inches. The method has the advantage of being directly applicable for dynamos the dimensions of which are known in inches, and it is, of course, possible to ignore entirely the derivation of the c.g.s. units of Induction, and regard it as a purely arbitrary unity, of which the Kapp unity is equal to 937.5. There is another advantage since speeds are generally measured in revolutions per minute, for if the total number of Kapp lines of Induction passing through the armature be multiplied by the number of revolutions per minute, and the number of turns of wire on the armature in the case of a cylinder armature, or twice that number in the use of a drum armature, the result will be the E.M.F. in the armature in micro-volts. The modification necessary in the case of dynamos with four or more poles will be at once apparent.

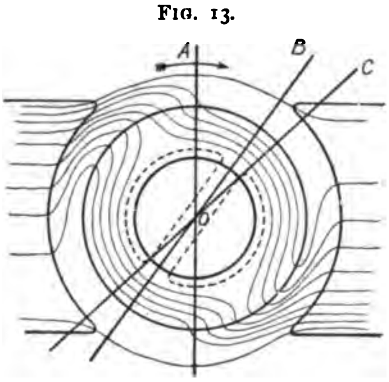
The bars, or segments, of the commutator are made of gun-metal, phosphor-bronze, or hardened copper, cast or rolled into the required shape, and firmly held in a suitable frame, from which, as well as one another, they are carefully insulated with mica. This substance alone seems to fill the requirements as the insulating material, being of high specific resistance, unaffected by heat and impervious to moisture, oil and its carbonised products, copper dust worn from the segments, etc., and of considerable mechanical strength. The conducting segments might with equal propriety be called *sectors*, since, owing to the wear to which they are subject, they are made of considerable depth, and require very careful shaping in order that the symmetry of the commutator may be preserved as the diameter decreases by wearing out and re-turning.

The brushes are, in British practice, most commonly constructed of copper wire gauze: carbon brushes are more common in American practice. In both cases, but especially in the latter, considerable breadth of contact must be given. Carbon brushes should allow a surface of not less than one square inch for every 50 ampères. The contact must be of sufficient breadth to bridge over the intervening insulation (about one-eighth of an inch) between two successive segments, and establish a sound connection with the second before receding from the first, since the current is to be maintained without variation during the change of connection. While a double contact is thus maintained for a short period, the intervening turns of the closed coil connecting the consecutive bars from a short circuit of very little resistance. According to the preceding elementary theory the E.M.F.

in these turns must be zero, or at least very small, and no great current would be produced; but the operation which in practice does take place in the short-circuited turns needs further discussion, modifying the previous theory by considering the effect of the current in the armature coil on the magnetic field.

The arrangement of the lines of force in armature core when no current is flowing in the closed coil has been illustrated in Fig. 9. The mere rotation of the armature will have little or no effect on this arrangement, as may be proved experimentally. When the armature circuit is completed through an external resistance, a current flows in the divided circuit from brush to brush, which, it is easily seen, supplied a Magnetic Force tending to convert the core into a magnet having poles, or rather distributed polarity, in the neighbourhood of the coils of zero E.M.F. In other words, the lines of force due to this Magnetising Force, if it existed alone, would, like the original field, form a double magnetic circuit in the iron core, and leaving in or near the plane of the brush contacts, return either by the field magnet poles, or the interior of the core. The lines of force in this field, when the brushes are in the positions previously indicated, would be at right angles to the original field, and hence the effect of the armature Magnetising Force, or *reaction* on the field, is commonly known as *cross-magnetisation*. The resultant effect is that of a distorted field such as that indicated by the lines in Fig. 13 (a very extreme case for a closed-coil dynamo), the direction of rotation being clockwise, as indicated by the arrow. The lines of force appear as if dragged round by the rotation of the iron, the distortion being such as one would expect if there were a great *lag* or delay in the magnetisation and demagnetisation of the iron. With a laminated armature-core the distortion is almost or entirely inappreciable till an armature current flows, though with a solid core eddy currents would produce a considerable distortion similar to that produced by the armature current, and in a similar way. It is evident from Lenz' Law that the distortion must be as shown, the current tending to prevent the change of flux through the various turns of the coil; and supposing a tension to exist along the lines of force, the mechanical force resisting the rotation, and necessitating the supply of mechanical power, is accounted for.

FIG. 13.



Distortion of Magnetic Field due to Reaction of Armature Current.

The cross-magnetisation has no *direct* tendency to decrease the total magnetic flux, through the armature, as long as the brush-contacts are with segments of the commutator connected to turns at right angles to the lines of force in the undistorted field. But *indirectly* the increased length of the lines, and the saturation of the polar tips, or horns, may have an equivalent effect by increasing the magnetic reluctance.

But now the positions of maximum flux, or zero E.M.F. are removed from their previous position, which we may call the plane of geometric symmetry (*OA* in Fig. 13) and advanced to the plane *OB*. If the brush contacts are advanced so as to make contact with the segments connected to turns in that plane, we shall divide the turns of the closed coil correctly according to the direction of their E.M.F. The effect of the advance, or *lead*, thus given to the brushes will be to modify the distortion, and, as will be shown later, to further weaken the field. But neglecting this effect, as inconsiderable in a well-designed dynamo, it will be when the brushes make contact with the coils in the plane *OB* that the highest E.M.F. will be obtained, since the E.M.F. in all the turns is used to the best advantage, and for any other position of the brushes some will be in opposition to others. But opposition of the E.M.F. in different turns does not necessarily mean a waste of power, and a consideration of far more importance than high E.M.F. necessitates a still further advance or lead, to be given to the brush contacts, namely the consideration of sparklessness on the surface of the commutator.

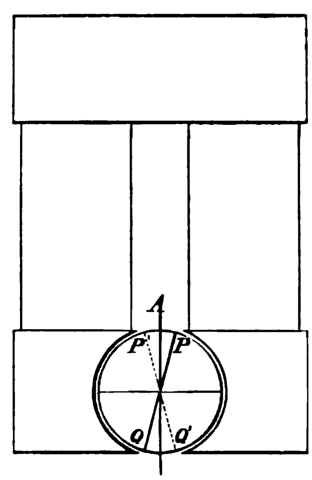
An electric current cannot be stopped or started in a circuit possessing self-inductance absolutely instantaneously. Now the turns connecting two successive segments of the commutator, being wound round laminated iron, have very considerable self-inductance, and the current flowing in them, that of half the output of the dynamo, has to be reversed during the time in which the brush contact passes from one terminating segment to the other. We have seen that the necessity of sufficient contact with the armature coil being maintained throughout the process of commutation requires a short-circuiting of the commutated turns for a finite time, and it is requisite that during this time the current, which had, for the previous half-revolution, been flowing without change in these turns, should be reduced to zero, and again grow to an equal magnitude in the opposite direction just at the moment of the recession of the brush contact from the leading segment. Should the current in these turns fail to reach, or have grown in excess of this current, which has to flow in the turns without change for the next half-revolution, the short-circuit will be maintained for an instant by the passage of a spark between the brush and the receding segment, a very high E.M.F. being produced in the turns as the flux through them changes, almost but not quite instantaneously, to suit the normal current. This spark is more or less of the nature of an *arc*, resulting in the burning of the segments of the commutator, the insulating strips, and the brushes, and in their speedy destruction.

A simple way of explaining how the exact reversal, and consequent sparklessness, is obtained, is to say that during the short period of short-circuiting, a small E.M.F. must be produced by the motion of the turns in the direction in which the current will subsequently flow, an E.M.F. just sufficient during that period to reverse the current in the turns, the self-inductance and the small resistance determining the requisite E.M.F. and time for reversal. Hence the turns must be freed from short-circuit when in a position somewhat advanced from that of zero E.M.F., to a position indicated by *OC* Fig. 13. This statement is not perfectly satisfactory, as the magnetisation due to the short-circuited coils is part of the distortion of the field, and the term *self-inductance* may be misleading. It would, perhaps, be more correct to say that the magnetic field within the armature needs re-arrangement during the time of short-circuit to suit the reversal of the current in the short-circuited turns, and this requires the reduction of the flux through the latter sufficient to allow for the reversal of their Magnetising Force, and an additional rate of change at the end to sustain the requisite current against their resistance.

The angle of lead should be very small in well-designed dynamos. It depends in part on the breadth of the brush-contact, and can only be found by actual trial. It increases with the current. The law of increase being roughly proportional to the square of the current. The output of some dynamos may be limited by the possibility of finding a sparkless plane at all, for if it be not reached on an inclination to within the horns of the field-magnet poles, further advance generally fails, as the E.M.F. in the turns does not increase. When carbon brushes are used, less difficulty is generally experienced as the resistance of the material is very much greater, and the decrease of the area of contact on the receding segment, with the increase on the advancing, assists the transfer of the current wholly to the latter from both circuits of the armature. Also the possibility of an excessive current flowing round the short-circuited turns at the commencement of the double contact, which is possible with metal brushes, is avoided.

It will be seen that while high resistance in the brushes is a gain in respect to the reduction of sparking and short circuit currents in the commutated turns of the armature, it has the disadvantage of adding to the armature resistance. To secure the advantages while avoiding the disadvantages it has lately been suggested to add to the thickness of the brush by using strips of high resistance metal on either side, with low resistance (pure copper) strips in the middle; the latter always carries the main current, and the high resistance metal causes a diminution of the current from the receding segment of the commutator, prevents an excess short-circuit current if the brush be too far back. A still more promising suggestion is the adoption of laminated brushes, of thin copper strips separated by thin insulation at the extremity touching the commutator and for some portion of the length, but without insulating films where it is held in the brush holder; this is equivalent to low resistance in the direction of the length of the brush, but high transversal resistance.

FIG. 14.



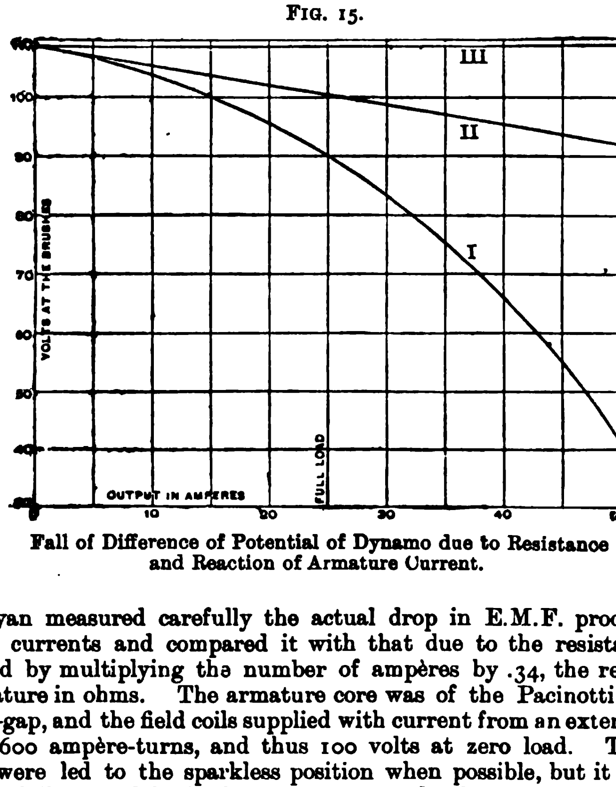
Demagnetising Turns of Armature.

A want of symmetry in the winding of the armature, or in the magnetic field, is certain to produce injurious sparking. The former is solely a question of care in construction, the latter may also be caused by a faulty design. If, for example, with a single magnetic circuit, the pole-pieces be of insufficient size, the extra reluctance offered to the lines of force proceeding to the further end of the poles may be sufficient to cause a difference in the density on the two sides of the armature-core. Especially probable is this inequality with cast-iron pole-pieces, and short magnetic air-gaps. Mather and Platt introduced the custom of boring the polar gap slightly larger than necessary, and subsequently closing them so as to have a shorter gap and a concentrated field in the middle, but a larger magnetic gap and less concentrated field near the horns: thereby reducing the possible inequality, and preventing the saturation of the horns by the distortion due to armature reaction.

The question of the reduction in the E.M.F. when a lead is given to the brushes may be treated as follows. In Fig. 14, suppose POQ to be the plane of the turns when commutated, AOB the plane of geometric symmetry, and call the angle POA, λ. Draw $P'OQ'$ so that $P'OA$ is equal to POA, that is to λ. Then the armature currents in the sections POQ', $P'OQ$ balance one another as far as regards the Magneto-motive Force in the magnetic circuit is concerned, and the net demagnetising turns are those in the sections POP' and QOQ'. These turns include practically all the lines of force in a drum armature, or one-half in the ring armature, provided the plane of commutation is within the polar gap, and it cannot be far outside if sparklessness is to be obtained at all. If m be the total number of armature turns the number within this space will be $m\frac{\lambda}{\pi}$. The demagnetising effect of the armature current is therefore that of $\frac{1}{2}m\frac{\lambda}{\pi}$ or $\frac{1}{4}m\frac{\lambda}{\pi}$ turns, according to the winding, carrying the whole current and wound in opposition to the field-magnet coils. This calculation does not, however, make allowance for the additional magnetic reluctance introduced by the field-distortion, nor the increase of the magnetic leakage past the armature, nor the opposition of the E.M.F. in certain turns of the armature. These can only be allowed for by supposing them equivalent to an additional resistance added to that of the armature, proportional to the lead, and determinable by experience.

In testing the effect of armature reaction with a small bipolar dynamo

FIG. 15.



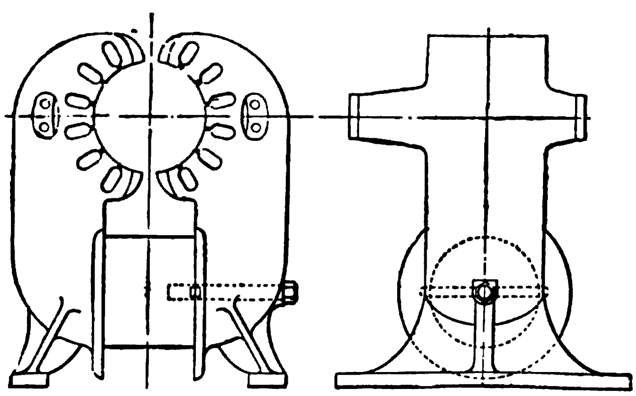
Fall of Difference of Potential of Dynamo due to Resistance and Reaction of Armature Current.

Prof. Ryan measured carefully the actual drop in E.M.F. produced with different currents and compared it with that due to the resistance alone, calculated by multiplying the number of ampères by .34, the resistance of the armature in ohms. The armature core was of the Pacinotti type, with short air-gap, and the field coils supplied with current from an external source, giving 2600 ampère-turns, and thus 100 volts at zero load. The carbon brushes were led to the sparkless position when possible, but it seems that from the full normal load of 25 ampères to the double load to which the experiments were carried sparklessness was not obtainable. The results are plotted in Fig. 15, the curve I showing the E.M.F. actually given with different currents, the former represented by the ordinates and the latter by the abscissæ, and the curve II the E.M.F. calculated as it should be if the drop were due to the armature resistance alone. It will be seen that at half-load the actual drop is not greatly in excess of the calculated, rising to nearly double (19 volts) at the full load of 25 ampères, and increasing with ever increasing rapidity till at 50 ampères the difference of potential between the brushes is only 41 volts.

Thus we may conclude that the drop in E.M.F. due to armature reaction varies as the square or even a higher power of the current, and while in a well-designed dynamo with an air-gap not too greatly reduced, its effect will be small in proportion to that of the resistance of the armature at low loads, it may become very great indeed with overloads, and restrict the possible current output.

By giving the brushes a backward instead of a forward lead, the field may be strengthened instead of weakened by the reaction of the armature,

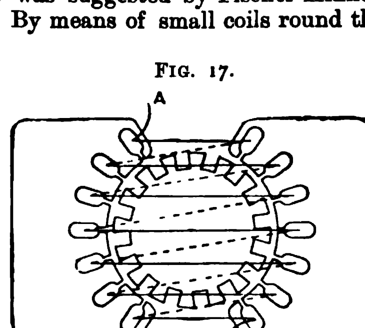
FIG. 16.



to such an extent that it is even possible for the armature current to maintain its own field, but this on the commutator as commonly constructed, will be at the expense of such destructive sparking as to be entirely non-permissible. With certain modifications in design, the strengthening of the magnetic field by "forward" armature induction has been utilised to compensate for the fall of E.M.F. due to the resistance of the armature, as will now be described.

A method of counterbalancing, or at least of reducing, the distortion of the field produced by armature reaction was suggested by Fischer-Hinnen (see *The Electrician* for May 26, 1893). By means of small coils round the necks, or narrowest section of the pole-pieces, a counterflow of induction was set up which opposed that of the armature current, at least so far as to prevent the saturation of the pole-tips. In a later design a single coil was wound in longitudinal grooves along the middle of the polar faces, this coil being joined in series with the armature current, and, surrounding the armature, tended to oppose the effect of cross-magnetic induction. A more perfect method of counterbalance is that due to Prof. Ryan, in which "balancing" coils are wound in deep grooves along the polar faces, and round the ends of the armature, so as to produce a cross-induction exactly similar and in opposition to that of the armature current. Figs. 16 and 17 show sections of the dynamo and the mode of winding. The number of "balancing" turns was half of that in the (drum

FIG. 17.



Ryan's Balancing Coils for eliminating Armature Reaction.

wound) armature, and joined in series with the external circuit. The effect was entirely to remove the distortion of the field, and with the broad carbon brushes used, commutation could be effected in the symmetrical plane without spark. By giving the brushes a small backward lead, the sparking still being insignificant, it was found possible to strengthen the field in proportion to the current, and so to "compound" the dynamo, or maintain a constant difference of potential at all loads by compensating for the drop due to resistance. The principal objection to Ryan's device seems to be the expense involved in slotting and winding the pole faces.

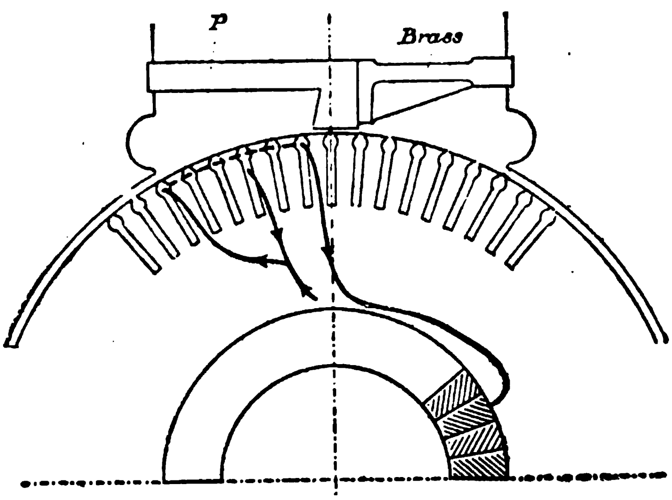
Elihu Thompson obtained sparkless commutation at heavy loads by winding the series turns necessary for compounding in two flat coils embracing the armature itself, instead of round the field magnets, and tilting them backward slightly in a direction counter to revolution. This proves sufficient to maintain the sparkless plane in one position, reducing the tendency to saturation of the pole-tips, and is far less expensive than the more complete method of preventing armature reaction devised by Ryan. Swinburne and others have used small auxiliary poles facing the armature in the polar gaps, thereby generating a supplementary E.M.F. in the plane of commutation which gives the requisite sparkless reversal, and introducing a cross-magnetising force opposing though not counterbalancing that of the armature current. To reduce or prevent sparking on the commutator, without in any way compensating for cross-magnetisation, a device called the "ammortisseur," invented by Hutin and Lebraun, has proved effective. This consists of a "squirrel-cage" of copper rods lying beneath and along the polar faces, terminating in two copper rings, the induced currents in which tend to damp the slight oscillation of the magnetic field consequent upon commutation.

The latest device for securing a constant sparkless plane of commutation has just been introduced by Holmes and Co. The pole-pieces are divided by a radial slot parallel to the axis of rotation of the armature into two parts, forming parallel magnetic circuits. By an extension of the leading pole-tip, and thus, by increasing the breadth of the air gap, decreasing the magnetic reluctance for the lines of force passing through the forward half of the pole-piece, this part of the magnetic circuit is practically saturated at all loads; the additional magnetic flux due to the compounding turns at heavy loads is therefore almost entirely confined to the less strongly magnetised trailing half of the pole-piece. The plane of maximum E.M.F. is thus kept in a constant position, in spite of the cross-magnetisation, or may be thrown back to any required degree, so that the plane of sparkless commutation may remain in a stationary position.

In 1893 Sayers introduced a method of utilising the armature reaction for strengthening the field with a backward lead to the brushes, while preventing sparking by the use of what he termed "commutator" coils. The connections between the closed coil and the commutator segments are no longer direct, but of comparatively thin wire on the surface of the armature core in the same grooves as the closed coil itself, so as to form a loop in which a small E.M.F. is produced. The commutator coils need only be of small section since they only carry a current when the corresponding segment is in contact with the brush, and do not add appreciably to the resistance of the armature (that of all the turns in two parallel series). The short circuit between two segments in contact with a brush consists of two commutator coils and the intervening section of the closed coil, and the difference of the E.M.F. in the former is sufficient to produce the requisite reversal of current, even when that in the intervening section is in favour of the original direction, as is the case with a backward lead. The preferred method of winding is to carry the connecting wire along a groove in the

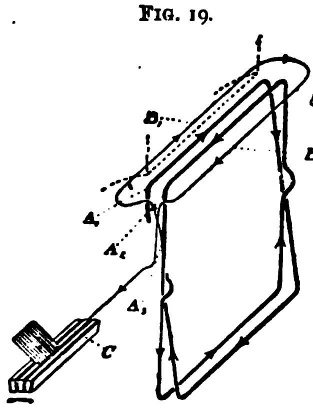
Pacinotti core somewhat behind the bar to which it is connected, so that with a slight backward lead it may be passing across the strong field under the pole-tip when brought into action, and return to the commutator end by a groove equally in advance. It has been found possible with commutator coils to allow the armature to create its own field, the magnetising coils

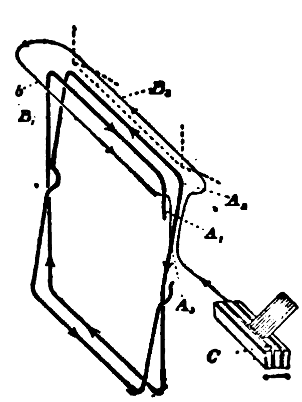
FIG. 18.



Sayers' Armature.

FIG. 19. FIG. 20.





Reversible Action of "Commutator Coils."

being rendered unnecessary, and using the field magnets simply as return circuits for the lines of force, or, as they have been termed, "keepers."

The method of winding the commutator coils adopted by Sayers is shown in Figs. 18 and 19. In order to increase the E.M.F. effecting the reversal in the commutator coils a polar extension P is added, so that the forward half of the coil is re-entering a detached part of the magnetic field as the backward half is leaving the pole-tip. Figs. 19 and 20 show the winding of two successive turns A_1, A_2, of the drum armature, with the intermediate commutator coil b connecting with the commutator C, and indicate the principle according to which the dynamo is reversible, the same direction of winding for the commutator coils being effective in whichever direction the dynamo is driven.

The closed-coil dynamo is used for parallel, or low-tension, systems of electric lighting, supplying most commonly an E.M.F. regulated for constancy at from 50 to 500 volts, and therefore, for large power, currents of considerable magnitude. The armature conductors, to carry large currents, need to be of great sectional area, 2000 ampères per square inch being the practical limit of current-density, and in order that no space may be wasted, consist of bars of square or oblong section. In such conductors the avoidance of eddy-currents is of great importance, more especially with smooth-cored armatures. The bars are commonly made of stranded copper cable, or thin strip, separately insulated with varnish, and forced into a rectangular section by hydraulic pressure or drawing through a die. Those compounded of strip should be placed so that their lamination is in a radial plane, and even then are subject to undesirable currents flowing forward in one strip, and backwards in another when the ends are soldered together and to the cross-connectors, the bar being often of sufficient breadth for the E.M.F. in one strip considerably to exceed that in another. To eliminate these a half twist is given to the bar in the middle, bringing the strips into the reverse position as regards lead on the armature, the shape being restored by hammering in a mould.

Multiple winding supplies a means of reducing the section of the conductors for dynamos supplying large currents. Double winding, for example, consists in constructing two separate closed coils connected to alternate sections of the commutator, placed in parallel by using brush contacts of sufficient breadth always to touch two successive segments, and bridge over the insulation to a third before leaving the first. The two closed coils may be entirely separate in their winding, or by using an odd number of commutator segments, the two may form a single coil, re-entering after two complete revolutions of the plane of winding. Triple winding consists of three coils, with brush-contacts capable of touching four successive segments, and so on.

In drum-winding for bipolar dynamos the cross-connectors commonly connect bars, or surface conductors nearly, but not quite, diametrically opposed on the armature core a slight advance of the plane for every turn requiring, for an even number of commutator bars, that the plane should not be exactly radial. With an odd number of segments, the plane of each turn may be exactly radial, and cross-connections between diametrically opposite bars be made at the pulley end, but not at the commutator end, of the armature. Swinburne introduced a system of "chord-winding," connecting bars far removed from opposition. This much simplifies the connections, allows of better ventilation of the interior of the armature, and brings conductors having less difference of potential into proximity. But the dynamo has a reduced E.M.F. owing to the turns not including the whole of the flux. It is claimed, but difficult to see by what process, that the cross-magnetisation of the armature is reduced by chord-winding.

The shape and arrangement of the cross- or end-connections in drum-winding have afforded scope for much ingenuity. We can only briefly summarise the most common methods adopted to preserve symmetry and uniformity. Edison invented one of the earliest devices, which consisted in, first of all, jointing all the bars on the drum-surface to flat radial plates, every alternate plate on the commutator side being also jointed to a segment of the commutator. Each plate was then joined to that nearly opposite (as explained above) by a semicircular connecting bar, the radii of these connectors being varied so that they may lie one inside the other in the same plane perpendicular to the axis. The objection to this method is that the semicircular connectors, being of different radii, are also of different length and resistance. A later method of Edison is to use a number of insulated copper discs, similar and similarly placed to the iron stampings for the armature core, the number at each end being half the number of the surface conductors. Two opposing bars are then jointed to lugs projecting from the periphery of a disc.

Spiral or *volute* cross-connection is effected with broad copper strip, bent into a spiral shape, so as to connect a bar of the commutator, or a corresponding bar at the pulley end, with a surface-bar diametrically (or nearly so) opposed, or with one in a radial plane at right angles to its own. The former, combined with direct radial connectors (lying, of course, in a vertical plane parallel to that of all the spirals) constitutes what is known as Crompton and Swinburne's winding. The latter, known as the Hefner von Alteneck, is that shown in the elementary diagram (Fig. 5), each cross-section consisting of two shorter spirals, with curvatures, in opposite directions, and arranged in two parallel planes. Eickemeyer's winding is similar in principle to that of Hefner von Alteneck, save that a whole turn or several turns forming a section of the closed coil between two commutator segments, is made without joints, and wound on a mould of the right shape previously to being slipped on the armature-core. It is wound so that any faulty section can easily be taken off and replaced without interference with the rest.

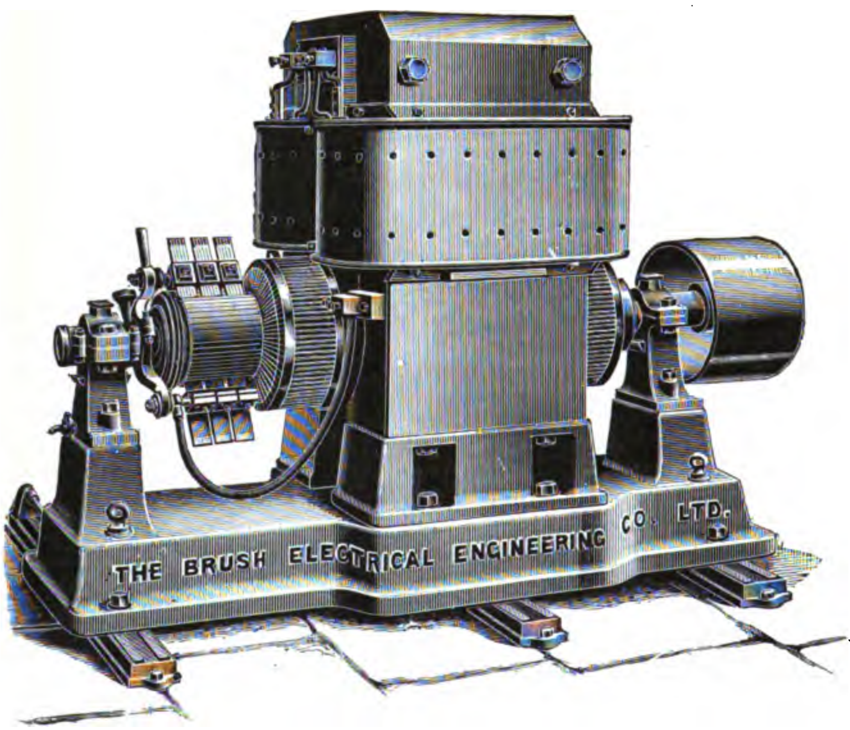
Helical connectors were first used by Kapp. These are plates or strips with their greatest breadth in vertical planes (ending in lugs for jointing to the surface conductors) the commutator connections being radial. They advance slightly along the direction of the shaft, as the threads of a screw, the alternate bars projecting some distance beyond the core to meet them. Helical conductors possess the advantage of all the joints being easily accessible for repair.

In multipolar dynamos the arrangement of the field in the core-ring, or cylinder, consists in lines of force entering and leaving by consecutive poles, which must be of differing kind, so as to form as many loops as there are poles. Any turn includes a maximum flux when midway between two poles, and in this position, neglecting the distortion, of which the effect is to necessitate a lead as in bipolar dynamos, requires to be short-circuited by a brush contact, and reverse its position relatively to the external circuit. If the armature be wound, as ring or drum, similarly to that of a bipolar dynamo, we should require a brush at each polar gap, and connect alternate brushes together, and to one of the terminals of the external circuit. This is sometimes done with dynamos supplying heavy currents, but is open to the objection that in the numerous circuits into which the armature is thus divided, the currents are liable to be unequal owing to inequality of the resistances of the brush-contacts, etc. It is more common to interconnect turns in similar positions, so that only one pair of brushes *need* be used.

Two-circuit winding for multipolar armatures consists in connecting all turns or sections of several turns, in similar positions with regard to magnetic flux in series, resuming the winding with those in consecutive planes in similar order, every turn or section being connected to a commutator segment in the same radial plane. There are then only two circuits, as in bipolar dynamos, through the closed-coil armature, and one pair of brushes only used. In drum-winding the circuit proceeds by a chord-connector from one bar to that advanced by a distance equal to that between two pole-centres, and again, still forward by a similar chord-connector at the other end of the drum to a bar in a similar position to the first, and so round the circumference to a consecutive set of bars, the advance, or *pitch*, being always forward till the closed coil re-enters.

It is in the design of the field-magnets of a dynamo that the greatest freedom of choice is allowed, and upon the choice of shape depends the characteristic external appearance. For the material a choice lies between wrought iron, cast iron, and steel. Cast iron was till recently employed for the pole pieces and other parts of the magnetic circuit where the shape renders wrought-iron forgings inconvenient and expensive. A much lower Magnetic Induction must then be employed in these parts, necessitating a multiplication of the sectional area two or three times. This is generally of little importance when weight is of minor consequence, or even a distinct

FIG. 21.



advantage on account of mechanical stability; but the employment of cast iron for the limbs upon which the magnetising coils are to be wound necessitates a much greater length of conductor for each turn, with extra sectional area, and thus the weight of copper must be multiplied many times. In multipolar field-magnets cast iron is more commonly employed than in bipolar field-magnets. Annealed mild steel has recently met with much favour, as it has been found possible to produce steel castings with a permeability little inferior to that of the best wrought-iron forgings except with low magnetising forces. The expense of the steel castings counterbalances the diminution in the labour of working.

The choice of shape is influenced by both magnetic and mechanical considerations, and also by the type of armature adopted. Generally the multipolar field is preferable for dynamos of very large size, and for slow-speed armatures of considerable diameter; there is generally less weight of iron, but greater weight of copper in the magnetising coils in multipolar field-magnets, than in bipolar field-magnets for dynamos of similar output. The winding of multipolar armatures introduces greater complication and

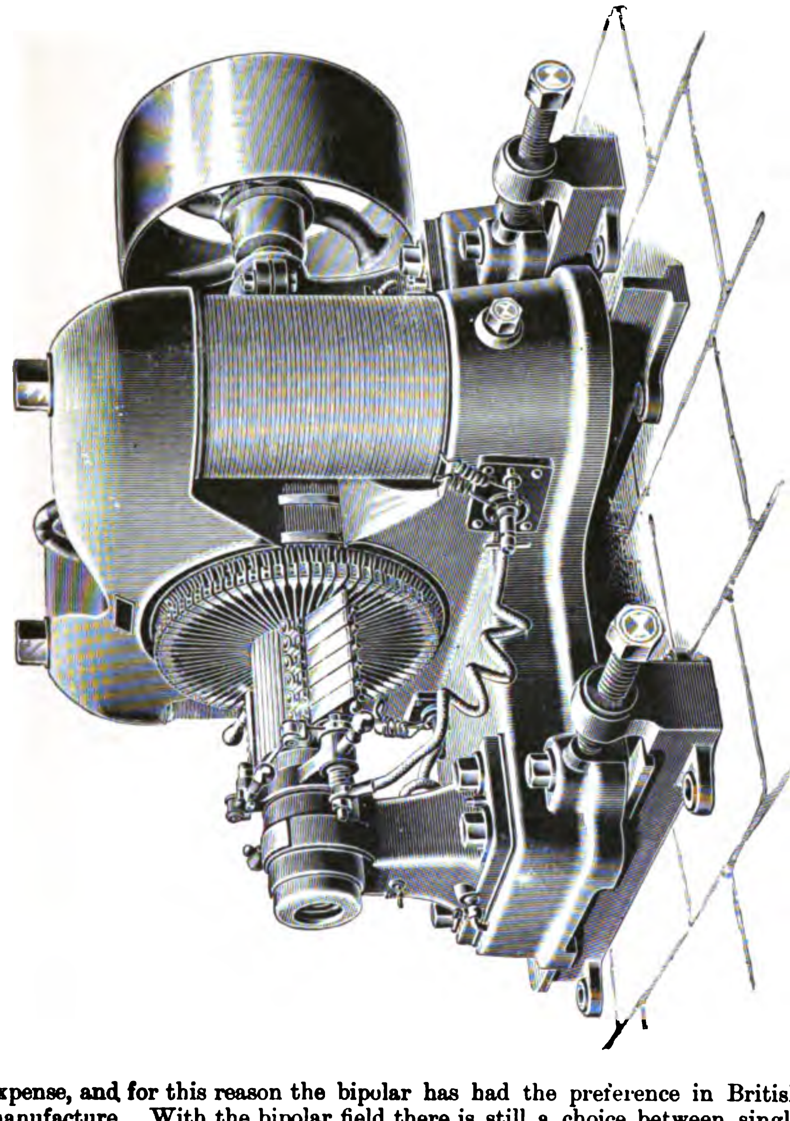


FIG. 22.

expense, and for this reason the bipolar has had the preference in British manufacture. With the bipolar field there is still a choice between single and double magnetic circuit external to the armature.

The leading types of field-magnets adopted for closed-coil armatures will be illustrated by a selection of prominent examples.

Fig. 21 illustrates a large two-pole single magnetic circuit dynamo by the Brush Electrical Engineering Company, suitable to an elongated drum-wound armature of small diameter, to be driven at high speed. The field-magnets are entirely of wrought iron, the long rectangular section of the limbs requiring considerable excess length per turn above what would be necessary for a circular section of the same area. With this shape it is somewhat difficult to maintain equal distribution of the induction across the polar gaps, especially with Pacinotti armature cores, but this is of minor consequence with drum-winding. The low position of the armature renders the dynamo comparatively free from vibration, and a similar type inverted, in which the armature is at the top, and for this reason the field-magnet yoke is formed by the cast-iron bed-plate, is only convenient with dynamos of smaller size. There is in all cases considerable magnetic leakage past the armature in all single magnetic circuit dynamos, more particularly in the type shown, in which a thick zinc plate is necessary between the field-magnet poles and the bed plate to prevent a magnetic short circuit.

The double bipolar magnetic circuit is illustrated by the Brush dynamo in Fig. 22, and for this type heavy cast-iron pole-pieces and wrought-iron limbs of circular section are most convenient. It is adapted for armatures of shorter length and greater diameter than the single-circuit types, and the symmetry of the magnetic field renders ring-wound armatures convenient. The large area for the radiation of heat, and the ready accessibility to the armature by removing the upper pole-piece, renders this type most advantageous. The magnetic leakage is, however, very large when the coils are wound as shown, the limbs being far removed in the magnetic circuit from the armature. A leakage coefficient (the ratio of the total flux of magnetic induction in the limbs to that through the armature-core) of about 1.4 must be allowed, whereas 1.3 is sufficient with the single magnetic circuit with a similar armature-core. The division of the magnetic circuit also necessitates double the number of turns in the magnetising coils for the same total flux, the length of conductor being greater than for a single circuit of the same area, though the employment of circular section will partly compensate for this.

The multipolar design is illustrated in Fig. 23. The armature is a ring or Gramme-wound two-circuit type designed by Kapp for an output of 500 ampères at 260 volts (130 kilowatts). The magnetising coils are wound on the eight poles which project inwards from a surrounding ring, and the leakage coefficient is extremely small. The arrangement is known as the "ironclad" type of field-magnets. The ironclad type possesses the advantages of producing practically no external magnetic influence, and having the coils in the interior and well protected from injury. It is not as a rule possible to extend the area of the pole faces in proportion to the sectional area of the magnetic circuit in the iron to the same extent with multipolar dynamos as with bipolar dynamos, and hence the Pacinotti or tunnel-wound armatures are more favoured as affording a shorter air-gap.

The above are typical forms of field magnets such as are now most commonly adopted for closed-coil armatures. Others, less commonly used for this type of dynamo, but quite permissible, will be illustrated in our descriptions of open-coil and alternating current dynamos for which they are better suited. The following general considerations should guide our choice and design:

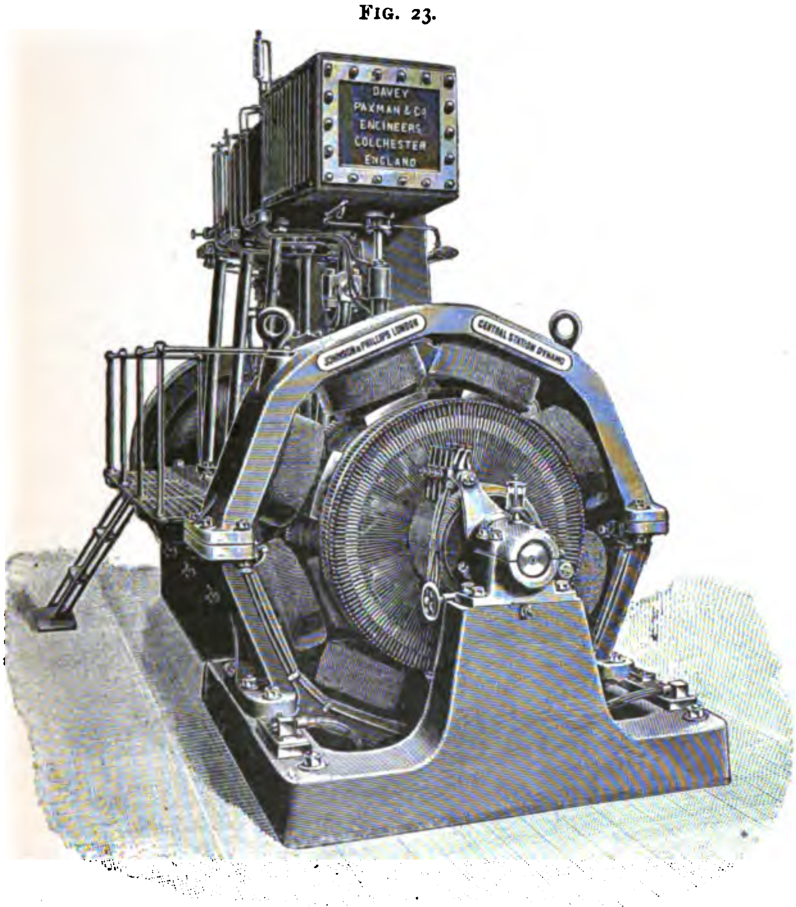
(1) It is better to reduce the length of the magnetic circuit or circuits as far as possible, to save weight and magnetic reluctance; but with iron of high permeability this is of less consequence. On the other hand it is not advisable so to shorten the length that the magnetising coils are crowded into too short a length, necessitating great depth of winding with extra length of each turn, and incurring difficulties in obtaining sufficient surface for the radiation of heat. Snell gives as the suitable length of the limbs available for the winding of the coils as .75 times the diameter of the

armature with the single-circuit bipolar field, .9 times the diameter with the double circuit bipolar, and .4 to .5 times the diameter with the multipolar fields.

(2) Sharp angles and turns in the magnetic circuit should be avoided as favouring leakage. The magnetising coils should, for the same reason, be preferably wound near the poles.

(3) Joints in the iron should be truly surfaced, and not too tightly

FIG. 23.



bolted, as this decreases the permeability without reducing the magnetic reluctance of the joint.

(4) A circular section for the limbs on which the magnetising coils are to be wound is theoretically the most efficient, but this will be modified by practical considerations.

With some large Central Station dynamos it is found convenient to supply the current for the magnetising coils from an additional small dynamo; the field coils are then wound with a comparatively few turns of copper strip or cable of considerable sectional area, and a large current is sent through them with a low E.M.F., thus expending little energy in magnetisation, while the current is regulated by hand with a rheostatic resistance to vary or keep constant the E.M.F. of the large dynamo as may be required. The more common arrangement is to obtain the current from the dynamo armature itself, and there are two ways in which the magnetising coil or coils may be connected.

In *series* winding the magnetising coils are wound with a comparatively few turns, capable of carrying the whole current output of the armature, and connected in series with it, so that the magnetising force is proportional to the whole current in the armature. In *shunt* winding the magnetising coils are of much finer wire, and many turns, giving considerable resistance, and connected between the brushes or terminals of the dynamo, thus forming a circuit independent of the external circuit of the dynamo. The current in the shunt-coils is determined by the E.M.F. between the brushes or terminals and its own resistance.

Series winding alone is generally employed with dynamos of high E.M.F., more frequently with open-coil dynamos than with closed-coil, on account of the difficulty of obtaining sufficient resistance in the shunt-coils without an enormous number of turns, or considerable waste of power. Shunt winding alone is employed for dynamos intended for charging secondary batteries, and large Central Station dynamos, where hand regulation is convenient. The combination of shunt and series winding, or *compound* winding, having certain regulative properties which will be dealt with in the next chapter, is adopted in by far the greater number of dynamos for Electric Lighting upon the parallel or multiple-wire systems.

CHAPTER VI.

The Closed-coil Dynamo (Design and Regulation).

The behaviour of a dynamo under all conditions of load, provided it be run at a constant specified speed, may be determined by tracing a curve which shows the relation between the electromotive force and current, or the number of volts generated in and the number of ampères flowing in the armature, when various external resistances are to be found between the dynamo terminals.

This graphic method was first used by Dr. Hopkinson, and applied to a Siemens' dynamo (series-wound), the results being given in a paper published by the Institution of Mechanical Engineers (*Proceedings Inst. M.E.* 1879, p. 246, and 1880, p. 266). The expressive term "characteristic" was applied to Hopkinson's curves in 1881 by Marcel Deprez.

It has been shown how the total electromotive force of the dynamo can be calculated in terms of the speed, number of turns in the armature, and the total flux of Magnetic Induction through the armature-core. The latter will depend upon the number of ampère-turns in the magnetising coils, which will in its turn depend upon the current flowing in the armature and external circuit in the case of a series-wound dynamo, and upon the difference of potential between the terminals in a shunt-wound dynamo.

The difference of potential between the terminals of the dynamo will not be the same as the total electromotive force obtained from the calculation made in the last chapter, but will be less than the total electromotive force by an amount equal to the products of the measures of the current in and resistance of the armature coils.

We, therefore, have all materials for the prediction of the characteristic curve by means of the principles of electromagnetism when we are given all the measurements of the dynamo. The first step will be to find the relation between the flux of magnetic induction and the number of ampère-turns in the magnetising field coils, and this relation will also be best represented by a curve. Such a curve must depend solely upon the properties of the magnetic circuit, and not upon the speed at which the dynamo is driven. This curve is commonly called the *normal* characteristic of the dynamo, and from this the characteristic curves predicting the action of the dynamo under various conditions may be traced.

The relation between the flux of Magnetic Induction through the armature and the current in the field coils in several different types of dynamos were very fully discussed in a paper by Drs. J. and E. Hopkinson presented to the Royal Society in 1886 (*Phil. Trans.* 1886, Part I. p. 331). We may follow some of the investigations recorded in this paper.

As a first approximation let us assume that there is no leakage of Magnetic Induction through the air, and that all the lines of force in the field magnet pass through the iron core of the armature. Let N denote the total flux of induction; A the sectional area of the armature transversal to the lines of force; l_1 the mean length of the lines of force within it; A_2 the area of the air spaces midway between the pole-pieces and the core of the armature; l_2 the distance between the pole-pieces and core; A_3 the area of the cores of the field magnets; l_3 the total length of the field magnets. Then assuming in each portion a uniform distribution of Magnetic Induction, we have in the armature core $B = \frac{N}{A_1}$, in the air spaces $B = \frac{N}{A_2}$, and in the field magnets $B = \frac{N}{A_3}$. In air B = H, and in the iron the relation between B and H is given by one of the curves described in the chapter on Electromagnetism. From these curves we may suppose H expressed as a function of B, say H = f (B). Then in the armature we $H = f\left(\frac{N}{A_1}\right)$, in the air space simply $H = \frac{N}{A_2}$, and in the field magnet $H = f\left(\frac{N}{A_3}\right)$.

Now the line integral of H through the whole magnetic circuit is due to the current C in the coils of the field magnets. Suppose the coils to contain n turns of wire, or that nC is the total number of ampère-turns in the coils, this Line Integral is equal to $\frac{4\pi nC}{10}$, C being measured in ampères, and, remembering that there are two air spaces, we have the equation,

$$l_1 f\left(\frac{N}{A_1}\right) + 2l_2\frac{N}{A_2} + l_3 f\left(\frac{N}{A_3}\right) = \frac{4\pi nC}{10},$$

which may be taken as the equation to the normal characteristic, giving the relation between N and the magnetomotive force $\frac{4\pi nC}{10}$

This curve may be traced by drawing the three curves, in the common notation of Cartesian co-ordinates

$$\text{(A) } x = l_1 f\left(\frac{y}{A_1}\right) \qquad \text{(B) } x = 2l_2\left(\frac{y}{A_2}\right) \qquad \text{(C) } x = l_3 f\left(\frac{y}{A_3}\right)$$

(which are really the curves giving the relation between H and B for the class of iron used, the straight line representing the quality of H and B in air, the ordinates being multiplied by A_1, A_2, A_3, and the abscissæ by l_1, l_2, l_3 respectively), and then forming a fourth curve whose abscissa corresponding to any ordinate is the sum of the corresponding abscissæ in the former curves.

There are several sources of error in this first approximation:

(1) In any actual dynamo the yoke and pole-pieces should be treated separately frcm the cores or limbs of the field magnet, owing to the difference of area of the magnetic circuit, and generally to the different material used.

(2) The magnetic reluctance of joints already spoken of may not be negligible.

(3) The lines of Magnetic Induction in passing from the pole-pieces to the armature core will at the edges of the pole-pieces spread out laterally, so that the sectional area A_2 will be greater than the area of the portion of the cylindrical surface which lies midway between the pole-pieces and the armature-core. To correct for this Hopkinson added to the portion of the cylindrical surface a strip on each side whose breadth was .8 of the distance between the core and pole-piece.

(4) There will be considerable magnetic leakage through the air from the pole-pieces and limbs of the field magnets, so that the whole of the Magnetic Induction passing through the field magnets will not pass through the armature. If N be the induction through the armature, to be used in calculating the electromotive force of the dynamo, νN may be taken to denote the Induction through the yoke and limbs of the field magnets, ν being a quantity to be determined experimentally for any particular dynamo, or estimated in designing. As N increases the magnetic permeability of the iron diminishes, and therefore ν increases. The value of B in the limbs or the field magnets will then be $\frac{\nu N}{A_3}$ instead of $\frac{N}{A_3}$ as before.

Employing A_4 to represent the sectional area of the yoke, and l_4 for the mean length of the line of Induction through it, A_5 and l_5 for the corresponding quantities for each pole-piece, the equation for the characteristic becomes

$$l_1 f\left(\frac{N}{A_2}\right) + 2l'_2 \frac{N}{A_2} + l_3 f\left(\frac{\nu N}{A_3}\right) + l_4 f\left(\frac{\nu N}{A_4}\right) + 2l_5 f\left(\frac{N}{A_5}\right) = \frac{4\pi nC}{10}$$

when A_2 is now corrected for the spreading of the lines of Induction as described above. If different kinds of iron, such as cast iron for the pole-pieces and wrought iron for the remainder of the magnetic circuit, are used, a different algebraic function, or a different shape of curve must be used for the pole-pieces and limbs, &c.

The above equation is built up to suit the case of the single magnetic circuit as used in the Edison-Hopkinson dynamo to which it was first applied by Dr. Hopkinson. The variations in the case of multiple magnetic circuits can be easily understood, it being only necessary to take the sum of the areas of corresponding parts of the multiple circuits.

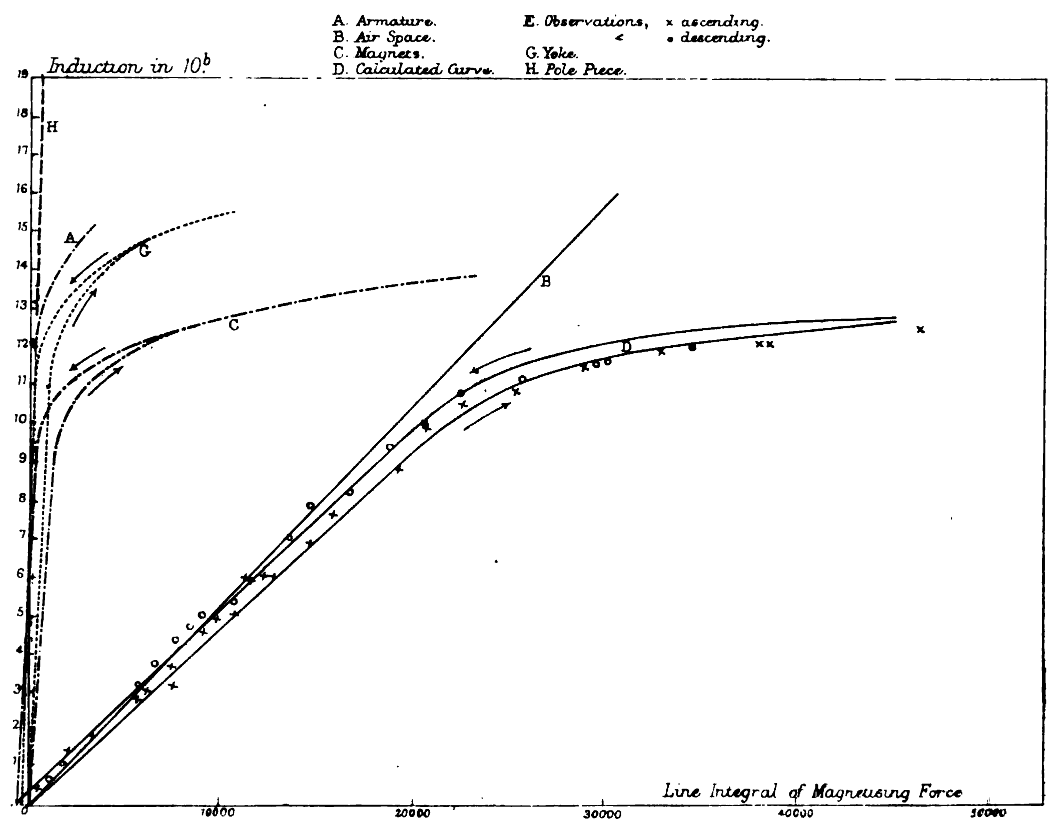
It will be seen that the measurement of some of the quantities, especially A_4, l_4 and A_5, l_5, must necessarily involve considerable uncertainty, since an average has to be taken, and the exact disposition of the lines of Induction cannot be determined. The errors thus introduced will not, however, be of very great importance owing to the preponderating magnetic reluctance of the air-gap.

In Plates IX., X., we have given reduced copies of curves published by Dr. Hopkinson in connection with the paper above mentioned, from which the characteristic curves of two typical dynamos were predicted, and the accuracy of the method verified by subsequent trial. It is not considered advisable to insert all the detailed measurements upon which the calculations for these curves was founded, as they involve a large amount of estimation which must be made in a different manner for any type of dynamo which may be similarly dealt with, and the principles upon which

J & E. Hopkinson.

Plate IX.

Sheet II.



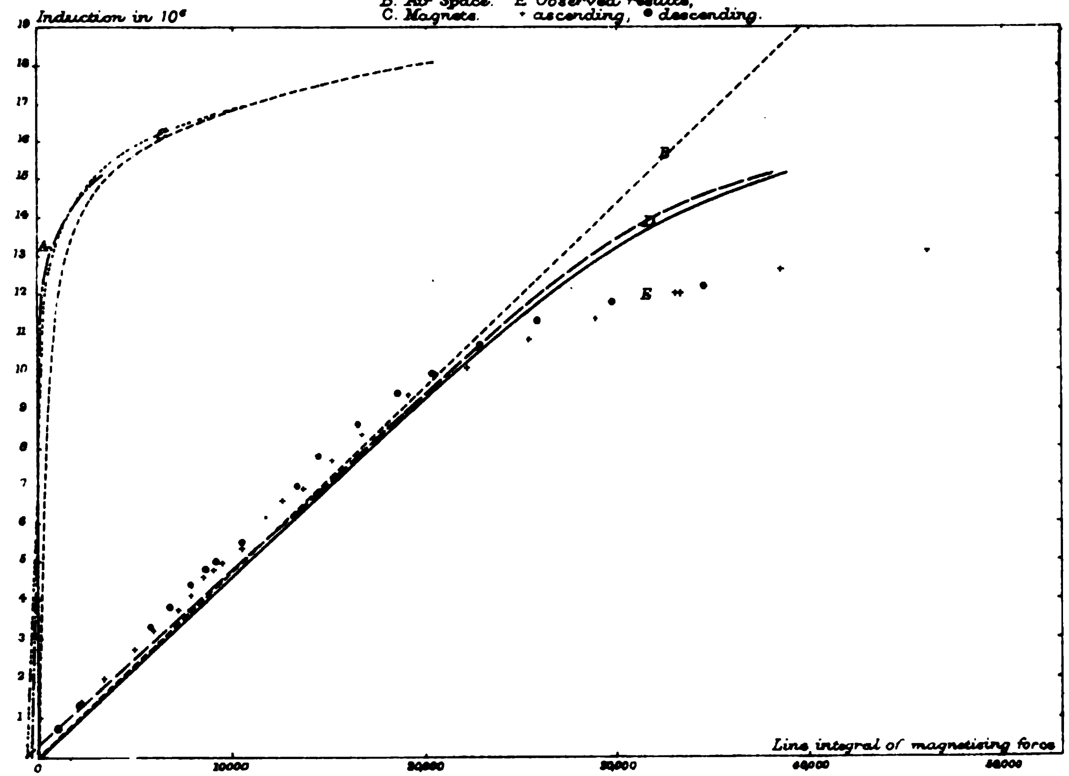
West, Newman lith.

Plate X.

Sheet II.

Approximate Synthesis of characteristic curve

A. Armature. D Deduced curve.
B. Air Space. E Observed results,
C. Magnets. · ascending, ● descending.



West Newman, lith.

the calculations are to be made has been given above. A few details may, however, be found useful.

Plate IX. deals with a bi-polar, single magnetic circuit dynamo of the Edison-Hopkinson type. The limbs of the field-magnets were rectangular in section, each limb and pole-piece one solid forging of hammered scrap, to which the yoke was attached by bolts. The shunt-wound field-magnet coils consisted of 3260 turns of No. 13 B.W.G., having a resistance of 16.93 ohms at 13.5° Cent. The armature was drum wound (Hefner Von Alteneck type) with 40 turns in two layers. The normal output of the dynamo was 320 ampères at 105 volts with a speed of 750 revolutions per minute.

The figures estimated from most careful measurements, and used for the calculation of the Line-Integral for various parts of the dynamo, were:

1. For armature core A_1 = 810 square centimetres; l_1 = 13 cms.
2. For air-gap (129° of surface of mean cylinder between armature and pole-pieces plus 4.8 cms. for spreading)

	A_2 = 1600 square cms.	l_2 = 1.5 cms.
3. For limbs	A_3 = 980 square cms.	l_3 = 91.4 cms.
4. For yoke	A_4 = 1120 square cms.	l_4 = 49 cms.
5. For pole-pieces	A_5 = 1230 square cms.	l_5 = 11 cms.

The quantities l_1, A_5, and l_5 could only be roughly estimated. The ratio of leakage $\nu = 1.32$ for the armature was obtained by comparison of the inducted instantaneous currents produced in turns of wire round the limbs and the armature respectively when the field magnets were short-circuited. This was found to vary according to the intensity of the Induction, and corresponding corrections made.

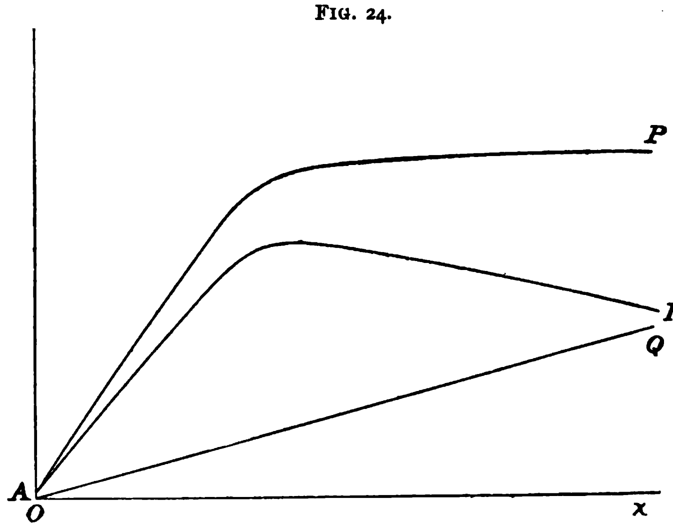
The observations made of the electromotive force produced when running, from which the total flux of Induction may be calculated, verify the extreme accuracy of the method employed.

Plate X. represents the application of the method to a bi-polar, double magnetic circuit dynamo made subsequently by Drs. J. and E. Hopkinson. In this type, Mather and Platt's "Manchester" dynamo, the opportunities for leakage were much greater, and though the results proved fairly accurate up to the point where the iron approached saturation, a rapid falling off of the observed characteristic from the calculated was noticeable from this point onwards. Owing to the comparatively excessive reluctance of the air-gap with low magnetisations of the iron, the illustration scarcely does justice to the accuracy of the calculations, but a figure showing the variation of the observed and calculated curves from a straight line would indicate a fairly close agreement.

The *external characteristic* of a dynamo is a curve drawn to indicate all the possible relations between the E.M.F. or difference of potential between the terminals, and the current flowing in the external circuit, as determined by the magnetic and electrical properties of the dynamo itself, when driven at a uniform speed. This curve will be practically useful to determine the values of the output in current and E.M.F. when the dynamo is subjected to various loads, by the alteration of the external resistance, as by the switching on or off of lamps. A second relation between the current and E.M.F. will be given by the conditions of the external circuit, either simply by Ohm's Law, or a modification due to the variable resistance of the filaments of incandescent lamps, and the regulating mechanism of arc lamps. The latter relation may also be represented graphically by a straight line or curve, whose intersection with the external characteristic will determine the actual output in current and E.M.F. under the given conditions, the two curves being equivalent to simultaneous algebraic equations for determining the two variables, and their intersection to the solution.

In the series-wound dynamo, which will first be considered, the current flowing in the external circuit is the same as that in the field-magnet coils, there being but one circuit outside the armature, and the external characteristic may be deduced immediately from the curve showing the relation between the flux of Induction through the armature and the Line-Integral of the Magnetising Force as predicted by the methods described above. A change of the scales for both ordinates and abscissæ will reduce the latter to measurements of the current in ampères, and the former, by the formula given in the preceding chapter, to those of the whole E.M.F. produced in the armature in volts. Such a curve may be termed the "total characteristic" of the dynamo. The available E.M.F., or the difference of potential

FIG. 24.



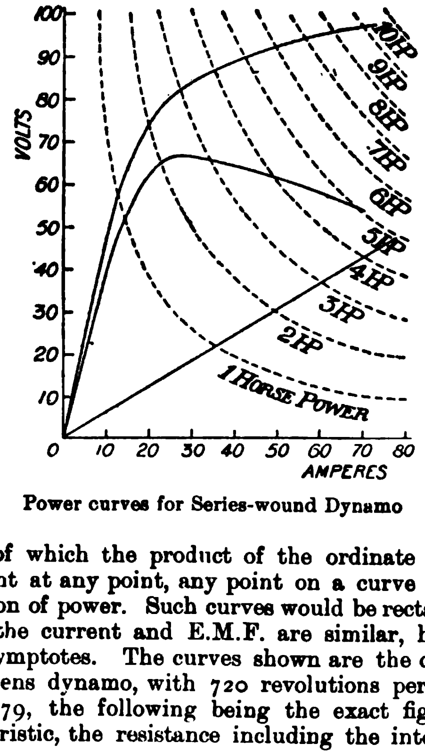
Characteristic of Series-wound Dynamos.

between the terminals of the dynamo, will be less than that produced in the armature, by the E.M.F. required to maintain the current through it and the series coils. There will also be a reduction due to the lead given to the brushes, sensible only with heavy loads, and considered negligible in the following discussion. Subtracting this reduction from the ordinates of the total characteristic we shall obtain the external characteristic of the dynamo.

Let AP in Fig. 24 represent the total characteristic curve obtained as described, the ordinates representing the E.M.F. generated in the armature, the corresponding abscissæ the current C in the field coils and external circuit. Draw the straight line OQ so that its ordinate at any point may represent the corresponding value of r.C, where r is the resistance of the armature and field magnet coils combined, construct the curve AR so that its ordinates are the difference of the corresponding ordinates of AP and OQ. Then AP is the external characteristic As previously shown, the slope of the AP rapidly diminishes when the induction reaches a certain point, on account of diminishing permeability. Generally it will be possible to find a point on AP where the tangent is parallel to OQ. The corresponding point on OR will be the highest point on the curve, and its ordinate will represent the maximum E.M.F. in the external circuit possible for the dynamo with the speed employed. With greater or smaller currents the external E.M.F. will diminish, but the current may vary over a considerable range with a fairly constant E.M.F. If OQ be produced to meet OP the abscissæ of the point of intersection will represent the maximum current obtainable from the dynamo, which will be when short-circuited. With most closed-coil armatures a short circuit would result in the speedy destruction of the commutator; but with open-coil armatures, to be described in a future chapter, this limitation of the possible current, much hastened by the armature reaction, is of great utility.

The product of the current in ampères and the E.M.F. in volts gives the total power absorbed in watts, and this product divided by 746 gives the power absorbed in horse-power. If, as in Fig. 25, a series of curves be

FIG. 25.



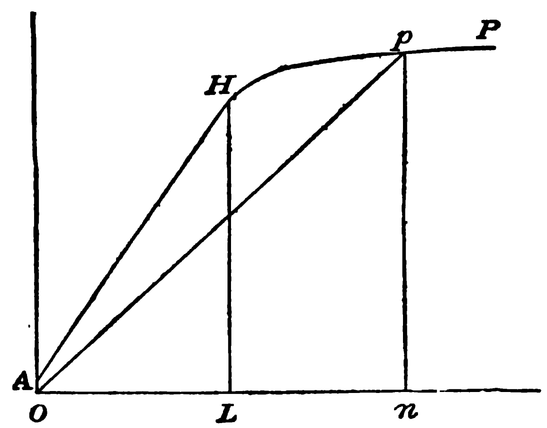
Power curves for Series-wound Dynamo

drawn for each of which the product of the ordinate and corresponding abscissæ is constant at any point, any point on a curve will correspond to the same absorption of power. Such curves would be rectangular hyperbolæ, if the scales for the current and E.M.F. are similar, having the axes of co-ordinates as asymptotes. The curves shown are the characteristics of a series-wound Siemens dynamo, with 720 revolutions per minute, tested by Hopkinson in 1879, the following being the exact figures obtained for the total characteristic, the resistance including the internal resistance of .6 ohms:

Current.		Resistance.		E.M.F.
0.0027	...	1025	...	2.72
0.48	...	8.3	...	3.95
1.45	...	5.33	...	7.73
16.8	...	4.07	...	68.4
18.2	...	3.88	...	70.6
24.8	...	3.205	...	79.5
26.8	...	3.025	...	81.1
32.2	...	2.62	...	84.4
34.5	...	2.43	...	83.8
37.1	...	2.28	...	84.6
42.0	...	2.08	...	87.4

If any point p be taken on the characteristic curve AP Fig. 26 and Op, pm be drawn, the resistance of the circuit corresponding to the point p is given by the ratio of *pn* to *On*, which is the tangent of the angle *pOn*. If this resistance, or the angle *pOn* be increased, the current will decrease till *p* reaches the point where the line *Op* becomes very nearly coincident with the curve. An exceedingly small increase in the resistance will cause a very great falling off in the current and E.M.F., and if it were not for the residual magnetism corresponding to *OA* would lead to the complete demagnetisation of the dynamo. The point *H* is thus a critical point on the curve, an increased resistance causing the conditions to be exceedingly unstable. An increase in speed of the dynamo will not alter the value of

FIG. 26.



Critical point of Characteristic

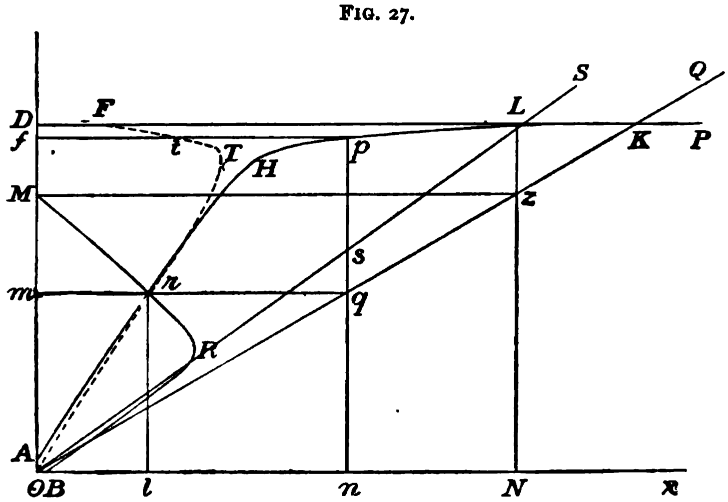
the critical current represented by *OL*, though the resistance in the circuit to which it corresponds will be raised by such an increase, and in practice it is not possible to use the dynamo to supply a smaller current. The difficulty presents itself frequently in series arc-lighting, for which series-wound dynamos are commonly used; for should the initial resistance of the circuit be too great, as when a pair of carbons are not in contact and the circuit is only complete through a shunt-coil, the residual magnetism will be insufficient to start a current such as will draw the carbons together.

In a shunt-wound dynamo the normal characteristic, or the curve expressing the relations between the Induction through the armature and the Line-Integral of the Magnetising Force due to the current in the field-magnet coils, *i.e.*, $\frac{4\pi}{10}$ times the number of ampère-turns, will be the same as for a series-wound dynamo with the same magnets and armature, since it depends solely on the reluctance of the magnetic circuit, but in this case the magnetising current is no longer the current in the external circuit, but dependent on the E.M.F., or difference of potential between the brushes and the resistance of the shunt-coil.

The relation between the current c in the field-magnet coils and the external E.M.F. E′, between the terminals of the dynamo is given by Ohm's law to be $\frac{E'}{s}$ where s is the resistance of the shunt-coils. Hence the relation between the E.M.F. and the magnetising current will be represented by a straight line drawn from *O* with an inclination to the horizontal whose tangent is s. Let this line be *OQ* in Fig. 27, and let *AP* be the normal characteristic. If these intersect at K, this point will correspond to a condition in which the whole E.M.F. is found in the external circuit. But since the current must meet with resistance in the armature this condition cannot be realised. If r denote the resistance of the armature, and a straight line OS be drawn inclined to the horizontal at an angle whose tangent is $r + s$, and cutting OP at L, we shall have represented the conditions requisite to maintain the magnetising current in the single circuit, including the armature and field magnet-coils, and no external current.

Draw any ordinate *psqn* cutting OS in s, and OQ in q. Then for the magnetising current c represented by On, the whole E.M.F. in the circuit will be represented by pn, and the external E.M.F. by qn. The intercept sp represents the E.M.F. required to maintain the magnetising current (On) in the armature, and therefore an amount represented by ps will

FIG. 27.

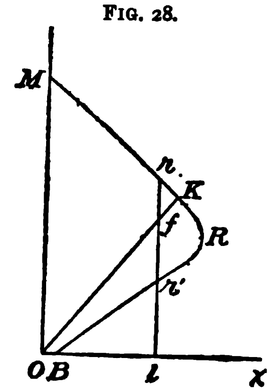


Formation of Characteristic of Shunt-wound Dynamo.

remain to maintain the *additional current through the armature* which that represented by qn sends through the external circuit. The current in the external circuit corresponding to the E.M.F. represented by qn will therefore be proportional to ps, or exactly represented by ps divided by the resistance of the armature in ohms (the latter is graphically represented by $\left.\frac{sq}{On}\right)$. If therefore we draw a horizontal line qm to the vertical axis, and cut off mr on a suitable scale proportional to ps, so as to represent the current flowing in the external circuit, r will be a point on the external circuit. As the resistance of the armature is in general extremely small, it will be necessary to make the scale of the abscissæ in this new curve, representing the currents in the external circuit, very much smaller than in the normal characteristic first drawn, where they represent the currents in the field-magnet coils. By taking a number of ordinates similar to pn, we may find any number of points on the external characteristic, and trace out the curve BRM. The point M where the curve meets the vertical axis, corresponds to zero current and maximum E.M.F., and is on a level with z, the point of intersection of OQ with the ordinate LN.

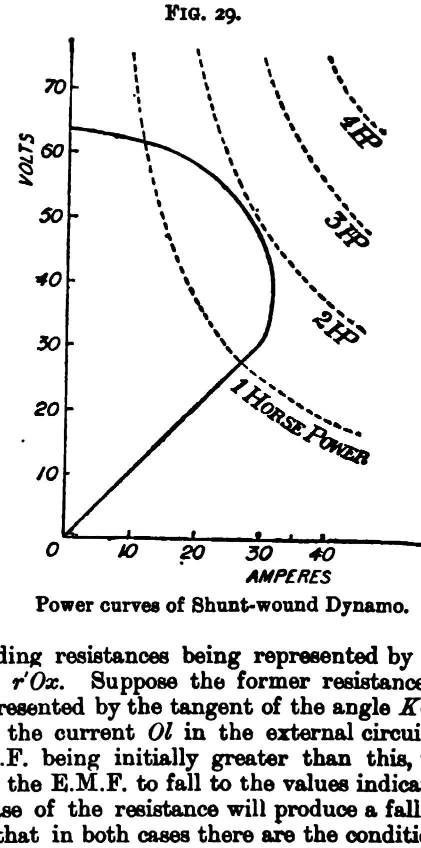
Let H be the point on AP where the tangentis parallel to OL. This will correspond to a point on the external characteristic where the tangent is vertical, say at *R*, for in the neighbourhood of *H* the intercepts *ps* have a stationary value. Near this point the E.M.F. of the dynamo may vary through a considerable range without very great change in the current, a fact sometimes made use of in charging secondary batteries, for which an unvarying current is advisable. It would seem as if it were possible to have two values of the E.M.F. corresponding to the same current, though with different resistances in the external circuit, but it may be shown that the lower value, corresponding to the lower resistance is unstable, and that it is impossible to maintain the conditions represented by the curve below *R*, the dynamo tending to demagnetise itself when the resistance of the external circuit is further reduced. For example, in Fig. 28 the two values of the E.M.F. represented by ***rl*** and ***r'l*** seem to be possible with the current

FIG. 28.



Critical point of Characteristic of Shunt-wound Dynamo.

FIG. 29.

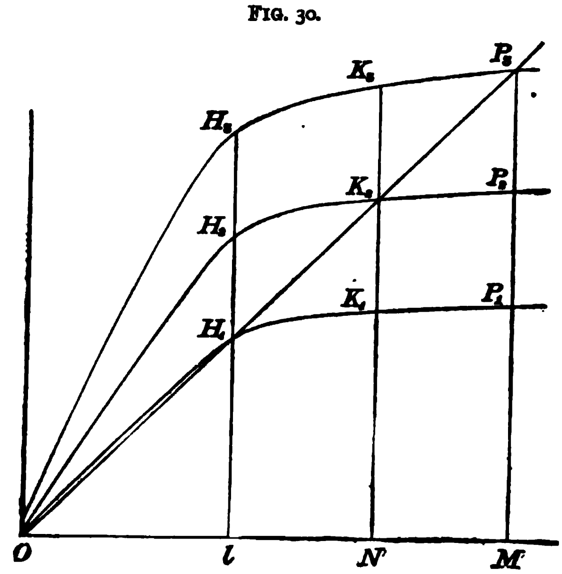


Power curves of Shunt-wound Dynamo.

represented by *Ol*, the corresponding resistances being represented by the tangents of the angles *rOx*, and *r'Ox*. Suppose the former resistance to be slightly reduced so as to be represented by the tangent of the angle *KOx*, the E.M.F. required to maintain the current *Ol* in the external circuit is represented by *fl*, and, the E.M.F. being initially greater than this, the current will begin to increase and the E.M.F. to fall to the values indicated by the point *K*. Also an increase of the resistance will produce a falling current and a rising E.M.F., so that in both cases there are the conditions for stability. On the other hand, with the condition represented by *r'*, the maintenance of the characteristic demands that an increase of the external resistance should accompany an immediate increase in the current, and *vice-versa*, which is the reverse variation to that which will initially be produced by the E.M.F., and thus the condition will be unstable, and cannot be practically maintained. There is a critical resistance, represented by the tangent of the angle *ROx*, below which the dynamo will not work with the speed for which this characteristic is calculated, but an increase in speed will lower the value of this critical resistance.

The abscissæ of the point *B* where the characteristic cuts the horizontal axis represents the current maintained by the residual magnetism when the dynamo is short-circuited, and therefore no current passes through the field-magnet coils. Fig. 29 represents the actual characteristic traced for a small Siemens shunt-wound dynamo as far as the vertical tangent, but the remainder of the curve is impracticable, if not incorrect. In Fig. 27 the resistance of the armature was made absurdly great in comparison with that of the field-magnet coils, as was necessary to produce a figure to illustrate the theory with clearness, so that the downward slope of the characteristic became intensified. The dotted curve represents the total characteristic giving the relations between the whole E.M.F. and the whole current produced in the armature, and is obtained by cutting off lengths

FIG. 30.



Effect of Speed on Characteristics

from the horizontal lines pf, proportional to pq (divided by the resistance of the armature in ohms).

The effect of a change in speed upon the characteristics of a series or shunt-wound dynamo may be studied by a reference to Fig. 30. The normal characteristics will be similar curves $OH_1K_1P_1$, $OH_2K_2P_2$, $OH_3K_3P_3$, as shown, the ordinates alone being increased or diminished in proportion to the speed. In the case of series-winding a higher total E.M.F. will be obtained with a higher speed and a given resistance in circuit; the increase of E.M.F. will not be merely proportional to the increase in speed, but in an excess ratio owing to a higher degree of saturation in the iron, the line $OH_1K_2P_3$ corresponding to the face resistance meeting the upper curves at more distant points. Moreover, the fall in E.M.F. due to armature resistance will remain constant, and proportionally less must be subtracted to obtain the difference of potential between the terminals of the dynamo. The maximum E.M.F. and the critical E.M.F. will however be found with the *same currents* for different speeds, though of course with higher values of E.M.F. and resistance at higher speeds, since the tangents at points on the various curves having the same ordinates are parallel. There is evidently no critical speed independent of the external resistance.

In shunt-wound dynamos the higher speeds will give an increased

E.M.F. at zero load in a somewhat greater proportion, with a higher degree of saturation in the field-magnets and armature-core. The current output will be increased in a much greater degree, as is evident if the preceding method of construction for the total and external characteristics be applied to the portions of three curves OH_1, OH_2K_2, $OH_3K_3P_3$, the line $OH_1K_3P_3$ representing by its inclination the resistance of the shunt-coils and armature. The maximum and critical current, though of course much greater with the higher speeds, will correspond to those points on the normal characteristic curve shown in the figure which are parallel to $OH_1K_3P_3$, and therefore to points having the same ordinate. Referring to the preceding construction for the external characteristic of the shunt-wound dynamo, it will be seen that the critical currents correspond to the same external E.M.F., and therefore to a much lower resistance in the external circuit. There will also be a critical speed, corresponding approximately to that which produces the normal characteristic $OH_1K_1P_1$, below which no appreciable E.M.F. can be obtained even on open circuit.

Shunt-wound dynamos are frequently employed for supplying constant E.M.F. to a parallel lighting system, driven at constant speed, the drop in the E.M.F. as the load increases being compensated for by removal of some additional resistance in the circuit of the shunt-coil. This method of regulation, commonly effected by the attendant though automatic regulators have been designed, is specially suitable in central stations where a considerable drop of E.M.F. in the mains has to be compensated for by an increase in the E.M.F. of the dynamo, so that it must be thoroughly under control, and the satisfactory running of the dynamos in parallel may be effected without complications. But when it is simply required that the E.M.F. should be kept absolutely constant, or rise a small definite amount in proportion to the current output, the method universally employed is to use a self-regulating or "compound-wound" dynamo adapted to the conditions.

Compound winding is a combination of both shunt and series windings for the field-magnet coils. We have seen that under ordinary conditions the E.M.F. of a series dynamo increases, and that of a shunt-wound dynamo decreases as the resistance of the external circuit is reduced. By a suitable combination the two variations may be made to counterbalance one another, or give, as commonly desired, a slight preponderance to the former, so as to compensate for the reduction in speed of the driving engine under heavier loads, and the drop in E.M.F. along the leads to the lamps.

When the dynamo is running upon open circuit, the magnetic field is maintained by the current in the shunt-coils alone, and the calculation to obtain the number of turns, and the resistance of the shunt coils, to give the required E.M.F. with the waste of energy permitted, is similar to that described above for the dynamo with shunt-coils only. A curve is drawn (the normal characteristic) showing the relations between the Induction through the armature, and the Line-Integral of the Magnetising Force $\frac{4\pi nC}{10}$; the requisite value of the former to give the E.M.F. being calculated, the latter, and therefore the number of ampère-turns is deduced from the curve; the current permissible being decided upon, the number of turns in the shunt coils is known. The drop of potential in the armature due to this current should be quite negligible.

To determine the number of series turns, let the conditions be considered when the maximum current C for which the dynamo is to be designed is flowing in the external circuit. The E.M.F. required to maintain this current through the armature and series coils (of combined resistance r) will be Cr volts, and if the Magnetic Induction through the armature be increased by an amount sufficient to produce this extra E.M.F., the difference of potential between the brushes will remain unaltered, provided the speed of the dynamo is maintained. A still further increase may be allowed for if desired.

There are two distinct methods of winding the shunt-coils to which attention must be called. They are most commonly connected as a single branch circuit to the brushes, in which case the difference of potential between the terminals is not identical with but slightly greater than that between the terminals of the dynamo, owing to the resistance of the series coils and consequent fall of the E.M.F. The latter should however be insignificant, and the current in the shunt-coils may be looked upon as invariable if the dynamo be regulated for constant E.M.F. (except for the temperature changes in their resistance). This is termed the "short" shunt winding. In the "long" shunt winding the shunt circuit is a branch between the terminals of the dynamo, and the number of series turns as calculated below must be subtracted from the larger number in the shunt-winding.

Supposing the current in the shunt-coils to be invariable, the extra Magnetic Induction must be produced by the Magnetising Force due to the current in the series coils. By the help of the normal characteristic we may calculate the extra number of ampère-turns required to raise the whole E.M.F. in the armature by the amount desired, and thence the number of series turns to give this number of ampère-turns with the maximum current.

From consideration of the normal characteristic, predictable from actual tests of samples of the iron used in the construction of the field-magnets, or of the external characteristic experimentally traced of an actual machine, we have shown how it is possible to determine not only the stable conditions under which the dynamo will work under given conditions of speed and resistance in the external circuit, but to some extent the degree of stability of those conditions. In another chapter we shall also show how the characteristic curves may be used to predict the manner in which dynamos will act when used conjointly, joined in series or parallel, to divide the power supplied to the same external circuit. Yet two other considerations, of the greatest importance to the engineer in charge of a supply station, can be determined, or at least explained, by a reference to these curves. These two considerations are the constancy of the polarity of field-magnets, and therefore of the direction of the electric current, after periods of inaction and practical demagnetisation; and the degree of certainty or rapidity with which the dynamo, on being started, will assume the calculated working magnetic conditions determined by the characteristic curves.

The difference between the ascending and descending curves traced as the external characteristic of any dynamo is found in actual practice to be inconsiderable for any moderate degree of magnetisation, the vibration inevitably removing any difference due to the property of retentiveness which would appear in the predicted curve from tests of iron samples. The difference is more considerable near the origin, and even with soft iron field magnets and smooth-cored armatures the magnetic circuit is generally sufficiently complete to retain sufficient residual magnetisation for re-starting, in spite of vibration for re-starting with little delay when the conditions which have been specified above as producing a stable magnetic condition near saturation are resumed. With cast iron or steel field-magnets, or countersunk armature-cores, the residual magnetism is fairly strong, and in all cases the reversal of the magnetism of the dynamo after inaction is a remote possibility, though not unknown. An increase of speed with shunt-wound dynamos, or a temporary short-circuiting, or "flashing," of series or compound wound dynamos has occasionally to be resorted to to hasten the process of magnetisation. To such a degree are the conditions of residual magnetism modified by the vibration, the elevated temperature, and even the manner in which the current is switched off from the dynamo in the process of "shutting down," that the conditions in resuming work after a period of inaction are most variable, and not amenable to any process of calculation.

Dynamos which are calculated to work with a low degree of magnetic saturation, and therefore, though generally of the highest efficiency, near to the conditions of instability, often present considerable difficulties in re-starting owing to a cause more difficult to combat than that of total demagnetisation when at rest. The working conditions of such dynamos are liable to excessive variations when their temperature is raised, and though their high efficiency may make them cooler than dynamos in which the magnetic saturation is higher, both on account of the reduced energy spent in the magnetising coils, and reduced hysteresis in the armature-core, the surrounding temperature in a small engine-room is subject to sufficient variations to cause difficulties.

The writer is responsible for the plant supplying an extensive institution, consisting of a $57\frac{1}{2}$K.W. steam-driven compound-wound dynamo, supplying 550 ampères at 105 volts, having as a sole reserve 70 ampère secondary battery. The field-magnets of the dynamo are of soft iron, and the dynamo is compounded at a fairly low degree of saturation, apparently close to the "knee" of the magnetising curve. The dynamo is generally run from dusk till 10.30 P.M., and loaded to the maximum for the last three hours. As the dynamo is considerably over-compounded, that is to say, the number of series turns is in excess of that required to give uniform E.M.F. at all loads, the gradually increasing current in the early hours of the evening automatically raises the electro-motive force slightly, as required to compensate for the fall in the leads, and little hand-regulation is required. In spite of the fact that the dynamo is rising all the time in temperature, it is only when the load has been excessive, or the ventilation of the engine-room poor, that the regulating resistance added to the shunt-coil has to be much reduced to maintain the full electro-motive force. As, however, the demand decreases, and the magnetising force due to the series coils is removed, it frequently becomes painfully evident that most of the magnetisation was due to the series turns, and the hot shunt-coil is now so much increased in resistance that the electro-motive force of the machine is impossible to maintain, except by increasing the speed of the engine. The dynamo begins to work below the "knee" of the magnetisation curve, becomes exceedingly unstable, and the electro-motive force may easily fall twenty or thirty volts.

After shutting down, the dynamo will not remagnetise itself if started before time has been allowed for cooling, nor even will it maintain its magnetisation at the normal speed unless loaded. The reason for this is that, working with the shunt coil only, the increased resistance when hot takes it below the critical point on the characteristic. Even if connected to a circuit of low resistance the hot dynamo will not self-magnetise, and it is necessary to send a current through the shunt-coils from the secondary battery, and switching the armature into parallel, give it a moderate load before the battery is removed. Then the dynamo will maintain its magnetism with a much lower output than that necessary to start it.

We have now to illustrate the methods upon which the calculations necessary to the design of dynamo machinery are made. From the preceding discussions it must be evident that a large amount of consideration and experience must precede calculation, since there are many great differences in the general type, and a multitude of differences in detail, between which it is impossible to decide as to superiority, and are left to the choice and ingenuity of the designer. The purpose of this discussion is not to enter further into these points, nor to give a detailed description of a model type, but, taking one of the simplest forms, to show how the electric and magnetic measurements to produce required results may be calculated, or when exact calculations are impossible, may be estimated with sufficient exactness to be a guide in their construction.

In making the calculations necessary with the design of a new type of dynamo, when the general shape of certain parts, which is chiefly a matter of choice and experience, has been decided upon, and the intention is to produce a specified output in E.M.F. and current, it is most convenient to fix arbitrarily upon certain dimensions, as near as experience has indicated will be sufficient for the purpose, and calculate as nearly as possible, the E.M.F. and current that can be produced with the requisite efficiency with these dimensions. Then, if a relation between the output and calculated dimensions of similar dynamos of various sizes can be determined, expressing the result of multiplying or dividing the dimensions arbitrarily assumed by certain factors, it will be easy to choose the factors which will modify the first design to suit specified conditions. This relation between different sizes will, moreover, be most convenient when a number of similar dynamos are required, for example, giving the same E.M.F. but adapted for different current-output. And the corrections which have to be made in the first design when carried out in practice will indicate the corrections in the similar designs with different dimensions.

Suppose, for example, we wish to find the effect of multiplying all the linear dimensions of the field-magnets, armature, etc., of a dynamo by a factor x but obtain the same E.M.F.; as this will frequently necessitate, owing to mechanical limitations, a change in the speed with which it can be driven, we will suppose this also multiplied by a factor s. The sectional area of the magnetic circuit is multiplied by x^2, and if the density of the magnetic induction is to be kept unchanged, the total flux will be multiplied by x^2. The number of turns in the armature winding to produce the same E.M.F. will be multiplied by $\frac{1}{s.x^2}$. The space for winding the armature conductors will be multiplied by x^2 (allowing a proportionate increase in the magnetic gap between iron and iron), and therefore their sectional area by $s.x^4$. The length of each turn will be multiplied by x, but since the number is multiplied by $\frac{x^2}{s}$, the length of the armature circuits from brush to brush will be multiplied by $\frac{1}{s.x}$. The resistance of the armature will thus be multiplied by $\frac{1}{s^2.x^5}$.

It follows that if the current output is limited by the current density in the conductors of the armature, it will be increased by the factor $s.x^4$; but if by the electrical efficiency, or drop of potential in the armature at full load, by the factor $s^2.x^5$. In general the peripheral speed of the armature is pushed up to the maximum that is safe, being limited by the danger of disruption by "centrifugal force," so that $s = \frac{1}{x}$. In this case the current output, for the same density in the conductors and same electrical efficiency, is multiplied by the factor x^3, or is proportional to the volume and weight of the dynamo.

But the larger dynamos have an advantage which does not appear in the above calculation. The space occupied by the insulation may be less owing to the reduced number of conductors, and very much less in proportion to the space available. And considering the commercial consideration of output in proportion to the cost, there will be a decrease in the relative cost of labour and waste of material in the larger dynamos. To set against this it must be noticed that the surface for the radiation of heat is only proportional to x^2, so that a higher efficiency, or a reduced current density in the armature current, is expected, if the rise in temperature above the surroundings is to be the same as for smaller dynamos.

Suppose we wish to design a large dynamo to supply a constant E.M.F. of 110 volts, with an efficiency at full load about 95 per cent. Following closely the design of a dynamo which has been constructed with the dimensions here laid down, we will presuppose a cylindrical Pacinotti armature-core, built up of stampings 35 cm. in external diameter, with an internal diameter of 12 cm.; the grooves between the Pacinotti "teeth" to be a centimetre deep, and the length of the cylinder 34.5 cm. Such an armature may be run safely at 1000 revolutions per minute, giving a peripheral speed of about 40 miles per hour.

The minimum cross-section of the magnetic field in the armature will have a breadth of 21 cm. (doubling the minimum depth of the cylindrical core) and a length of 34.5 cm., giving a total section of 724.5 square cm., or, allowing 10 per cent. for thin paper insulation between the discs, of 6.52 square cm. of solid iron. Across this section there will be the maximum density of Magnetic Induction, and it is advisable that this density should never exceed 12,000 c.g.s. units, or lines of force. As the E.M.F. developed in the armature must rise to about 115 volts at the maximum load, we shall calculate the requisite number of turns on the supposition that the Induction reaches its full value of 12,000 units with this E.M.F. If n be the number of surface conductors

$$115 = \frac{652 \times 12000 \times n \times 1000}{10^8 \times 60}$$

whence n = 88 very nearly.

The circumference of the armature-core will be π.35 or about 105 cms., giving, with 88 surface conductors, a circumferential breadth of 1.2 cms. for each conductor. Supposing the Pacinotti "teeth" to be of equal breadth to the intervening grooves, and one conductor only to be laid in each groove, the space left for each conductor, with insulation, will be .6 cm. by 1 cm. Copper strip .9 × .5 or .45 square cm. (.07 square inch) may be used, and this at 2000 ampères per square inch will carry 140 ampères. There will be no objection to exceeding this current density to give 150 ampères, or 300 ampères for the total output. As the Magnetic Induction will pass almost entirely through the teeth, avoiding the intervening gaps in which the conductors are wound, lamination of the copper strip need not be resorted to, as eddy currents will not be formed to any extent. It will be advisable perhaps to employ two strips, .9 × .25 centimetre, for ease in manipulation. To estimate the resistance of the armature: the length of a turn in ring-winding will be about 100 cms., and the total length from brush to brush 4400 cms., with a total section of .9 square cm. This, if of high conductivity copper, should give a resistance of about .008 ohm when cold, rising to about .01 ohm when raised to a temperature of 50° Cent. With drum-winding a slightly lower resistance could be secured, but with the relative length and diameter of the core here employed the reduction would be small.

With the low value of the Magnetic Induction assumed the leakage of the field past the Pacinotti armature cannot be great, and may be estimated at 25 per cent. of the flux through the armature. If the same density is to be maintained in wrought-iron field-magnets (it might perhaps with advantage be increased) a sectional area of 815 square cms. will be required. In the limbs, on which the coils are to be wound, the section may be made rectangular, measuring 33 × 25 cms. with corners slightly rounded off. The centres of the limbs would be about 40 cms. apart, and the yoke slightly wider and thinner.

We will suppose that the length of each limb of the field-magnets is 50 cms., the length of the mean path of Induction in the yoke 43 cms., and in each pole-piece 20 cms. The Induction is nearly uniform throughout, except that it is somewhat less in the pole-pieces than in the rest of the circuit. We may thus take the total length in the field-magnets as 183 cms.

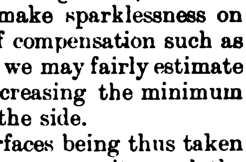
It is not possible to determine the mean length of the lines of Magnetic Induction in the armature-core with any great degree of accuracy. Supposing the width of the gaps between the horns of the poles to be 12.5 cms. (corresponding to an angle of about 40° at the centre of the shaft), the mean length may be taken as double, or 25 cms. There will thus be a total length of 208 cms. in iron, and if the joints be duly surfaced and tightly bolted together, we may safely neglect their magnetic reluctance.

The number of ampère-turns in the shunt-coils necessary to maintain the Magnetic Induction in the iron portion of the circuit only may now be calculated. At zero load, the E.M.F. generated in the armature being 110 volts, we may take the Induction to be 11,500 c.g.s. units. For this density the value of μ may be taken as 1550, and the value of H as 7.42. Multiplying this by 208 we have for the Line-Integral of the Magnetising Force $\left(\text{or } \frac{4\pi}{10} nC\right)$ the value 1543, giving 1218 ampère-turns.

The magnetic reluctance of the air-gap will, in this dynamo, be the more important term. The surfaces of each pole-piece will subtend an angle at the centre of the shaft of 140°, and, allowing a little for the spreading of the lines at the horns, we may take the width of the air-space as 44 cms., the total area over which the lines are spread as 1524 square cms., giving a density of 4920 c.g.s. units.

The opposing surfaces of iron on the two sides of the gaps are by no means uniformly distant. If a clearance between the extremities of the teeth be not greatly less than the width of the teeth, say half a centimetre, the arrangement of the lines of force in the gap will be somewhat similar to that shown in Fig. 31, and it will be seen that on entering the surface of the pole-pieces the field is fairly uniform, and the wasteful eddy currents and heating of the pole-pieces by the rotation of an irregular field will be eliminated. When larger teeth are preferred it will be necessary to stamp the discs so as to broaden the extremities of the teeth, and leave only a narrow neck to the grooves on the outer circumference. The clearance may then be reduced to that necessary for free rotation; but the cost of stamping and winding will be greater, and the reaction of the armature current on the field will make sparklessness on the commutator difficult to secure unless a method of compensation such as that previously described is employed. In our design we may fairly estimate the average length of lines in the gap as .65 cm., increasing the minimum of .5 cm. to allow for those which enter the teeth at the side.

FIG. 31.



The length of the double gap between the iron surfaces being thus taken as 1.3 cms., the intensity of the Induction is 4920 c.g.s. units, and the permeability being unity the requisite Line-Integral of Magnetising Force will be 6396 so that the number of additional ampère-turns to maintain the Induction through the gap will be 5090, giving a total of 6318.

If we allow a current of 4 ampères, slightly over 1 per cent. of the total output, to flow through the shunt-coils, we shall require 1580 turns to obtain the required number of ampère-turns, or 790 on each limb, and a total resistance of 27.5 ohms. The circumference of each limb will be 116 cms., but allowing space for insulation and, if desired, ventilation between the bobbin and the field-magnet limbs, and for some depth to the winding, the average length of a turn can hardly be less than 140 cms., giving a total length of 221,200 cms. For this length a resistance of about 24 ohms will be given by a single No. 17 s.w.g. wire at 15° Cent., rising to the required 27.5 with a rise in temperature of about 35° Cent.

It will require but 3 volts to force the full current of 300 ampères through the armature (.01 ohm). The high magnetic reluctance of the air-gap compared with that of the field-magnets and armature indicate that a very small lead of the brushes will be sufficient to obtain sparkless commutation, and the fall of E.M.F. thereby occasioned will be small in comparison to that due to the armature resistance. To allow for this, and for a slight decrease in in the speed, we shall consider the number of series necessary to raise the E.M.F. in the armature to 115 volts at full load. For the air space the increase in the necessary ampère-turns is proportional to the increase of the Induction, giving an increase of 231. In the iron part of the circuit we have to allow for a decrease in the permeability of the iron, which, according to the measurements of Ewing, reduce for a value of the Induction of 12,000 units to 1412. The necessary number of ampère-turns will therefore be $1228 \times \frac{1550}{1412} \times \frac{115}{120}$, or 1406, giving an increase of 178 ampère-turns. The total increase will therefore be 409 turns, making no allowance for additional leakage. Two turns of series winding, carrying the whole current of 300 ampères, should be sufficient to slightly over-compound the dynamo, maintaining constant potential between the mains at some little distance from the dynamo, or compensating for a diminution of speed at full load.

The total weight of wrought iron in the field-magnets and armature will come to about 33 cwt. The weight of copper in the armature conductors about 80 lbs., and in the shunt-coils 60 lbs. Wrought iron has been supposed used throughout, regardless of expense. If cast iron be used for any part, as is frequently considered advisable for the pole-pieces or the yoke, the sectional area should be increased at least 50 per cent., with a corresponding increase in weight, reducing the maximum induction to 8000 units. Even thus the permeability will be reduced to about 100, and if cast iron with this sectional area were used for the field-magnets throughout, the length of the magnetic circuit being 190 cms., the number of ampère-turns required for this part only, will work out as 10,580, or for the whole circuit 15,826, increasing that calculated above about 2.5 times. Moreover, the length of each turn of shunt-winding must be increased 1.24 times, and therefore the total length 3.3 times, and the weight of copper giving the same resistance 11 times. Even thus no allowance has been made for the increased leakage of the Magnetic Induction. Cast steel is a better substitute for wrought iron, giving higher permeability when saturated, and its employment is increasing in favour. Wrought iron will require a similar Magnetising Force to that of cast iron if the sectional area of the field-magnets be decreased so that the Induction rises to 18,000 units, but owing to the smaller circumference the weight of copper will only be increased about five times, while the weight of iron is reduced by about 10 cwt. The number of ampère-turns in the series coils works out as 1511, or five turns for correct compounding.

The energy absorbed owing to hysteresis and eddy currents in the armature-core may be calculated as follows. The total volume of the core is, allowing 10 per cent. for paper insulation between the discs, nearly 22,700 cubic cms. The hysteresis loss in a complete cycle of Magnetisation reaching 12,000 units, should be about 6675 ergs per cubic cm., or nearly 150 million ergs in the armature-core per revolution. Multiplying by the number of revolutions per second and dividing by 10^7 we find the power wasted to be 250 watts, or about one-third of a horse-power, and .75 per cent. of the total output. If the core plates or stampings are a quarter of a millimetre thick, the eddy current loss will be a little more than half this amount, and the total core losses will be about 1.2 per cent. of the total output of the dynamo.

The permanent temperature to which any part of the dynamo will rise when working will be that at which the heat escapes by conduction and radiation at the same rate as it is being generated. It is commonly specified that the temperature of the dynamo should not, for any part, rise beyond a certain number of degrees Centigrade above the surroundings in continuous working. The Admiralty specify that the temperature of any accessible part of the dynamo should not rise more than 30° Fahr. (16° C.), nor in the armature more than 70° Fahr. (39° C.), above the surroundings. These limits are unnecessarily low, or would be for dynamos to be used in well-ventilated engine rooms and temperate climates. Limits of 40° and 70° Centigrade respectively are in general quite satisfactory. Exact predictions of the rise of temperature are difficult to make, but the following estimations may serve as a guide.

From the armature the heat escapes largely by convection, a considerable current of air being drawn between the polar faces and the armature by the rotation of the latter; and escape at a higher temperature. In our design we may assume that the air would cling preferably to the rougher surface of the armature, but assuming a velocity of the air in the interspace of one-half the peripheral speed, or about 30 feet per second, a current of air of about .6 cubic feet per second would be drawn past each polar face, and thrown off by "centrifugal force" at the horns. To raise 1.2 cubic feet by one degree Centigrade every second would absorb the heat generated by 12 watts. The total power absorbed by the armature conductors due to resistance, and the core due to hysteresis is 900 + 250 or 1150 watts. This method of dissipation of heat would require a rise in temperature of nearly 100 degrees, but conduction to the field magnets and radiation and convection from them and from the ends of the armature will probably reduce the limit to less than half. The rise of 20 per cent. in the resistance of the armature conductors allowed for above corresponds to a rise in temperature of about 50 degrees. The escape of heat by radiation depends upon the colour and brightness of the surface and the rise of temperature above the surroundings. The mean between bright and dark metal would give a rate of radiation of .00025 calorie per second, or .001 watt, per square centimetre for every degree of the excess temperature. With an excess temperature of 50 degrees the heat developed 575 watts, or half the power absorbed in the armature could be radiated from an area of 2875 cms., and this will not greatly exceed the area available at the ends of the armature. In the shunt-coils the power absorbed is 440 watts, and to obtain a permanent excess of temperature of 35 degrees a surface of 12,600 sq. cms. would be required for radiation. The heat will be partly conducted to the field magnets, and radiated thence, but the total surface will not differ much from that required in the above calculation. Before the shunt-coils reach the temperature which is thus allowed for, their resistance will fall short of that requisite by several ohms, allowing a larger current to pass, and a higher induction and E.M.F. in the dynamo. The normal value will, however, be reached after a few minutes running.

With a bright coloured or polished surface to the metal, the radiation will be much slower for the same rise in temperature, and efficiency will be sacrificed to appearance. Esson found the radiation from a varnished cotton covered coil to be sufficient to remove the heat absorbed by 1 watt from a surface of 355 sq. cms. with an excess temperature of 1° Centigrade. An area of 7.3 sq. cms. per watt dissipated gave a rise of 35° Centigrade. For the armature the rise in temperature was given approximately in degrees Centigrade by the expression $\frac{355w}{s(1+.0006 \cdot v)}$, w being the watts absorbed; s the area of the surface in square centimetres, and v the peripheral speed in feet per minute.

One of the most important advantages inherent in the Pacinotti form of armature-core is that the driving of the conductors is effected by the teeth, and there is no possibility of their displacement under the heavy stress. It is, in fact, more than probable that the stress falls on the teeth, and not on the conductors at all. In designing smooth-cored armatures provision to meet the shearing stress has to be made by means of plugs or stops here and there on the surface, and binding wire tightly wound round the armature. It may be useful to calculate the driving force on each conductor. Assuming the Intensity of Magnetic Induction to be practically uniform in the air-space, the driving force will be applied equally to all those conductors within the polar horns, and be very small indeed on those outside, or opposite the gaps between the horns. Assume, then, that the driving force is divided equally among the former, in number about seventy-two, the total electrical horse-power developed in the armature is at full load $\frac{304 \times 115}{746}$ or forty-seven nearly. At 1000 revolutions the peripheral speed of the conductors is about 3600 feet per minute, so that to correspond to 47 h.-p. a force of $\frac{33000 \times 47}{1800 \times 72}$ or almost exactly 6 pounds weight is applied to each conductor.

A further stress to be considered is the tendency of the conductors to fly outwards owing to "centrifugal force." The mass of a surface conductor is about 177 grammes, the distance from the axis of rotation 17 cms. Multiplying the product by the square of the angular velocity, $2\pi . \frac{1000}{60}$, we get a centrifugal force of nearly 33 million dynes, or 75 pounds weight for each conductor. If the conductors be kept from flying off, or bulging in the middle, by a lapping of binding wire, the problem of finding the necessary tension is similar to that of finding the stress on the plates of a circular boiler, or a steam pipe. There being 75 lbs. outward pressure per 1.2 cms. of circumference, the radius being 17 cms., the total tension necessary is $\frac{75 \times 17}{1.2}$ or nearly 1063 lbs. Many turns of fine steel piano-wire may be used, the low permeability making it practically non-magnetic, but a high safety factor will be advisable.

The other sources of waste of power in the dynamo are mechanical friction, hysteresis in the iron core of the armature, and eddy currents in the iron core, pole-pieces, and conductors. The question of hysteresis and eddy currents in laminated iron will be treated with some care in dealing with the subject of transformers, where it is of the greatest importance. It will be shown that the eddy current loss varies as the square of the speed, the square of the intensity of Magnetic Induction, and the square of the thickness of the plates employed, the loss per cubic centimetre of iron being given in ergs per second by

$$\frac{4\pi^2}{6\sigma} . v^2 . h^2 . B^2$$

where v is the number of revolutions per second in a bipolar field; h half the thickness of the plate in millimetres; σ the specific resistance of the iron in electromagnetic units (about 10,000). This formula only applies to thin plates.

Taking $v = 1000$, $B = 12,000$, $h = \frac{1}{40}$ (or the thickness of the core-plates one-half millimetre), the eddy-current loss becomes 16,300 ergs per cubic centimetre of iron per second, or .00163 watt. The loss due to hysteresis with this intensity of Magnetic Induction (12,000 units) should be about 7000 ergs per second; to reduce the loss due to eddy-currents below this, the thickness of the core plates should be reduced to one-quarter millimetre, giving a loss of nearly 4000 ergs per cubic centimetre of iron per second. But with slower speeds a greater thickness will be permissible.

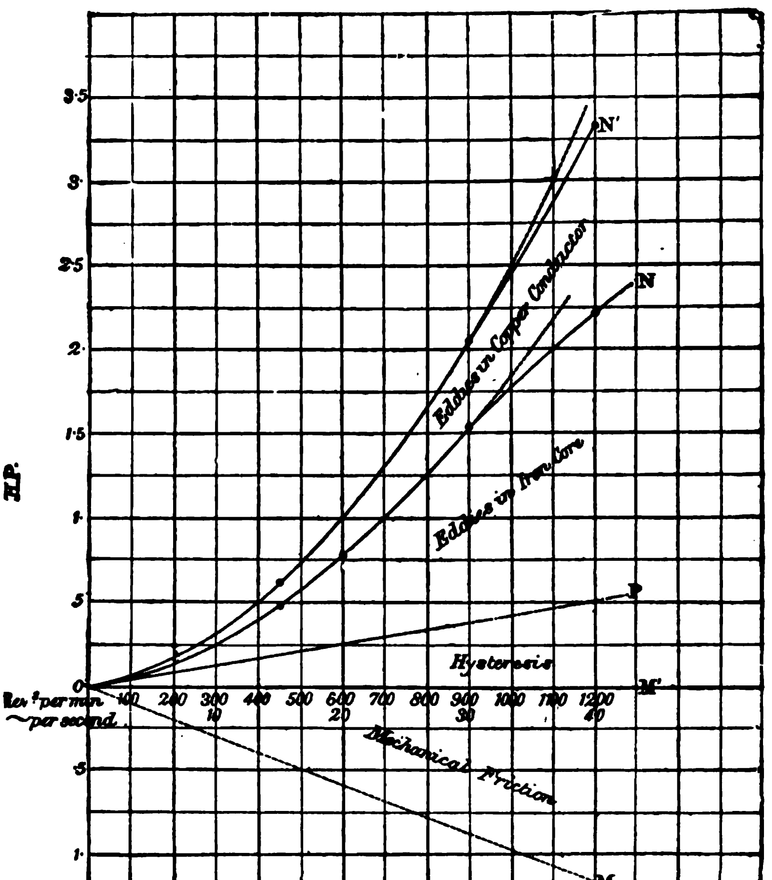
The absorption of power by mechanical friction and by hysteresis will be proportional to the speed at which the dynamo is driven. That absorbed by eddy-currents in the iron core and the copper conductors will, on the other hand, be proportional to the square of the speed, except that there will be a slight falling off at high speeds due to magnetic screening of the interior of the iron or copper. These laws of variation give a means of separating the various losses in a practical test of a dynamo when the power required to drive the dynamo at zero output has been measured with a transmission dynamometer at various speeds. Mordey has applied such a method of testing to a four-pole Victoria dynamo, intended for a maximum output of 18,000 watts when driven at a speed of 1200 revolutions per minute. The armature-core was built up of iron strip .3 millimetres thick (.012 inch), and the density of magnetic induction in the core was 12,000 units. As there will be two complete cycles of magnetisation per revolution, or 40 per second, the hysteresis loss should be about 14,000 ergs per cubic centimetre of iron per second when run at full speed; while, according to the above formula, we may expect a loss through eddy-currents in the iron core of about 36,000 ergs per cubic centimetre per second.. Further eddy-current loss is. however, likely to be added in the core framework, etc., which will be difficult to separate from that in the stampings.

The horse-power absorbed at different speeds was measured before and after the armature conductors were wound on the core, and the calculated losses are shown by the ordinates of the curves in Fig. 32. Those due to mechanical friction were first measured at different speeds, the dynamo being run without magnetisation, and shown by the downward-drawn line *OM*. The dynamo was then run at various speeds, the horse-power absorbed measured, and plotted as shown by the curve *ON*. The armature was then wound, and similar readings taken giving the curve *ON'*, the armature being upon open circuit. The difference of the ordinates of *ON* and *ON'* is due to eddy-currents produced in the copper conductors. The ordinates of *ON* representing the combined expenditure of power due to hysteresis and eddy-currents in the iron core may be analysed into its two components by drawing a tangent line *OP* to this curve from the zero point. The hysteresis expenditure of power will be represented by the ordinates of *OP*, except, perhaps, at the higher speeds, being proportional to the speed. The expenditure of power due to eddy-currents in the iron is, on the other hand, proportional at moderate speeds to the square of the speed, as its representation by the difference of the ordinates of *OP* and *ON* approximately indicates. The falling off from this square law at higher speeds indicated by the variation of *ON* from the dotted line, is to be accounted for by the magnetic screening of the middle part of the wrought-iron stamping, the eddy-currents being confined to a moderate depth on either side (see chapter on Alternating Current Theory).

Dr. Hopkinson devised a means whereby actual tests might be made of the commercial efficiency of dynamos at all loads without the expenditure

FIG. 32.

Determination of Losses in Dynamo Armature



of more than the wasted power during the test. The device consists in a simultaneous test of two exactly similar dynamos, of equal size and power, which are coupled together. It appears from theoretical considerations that the wasted power is the same for the same armature current whether a machine is used as a dynamo or motor. If the two dynamos be coupled together, one used as a dynamo and the other as a motor, the efficiency might be measured by comparing the electrical power produced by the former with that supplied to the latter. The square root of the ratio of these measurements would give the efficiency of either machine expressed as a decimal. An improvement consists in using the dynamo to supply the extra current to the motor, the former being magnetised so as to supply a slightly higher E.M.F. at the same speed; practically this amounts to a cycle of interchanges of power between the machines, by mechanical force through the shaft returning as electrical force through the armatures, and any armature current may be established in the two machines without expenditure of the extra power above that wasted in the two machines. The extra electrical power that must be supplied owing to the various expenditure with various armature currents is given by an ampère-meter and volt-meter. The principle of the Hopkinson test has been modified to meet the requirements of many types of continuous and alternating machines, it being possible with the latter to subdivide the armature into two parts, so as to perform an efficient test with a single machine.

CHAPTER VII.

Storage Batteries.

The primary cell has long been entirely superseded by the dynamo as the source of electric power for lighting, traction, and similar purposes, it having as yet been found impossible to generate electric power by direct chemical action so as to compete commercially with its indirect production from the heat-energy of coal, converted into mechanical energy by the steam- or gas-engine, and again into electric energy by the dynamo. The primary cell still holds its own as the source of electric power in small quantities, for telegraphy and laboratory purposes, and occasionally for lighting and motive power on a very small scale, when convenience is of more importance than the actual cost of generation of power. If the chemical action of a primary cell could be reversed by the reversion of the current through it, the original conditions of the electrodes and electrolytes being thus restored, the decomposition of the same material could be used again and again as the source of power in discharging. For the reversal of the current power must be supplied from some other source, say by a dynamo whose E.M.F. is superior to that of the cell, this power being measured by the product of the measures of the E.M.F. and the reversed current, and absorbed or stored up by the restoration of the chemical conditions, so that it may reappear (in part) as electric energy when the cell is once more supplying a current in the usual way.

A cell capable of being used in this way is termed a *secondary* or *storage* cell, or an *accumulator*. Many of the common types of primary cell can to some extent be used as secondary cells. For instance, by the reversion of the current in the Daniell cell the copper may recombine to form copper sulphate, and the zinc be deposited on the zinc electrode. But this can only go on very slowly and to a very limited extent, and a very small proportion of the electric energy absorbed in the reversion can be recovered. Much of the energy will be absorbed in heat owing to the high resistance of the electrolyte, and other chemical actions ensuing in charging the cell than the reverse of those in the discharge. The methods adopted in primary cells to de-polarise or remove the hydrogen, mechanical or chemical, prevent its reappearance when and where required for the reversal of the chemical action.

Grove's gas battery is the most elementary form of a reversible or secondary cell. It consists simply of two platinum plates, or *electrodes*, immersed in slightly acidulated water, and arranged so that the gases liberated on the platinum plates by the electrolysis of the water may be collected in receivers placed above them. To separate the constituents of water, hydrogen and oxygen, requires an E.M.F. of not less than 1.46 volts. If the platinum electrodes be connected to the terminals of a Daniell cell, whose E.M.F. should be about 1.07 volts, no current will pass, except a very small transitory current, and a subsequent current of almost infinitesimal magnitude. If the Daniell be replaced by a Bunsen or Grove cell, giving an E.M.F. of about 2 volts, a moderate current will pass and the oxygen will be collected in the reservoir over the negative electrode and hydrogen in the reservoir over the positive electrode. When the source of power is removed, and a galvanometer is connected in its place, a current will pass through the latter from the platinum in the oxygen reservoir to that in the hydrogen, the gases being slowly recombined to form water. The current can of course only be exceedingly minute, the internal resistance of this secondary cell being very great.

In 1869 Planté produced the first practical storage cell by using lead instead of platinum plates as the electrodes. In the first type large plates were used laid upon one another with strips of gutta-percha to keep them from contact, and these were rolled together so as to form a cylindrical spiral. Thus large surfaces of metal at a short distance apart are obtained without occupying much space. The roll was then immersed in dilute sulphuric acid (one in ten) and an E.M.F. of several volts applied. The oxygen liberated on the lead plate connected to the positive terminal of the generator combined with the lead to form peroxide of lead (PbO_2), while hydrogen was liberated on that connected to the negative, and escaped in bubbles, the lead being unaffected. After the current had flowed for some time the coating of peroxide of lead formed on the positive plate effectually protected the lead against further action. Oxygen gas was then liberated from the surface, and it was useless to carry the process any further.

On connecting the lead plates through an external resistance a current in the reverse direction through the cell was produced for some time, at first fairly constant, and then rapidly falling off to zero. During this operation, that of "discharge," one-half of the oxygen was carried over to the negative plate, so that on each plate lead monoxide (PbO) was formed. combining as soon as formed with the sulphuric acid to form lead sulphate ($PbSO_4$) (which was deposited so as to coat either plate), and water (H_2O) so that the acid solution was weakened.

After the first charge and discharge Planté proceeded to charge the cell again, but this time the connections were reversed so that the plate which was formerly the negative now became the positive. Lead peroxide was now formed on the latter, while the plate which was now the negative was coated with pure lead. On again discharging both plates were once more coated with lead sulphate, and the connections were once more reversed for a third charge. It was found that the charging could now proceed for a longer time before the oxygen was liberated as gas, and the discharge with the same current was correspondingly lengthened. The process of charge and discharge with reversals of connections for each operation was repeated a great number of times, the first charging occupying about a quarter of an hour, and the time of subsequent charges increasing to an hour after six or eight operations. The cell was then left charged all night. On the second day it was discharged and then recharged in the opposite way during two hours; again discharged, recharged afresh in the opposite direction, and finally was allowed to stand charged for eight days, After eight days it was again charged during some hours without being reversed, and was then allowed to stand charged for fourteen days, and so on. In this way the *capacity* of the element was more and more increased." About two months were required for the proper "formation" of Planté's cell.

The reason for the increased capacity, or total energy stored up by the charge after these prolonged operations, was at once made clear by an examination of the plates. The negative plate, when the cell was charged, was found to be reduced to some depth to a porous, spongy condition, and the peroxide coating on the positive extended to a corresponding depth. In other words, a much larger quantity of lead was reached by the dilute acid electrolyte, and thus accessible to the chemical action. The reduction of the lead to this state is probably effected by local action in the positive plate when charged, the peroxide losing an atom of oxygen which oxidises the lead further within the plate, causing it to become chemically active on the next charge.

Planté suggested and experimented with other methods for obtaining a similar result to that produced by the first tedious and expensive process. A galvanic deposit of lead on the plates, and raising the temperature to hasten the formation by reversals, were tried. In 1882 a rapid formation was effected by previously immersing the lead plates in nitric acid, diluted with one half its volume of water. The plates were immersed for from 24 to 48 hours, and then taken out and thoroughly washed till all traces of the acid were removed. The plates were then found to be already rendered porous to some depth, and coated with lead salts which were easily acted upon, so that a much larger capacity was found at the first charge, and after a few reversals the formation was as advanced as the earlier method had effected in many weeks.

Meanwhile, however, a totally different method of manufacture had been discovered by Faure, by which a much larger capacity in proportion to the weight of the plate was obtained, and which first made the storage of electric power a commercial success. Faure's method consisted in a separate manufacture of the active material by a chemical process, and subsequently attaching it to the lead plates. A paste of lead peroxide and lead sulphate was made by mixing red lead, or minium, with dilute sulphuric acid, the chemical reaction ensuing being represented by the formula,

$$Pb_3O_4 + 2H_2SO_4 = 2PbSO_4 + PbO_2 + 2H_2O.$$

This paste was then spread over the plates, overlaid with slips of parchment to prevent it falling off. The plates were separated with strips of felt, rolled together, and immersed in dilute sulphuric acid as in Planté's first cell. The plate was then immediately ready for use, giving a large capacity on first charging. The lead sulphate on the positive plate was converted into peroxide, that on the negative, as well as the peroxide, reduced to pure spongy lead. In the modern developments of the Faure cell, or "pasted plate" type, it is customary to use a paste called litharge (PbO) mixed with dilute sulphuric acid for the negative plate, thus forming lead sulphate only, avoiding the necessity of the reduction of peroxide by the first charge.

The main difficulty to be met in the manufacture of pasted plates is to secure the adhesion of the paste, or active material, to the lead plate, or framework, which supports it. The active material is subject to considerable stress owing to its expansion and contraction during the chemical changes of charge and discharge, which tend to make it break away from its support. Faure secured adhesion by scoring the plates with deep grooves so that the paste, which is itself fairly coherent, might be secured to the plates in the same way as is found effective in plastering. This method was not found sufficient when large flat plates were introduced, and Elwell and Parker introduced the system of casting a lead framework in the form of a "grid," or lead network with square perforations, into which the paste was forced. The paste speedily hardens into pellets, and it was found advantageous to make the perforations somewhat smaller in the middle of the plate than on the surface, giving them an "hour-glass" form, so that the pellets keyed themselves into the grid. For further security Drake and Gorham introduced the practice of burring over the outer edges of the perforations, by hammering or rolling, so as to enclose the pellets in a barrel-shaped enclosure. The pellets expand when the sulphate is formed, keying themselves the more firmly, but subjecting the positive grid to considerable stress. Pure lead has but little elasticity, and it is advisable to use an alloy with a small amount of antimony to give greater elasticity as well as mechanical strength to the positive plate. A ten per cent. alloy is frequently used for the positive, and pure lead for the negative grid.

Secondary cells are commonly classified as belonging to one or other of these two classes, the Planté or "formed" cell, and the Faure or "pasted plate" cell. In the former class is included all those types of cell where the active material is formed out of the lead plates themselves, which are reduced to porosity, or the actual surface exposed to the electrolyte is increased, by mechanical or chemical means. Those in which an electrolytic deposit of porous lead is obtained from lead salts will also be included, as the method was first suggested by Planté. The latter class, or Faure type, includes all those in which the active material is separately made by chemical means, whether the same as or different from that used by Faure, and subsequently supported by a lead framework. The difference is solely in the mode of manufacture, the chemical action being exactly the same in the two classes, and the plates in each case consisting of a certain quantity of chemically active material supported by a head plate or framework. The chemical action of charge and discharge is summed up in the formula,

Discharged State.			Charged State.	
Positive plate.	Negative plate.		Positive plate.	Negative plate.
$PbSO_4 + H_2O$.	. $H_2O + PbSO_4$	=	$PbO_2 + H_2SO_4$.	. $H_2SO_4 + Pb$.

As a general rule the Planté type of cells are capable of withstanding rougher usage, of being more completely discharged without injury, and of being used for rapid discharges without buckling. But the capacity is generally smaller for the same weight, and the cost of manufacture for the same capacity somewhat greater.

Before discussing the details of design and manufacture of some of the principal types of modern manufacture, a general sketch of the features common to all or most of them will be convenient at this point.

Large flat plates are used, generally of a standard size, a number of positive and of negative plates being separately connected in parallel to increase the capacity and the current that can be used in charging and discharging. Nearly all manufacturers adopt as the standard size of their plates, except for small and portable batteries, about eight by nine inches, giving a total area, for both sides of the plate, of one square foot. For this area a current of four ampères in charging is found to give the best results, though it may generally be exceeded, and even doubled, without injury to the plates, but at the expense of a decrease in the capacity owing to the rapid formation of the peroxide on the outer surface of the positive plate preventing access of the action to the interior. With some forms of cells, where the surface has deep grooves, the actual surface freely exposed to the electrolyte is much greater, allowing a proportionally rapid charge and discharge, but at some expense in efficiency.

In order to minimise the internal resistance the plates are brought as near together as possible without running risk of contact, or short-circuiting by particles of material falling from the surfaces, or irregularity of action owing to the surfaces being nearer at one point than another. The current will prefer to pass at the points where the plates are close together on account of the reduced resistance, and the slight irregularity in the surface will be of more consequence as the average distance is reduced. A distance of from one-quarter to one-half an inch is commonly preferred. In order to equalise the action over both sides of the positive plates, it is found absolutely necessary that all of these should have negative plates facing them on either side. Otherwise the expansion and contraction of the active material in charging will cause it to break away, and the plates to bend or "buckle." The negative plates are not subject to similar strain, so that it is found possible, by using one more negative plate than positive, placing them alternately, with a negative plate at each end of the series, to avoid injury from this cause, unless an excessive charging or discharging current is employed.

The E.M.F. of a cell with electrodes of lead peroxide and pure lead, with pure sulphuric acid as the electrolyte, may be calculated theoretically to be 2.627 volts; with pure water it should be 1.35. Actual measurements by Gladstone and Hibbert gave 2.601 and 1.36 respectively. It would be impossible to use pure sulphuric acid, owing to the violent chemical action on the negative plate. The following measurements of the E.M.F. with dilute acid of various strengths are also given by Gladstone and Hibbert, the measurements being taken with two fully charged pasted plates:

Density of Electrolyte.	Percentage of Pure Acid.	E.M.F.
1.045	6.5	1.887
1.065	9.5	1.898
1.080	11.5	1.915
1.115	16.2	1.943
1.157	21.7	1.978
1.217	29.2	2.048
1.254	33.7	2.088
1.333	43.0	2.17
1.530	63.0	—
1.750	81.0	—

The specific resistance of dilute sulphuric acid varies very greatly with the density of the solution, and with the temperature. The resistance is a minimum with a solution of about 30 per cent. pure acid, for which the specific resistance is about 1 ohm at 6° Cent., increases rapidly with either a stronger or weaker solution, and decreases with a rise of temperature. The following comparative resistances, representing the minimum by unity, were given by Kolrausch for solutions of different strengths:

Percentage of Sulphuric Acid.	Relative Resistance.
2.5	6.73
15.0	1.33
30	1.00
50	1.35
71	3.79
95	7.29

The density of the electrolyte used in secondary cells is a little under that which gives the minimum resistance. The chemical action in charging the cell strengthens the solution by the decomposition of the lead sulphate, producing additional acid, which is again absorbed in discharge. It is commonly arranged that the density of the electrolyte should vary from 1.117 to 1.121, the E.M.F. of the cell thus being about 2 volts, but slightly higher when the cell is fully charged than when nearly discharged. Owing, however, to the slow diffusion of the acid liberated during charging the variation of E.M.F. will be greater than appears from the above tables, and will need further discussion later on.

The following table will give the specific resistance of sulphuric acid solutions at different densities and temperatures:

SPECIFIC RESISTANCE OF SULPHURIC ACID SOLUTIONS.

Specific Gravity.	Specific Resistance in Ohms at Temperatures in degrees Centigrade of							
	0°	4°	8°	12°	16°	20°	24°	28°
1.10	1.37	1.17	1.04	.925	.845	.786	.737	.709
1.20	1.33	1.11	.926	.792	.666	.567	.486	.411
1.25	1.31	1.09	.896	.743	.624	.509	.434	.358
1.30	1.36	1.13	.94	.79	.662	.561	.472	.394
1.40	1.69	1.47	1.30	1.16	1.05	.964	.890	.839
1.50	2.74	2.41	2.13	1.89	1.72	1.61	1.52	1.43
1.60	4.82	4.16	3.62	3.11	2.75	2.46	2.21	2.02
1.70	9.41	7.67	6.25	5.12	4.23	3.57	3.07	2.71

Taking the specific resistance of the electrolyte as an ohm, the clearance between the plates one-half an inch, we may estimate roughly the resistance between a positive plate and the two adjacent negative plates. Taking the area 1 square foot, the resistance works out as .0014 ohm, so that with a current of 4 ampères this would account for a reduction of the difference of potential of only .0056 volt in discharging below the proper E.M.F. of the cell, and a corresponding extra E.M.F. would be required to drive the current through in charging. A difference of about .011 volt would thus be required between the E.M.F. in charging and discharging. The actual difference observed between the E.M.F. required for charging at the normal rate and the E.M.F. of discharge, is never much less than one-tenth of a volt, showing that the actual distance between the plates only accounts for a small part of the internal resistance of the cell, and little is gained by attempts to reduce it. The main resistance is to be found in reaching the interior active parts, through the pores of the lead or peroxide, where the strength of the electrolyte, owing to the slow diffusion as the acid is formed or absorbed, is stronger or weaker than that between the plates, either of which causes will increase the resistance. This increase of the internal resistance through slow diffusion will be intensified with a rapid charge or discharge. Ayrton found the resistance of an E.P.S. pasted cell to average .011 ohm per positive plate during a charge with 3.787 ampères; and .009 ohm during a charge with 4.205 ampères, rising, in either case, towards the end of the operation.

A secondary cell is fully charged when all the lead sulphate on the positive plate to which the electrolyte has access is converted into lead peroxide, and the negative plate is reduced to pure lead. A continuation of the charging current liberates oxygen and hydrogen from the positive and negative plates respectively, the former no longer combining with the lead, the gases rising as bubbles, the surface of the electrolyte assumes a milky appearance, and the cell is said to "boil." This boiling was formerly thought to be harmful to the plates, as well as a waste of energy, but experience has shown that it is not only harmless but distinctly beneficial occasionally to continue the charging current for some time after the plates are fully charged, so as to reduce or remove certain insoluble compounds which are formed during discharge, and are injurious to the plates. Boiling should be continued for some time once a week when the cells are in constant use, and will be found well worth the expenditure of power; but the current should be only about half the normal charging current.

The decomposition of lead peroxide is chemically equivalent to the passage of .227 ampère-hour per gramme reduced to lead monoxide, or to nearly

100 ampère-hours per pound. It appears that in practice a capacity of only six to twelve ampère-hours per pound of positive plate is obtained with cells used for electric lighting, though in cells specially designed for portability a somewhat higher capacity can be obtained. It follows that the proportion of really active material is very small, and considerable improvement is theoretically possible. But it may be remarked that capacity and efficiency are totally different matters, and except where portability or the saving of space is a paramount consideration, the increase of weight due to the addition of a considerable quantity of such a cheap material as lead is subsidiary to the question of efficiency and durability of the plates.

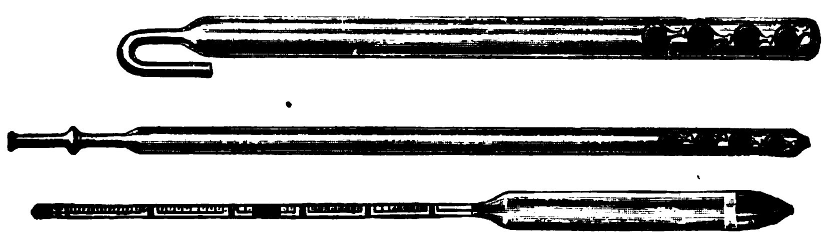
According to chemical tests made by Robertson with pellets forced out of the grids of a pasted plate, only about a half of the peroxide was decomposed in a complete discharge at the rate of four ampères per positive plate, the lead sulphate forming an impervious coating round the remainder that protects it from further action. In a non-pasted plate (formed by the Planté process) it is probable that a more complete decomposition takes place, but the nominally active material generally forms a smaller proportion of the total mass. A more rapid discharge results in still less complete decomposition, and the capacity of the cell is greatly reduced. At the normal rate of charging, four ampères per positive plate of one square foot total area of surface, the time of charging is most commonly arranged to be about twelve hours. Higher rates, up to even twenty ampères, may be employed, when by grooving or other means the actual surface, that is to say, the free external surface in contact with the electrolyte, is increased. Discharged at the same rate, the cell will maintain the current from nine to ten hours; doubling the discharging current will reduce the time of discharge to about three hours, thus returning only about seventy-five per cent. of the current integral, or the number of ampère-hours discharged at the slower rate. Some forms of cells are adapted to give very high rates of discharge without injury, and may be discharged in one hour with nearly five times the normal current of charging, but the capacity (of discharge) is thus only about one-half of that when discharged slowly. It does not follow that the efficiency of storage is in the latter case reduced fifty per cent., since the quantity of peroxide remaining undecomposed will shorten the time of renewed charging.

Owing to the variation of the extent of the chemical action according to the rate of discharge the efficiency of the cell can only be determined correctly by taking the average in actual practice after many operations of charging and discharging. With a uniform slow rate of charge and discharge there will be a difference of potential in discharge below that of charging of upwards of .1 volt, or about five per cent., corresponding to the *loss of energy* owing to the internal resistance of the cell. With larger currents this loss will be greatly increased, rather more than in proportion to the square of the current, as the resistance also will be increased by the concentration of acid on the plates in charge, and weakening of the acid solution in discharge. A further loss will be realised in the reduction of the number of ampère-hours, or the current integral, obtained in discharge below that absorbed in the charge. The corresponding energy will be wasted in irregular chemical actions, the evolution of gas, &c. In practical work a total efficiency of about eighty per cent. may be considered good, and is obtained where the cells are under careful supervision, and kept in good order. The efficiency often falls much below this when rapid charging and discharging is frequently called for.

The extent of the charge remaining in the cell at any time may be estimated in three different ways by the attendant. In the first place the colour of the plates will, to an experienced eye, give a rough indication.

When the cell is fully charged the positive plate assumes a deep black, and the negative a grey slate-coloured surface. In discharging the positive tones down to a dark plum colour, and then into a brown as the whole surface is reduced to lead sulphate, the colour of both plates being the same when the cell is discharged. Another more satisfactory criterion is the density of the acid solution, which should be of specific gravity, about 1.21 when the cell is charged, and should never fall below 1.17. A handy form of hydrometer to measure the density of the electrolyte is a necessary instrument in the second battery room. Fig. 33 shows three forms supplied by Drake and Gorham for this purpose. The ordinary floating hydrometer has the objection that an unskilled attendant is not always to be trusted to read a finely graduated scale correctly, and it is only available for reading the density on the surface of the electrolyte, which is often through the slow diffusion very different from that at some depth, or between the plates. A more suitable form is a narrow tube which can be lowered down between the plates and filled with a sample of the liquid from any desired depth. In this tube small differently-coloured glass balls are sunk, carefully adjusted

FIG. 33.



Storage-cell Hydrometers.

to rise with different densities of the sample liquid (viz., 1.105, 1 170, 1.190, and 1.200), which is a convenient and unmistakable, if not a very accurate, method of measurement.

The third means of indication of the state of charge is the E.M.F. of the cell. This will be fairly constant during the greater part of the time in charging or discharging at moderate rates, rising or falling uniformly between the limits of 2 and 2.1 volts, the actual difference of potential being in excess of this during the charging by about .05 volt or so according to the internal resistance; and a similar decrease when discharging. Towards the end of the charge the E.M.F. rises rapidly, accompanied by more and more vigorous "boiling" until an E.M.F. as high as 2.58 or 2.60 may be reached. At the beginning of the discharge the E.M.F. falls to its more moderate value in a few minutes, and then decreases very slowly for many hours. After reaching two volts the fall is more rapid, falling a further tenth of a volt in an hour or so, and then completely discharging in a few minutes. It is likely to prove most injurious to the plates if the discharge is made complete, and it is generally considered inadvisable to allow the E.M.F. of the cell to fall below 1.9 volts, or the actual difference of potential between the terminals below 1.85 volts in slow discharging (1.8 may be allowed in a rapid discharge). Very little of the capacity is lost by this restriction, and the deleterious action that will follow further discharge will appear from the following discussion of the chemical action.

The chemistry of secondary cells was investigated with some care by Gladstone and Tribe in 1882, their results being published in some papers in *Nature;* more complete investigations by Gladstone and Hibbert are recorded in a paper read before the Institution of Electrical Engineers in

1892, to which we shall be indebted for much of what follows. In this paper it was most conclusively proved that the variations in the E.M.F. of the secondary cell must be attributed entirely to the varying quantity of acid in the electrolyte during charge and discharge, greatly intensified by the slowness of diffusion which causes great variations of the density of the electrolyte close to the surface, and within the pores of the plates.

At the termination of the charge, especially if rapid and carried up to the highest limit, a film of the strongest, almost pure, acid covers the surface of the positive plate, and may actually be seen descending by its heavier weight and flowing round the bottom of the plate. After the charging current has been stopped the evolution of oxygen still goes on; this is due to the presence of persulphuric acid and hydrogen dioxide. These while liberating oxygen also react on the peroxide, reducing it and liberating further oxygen. Local action with the lead framework also goes on to some extent, and thus by diffusion, local action, and reduction of the lead peroxide, the acid strength of the electrolyte within the pores of the positive plate is weakened. On the negative plate the acid is also very strong, and a slow action on the lead, liberating hydrogen and forming lead sulphate, proceeds. These actions increase the capacity of the cell. If the discharge immediately follows on the cessation of the charge, an E.M.F., very nearly that of a pure acid cell (2.6 volts), is obtained, but speedily falls as the acid strength is reduced, this occupying only a few minutes. The higher E.M.F. may, however, be restored by changing the plates to a vessel containing a stronger acid solution. It was formerly thought that the higher E.M.F. obtained after boiling was due to the hydrogen bubbles occluded in the negative plate, but the length of time the E.M.F. is maintained in discharging shows this explanation to be insufficient. It had also been suggested by Gladstone and Tribe that the higher E.M.F. was caused by the active oxygen produced by decomposition of the persulphuric acid.

After a careful chemical analysis of pellets of active material forced from the grids of a pasted plate cell at intervals during the charge and discharge at the normal rate, and from different parts of the plates, Robertson summed up his results in the following statements:

"(a) The particles of the peroxide very soon get coated in the discharge with a layer of lead sulphate, which protects the peroxide from further action.

"(b) The analysis shows also that a large proportion of active material is still remaining at the end of the discharge.

"(c) The loose powdery surface of the positive plate seems to be thoroughly converted into lead sulphate.

"(d) When the peroxide on the surface of the positive plate falls to about 31 per cent. the cell loses its E.M.F. very rapidly, owing to the inactive layer of sulphate impeding the action of the sulphuric acid on the active material behind it, and also to the formation of peroxide on the negative. The 'diffusivity' of the acid is also then increasing, while it has to penetrate further into the plate to find active material. When the whole of the paste approaches this composition of 31 per cent. peroxide, the cell loses its E.M.F. entirely.

"(e) The action seems to take place most rapidly where the current density is greatest; the plate gets hard there from sulphate soonest on discharge, and oxidises quickest on charge."

During the discharge of the cell, especially if rapid, the electrolyte on the surface and within the pores of both plates is much weakened by the combination of the acid with the lead monoxide to form lead sulphate and water,

$$H_2SO_4 + PbO = PbSO_4 + H_2O.$$

The acid strength must be restored by diffusion from the fluid between the plates, but this will frequently be so slow that the internal resistance is much increased. Furthermore a mischievous chemical action is likely to follow, owing to the deficit of acid, in the formation of a white basic sulphate, $PbSO_4PbO$ or Pb_2SO_5. This action is known technically as "sulphating," and also ensues if the cell is left standing for a long period in a discharged state, whether the acid strength of the electrolyte be weak or strong. This basic sulphate is insoluble, a bad conductor, and when formed between the active material and the supporting lead is liable to detach the former. The only effective way to remove it is to continue the charging for some time with a moderate current (about two-thirds the normal) after the cells begin to boil. The basic sulphate then falls off, or is loosened and can be scraped away in white flakes. To avoid the formation it is advisable to maintain a constant circulation of the electrolyte during rapid discharges, and on no account to leave the cells in a discharged, or even a partially discharged state for long periods. The formation of the basic sulphate may be checked by the addition to the electrolyte of a small quantity of caustic soda; Sir David Salomons recommends the addition of one ounce of solid caustic soda (previously dissolved) to every five gallons of the electrolyte. Other remedies found effective are potassium sulphate, sodium sulphate, and oxalic acid.

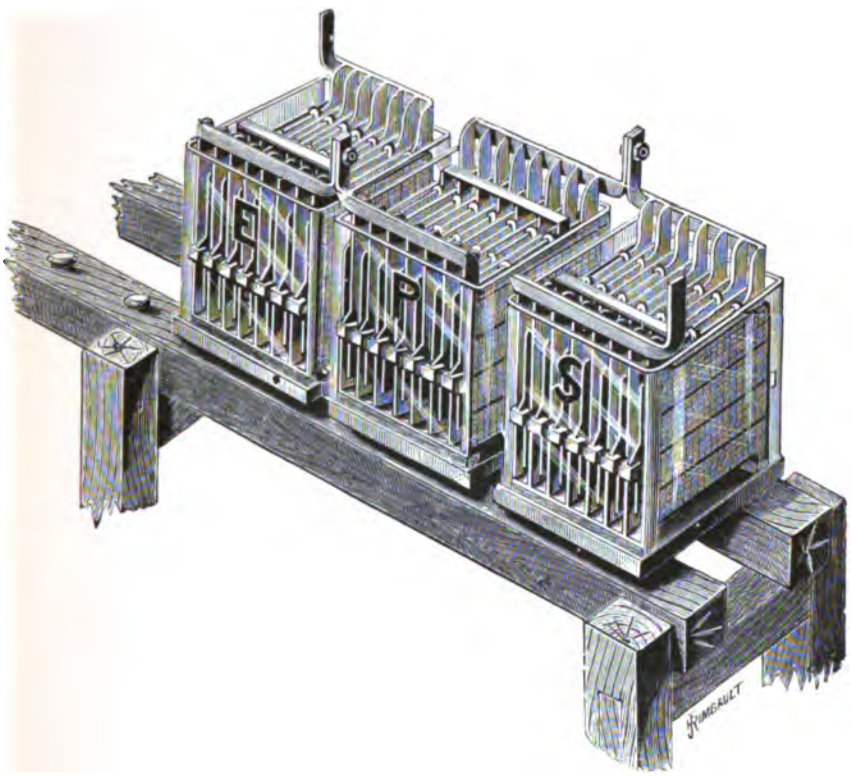
To illustrate the variation of the internal resistance during discharge we may give the following measurements by Ayrton: After over-charging for some time the internal resistance had risen to .0115 ohm, the actual E.M.F. of the cell being 2.30 volts. After standing for some time to allow complete diffusion of the acid the resistance fell to .0038 ohm, the E.M.F. being then 2.06 volts. During discharge at the normal rate the resistance remained fairly constant. When towards the end of the discharge the E.M.F. had fallen to 1.95 volts the resistance had risen to .0055 ohm.

Leading Types of Accumulators.

In dealing with a selection of the principal types of secondary cell, those of the Faure, or pasted plate type, will be considered first, as it was by this method of manufacture that cells were first made of sufficient capacity, and sufficiently cheaply to be of value for electric lighting. The manufacture of pasted plates has been until recently a monopoly in Great Britain, held by the Electric Power Storage (E.P.S.) Company. The most important of the patents held by this company have recently lapsed, but it is doubted whether the inventions will be made much use of by others, as the monopoly has encouraged the development of many forms of the Planté type, so as to bring them into vigorous competition, and it is still impossible to say which type is intrinsically the better.

The "grid" lead framework, or lead plate with square perforations into which the paste is forced so as to form "pellets," was adopted at a very early period, and still remains the standard form of the E.P.S. cell. This shape certainly will give the maximum proportion of active material to the whole mass of the plate, and for cells under good management, charged and discharged at moderate rates, can scarcely be bettered. But it is open to a serious objection when the cell is to be subject to very rapid discharges. The conductivity of the active material is very low, especially when reduced to sulphate, and the current has to find its way by the lead grid from the active material in different parts of the plate to the connections, this path being of small sectional area, and much longer from some parts than it would be in a non-perforated plate. Now it has of recent years been recognised that one of the most valuable uses of secondary batteries in central station supply is that it may occasionally be used as a "stand-by," to maintain the supply for a short time during the night and in the event of a breakdown of the generating plant. For this purpose a type of cell capable of being discharged at a very rapid rate is needed, high efficiency being a minor object. The cells designed for this purpose have for the positive plate a massive lead casting with rows of horizontal ridges on either face. These ridges, or shelves, are turned upwards, and the paste

FIG. 34.

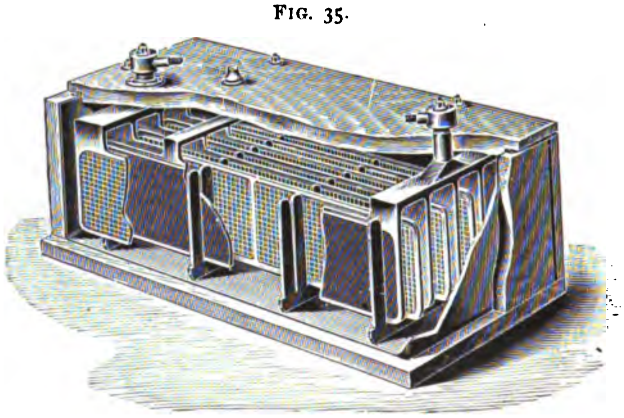


Secondary Batteries—Electric Power Storage Cells.

packed between them. The actual surface, owing to the ridges, is much larger than with the grid type, and the resistance of the plate itself is greatly reduced: the normal rate of discharge is 8 ampères per positive plate (instead of 4 ampères, as with the flat-surface grid plates), and this may be greatly increased without injuring them. For the negative plate a light grid is cast, with very large perforations in which the litharge paste is further secured by projecting lead prongs. This cell is known as the K, or central station type, it being customary among secondary cell manufacturers to denote their different types by distinguishing letters. The L type, that adapted for stationary batteries to be charged at moderate and efficient rates, has plates with the grid framework as previously described. Fig. 34 shows three L type cells in glass boxes connected in series, and mounted in the customary manner on wooden shelves, the wood being thoroughly coated with shellac varnish to protect it from the acid fumes which are invariably present in a secondary battery room. The rims of the glass boxes are also coated with shellac varnish to prevent creeping. The cells are placed in wooden trays containing sawdust, and rest on "mushroom" insulators. Fig. 35 shows a single cell of the C type, a modification of the L adapted for portability; as for such purposes as train lighting, the cell being completely enclosed in a lead-lined wooden box, and occupying a small space, the plates are longer and narrower than in the K and L types, and thus less subject to injury through vibration.

The method of supporting the plates in the cell also differs considerably in the various types. In the L type the negative plates are cast with projecting lugs at three of their corners. These are for all the negative plates in one cell secured by "lead burning" to strips of lead, one of which forms the connecting piece for the next cell; the other two form bases upon which the system rests, supported about 1½ inches above the bottom of the cells upon blocks of paraffined wood. Two additional strips upon the sides of the plates about half-way up secure additional rigidity, and also form shelves

FIG. 35.



Portable Storage Cell.

upon which the system of positive plates is supported. The positive plates have lugs at one corner by which they are burnt on to the same connecting strip, and have projections from their sides by which they are supported, these resting upon ebonite shoes supported by the above-mentioned shelves attached to the system of negative plates.

The clearance between the plates is further secured by long ebonite forks, or U-shaped pieces, two of which are pushed over each positive plate, and prevent any possibility of contact. The tops of these can be seen in Fig. 34, and the method of interconnection is illustrated. The cells must be mounted so that the positive and negative connecting strips are alternately reversed in position.

In this method of arranging the cells of the L type it will be seen that the path of the current in the lead connecting strips is unnecessarily long. An improvement is effected in the K type, in which the connections are made directly over the adjacent edges on the cells. The positive plates are here suspended from two massive lead bars supported upon the negative plates through the medium of insulating blocks. The negative plates are connected to two similar bars underneath. Large currents can thus be carried with safety and little loss, the conducting bars being much shorter as well as stouter. Another advantage is that the electrical action is better distributed over the plates, owing to the current having necessarily to pass from top to bottom over either the positive or negative plates, and the length of the current circuit in the plates is thus the same at whatever point it may pass through the electrolyte.

The plates are made for the K and L types of a uniform size of 8½ by 9½ inches, and the number is from 7 to 33, the maximum rate of discharge being 64 ampères in the L type, and 135 in the K type. For central stations where high rates of discharge are called for a special cell of the K type is supplied, giving discharges up to 1300 ampères. These are supplied in lead boxes, and are really several cells placed in parallel, the positive plates of each of which can be separately removed for inspection. The largest size supplied has 145 plates arranged as 5 sets, and can supply 1300 ampères for one hour, or 370 ampères for 7 hours, the normal rate of charging being 570 ampères. It may here be noted that if single cells be connected in parallel a difficulty may arise if the plates are in separate boxes, so that the acid solution may become stronger in one than the other. A consequent difference in electromotive force may cause a discharge of one cell into the other. The practice of connecting two separate cells in parallel, especially when the arrangement is temporary, is reprehensible. In the Central Station E.P.S. cells the arrangement is, of course, equivalent to an extra number of plates in the same cell, the electrolyte being the same. The arrangement of two complete batteries in parallel, the electromotive forces being measured and found the same, is on the other hand, sometimes a source of safety. In the event of the circuit of one battery being broken, as by the fracture of a glass box and consequent escape of the electrolyte, the electromotive force of the charging dynamo if shunt-wound may suddenly rise considerably, and if lamps in parallel circuit are being supplied at the same time the result may be disastrous. A second battery in parallel will check this. Sir David Salamons mentions a case in which the lamps in a private installation were thus saved from destruction. The electromotive force would, except for the second battery, have risen about 20 per cent., sufficient to destroy the lamps speedily, but not to blow the fuses.

The capacity of a cell depends partly upon the rate of discharge, for a rapid discharge causes the peroxide to be converted into sulphate upon the surface of the active material, forming a coating impervious to the acid, and preventing access to the peroxide in the interior. Greater capacity as well as efficiency is therefore obtained by slow discharge. But if the discharge is too slow inconveniences may arise. The slow deposit of pure lead upon the negative plate tends to form fine needles of lead which, even if they do not short-circuit the plate themselves, endanger a short circuit by preventing any basic sulphate or other material from falling freely to the bottom of the cell. The most satisfactory rate of discharge is a little more than half the best charging rate (4 or 8 ampères per positive plate). Taking the capacity of a 7 hours discharge as 100, that of a 5 hours discharge is about 90, 3 hours 75, and one hour 50. At its maximum rate of discharge, 4 ampères per positive plate, a cell of the L type should maintain the current for 10 hours. The total weight of the cell in glass box is about 10 lbs. per plate of both kinds, so that the capacity is a little over 2 ampère-hours per pound of total weight, or about 80 lbs. per horse-power hour.

In the K type the maximum rate of discharge is given as a little over 8 ampères per positive plate, and at this rate the discharge should last 3½ hours. At one half the rate the discharge should last nearly 9 hours. The total weight of the cell in glass box is about 15 per cent. greater than that of a cell of the L type with the same number of plates. The width of the cells in glass boxes in the K and L type is from 11¼ to 11⅝ inches, for the central station cells from 2 to 5 feet according to the number of sets of plates. The length varies from 5 to $19\frac{3}{8}$ inches according to the number of plates. The height of the cells over all is $16\frac{3}{4}$ inches in glass boxes, and about 20 inches in lead-lined wood boxes. It is customary when mounting them in tiers to leave a clearance of at least 14 inches between the top of the connections of the lower and the wooden supports of the upper tier. When this is done, and glass boxes are used, the cells being connected so that the plates stand in planes at right angles to the line of the shelves and the interconnections, constant inspection is easy, it being possible to watch the surfaces of the plates from the side, and obtain access from above for hydrometer tests, &c.

A few other designs of supporting framework for the Faure paste may now be mentioned. Reckenzaun moulded the paste into short pencils, three-sixteenths of an inch in diameter, and a little over an inch in length, these pencils being partially buried in a solid lead plate, and in a horizontal position. Tending to expand, when the cell is charged, in the direction of their length, they are said to be less likely to cause the buckling of the plate, or to be wrenched out if the plate is buckled. The Pitkin accumulator, intended only for small portable hand lamps, uses thin lead plates studded with small lead pins, with flat heads, which are found sufficient to retain the paste on a small plate, and gives very great capacity in proportion to the weight of the cell. Others have used a porous covering material to prevent the active material from falling off the plate, as was done by both Planté and Faure in the first secondary cells with strips of felt. Carrie, using rods in the place of plates, protected them by asbestos tubes. In the Hatch accumulator corrugated lead plates are used, the corrugations being filled in with paste, and the plates separated by porous earthenware, which is permeated by the electrolyte, thus making a "solid" cell. The objection to these methods is the comparatively high internal resistance of the cell, especially when a rapid discharge is used, the diffusion of the acid being extremely slow. For portable accumulators they may be valuable, as the ordinary types are generally injured by vibration.

The Chloride accumulator must be classed as of the Faure type since the active material is made separately, and not out of the lead-supporting framework, though it is made by a totally different process to that of Faure. Fused Chloride of lead is poured into moulds so as to form discs, or buttons with rounded edges, and these are set in lead plates. The chloride of lead is then reduced to pure spongy lead by using it as the positive plate of a primary battery, with a zinc plate as the negative, and dilute chloride of zinc as the electrolyte. This battery is short-circuited, and the hydrogen formed on the positive plate combines with the chlorine, reducing the buttons to a mass of spongy lead. A slow preliminary charging in dilute nitric acid frees the pores, and great capacity is obtained. The ordinary (R) type of cells for electric lighting supplied by the Chloride Electrical Storage Syndicate gives about 6 ampère-hours discharge per pound of positive plate in a 9-hour discharge, a little more than half this with a one-hour discharge. The normal rate of charging is from 13 to 20 ampères per positive plate, of the standard size.

Efforts have been made to do away with the supporting lead framework, using the active material alone, and thus effecting a great saving in weight. The difficulties are that the specific resistance of the active material is very great, especially when reduced to sulphate, and that its coherency and mechanical strength are not sufficient to stand the strains of expansion and contraction in the processes of charging and discharging. The coherency depends mainly on the presence of the sulphate, so that the positive plate would easily break up when fully charged. Efforts have also been made to replace the lead framework with one of some metal of material of better conductivity and mechanical strength—iron, copper or aluminium, of course covered completely with lead to prevent access of the electrolyte and formation of a primary couple. This protecting coating of lead seems to be difficult to maintain at all points, especially in the positive plates, and only for the negative has the device in any way succeeded. In very small plates it has been found possible to combine the Faure paste with other materials so as to obtain sufficient coherency for it to be used alone. In the Bristöl accumulator a binding material, such as animal hair, asbestos, fibre, &c., is used. Fitzgerald mixed the paste with glycerine to give greater coherency, subsequently using sulphate of ammonia. The latter method produced the material known as Lithanode, which has been largely used for the positive plates of small portable batteries alone, and for large cells has been used in the form of flat cakes, several being combined in a light lead framework to form a plate of large size. Litharge (PbO) is mixed with a semi-saturated solution of sulphate of ammonia, moulded into small plates under great hydraulic pressure. When thoroughly set and hard it is coated with peroxide of lead in a semi-fluid condition, and subjected to a slow electrolytic process of formation in a bath of sulphate of magnesia. The resulting material is almost entirely peroxide of lead, and the electrical capacity is as high as one ampère-hour per ounce. Lithanode is only used for the positive plate, a spongy lead plate being used as the negative.

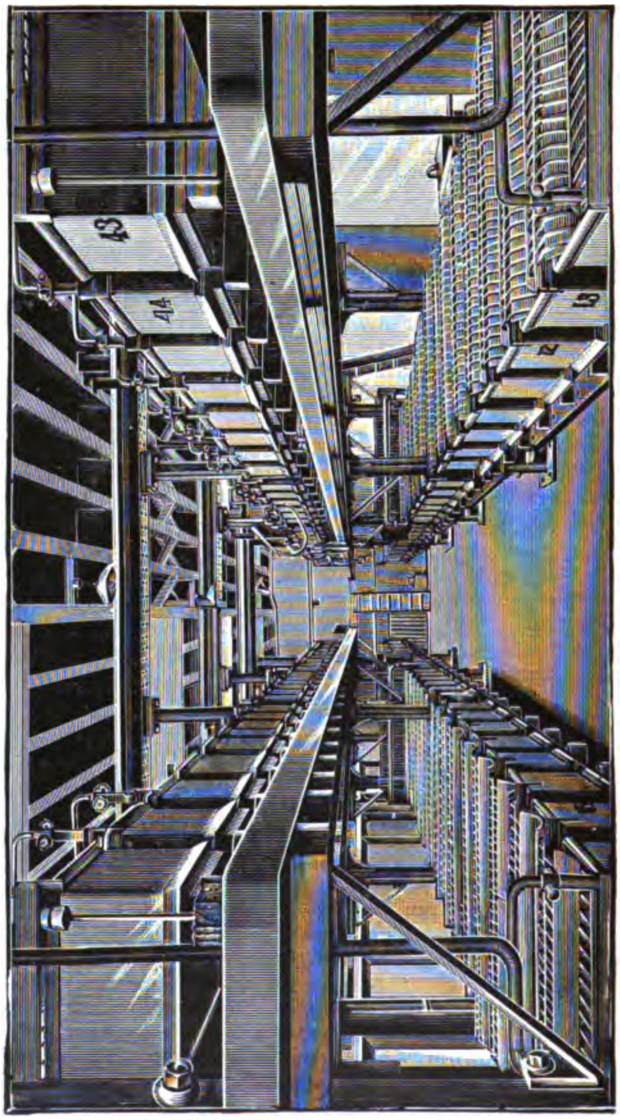
Another self-supporting paste plate was manufactured by Hering in the following manner. A dry mixture of powdered peroxide, minium, and lead carbonate or sulphate, is mixed with a solution of acetate of lead, and kneaded to a stiff paste. This is pressed into a mould and dried in an oven; hardened by immersion in sulphuric acid, and formed by charging in a solution of sodium or potassium sulphate. A further electrolytic deposit of lead peroxide from nitrate of lead produced an extremely hard surface.

In the "Planté" types of cells the active material is formed out of the lead plate itself, and either chemical or mechanical methods, or both, are used to increase the effective area of the plate worked upon, and to hasten the electrolytic process of "formation."

The Epstein Co. manufacture a type of cell which is claimed to be unequalled for mechanical strength and durability, and to require no skilled attention. Very thick lead plates are used, which are deeply grooved horizontally, so that the actual area exposed to the fluid is multiplied by five. To hasten the process of formation by "reversals," as in the original Planté cell, the plates are previously boiled in a one-per-cent. solution of nitric acid, which renders the lead-plate porous to some depth. The plates then assume a dull greyish appearance due to the formation of lead salts, and are thoroughly washed to remove the traces of nitric acid. They receive a very strong first charge, and the capacity is somewhat increased by a few reversals. The active material thus formed tends on expansion to key itself between the ledges or corrugations and then to adhere very firmly to the plate. The resistance of the plates themselves is very low, and the acid has free access to all parts of the active material, which forms a comparatively thin layer over the whole surface. The cell is capable of very rapid charge or discharge without injury. Since the area of the corrugated surface is 5 times that of a corresponding plane surface, a rate of charge of 20 ampères per positive plate (8″ x 9″) and a rate of discharge of 26 ampères per positive plate are specified as the normal rates. The positive plates are more massive than the negative. The M type, suitable for stationary lighting installations is made in sizes from 3 to 31 plates of the ordinary size. For the smaller sizes (up to 9 plates) glass boxes are used, and for the larger lead boxes, since constant inspection of the plate surfaces is not considered necessary. The capacity of a 31-plate cell is 2880 ampère-hours in a 12-

hour discharge, or 1800 ampère-hours in a 3-hour discharge. The weight of the lead plates is 575 lbs., and of the complete cell 1123 lbs., so that a

FIG. 36.



Secondary Battery Room (Crompton-Howell Cell).

maximum capacity of about 6½ ampère-hours per pound of lead, or about 2½ ampère-hours per pound of total weight is attained.

The D.P. secondary cell, a design due to Dujardin, Drake, and Gorham, employs plates built up of strips of thin lead ribbon, placed horizontally, the ends burnt together, and held in a framework of lead and antimony alloy. The strips of lead-ribbon have points or projections on their faces, preventing contact except at these points and allowing the electrolyte to permeate the intermediate space. Thus a very large initial surface is provided for the electrolytic action, and the effective area is increased by a few reversals. The cell is capable of giving a very rapid discharge, and the capacity per pound of lead used in the positive plate is 12 ampère-hours, which is one of the highest obtained with plates of large size. The De Kabbath accumulator is similar save that the lead ribbon is placed vertically, and alternate strips are corrugated to allow the electrolyte to permeate the plate.

The Crompton-Howell secondary cell illustrates another mechanical method of increasing the effective area by producing a porous plate. The special object desired by the manufacturers of these cells is to construct one suitable to the requirements of central station practice, where durability, freedom from possible failure, and capacity for rapid discharge in an emergency is of more importance than high efficiency, or great capacity in proportion to the weight. Lead plates, porous *throughout*, but yet of sufficient mechanical strength, are manufactured as follows. A quantity of molten lead is allowed to cool slowly, and begins to solidify in the form of crystals of lead at the bottom of the cauldron. These crystals are removed as they are formed by means of perforated ladles. Large iron moulds are then filled with the crystals, and the addition of a certain quantity of molten lead causes the whole mass to solidify in the form of a solid block of porous lead. These blocks are approximately 2 feet long by 10 inches square, and are cut into slices of $\frac{1}{2}$ inch thick, which are trimmed down to $8\frac{1}{2}$ inches square.

The plates are then about 10 lbs. in weight, and their capacity about 30 ampère-hours when discharged in 5 hours, or about 15 ampère-hours when discharged in 1 hour. The cells are made in a gradation of size up to 121 plates, the latter giving a total capacity, with slow discharge, of 3630 ampère-hours, or supplying a current of 1815 ampères for 1 hour, the total weight of the cell being (in lead box) 2300 lbs. Fig. 36 shows a central station battery room (Notting Hill) employing Crompton-Howell cells. As constant inspection is not considered necessary, lead boxes are preferred, and the cells are placed so that their plates stand lengthways along the line of cell-connections, and mounted in the following simple manner, which gives the minimum length of path in the lead-connections. Combs of celluloid at the top and bottom of the plates maintain the clearance between them (about half an inch), the plates being let in between the teeth of the combs. Very ponderous lugs are burnt on to the corners of the plates, and to large bars which make the connection with the next cell over the adjacent edges.

A secondary cell of higher E.M.F., about 2.5 volts, may be obtained by the use of a zinc plate for the negative, and a peroxide of lead plate for the positive. The zinc plate must of course be of pure zinc, or carefully "amalgamated" with mercury to prevent local action. In the discharge zinc sulphate is formed, which is soluble, and the zinc is re-deposited in charging. The principal objection to this cell is the high internal resistance obtained towards the end of the discharge owing to the zinc sulphate in solution, and at present it has not come into extensive use, except in small portable batteries.

Use of Secondary Batteries for Lighting.

Where 100-volt lamps are used in parallel circuit, 50 cells connected in series will, at the normal rate of discharge, maintain the requisite difference of potential between the mains. But a surplus will in general be required to raise the E.M.F. somewhat, in order to compensate for the fall of potential to distant mains, and if the cells are to be allowed to discharge to the point at which their E.M.F. is 1.9 volts, 55 cells in series will be necessary to keep the difference of potential at the terminals of the battery at 104.5 volts at the end of the discharge. It will also be advisable to have two or three extra calls to replace any found defective, and that must be removed from the circuit for repairs. To charge the battery a dynamo will be required whose E.M.F. can be made to range between 100 volts and 125 volts (the latter giving 2.25 volts per cell) in ordinary working, and should be able to give a still higher E.M.F. when required, so as to cause the cells to "boil" occasionally, in order to get rid of the white sulphate.

A shunt-wound dynamo is the most suitable for charging a secondary battery, for more than one reason. Firstly, the falling characteristic, giving a lower E.M.F. should the current increase, evidently tends towards the condition for a constant current in charging. Secondly, the shunt-coils now being connected across the terminals of the battery as well as across the terminals of the dynamo, the current in them will be supplied by the battery, without much decrease, even should the E.M.F. produced in the dynamo armature fall below the E.M.F. of the cells, owing to the rise of the latter during charging and any slackening in the speed of the driving engine. In this event a small current will also be driven from the battery through the armature, which being in the opposite direction to the E.M.F. produced by its rotation will drive it as a motor, supplementing the driving power so as to maintain the speed. With anything short of a complete break-down of the engine this motor current will be small, and a slow discharge of the battery will proceed until the defect is attended to (by speeding the engine or reducing the resistance in circuit with the shunt-coils to strengthen the magnetisation of the field-magnets) so that the E.M.F. in the armature may rise above that of the battery and the charging proceed. On the other hand, a series-wound dynamo will depend for its magnetisation upon the maintenance of the charging current, and when this is reduced by the rising E.M.F. of the battery, the E.M.F. of the dynamo also falls. The E.M.F. and current thus reducing together the dynamo is speedily demagnetised, and re-magnetised in the reverse direction by a discharge, which will become more rapid owing to the reversed E.M.F. of the dynamo. The plates would probably be seriously injured by the rapid discharge, even before a fuse could blow, and it would be difficult to regulate the dynamo for constant current to prevent this happening. A compound-wound dynamo would have the same objection, especially if "over-compounded," though of course in a less degree, and could only be used where constant attention is supplied.

In some small installations, for lighting small country houses, for example, the most convenient practice is to store the whole of the power, running the engine only in the day-time to charge the battery, and supplying only from the battery at night. No difficulty then arises from the variation of E.M.F. in charging, which may be effected with all the cells in circuit till the E.M.F. rises to 125 volts (and occasionally higher). If a few lamps be required to burn during charging, they may be connected across part of the battery (from 50 to 45 cells, reducing the number as the E.M.F. rises), this part of the battery receiving a slightly reduced charge. In commencing the discharge 50 cells, or less, will give the requisite E.M.F., and the extra cells must be switched in one by one as the E.M.F. falls. It is well to arrange the battery that these extra cells are interchanged with others daily, as they will be only partially discharged, and on re-charging will begin to boil before the others. By doing this systematically all the cells will undergo boiling in turn. The dynamo may be placed in parallel with the battery, at the time of the heaviest load, and the distribution of the output with a shunt-wound dynamo will depend on the relation of the E.M.F. in the armature to that in the cells: the load may therefore be divided in any desired proportion by altering the speed of the dynamo or its magnetisation. It will not, however, be possible to proceed with the charging of the whole battery while supplying incandescent lamps directly from the dynamo terminals, as the charging will require an excess E.M.F. Part of the battery, 45 to 50 cells, could be charged while lighting if the dynamo be of sufficient capacity; but this would entail frequent changing of the connections to ensure the charging of all. The value of the secondary battery thus used is: firstly, to increase the total output; secondly, to allow periods of rest for the generating plant, and perhaps to take its place altogether in the event of a breakdown; and thirdly, it affords the simplest and best method of regulating the E.M.F. in a small installation, where attendance is reduced to a minimum; gas and oil engines, which are frequently used in these small installations, are often irregular in speed, and for this irregularity the compounding of the dynamo will not compensate.

When it is desired to proceed with the charging of the battery while supplying a moderate number of lamps directly from the dynamo, so as to minimise the time during which the latter need be run, a convenient method is to use a small dynamo in series with that supplying the lighting circuit, its E.M.F. being about 25 per cent. of the larger so as to supply the extra E.M.F. for the whole battery. A continuous-current transformer, having a reducing ratio of about 4 to 1, from 100 to 25 volts, is most convenient. The dynamo armature of the transformer is connected in series with the generator, while the motor armature is connected in parallel; this is better than direct multiplication in ratio 100 : 125 for obvious reasons.

In cases where the secondary battery is used as a reservoir of power, never discharging for long periods so as to vary greatly in E.M.F., it may be worked in parallel with the dynamo when running so as to regulate the E.M.F., being charged or discharging slowly without more than the permissible variation allowed for incandescent lamps, and so needing no disconnection for a separate charging. An example is given by Stone's system of lighting for railway carriages. Each carriage has its own generating plant, complete in itself and automatic, a small dynamo being driven by a belt from a pulley on one of the axles of the carriage, with a secondary battery to act as a reservoir of power during stoppages, or with speeds too slow to maintain the requisite E.M.F. in the dynamo. The dynamo is suspended from the floor of the carriage by one corner of its frame, and by means of an adjustable link in such a manner that the dynamo is free to move towards or away from the driving pulley on the axle, with which it is on a level. The suspending link is provided with an adjusting screw which allows the tension on the belt to be varied when required, and to be so adjusted that the belt begins to slip when a certain load is thrown on the dynamo. A centrifugal governor automatically switches the dynamo into parallel with the battery when the speed exceeds a certain amount (corresponding to a train speed of 15 miles an hour, or more or less as required). At this speed the E.M.F. of the dynamo is calculated to be that required by the lamps in the carriage (40 volts). A further increase in speed will cause the E.M.F. to rise, the lamps burning somewhat brighter than the normal, and a charging current being driven through the battery. When the E.M.F. has risen as high as is permissible, it is arranged that the belt should begin to slip, and very little further power can be developed by the dynamo however much the speed of the train may increase. According to certified tests, the speed of the dynamo seems to be maintained with marvellous constancy under the same conditions of load after attaining a certain limit. After being switched in at a speed of 650 revs. (corresponding to about

15 miles an hour), the output in lighting and charging current rose steadily from zero to 16 ampères as the speed was increased to 870 revs. (21 miles per hour), at which point slipping began. A speed of 915 revs. with an output of 20 ampères was reached with a train speed of 24 miles per hour, both remaining unchanged though the train speed rose to 72 miles per hour. Of course the slipping of the belt means a waste of power, but this is of comparatively little consequence as compared with the total power absorbed in driving the train at high speeds. According to tests by Prof. Capper, the power absorbed by the plant at "normal speeds" (presumably when the maximum output was first attained) was 0.6 horse-power, and rose to 1.1 at full speed, the corresponding consumption of coal being about the same per train mile in each case, and estimated at one-twentieth of a pound. The battery will supply lighting power with a slightly reduced E.M.F. for some time at rest or slow speeds, an extra large, or double battery being supplied for underground railways, or when long stoppages are frequent. External switches are provided to extinguish half or all the lights when required.

An improvement on the above system, enabling more uniform E.M.F. between the terminals of the lamps to be obtained in charging and discharging, is obtained by the use of two similar batteries, one of which is, at all times, connected across the terminals of the lamps, and the other, when the train speed exceeds a certain number of miles per hour, to the terminals of the dynamo. The two batteries are further connected together, by their corresponding terminals, through a low resistance, enabling a somewhat higher difference of potential to be maintained between the terminals of the dynamo and the battery to which it is directly connected, and thus charges, than between the terminals of the lamps; the latter are supplied, with a slight waste of power, directly from the dynamo when the excess of its E.M.F. is sufficient. When the dynamo falls in E.M.F. or is cut out by the automatic switch, the current through the lamps is supplied by the discharge of the battery directly connected to them with an unreduced E.M.F. An arrangement is supplied which interchanges the batteries every time the direction of travel of the carriage is changed, so that each is alternately in the positions where they are charged, and where they supply the lighting current when the dynamo is not working.

Other systems of train lighting are supplied by a single generator in the guard's van for the whole train. A train-lighting dynamo designed by Holmes and Co. obtains a constant E.M.F. at all speeds (above a certain speed at which it is switched into the circuit) by the use of a small additional dynamo upon the same shaft as the generator, the E.M.F. of which is made to cause a weakening of the field magnetism of the generator as the speed is increased, and so maintain constant E.M.F. in the lighting circuit. For this purpose the field-magnets of the generating dynamo are supplied with two coils, each connected across the terminals of a secondary battery, but in the circuit of one of these coils the armature of the small dynamo is connected so that its E.M.F. opposes the battery and reduces the magnetising current in this coil as the speed is increased. A separate secondary battery is used for storing the power under each carriage, and when the dynamo is switched off all these batteries are in parallel with each other and with all the lamps. When the dynamo is switched in, its E.M.F. rising above that of all the batteries so that it can supply a charging current, an automatic relay throws a small additional resistance (about $\frac{1}{4}$ ohm) in series with the lamps in each carriage, so that with the raised E.M.F. they continue to burn with the same brightness, though supplied directly from the dynamo. 35-volt lamps are employed, and batteries of 18 cells, and a further permanent resistance of $\frac{1}{4}$ ohm is placed in series with each battery to ensure uniform distribution of the current in the many parallel circuits.

In central station practice the use of the secondary battery will be chiefly to supply the light load during the daytime (particularly with newly erected stations), thus saving the cost of labour in attendance on the running machinery, and the extra cost per unit in running the machinery at light and variable loads, at which its efficiency is often much lower than with heavy loads, and the oil, &c., used is much the same. The secondary battery is also of value as a "stand-by" in the event of break-down, provided it can be discharged at high rates. As a rule, however, the battery need be only of sufficient size to supply about ten per cent. of the maximum output of the station at the normal and efficient rate of discharge. As there will be a number of separate dynamos available, the difficulty of the excess E.M.F. of charging can be easily got over by using a separate dynamo for the purpose. By proceeding with the charging during times of moderate demand, and ceasing when the demand approaches the maximum, it will be possible to fairly equalise the rate of steam generation during the night, thus using the boilers and engines under their best conditions. As only a small proportion of the total energy output from the station will then be stored, say 10 per cent., the high efficiency of the secondary battery is not of paramount importance, a loss of 20 per cent. meaning a loss of only 2 per cent. of the total number of units supplied, and this will be saved many times over in the cost of labour, &c.

In a central station or private supply system worked by water power, especially where the supply of water is limited, and there is no convenient means of storing the water in a reservoir of sufficient size, the secondary battery is of incalculable value, enabling the total number of lamps that may be supplied by the generating station to be multiplied several times, because the generation of the electrical energy may then proceed uniformly throughout the day and night, except during the hours of heavy load, when the battery may be discharged in parallel with the generators. Supposing that the average length of the time of burning of the lamps on the shortest and darkest day of the year is four hours, a proportion that will hardly be exceeded except where there are many clubs, public-houses and the like to be supplied, or the district is subject to fogs, sufficient energy may be stored up during the hours of light load, say in about fifteen hours, to light three times as many lamps as can be lighted by the generating plant at the maximum output of the direct supply, or four times as many when the battery is discharged in parallel with the generating plant. This allows for a loss of 20 per cent. of the energy in storage, and a loss of time available for charging as all the lamps will not be lighted at the same time, and, therefore, more than four times the number of lamps that could be supplied directly from the generating plant could be connected to the system without fear of failure in the supply. Another case where the employment of secondary batteries is of great value for increasing the maximum output is where the supply of steam for the engines is obtained from boilers heated by dust destructors, where the consumption of the fuel should proceed at a slow and uniform rate throughout the whole day, and therefore, unless some system of thermal storage is adopted, the generation of the electric energy must be uniform. A uniform rate of generation may be employed with the necessary irregular rate of output of energy in stations where secondary batteries are established, so that even where the steam can be generated as it is needed, the secondary battery increases the maximum possible output from the station, when limited by the number and sign of the generators.

Other uses of secondary cells and batteries, to vary the E.M.F. in various feeder mains from a central station, to effect continuous current transformation from high to low potential, &c., are described in their proper places. It remains only to complete this part of the subject by describing some of the additional apparatus used in charging and discharging secondary batteries. In charging with a shunt-wound dynamo, some means has to be afforded to increase the E.M.F. of the dynamo as that of the cells rises, so that a constant charging current may be maintained. This will be either by an adjustment of the governor to increase the speed, or more commonly a rheostatic resistance in series with the shunt-coil, by means of which the current in it and the magnetisation of the dynamo may be increased by the attendant as the charge proceeds. Automatic machinery for this purpose is best avoided, as some degree of attention must necessarily be given to the cells. A "current alarm" calling the attention of the attendant by causing a bell to ring when the current exceeds a safe amount is easily designed, and a great convenience. Another device that is absolutely essential is an automatic cut-out which will break the circuit if the current should reverse so as to drive the dynamo as a motor, this being a safeguard against the rapid discharge which would follow upon the break-down of the engine. A fusible cut-out would not effect the same purpose, though it might be used to stop an exceedingly rapid discharge; it could take no cognisance of the direction of the current, would generally be too slow in action to prevent injury of the plates, and is troublesome to replace. A spring switch, held in the position of contact by a solenoid attracting a core, so as to release when the current falls before reversing, and to be replaced by hand, is often considered sufficient. A more elaborate automatic switch, the "Nevile" patent, effects automatic replacement. A permanent magnet moves between the poles of a horse-shoe electromagnet, actuating a switch consisting of a copper fork dipping into a pair of mercury cups. The electromagnet is wound with a thick wire coil in series with the switch, and a fine wire coil shunting the switch. When the E.M.F of the dynamo rises above that of the battery, the current in the latter causes the permanent magnet to lift the fork dipping into the mercury contacts; the magnetism of the electromagnet, and therefore the contact of the switch, is then maintained by the current in the series coil. The switch is thus not only turned off by the decrease or reversal of the charging current, but automatically replaced when the E.M.F. of the dynamo has risen sufficiently above that of the battery.

In discharging the battery, the difference of potential between the terminals of any cell varies from about 2.05 to 1.90 volts with a slow discharge, or a somewhat lower value throughout with a rapid discharge (the extra high E.M.F. after a "boiling" charge not being considered). A variation of .15 volt per cell is equivalent to that of about 8 volts in a battery of 45 cells. To maintain a sufficiently constant E.M.F. in the lighting circuit, convenient arrangements must be made for the removal of at least four cells, preferably six or more, from the battery when the discharge begins, and their restoration, one by one, as the E.M.F. of the battery falls. This will produce variations of the E.M.F. by 2 volts at a time, meaning only a variation of 1 volt above and below the declared E.M.F., which is well within the permissible limits. A circular multiple-way switch, such as shown in Fig. 37 (E.P S Co.), forms a convenient hand regulator. The revolving handle is connected to one of the supply mains, the successive contact pieces to the interconnections of the last few cells of the battery. In order that the circuit may not be broken even for an instant in passing from one contact to the next, the moving contact is double, one piece being connected directly to the central axis and supply main, the other through a short thick spiral of german-silver wire, through which a single cell may be short-circuited without injury for a moment.

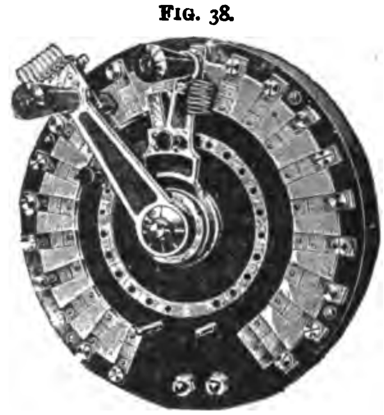
The double contact bridges over the intervening gap in passing, but should not be left in this position. Fig. 38 shows a double regulator, intended for simultaneous charging and lighting, one handle being connected to the dynamo, and the other to the supply main, so that a different number of cells may be used.

The method of regulation by cutting out cells from a battery is distinctly convenient, and not likely to be superseded for small installations. It is, however, almost as mischievous to overcharge cells, except with a reduced current, as to allow them to discharge too far; and with any system involving a separation of cells from the rest of the battery both events are likely to occur except where careful supervision is exercised. For this reason central station engineers have of recent years preferred to introduce methods of working whereby the battery may always be used complete, alike for discharging and charging. This is effected by means of the continuous current transformer, or "booster," mentioned above, which may

FIG. 37

Storage Battery regulating Switch.

FIG. 38.



Storage Battery Charge and Discharge Switch.

be reversed in action for discharge. The details are varied according to circumstances, and automatic as well as hand regulation may be obtained. For power supply, electric tramways and railways, where sudden and irregular changes of load are called for, batteries thus regulated are of the greatest value; but further description would extend too greatly the scope of this work.

CHAPTER VIII.

Continuous Current Transformer Systems.

THE multiple-wire systems reach the limit of their commercial efficiency when the average distance of transmission is about one mile. For even if it be considered safe to use electromotive forces exceeding 250 volts between any conductor and the earth in internal wiring, the five-wire or three-wire system, with 400 volts (or preferably 420 volts) between the external mains, introduces the maximum complexity permissible. Further multiplications of the number of wires cannot be seriously entertained. The exact point at which it is advisable to drop the direct systems, and use one of the transforming systems, is determined by numerous local considerations.

In making any economic comparison we have to consider both the capital and annual expenditure. In critical cases it will generally be found that the direct current systems demand the larger capital expenditure, but that at lower consumption of fuel per unit sold will be possible. Considering the latter, care must be taken to allow for the efficiency of the system at all loads, from the minimum to the maximum, in view of the varying demand day and night, summer and winter.

We may here call attention to two intrinsic advantages of transforming systems which are often forgotten in considering their relative commercial values. Firstly, the percentage loss of power in distribution is greatest with direct current systems at full load, and therefore the real maximum output of the former is often considerably less than the nominal output of the generators. The deficiency is generally less with transforming systems, and therefore the maximum output of the station may often be taken as much as ten per cent. greater than that of a direct current station with similar generating power.

Secondly, it cannot be but a great advantage to separate the house circuits from the supply mains, so that there is no electrical connection between them. For faulty circuits then can be easily detected, and the existence of faults upon one minor circuit does not affect the distribution of potential upon another. It is possible, by maintaining high insulation on each of the parallel mains of each separate house circuit, to have a double safeguard against the mischief and danger produced by leakage. In a direct supply the whole system supplied from the central station, or at least the whole section supplied by one large unit of plant, is certain to be faulty in some one part, and all other parts are thereby affected so that a single "fault" is nearly sure to have immediate consequences.

By the "transformation" or "conversion" of electrical power is meant the transfer of that power from one circuit to another, without contact of the conductors, so that the power reappears as another electric current flowing with a different electromotive force. The first circuit, in which the electrical power is initially generated, is called the primary circuit; the second, in which it is absorbed, or rather re-converted into light, heat, or mechanical power, is called the secondary circuit.

It is less easy to transform electrical power in the form of continuous currents than in the form of alternating currents, for with the former mechanical motion or secondary batteries, and therefore attendance at the point of transformation, is necessary. Alternating current transformation is effected by a purely magnetic linking, without mechanical motion, for which no attention is necessary, much higher efficiency is possible, and therefore its use is very much more extended. Certain advantages, principally that of the possibility of storage, remain with continuous currents, and they may yet offer the most efficient and reliable system of distribution, when the distance of distribution is not excessively great.

Continuous current power may be transformed by two methods, the combination of which is necessary to enable the system to compete with other systems of distribution. The first involves the use of storage batteries, charged in series with high electromotive force, and discharged in parallel with low. The second is the use of *dynamotors*, or continuous current transformers, which transfer the power directly from the primary to the secondary circuits. The transformation must be effected in substations at various convenient points in the area of distribution, and distributed to consumers by a low-tension parallel two or three-wire network. Substations are compact and inexpensive constructions, which may be placed in cellars in the midst of crowded districts without fear of annoyance to neighbours. Even with alternating current distribution the value of sub tations transforming upon a large scale is becoming more and more recognised as the cheapest and most efficient system.

Battery Transformation.

It was at Chelsea, in 1889, that the first extensive trial of continuous current transformation was made, at first using only battery transformation, sufficient storage capacity for 10,000 lamps being provided. The subsequent addition of transformers, worked in parallel with the batteries at the time of extensive demand, has enormously increased the possible output of the station, and now more than 50,000 lamps are connected, the capital expenditure in generating and transforming plant and mains being one of the least in proportion to the total number of lamps supplied of any central station in this country. Four substations were built, and each stocked with 440 secondary cells of the E.P.S. 31 L type, charging and discharging at 60 ampères, with a capacity of 660 ampère-hours. These were divided into two half-batteries of 220 cells each, which were connected respectively to the primary, or charging mains, and to the secondary or discharging mains, the half-batteries periodically changing places.

In the half-battery connected to the charging mains all the cells are arranged in series, and at the rate of from 2.2 to 2.5 volts per cell, require a total electromotive force of from 484 to 550 volts. The four substations are connected in series by the charging mains, so that a maximum electromotive force of 2200 volts is required. The substations are supplied from the generating station by four Victoria dynamos in series (one for each substation), each capable of giving a current of 75 ampères with 550 volts. The field magnets of all these are excited by currents from a single compound-wound dynamo, driven by a separate engine, the coils being supplied in parallel, with regulating resistances. A magnetic cut-out prevents a back-discharge from the batteries through the armatures. Should the half-battery of any substation be disconnected for any length of time, a short circuit is inserted in its place, and the exciting current of one of the generators cut-off, the generator itself being then short-circuited and removed at leisure; the passage of the current through the armature meanwhile will do no harm. But during the rapid interchange of the half-batteries the circuit is maintained through a large carbon resistance.

When discharging, the half-battery is divided into four sets of 55 cells, which sets are connected in parallel, and are intended to supply 100 volt lamps, with an excess electromotive force to allow for the fall in the mains. To maintain regularity during the discharge without the complication of cutting out cells and thus discharging them unequally, fourteen "back-electromotive force" in each substation are used to reduce or increase the electromotive force of sections of the batteries at different periods of the discharge.

The operation of changing over the batteries from charge to discharge requires some explanation. The fully charged battery is first short-circuited by a carbon resistance capable of carrying the full charging current, and having a resistance of a few ohms. The half-battery may then be removed from the charging mains, and split up into sections of 55 cells each, which are connected in parallel. It should then be placed in parallel with the half-battery at present discharging, a few "back electromotive force" cells being inserted to reduce the excess E.M.F. in the fully charged half-battery. The partially discharged battery may then be removed without cessation of supply, and subsequently connected to the charging mains. Elaborate automatic switches have been designed to effect the requisite changes, and variation of the back E.M.F. cells for regulation. The most ingenious of these is a switch which disconnects from the charging mains, after previously inserting the carbon resistance, when the cells are charged to "boiling." The gas from one of the negative plates is collected in a gasometer, and the rising pressure moves the switch. Whatever contrivances be thus used, skilled attendance in the substation is of course necessary.

Batteries used with so high an E.M.F. must of course be mounted and handled with peculiar care. At Chelsea the cells are arranged in five tiers, on wooden shelves with cast iron supports, care being taken to separate the cells with great difference of potential as widely as possible.

Initially the whole of the output was thus stored in and discharged from the batteries This means a large amount of loss, for with the best of secondary cells an efficiency of 80 per cent. is considered good practiçe, which with the loss in primary and secondary circuits will reduce the station efficiency to a very poor figure; but this loss is greatly compensated for by the fact that the engines and dynamos may always be worked at their most efficient load. The combination of the transformers with the battery transformation, the power being run in parallel with the discharging batteries at times of large demand, not only increases the efficiency of the transformation, but enormously increases the maximum output possible with the same generating plant. The principle of the continuous current transformer must now be described.

The Continuous Current Transformer.

The earliest conception of a continuous current transformer was simply that of a high tension motor driving mechanically a low tension dynamo. In this way by the medium of mechanical power transformation might be effected, and a constant electromotive force might be obtained in the secondary circuit if the motor be regulated for constant speed, and the dynamo be compound-wound. But it is difficult to regulate continuous current motors for constant speed with the requisite exactitude under varying loads. An alternating current motor, designed upon the principle of synchronism, would follow exactly the speed of the generator, and thus by using alternating currents in the primary circuit we may still retain the advantages of continuous current in the secondary, with storage batteries, and avoid many difficulties in regulation, and in the use of high tension commutators. This system may very probably be applied extensively in the future.

In the developed form of dynamotor, or continuous current transformer, the motor and dynamo armatures are mounted on the same shaft, between the same field-magnets, and frequently wound on the same core. Not only is space thus economised, and the power wasted in mechanical friction reduced to that of two bearings, but a regulative property is secured whereby the E.M.F. generated in the dynamo, or secondary, armature is caused to bear a fixed ratio to the E.M.F. in the motor, or primary, armature. This ratio is termed the ratio of transformation, and being independent of the current output from the secondary armature, except for a slight reduction due to the resistances of both armatures, which will be presently explained, ensures that constant difference of potential shall be maintained between the secondary conductors provided that the higher difference of potential between the primary mains leading from the generator be regulated for constancy, except for the aforesaid reduction or fall.

The subject of electric motors has been carefully avoided in this work, in order that the scope may not be too extensive, and the briefest explanation must here suffice. In the motor armature, the design of which is exactly similar to that of the closed-coil dynamo armature, the current flows in the opposite direction to that of the E.M.F. generated by its rotation. If E be the difference of potential between the terminals of the motor, R_1 the resistance of the armature circuit, the current c which

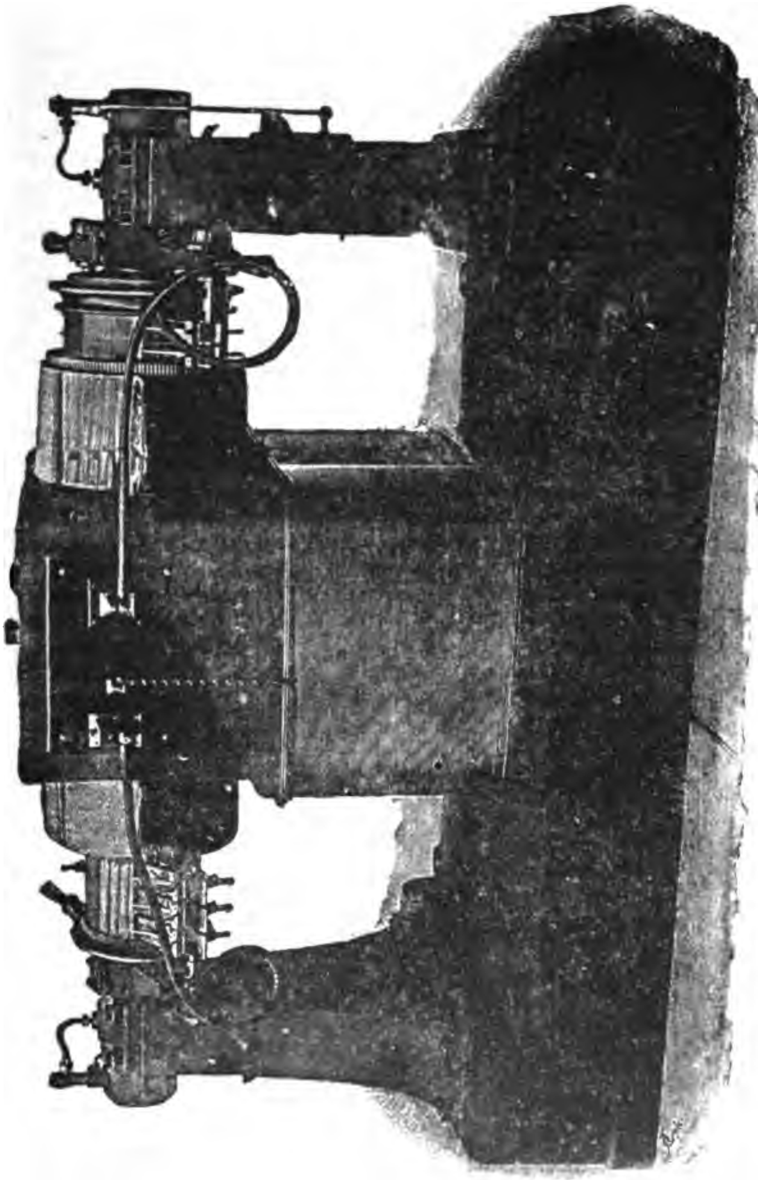


FIG. 39. Continuous Current Transformer. (Electric Construction Co.)

will flow through the armature will be of such a magnitude that E.c represents, in watts, the power required to drive the motor, overcoming the mechanical friction and other resistance to its rotation, and including the power absorbed by the resistance of the armature, hysteresis, and other losses; also the motor armature must rotate at such a speed that an E.M.F. is generated in opposition to that impressed by the generator which is given by

$$E_1 = E - cR_1$$

This being simply Ohm's law applied to the armature circuit, taking account of the two sources of E.M.F.

When the dynamo armature is on open circuit, and no mechanical power is taken from the motor, the driving current c is extremely small, and the "back E.M.F.," or that generated in the motor armature, is very nearly equal to that impressed by the generator, or between the motor terminals. The back E.M.F., E_1, will be given by the usual formula for the closed-coil armature depending on the product of the measures of the flux of magnetic induction, the speed of rotation, and the number of turns in the winding (n_1). If the dynamo, or secondary, armature be wound exactly similarly on the same armature-core, so that the flux of Magnetic Induction and the speed of rotation are identical with those for the motor armature, but the secondary armature be wound with n_2 turns, the E.M.F. generated will be given by a similar formula with n_2 in the place of n_1, and we shall have

$$E_2 = \frac{n_2}{n_1} E_1 = \frac{n_2}{n_1} E \text{ approximately,}$$

$\frac{n_2}{n_1}$ is called the ratio of transformation.

If the circuit of the dynamo armature be closed through an external resistance, such as a number of lamps, so that a current, C_2, is allowed to flow, the result will be to throw a load on the dynamotor, slackening its speed, so that the back E.M.F. of the motor armature is reduced, and a larger current passes. The additional primary current, C_1, must be sufficient to supply the power absorbed in the secondary circuit; if the current C_1 produce a similar number of ampère-turns in the armature to that of the secondary current C_2, but flow in an opposite direction, the driving force produced by the double winding will be the same as before, overcoming the frictional and other losses; therefore we must have

$$C_1 = \frac{n_2}{n_1} C_2.$$

The back E.M.F. of the motor armature will now be given by

$$E_1 = E - [c + C_1] R_1.$$

And if R_2 be the resistance of the dynamo armature, the difference of potential between the secondary terminals will be

$$E_2 - C_2 R_2 = \frac{n_2}{n_1} E_1 - C_2 R_2$$

or

$$\frac{n_2}{n_1} E - \frac{n_2}{n_1} cR_1 - \left\{ \left(\frac{n_2}{n_1}\right)^2 R_1 + R_2 \right\} C_2.$$

By reducing the frictional and other losses in the dynamotor the driving current c, and therefore the second term, may be made very small; the third term represents the fall of potential in the secondary circuit, due to the armature resistances of the dynamotor, when a secondary output of C_2 ampères is called for.

It is customary, as giving the highest efficiency for a fixed amount of copper, to make the fall of potential due to the resistance of the motor and dynamo armature approximately the same, that is to say,

$$\left(\frac{n_2}{n_1}\right)^2 R_2 = R_1.$$

This will mean that the same amount of copper is used in both armatures, the conductors in the dynamo armature exceeding in sectional area of those in the motor armature in the inverse ratio of transformation, and the total length of the armature circuits being in the direct ratio, their resistances are as the inverse square of the ratio of transformation.

The field-magnets are best excited by a shunt current from the secondary circuit, but the self-regulating quality of the transformer independent of the constancy of this excitation, provided it is the same for both dynamo and motor. The surest way of securing equality in the magnetic field is to use the same field-magnets for both armatures, if possible winding them upon the same core. Great care must be taken to secure good insulation between the primary and secondary windings, as a failure at any point would raise the secondary mains to a high potential, and be dangerous. An "earthing device" may be used to prevent injury being done to anything but the tranformer itself, as will be described in connection with alternating current distribution. A safer arrangement is to mount two armatures end to end on the same shaft, and between prolonged poles of the same field-magnets, inserting a disc of ebonite between them. A great advantage obtained by using the same field-magnets, and winding upon the same core is that the effect of armature reaction, which was not allowed for in the above calculation, is thereby almost entirely eliminated. For the currents in the two windings are opposed to one another, and have the same number of ampère-turns, except for the small excess current in the primary. The distortion is therefore practically insignificant, and the sparkless commutation on the two commutators can be effected at all loads without varying the lead of either brush. Furthermore, a Pacinotti, or short air-gap, armature may now be used without allowing for reaction, so that an intense field is possible; and as, with a motion purely rotary, a high speed presents no difficulty, the transformer is very much reduced in size as compared with a generator of similar capacity.

The two commutators are always placed at opposite ends of the double armature, in order to separate the low and high tension terminals as much as possible.

The transformers in use at Chelsea are made by the Electrical Construction Corporation, and are of the two-pole inverted type, with two cylinder windings on the same core, the high tension primary windings being threaded through ebonite tubes under the surface. Running at 1000 revs., the transformation capacity is 33½ kilowatts, and the efficiency appears to be at full load about 82 per cent. The transforming ratio is from 5 to 1 at zero load.

The following tests at full load of the first dynamotor employed at Chelsea have been published :—

Primary.			Secondary.			Efficiency.
E	C	Watts	E	C	Watts	Per cent.
604	72.5	43,790	111.5	320	35,334	81.3
606	72.5	43,935	111.5	327	36,313	82.5
588	64	37,632	110.5	280	30,814	82.2

An improved type more recently introduced attains an efficiency of 92 per cent. at the full load of 40 kilowatts, and 81 per cent. at one-third load. The transformers are intended to be run in series on the charging mains, and in parallel with the batteries upon the secondary, at times of heavy load only. The electromotive force need not therefore be regulated with very great care, as it is controlled by the cells. It is, however, arranged to force the pressure somewhat in excess of the batteries so that the transformer may be fully loaded, and only the excess of the demand drawn from the batteries. The electromotive force also requires to be kept high at the time of heavy demand.

A system of continuous current transformation differing very considerably from the Chelsea system has been established at Oxford since 1892. The transformation is here effected entirely by dynamotors, of which the primary armatures are connected in parallel instead of in series. The generating station is at Osney, on the outskirts of the city, where water is obtainable in large quantities from the river for condensing purposes, and where, owing to the proximity of the Great Western Railway, the coal can be obtained with the minimum expense in carriage. Triple expansion engines drive dynamos giving 80 ampères at 1050 volts with 400 revolutions per minute. A small exciting dynamo is driven from a pulley on the shaft of each, for the high tension of the dynamo itself is inconvenient in shunt winding. Three substations are erected in which transformation is effected from 1000 to 108 volts by means of transformers, consumers being supplied with a specified voltage of 105. The full load of each transformer gives 40 ampères in the primary, and 360 in the secondary armature. The speed of each is 550 revolutions per minute, and the efficiency at full load as high as 92 per cent., at half-load about 86 per cent. In one substation only is installed a secondary battery of 114 cells of the 31 L. E.P.S. type. These are charged in the daytime off the secondary mains in parallel with the lamps, being connected for this purpose as three sets of 38 cells in parallel. They are never connected to the high tension mains as at Chelsea. The battery is used only to maintain the supply during the light load after midnight, and as a stand-by in the event of a breakdown. For discharging they are connected as two sets of 57 in parallel. The secondary mains form a complete network, and can be supplied from this single battery when the load is light.

All the operations to be performed at the substations, the starting and switching on and off the secondary mains of the transformers and batteries, are under the control of the engineer at the generating station. The dynamotors need only very occasional attention when running, so that constant skilled attention in the substations is unnecessary. Pilot voltmeter lines are carried back to the generating station, and by short-circuiting these the switch that connects the transformer to the mains is turned by means of a solenoid in which the pilot line is wound.

CHAPTER IX.

Series Distribution.

Series distribution, involving the subdivision of the electromotive force factor of electric power, is the system which offers the highest possibilities of efficiency in working and economy in capital expenditure in distant transmission. There are, however, several considerations which render series distribution inconvenient, if not absolutely impossible, for interior lighting, so that for such purposes it has been totally abandoned, except so far as the multiple-wire systems may be considered a combination of series with parallel distribution.

The high efficiency and economy of series distribution arises from the high E.M.F. and small current which may then be employed. But with high voltage lamps on the simple parallel system, or with the multiple-wire systems, the limiting E.M.F. determined by conditions of safety for interior lighting may be reached, with greater convenience in the subdivision, and as long as incandescent lamps are employed of the present customary candle-power these systems are not likely to be superseded. A higher efficiency in the smaller sizes of incandescent lamps might, however, be secured if shorter and stouter filaments were employed, with a much lower difference of potential between their terminals, and such lamps would be preferably employed on a series circuit. Lamps of larger candle power than are really necessary are frequently employed, owing to the difficulty of obtaining small incandescent lamps suitable to the E.M.F. commonly used in parallel systems, and the adoption of series connection in branch circuits, though involving certain obvious difficulties, might effect considerable economy, provided these lamps are intended to be lighted simultaneously.

This device would not, however, effect any reduction in the size of the conductor, except so far as the current is reduced by the use of smaller lamps, or lamps of higher efficiency; and unless the lamps connected in series form a range, and not a group fed in all directions from a centre, the amount of copper required will be greatly increased.

Very extensive subdivision of the electric light, using lamps of small candle power, is evidently impossible with a system where all the lamps supplied from one generator are connected in series. It is suitable to a system where all the lamps require the same current, of moderately large amount, a comparatively low E.M.F.; also to circumstances where a high electric pressure may be employed without danger and where the arrangement of the lamps is more or less that of a line or range, instead of a group supplied from a central point. These conditions are exactly those afforded in the lighting of streets by arc lamps, for which purpose the series system possesses enormous advantages over any other. To a limited extent it is possible to place single incandescent lamps or groups of lamps on the same circuits but as a rule the adoption of a series distribution for street lighting requires that entirely separate generating plants and systems of distributing mains should be installed for this and for the lighting of interiors.

Looking through the records of the Patent Office in this country for the early days of electric lighting, from 1865 onwards, when the problem of subdivision was being slowly solved, one finds a large number of applications with regard to a series arrangement of lamps. The low voltage incandescent, arc, and semi-incandescent lamps were then in their elementary forms competing for favour, and the comparatively high E.M.F. lamps first introduced by Edison were needed to settle the question finally in favour of parallel distribution. Convenience has proved of more importance than the high possibilities of efficiency, for even to-day it is unquestionable that much higher efficiency could be obtained by using low voltage lamps, with short thick filaments, with a partial adoption of the principle of series connection. The arc lamp series system is therefore the oldest, and has survived unchanged through all the modifications to which incandescent lighting has passed in its evolution.

In addition to the high efficiency and economy in the distributing mains effected by series distribution, other advantages are to be obtained. With the regulation for constant current necessary for series distribution, better regulation of arc lamps can be effected than with a supply at constant E.M.F.; as shown in the chapter on arc lamps an additional steadying resistance with continuous currents, or impedance coil with alternating currents, is required for parallel working of arc lamps, in both cases, but especially the former, involving some waste, and seldom affording equal steadiness to that which may be obtained when the series arrangement is adopted. The higher luminous efficiency that can be obtained with continuous current arc lamps than with alternating currents (though denied by some), is a strong argument in favour of the adoption of a separate series continuous current system when an alternating current transformer system is used for the incandescent lighting of interiors. The separation of the street lighting from the interior lighting plant also enables the labour of switching on and off the lamps to be dispensed with, these being lighted and extinguished simultaneously when required. On the whole, though the extra conduits for the conductors, and the additional generating plant for street lighting, will in general cost more than the requisite addition to a system supplying interior lighting, the separate system is unquestionably preferable for the lighting of large towns and cities from a central station.

The standard size of arc lamp preferred for street lighting is the ten-ampère arc, adjusted for a length of arc gap of two to three millimetres, this length requiring a difference of potential between the electrodes of a little less than 45 volts, and between the terminals of the lamp of from 45 to 50 volts, the higher value being generally reached when the coils that control the mechanism are hot, and the lamp trimmed with carbons of full length. The energy thus absorbed is seldom less than 500 watts, or two-thirds of a horse-power. Sixty such lamps connected in series will require an E.M.F. of 3000 volts, which is about the highest that can safely be employed, though this has been greatly exceeded with special precautions. The electrical power expended in the circuit, in addition to that absorbed in the mains, will be 40 E.H.P., affording a load for a unit of plant of sufficient size to obtain high efficiency in generation. To all intents and purposes it is sufficient to calculate that one indicated horse-power will be required for every arc-lamp employed.

A conductor of 7/16 S.W.G., giving a sectional area of copper of .0229 square inches is most commonly employed for this system. The current density when ten ampères are carried is 436 ampères per square inch. The resistance per square mile, with copper of standard conductivity, should be 1.953 ohms, giving a fall of potential per mile of 19.53 volts, and an absorption of power of 195.3 watts. In other words it requires 2½ miles of conductor to absorb the power that would supply one lamp. Allowing for the return conductor, which must in all cases be carried back over the same route, and in the same conduit as that carrying the current to the lamps, the efficiency in distribution to a distance of 2½ miles, the power for sixty arc lamps being carried on this small conductor, will be 96.7 per cent. The supply will be regulated for constancy of current, which may be effected to any degree of accuracy that may be considered necessary, though with arc lamps for street lighting a much larger percentage variation is permissible from the specified current than is permitted with incandescent lamps from the specified E.M.F. For while with incandescent lamps a variation of one per cent. in the E.M.F. produces about six per cent. variation on the candle power, and, a fact of still greater consequence, considerably alters the colour and apparent brilliancy of the filament surface, the candle power of an arc lamp is only affected to the same extent as the current is varied, and the colour and apparent brilliancy being unaltered a variation of ten per cent. will scarcely be noticed.

Furthermore, with series distribution no difficulty will arise to correspond to the difficulty of obtaining uniformity of potential difference at all parts of the system which is the most important consideration in parallel distribution. The current must necessarily be the same throughout the single circuit, provided it is effectively insulated throughout so that the leakage may be insignificant. But as the current is now much smaller than in a parallel system conveying similar power, and leakage will directly effect the uniformity of the lighting throughout the system, more care must be used to prevent leakage, which the high electric pressure and the exposed position of the lamps tend to promote.

The circuit needs, of course, to be insulated as highly as possible throughout. Circumstances prevent our ensuring insulation in arc lamps to any high degree in exposed situations and during wet weather, so that a slight leakage over the insulating supports is unavoidable. Happily the heat of the lamps tends to prevent the creeping of damp and to uphold the insulation during the time of supply. Supposing the whole circuit as well as the dynamo supplying the current are equally well insulated, the potential throughout the 3000-volt circuit would vary from +1500 volts at the positive terminal to −1500 volts at the negative terminal. If, however, there be a point of low insulation, or a "fault," at any part of the circuit, that point will be lowered or raised to zero, the earth's potential, while the potentials at the terminals of the dynamo will be positive and negative, and proportional to the number of lamps between either terminal and the fault. By finding these potentials with an *electrostatic* voltmeter we have a fairly accurate method of locating the fault while the lamps are alight.

If there be two points of low insulation there will be a leakage current between them through the earth, and may result in the extinction of, or at least the reduction of, the current in the intervening lamps.

By connecting the central point of the circuit permanently to the earth, we could prevent the potential of any point upon the circuit becoming greater in magnitude than 1500 volts positive or negative. This is not to be recommended, as in that case leakage ensues when the insulation fails at any one point on the circuit. A breakdown of the insulation of some one lamp will inevitably occur, even in the most careful practice. But if this be rectified as soon as possible, the simultaneous occurrence of two such faults, which alone is of importance, may be made a remote contingency.

Arc lamps connected to a series circuit may be extinguished by effecting a short-circuit past the lamp, which maintains the series circuit with practically no resistance at the point where the lamp is connected. It is advisable so to design the short-circuiting switch as entirely to remove the lamp from the circuit after the short-circuiting has been effected, so that it may be handled without danger. Automatic short-circuiting devices are an essential part of the arc lamp mechanism when intended for series distribution, and the principle of their action is described in the chapter on arc lamps. The real object of these devices is to protect the arc lamp from injury in the event of the arc breaking and the carbon electrodes failing to come together. Such an event, by no means uncommon in the best forms of arc lamp, would result in the speedy destruction of the shunt-coil, which would carry the whole current of the series circuit, but little reduced from the normal ten ampères by the additional resistance of the shunt-coil (from 100 to 150 ohms), until it is fused into a solid mass. There is little danger of the circuit being broken by any such event, as a considerable break is necessary to stop a current maintained by 3000 volts.

Arc-lighting Dynamos.

Closed-coil dynamos are ill adapted for the supply of power in the form suitable for series distribution, on account of the high tension involved. The difficulty lies principally with the commutator. The form previously described would need to be of a very large size to be safe with a difference of potential between the brushes of more than 500 volts. About 10 or 12 arc lamps of the ordinary 500-watt type would therefore be the greatest number conveniently supplied in series by a closed-coil dynamo, this representing an output of only seven or eight horse-power.

At the St. Pancras central station most of the power for arc lighting is

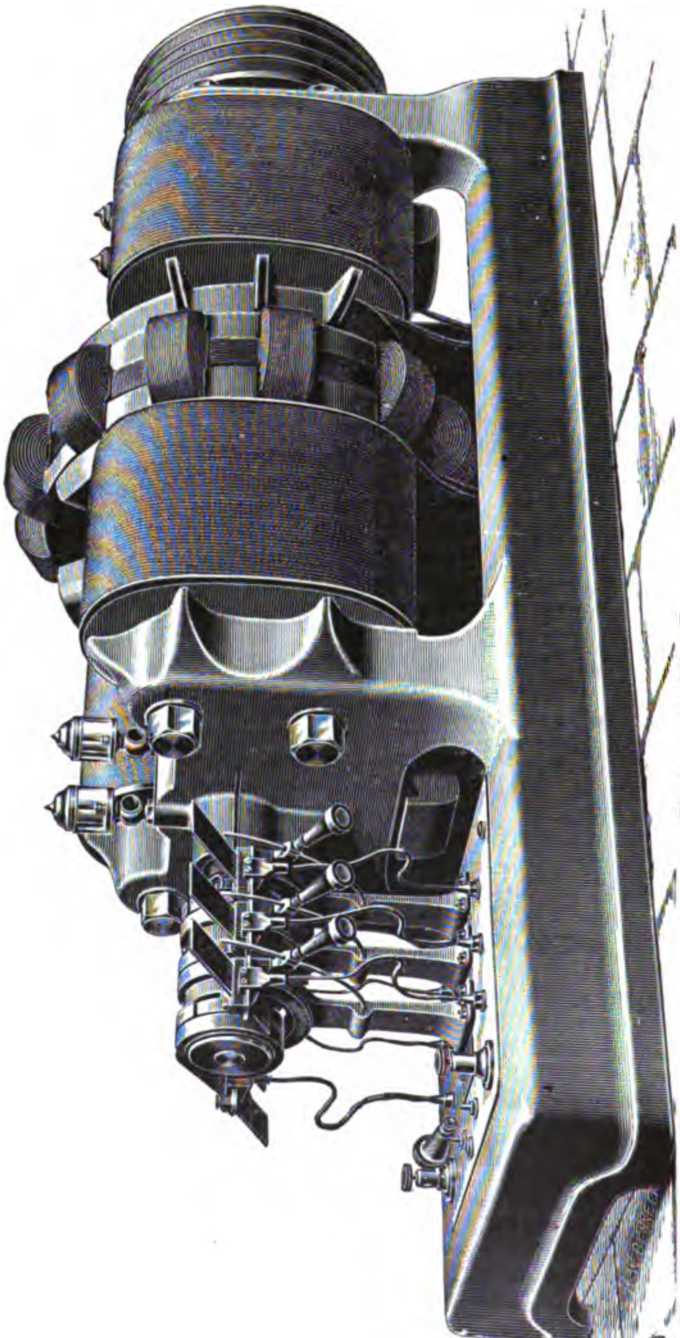


Fig. 40.

Brush Arc Lighting Dynamo.

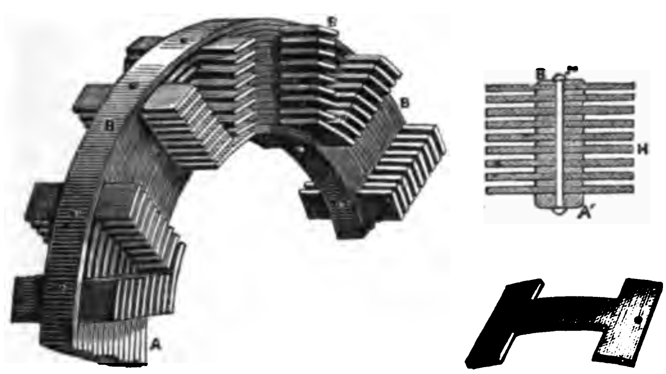
supplied from a four-pole Gramme machine, giving 50 ampères at 500 volts, and thus supplying 55 lamps in 5 parallel circuits of 11 in series. In this

case, however, the maximum distance of distribution is comparatively small, and a moderate potential has advantages. For perfect regulation this combined system of multiple parallel circuits requires the insertion of an equivalent resistance in the event of the extinction of any lamp in one of the circuits; in a single circuit the regulation may be effected by a corresponding reduction in the electromotive force, with no loss in efficiency.

For electromotive forces greater than 500 volts, it is advisable to adopt some form of open-coil armature. There are only two types of this class in common use—the Brush and the Thompson-Houston. Of these we shall give a short description.

The *Brush arc-lighting dynamo* is illustrated in external appearance by Fig. 40, a portion of the armature core-ring before winding in Fig. 41. The disposition of the magnetic field in the core-ring is similar to that in the two-polar ring in closed-coil dynamos, consisting of a double magnetic circuit through the upper and lower halves of the ring. The lines of force enter and leave the ring at the sides from the flat surfaces of wide-extended poles.

FIG. 41.



Core Ring of Brush Arc-lighting Dynamo.

The field magnets consist of two horse-shoe magnets placed horizontally, with similar poles facing each other across the intervening armature-core.

The armature-core is built up on the rim of a foundation ring **A**, Fig. 41, by winding a strip of thin wrought iron **B**, .022 inch in thickness, in successive convolutions, binding in a number of exactly similar **H**-shaped stampings as illustrated, so as to lie radially one above the other in the positions shown, the central limbs of a bunch subsequently forming the core on which a coil of the armature is to be wound, and the side projections fulfilling the purposes of Pacinotti teeth. The core is then securely bolted together with radial bolts, and to the supporting rim **A**.

In the type illustrated, the "sixty-light" dynamo, intended to supply a current of 10 ampères at 3000 volts, the armature consists of 12 separate bobbins, each of many turns, in each of which a high E.M.F. is generated. The coils are wound by hand, each with about 900 feet of No. 14 S.W.G. wire. The specified speed of rotation of the armature is 800 revolutions per minute. For arc lighting dynamos of smaller size, eight coils are employed instead of twelve, and the modification of the following description to suit this case will be obvious. The field-magnet coils are series wound, the resistance of the coils being about 14 ohms, and thus absorbing nearly 2 electrical horse-power.

To describe the method of connection of these coils to the commutator, and to show how an E.M.F. continuous in direction, subject to slight fluctuations as the armature revolves, is generated and the current collected, the description is much simplified by observing that the armature really consists of three separate sets of four coils in each, each set having a separate commutator, and the three sets entirely distinct save that by inter-connection of the collecting brushes they are always joined in series.

The four coils forming a separate set are mutually at right angles on the armature ring. Any two coils diametrically on opposite sides of the armature ring have at any moment electromotive forces of equal magnitude generated by the revolution of the armature; these opposing coils are always joined in series so as to obtain the sum of their electromotive forces, and the extremities of the connected coils terminate in opposite segments of a four-part commutator. The pair at right angles to these on the armature ring are also connected in series, and the extremities to the remaining segments of the same commutator. When the former pairs are in the position of maximum E.M.F., the brushes will make contact with the corresponding segments of the commutator, and these coils alone will form the armature circuit for this set of coils, the other pair, which will be then in the position of zero E.M.F., being thrown out of circuit. In a semi-revolution of the armature the pairs will change places, each pair being rendered active, or placed on open circuit, in turn.

The current is thus transferred from one pair of coils to the other pair of the same set of four alternately, and, unless the change is to be accompanied by violent sparking at the commutator, it is necessary that the pairs of coils should be placed in parallel for a short period in order that the interchange of the current may be effected gradually by the rise of E.M.F. in the pair that are about to become active, and the fall of E.M.F. in the pair about to be placed on open circuit. The operation is thus analogous to the reversal of the current in the sections of a closed-coil armature short-circuited by the brush contacts, and sparklessness at the commutator will be secured if the terminating commutator segments of the pair of coils about to be placed on open circuit recede from the brush contacts at the moment when the current in this pair has just fallen to zero.

A temporary connection of the pairs of coils forming a set in parallel might be effected by a broad brush contact, as on the commutator of the closed-coil armature. But, owing to the high self-inductance of the coils of the Brush armature, each consisting of many hundreds of turns, a somewhat prolonged period during which each brush is in contact with two commutator segments will be required for the complete interchange of the current, which would be difficult to effect by a broad brush contact alone. In place of this the commutator segments are T-shaped, so placed that they overlap to the extent of nearly 45° of the commutator circumference, thus permitting, with a narrow brush contact, the pairs of coils to be placed in parallel for periods equal to those during which each pair in succession are on open circuit. During the period of parallel connection (one-eighth of a revolution) the current gradually shifts from one pair of coils to the other, the lower internal resistance of the parallel arrangement partly compensating for the reduced E.M.F. obtained from the set of four coils in this position. The difference of potential between the brushes will, however, fluctuate considerably, reaching a maximum value four times during a revolution.

The three sets of four coils which compose the whole armature are practically equivalent to three dynamos connected in series by the inter-connection of the brushes. But, since the fluctuations in E.M.F. in the three sets pass through their corresponding periodic values at successive intervals, the E.M.F. of the whole armature is rendered much more uniform than that of the distinct sets, or between any pair of brushes touching the same commutator. The self-inductance of the field-magnet coils and the series coils of the arc lamps in the circuit will also tend to reduce the fluctuations in the current, so that, according to careful tests, a variation of only 1.5 per cent. in the current seems to result in a twelve-coil machine. Though this variation might be objectionable for some purposes, such as the charging of secondary batteries, it is of little consequence, if not distinctly beneficial, for arc lamp supply.

The commutator segments are separated by air-gaps about ¼ inch broad. The brushes are of flexible elastic copper strip, of the same breadth as the commutator, slit longitudinally for some distance from the points of contact. These are mounted on a rocking support, so that any pair can be rotated through a considerable angle, while preserving opposition of their contacts on the commutator, and the holders are connected by flexible conductors to terminals on a slate base, under which the interconnections are made, which joins the three divisions of the armature in series.

A very intense Magnetic Induction (as high as 27,000 C.G.S. units) is produced in the armature-core, while that in the field-magnets is exceedingly low (4200 C.G.S. units). The result is that the distortion due to armature reaction is exceedingly great, the lines of force being dropped forward to the trailing pole-tips, while the large side projections, or Pacinotti teeth, cause a considerable oscillation of the magnetic field as the armature rotates. The best position for the generation of E.M.F. will therefore be where the coils emerge from the polar interspace, and the brushes should be placed so as to make contact with the segments terminating coils in these positions, while the pair at right angles is upon open circuit. A slight additional lead would be necessary to obtain sparklessness at the commutator, but it is inadvisable to give the full lead required for absolute sparklessness for an important reason which must be carefully explained.

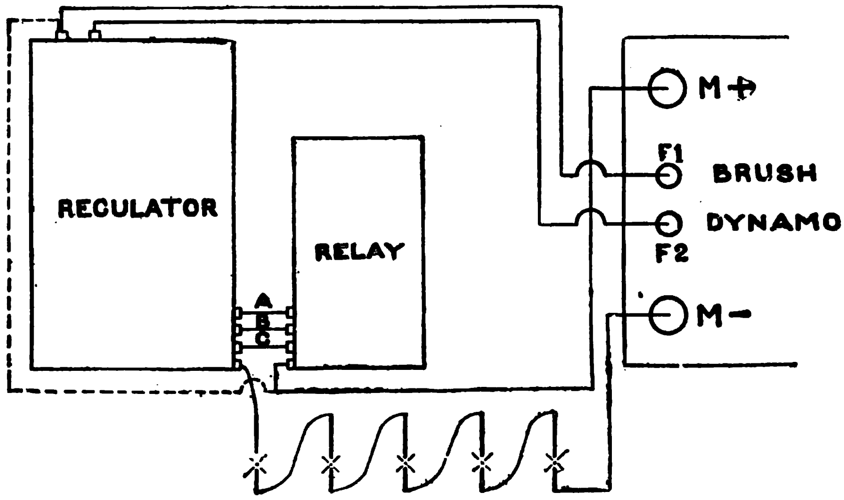
If a lead somewhat less than that required for sparkless commutation be given to the brushes, the result will be that each pair of coils successively will be disconnected from the circuit just before the current in them has been reduced to zero, and sparks will be produced by the current leaping from the retreating segments of the commutator towards the brushes. These sparks represent the passage of a current which is decreasing owing to the falling E.M.F. in the open-circuited pair of coils, and are therefore instantaneously extinguished. It is advisable to allow these sparks, which appear as a continuous discharge, to remain about a quarter of an inch in length, or even half an inch if there be any doubt about the steadiness of the engine or of the arc lamps in circuit. Sparks of this length should not injure the commutator surface, as there is no insulation between the segments to become carbonised. Oiling of the commutator must however, be avoided, except to a minute degree, as carbonisation may result, followed by burning of the copper brushes and commutator segments. As long as the sparks remain with a bluish tint they are quite innocuous, the first sign of destructive sparking being a greenish appearance.

If, however, the brushes be pushed forward to the sparkless point, it may happen, through a slight slackening in the speed of the engine or an increase in the resistance of the external circuit, that the current will fall, the distortion of the magnetic field will decrease, and the position of sparklessness may fall back leaving the brushes with too great a lead. In this event the current in the pair of coils about to be placed on open circuit will have decreased to zero, and a reversed current started in them while in parallel with the active pair. The ensuing spark will represent a current generated by the higher E.M F. of the active pair, tending to still further increase, and an arc will be formed between the commutator segments. The active pair of coils will thus be short-circuited through the inactive pair of coils through two short arcs, and an enormous current will pass. Happily, this will not result in the destruction of the commutator or the coils, as the heavy current is sufficient to demagnetise the field, and the only result will be the extinction of the lights. This accident is commonly known as a "flash over," and for the dynamo to recover itself it is generally necessary to slacken the speed, pulling the brushes back, and again advancing them as the speed is restored.

Owing to the high intensity of Magnetic Induction in the armature core-ring, a considerable amount of power is wasted in hysteresis. The large size of the side-projections from the core, or Pacinotti teeth, causes considerable fluctuations of the magnetic field in the wrought-iron pole faces,

FIG. 42.

DIAGRAM OF CONNECTIONS OF BRUSH-GEJPEL REGULATOR.



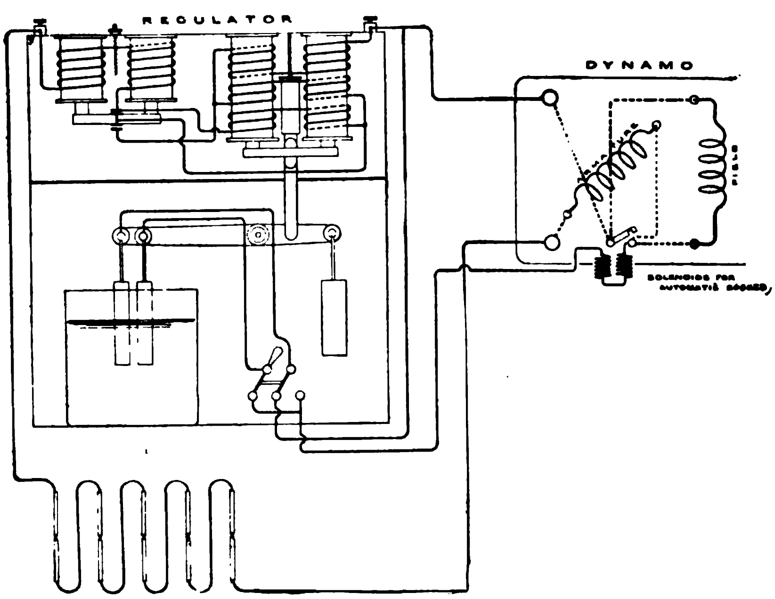
and the consequent heating by eddy-currents causes further loss, which might be almost entirely eliminated by lamination of the pole faces. It appears however, that an efficiency of 78 per cent. is to be attained by the Brush arc-lighting dynamo, and as it is intended to be used only at full load, this is considered sufficiently satisfactory. With the high E.M.F. generated and the purpose for which it is intended, durability and immunity from breakdown is of more vital importance than high efficiency, and in these respects the success of this type of dynamo has been phenomenal.

It would be impossible to compound a dynamo intended for series lighting so that a constant current is maintained, whatever be the resistance of the external circuit. It would, in fact, be most inconvenient to employ shunt-winding at all, since the high E.M.F. of the dynamo would render necessary a shunt-coil of great resistance and an enormous number of turns to give the required magnetisation, with a current small in proportion to the output current. A series coil is alone practically possible. Owing to the comparatively high resistance of the armature and field-magnet coils, and the reaction of the armature current on the magnetic field, the external characteristic of the Brush dynamo is such that the E M F. falls rapidly if the current is increased above the normal 10 ampères, and the limiting magnitude of the current, to be obtained on short-circuit, is barely double the normal, or about 20 ampères. As this current will not injure the arc lamps or mains, unless maintained for a considerable period of time, a fuse is entirely superfluous.

As the Brush dynamo will in general be employed with an unvarying load, there will really be no necessity whatever for automatic regulation of the current provided the driving engine be reasonably steady, and properly attended. The current may be initially and from time to time adjusted,

FIG. 43.

DIAGRAM SHOWING CONNECTIONS OF BRUSH-GEIPEL REGULATOR



either by alteration of the speed of the engine, or by a rheostatic resistance arranged to shunt some of the current from the field-magnet coils. The latter may, however, be effected automatically by the Brush-Geipel regulator, the connections of which are illustrated in Figs. 42 and 43.

The shunt, or "teazer" circuit, by the variation of whose resistance more or less current is removed from the field-magnet coils, consisted in the original form of this regulator of a number of carbon blocks, built up in four columns through which the current passed in series, and whose resistance was reduced by the application of greater pressure, and *vice versâ*. In the later type illustrated an electrolytic resistance is substituted, varied by the raising or lowering of suspended electrodes, and provided with a reversing switch for occasional reversal of the direction of the current through the electrolyte. The electrodes are raised or lowered on a lever by the action of a double solenoid carrying the main current and attracting a core attached to the lever. To further increase the range of variation in E.M.F. through which the regulator will maintain approximate constancy of current and the sensitiveness of regulation, a relay is provided, worked by another double solenoid in series with the main current, and lifting a core which effects alterations in the number of turns of wire in the solenoid directly controlling the regulator resistance. Tracing the connections shown in the diagram, it will be seen that the regulating solenoid is wound with three coils, through the lower of which the current can only pass in the opposite direction round the solenoid to that in the two upper coils. The current only passes through all three coils when the relay core is in the middle position, balanced by the attraction of the relay solenoid and an adjustable spring against its weight. If the relay core falls through too small a current in the external circuit, the middle coil of the regulating solenoid is short-circuited, its attractive force is reduced, and the core falls, raising the electrodes and lowering the resistance of the shunt across the field-magnets, and thus increasing the magnetisation and E.M.F. of the dynamo. If the current in the external circuit be too great the relay core is raised, short-circuiting the lower or opposition coil in the regulating solenoid, increasing its attractive force, lowering the electrodes and the resistance of the shunt across the field-magnet coils, and thus lowering the magnetisation and E.M.F. of the dynamo. An automatic rocker for adjusting the lead of the brushes as the current varies is also combined with the regulator.

The Thomson-Houston arc-lighting dynamo.

The only other type of dynamo that has been brought into extensive use for the purpose of series distribution is an American design by Professors Elihu Thomson and E. J. Houston. A general view of this machine is given in Fig. 44, and it will be seen by what follows that the theory of its action is as unique as its appearance.

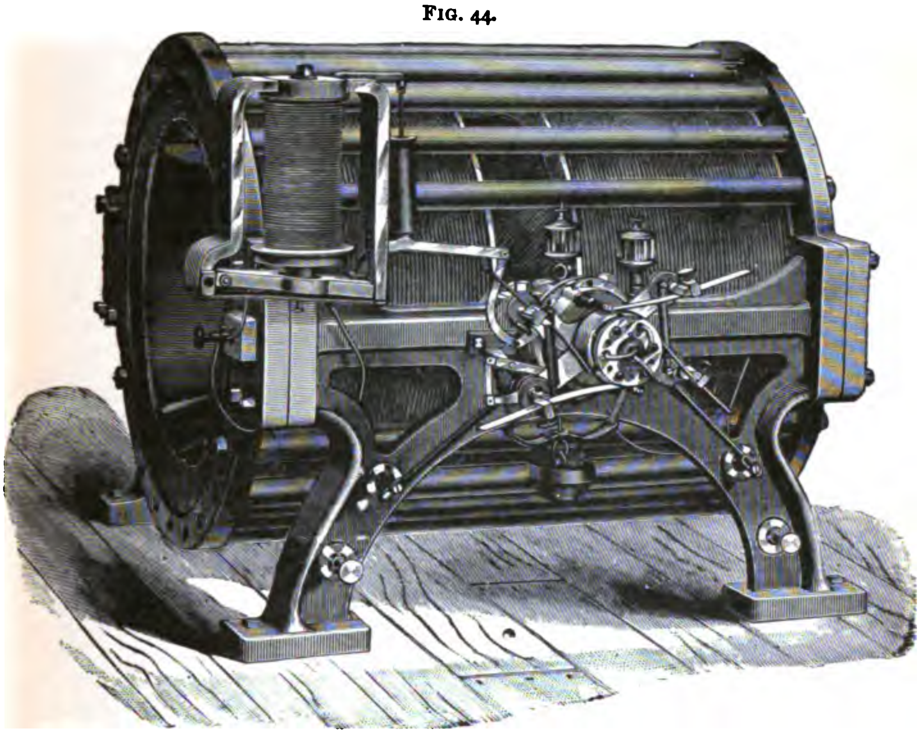
The armature is approximately spherical, and revolves between two cup-shaped poles which terminate tubular-shaped field-magnet limbs upon which the field coils are wound, the return circuit consisting of a "squirrel-cage" of wrought iron bars. There are only three coils in the armature, wound one over the other, but carefully insulated from each other upon a specially shaped iron frame-work. This frame-work consists of two concave iron discs keyed into the shaft, between the circumferences of which are wrought iron ribs, over-wound with a number of layers of soft iron wire.

The three conductors which are to form the coils are first connected together, and to no other conductor. They are then wound over the iron core so as to form three coils whose planes make angles of 120° with one another, the other ends terminating in segments of a three-part commutator.

In these three coils alternating electromotive forces are produced whose maxima occur successively at equal intervals during a revolution. Suppose the segments are so placed that the radial plane bisecting each is the plane in which the corresponding coil is wound, let us consider first what would happen if there were a single pair of brushes making narrow contacts in the plane of generation of maximum electromotive force. The brushes would always be making contact with the two segments of the coils that have the highest electromotive force, and there would be a single armature circuit through them, while the third coil is idle on open circuit. As soon as the electromotive force in the third coil exceeds that in either of the others, it takes its place. So far the action would be simple, but the narrow brush is impracticable owing to the self-inductance of the coils. The operation of changing from one coil to another must be performed gradually by placing the two coils in parallel for sufficient time for the rising electromotive force in one, and the falling electromotive force in the other to effect the transfer of the current before the latter is eliminated. This operation, identical in theory with that of the Brush dynamo, is here effected by having two brushes on each holder, connected together and making contacts at a short distance apart, so as to be practically equivalent to one broad brush. There will then be no sparking if a commutator section leaves the more advanced brush just when the corresponding coil has had its current reduced to zero.

The field-magnet coils are series wound. One of the most distinctive features in this dynamo is the exceedingly ingenious and effective method of regulation which is employed to maintain constancy of current. Instead of altering the current in the field coils as is the usual method, the armature reaction is made to vary by separating or closing together the two brushes on each holder. By rotating the trailing brush backwards round the com-

FIG. 44.



Thomson-Houston Arc-lighting Dynamo.

mutator the idle coil is thrown into parallel sooner. This may cause a current to be sent primarily in the reverse direction through this coil, but in all cases it will tend to lower the electromotive force by introducing the idle coil too soon. The armature reaction will be increased and the magnetic field become more distorted, so that it is found to be advisable at the same time slightly to advance the leading brush by an amount equal to about one third the retreat of the trailing brush. The brush-holders somewhat resemble a pair of scissors, one lever of which supports the two trailing brushes, and is moved forward or backward by a solenoid in series with the main current (assisted also by a relay as in the Brush-Geipel regulator). The other is made by a system of small levers to move a proportionate distance in the opposite direction.

By this arrangement the brushes are shifted without much effect upon the sparking. Another ingenious arrangement completely eliminates the difficulties due to sparking. A small nozzle placed just in front of the leading brush is made by means of a specially designed blower to deliver a blast of air just at the right moment to prevent the spark developing into an arc, and thus prevent the possibility of a "flash-over." For the design of this blower we must refer to more detailed works upon this subject.

The largest size of dynamo of this type is intended to be run at 820 revolutions per minute, and to supply 50 arc lamps in series, the current being 9½ ampères. This should be equivalent to 22½ kilowatts, or 30 electrical horse-power; and it is stated that 38 horse-power is required for driving, giving a commercial efficiency of nearly 80 per cent. The dynamo is exceedingly well ventilated, great durability and perfect regulation with very little attention is claimed as its principal features.

Until the last few years the two types of open-coil dynamos already described have practically held the monopoly of series arc lighting, and by far the greater number of arc lamps in existence were supplied from one or the other. These types are not adapted to be built as very large units, such as are advisable for central station supply for large cities in order to minimise the attendant labour and subsidiary expenses, and to economise space and power. Considerations of safety in using high E.M.F. impose a limit on the number of arc lamps which can be connected in a single series circuit, and some, perhaps not insuperable, difficulties would arise in the regulation for constant current if large units of these types were employed to supply several such circuits in parallel. In some cases several open-coil dynamos have been employed driven by the same large engine, thus partially overcoming the difficulty. In other cases motor-driven open-coil dynamos have been installed, so that the large units supplying the incandescent lighting for interiors may also be used as the primary generators of power for the series arc-lighting circuits; this system must involve unnecessary waste of power.

It is most frequently in combination with high pressure alternating current systems, as these are adapted to the supply of extensive areas, that series arc lighting will be advisable, and means whereby the two systems may be supplied from the same generators, other than motor-driven open-coil dynamos, have been introduced. To employ directly the power generated by the single-phase alternator for series arc lighting we require that the current should be "rectified," or commutated so as to flow in a uniform direction, and the regulation in the series circuit modified from that of constant E.M.F. given by the generator to that of constant current. The "rectifier" system designed by Ferranti fulfils both these requirements.

The current supplied by the alternator with constant E.M.F. (generally of 1000 or of 2000 volts), is first transformed by a modified alternating current transformer, which produces an approximately constant current in the secondary circuit, whatever may be its resistance. The current in this secondary circuit is rectified by a revolving commutator, driven by a small synchronous motor, the current for driving which is obtained from a transformer of the common type, connected to the primary alternating circuit. Fig. 45 shows the complete apparatus. The constant current transformer forms the table upon which the motor commutator stands. The magnetic circuit of this transformer includes two somewhat elongated horizontal limbs, round the middle of which the secondary coils are wound. The primary coils are wound in two equal coils on movable discs placed on either side of the secondary, and so suspended that they are capable of moving freely in opposite directions along the limbs of the magnetic circuit, from or towards the secondary coil. When currents are flowing in both primary and secondary coils, a repulsion exists between them, causing the movable coils to be repelled further apart when the current increases. The repelling force is balanced by adjustable weights, forcing the two sections of the primary coil towards the secondary coil. If the current in the secondary circuit rises above the normal amount, and the movable coils are repelled further apart, great magnetic leakage in the field created by the primary circuit ensues, and the E.M.F. in the secondary circuit falls below that given by the transforming ratio, as determined by the ratio of the number of turns

FIG. 45.

Ferranti Rectifier.

It is sufficient to arrange that the current should not rise in the secondary circuit more than about 100 per cent. above the normal when all the external resistance is removed. Regulation of the current may then be effected by shifting the adjustable weights, so as to alter the positions of the movable coils, and the automatic action of the transformer will prevent any dangerous increase of the secondary current.

The commutator is driven by a small synchronous motor, which is run up to the speed of synchronism with the alternating current generator by a modification of the connections which converts it to a non-synchronous motor, and thenceforth keeps in exact step with the alternations. It is preferable that a low frequency be employed for the purpose of rectification; with a frequency of 50 alternations per second, or 3000 per minute, a four-pole synchronous motor will rotate at a speed of 1500 revolutions per minute, and a commutator of eight sections be required. This commutator has the alternate segments connected together, one set being connected through a sliding contact touching an insulated ring on the motor shaft, to one terminal of the transformer secondary coil, the other set to the other terminal. Brushes, leading to the series arc circuit, are arranged to touch successive segments; two such pairs to divide the duty of collecting the current are generally employed. The commutator-segments are separated by air-gaps, and the brushes must be advanced to such a position that sparks of about a quarter of an inch in length appear to trail from the brush contacts; otherwise the commutator will be subject to "flashing over," for reasons that have been already explained in dealing with the Brush open-coil dynamo, and which apply equally to the rectifying commutator. As many as sixty arc lamps may be connected in series to the rectified circuit, the tranformer being wound to give 3000 volts in the secondary coils when there is no magnetic leakage. Owing to the heavy load thus thrown on the alternating current generators, it is advisable to perform the operation of switching on the current gradually; for which purpose a specially designed fluid resistance is supplied.

The direction of the current in the series circuit will now be constant, but its magnitude will fluctuate between a zero and maximum value. It is therefore termed a "pulsating" or "rectified oscillatory" current. The efficiency of arc lamps supplied with a pulsating current appears to be little, if any, inferior to those supplied with a continuous current, that is to say, one of invariable magnitude as well as direction. It is, in fact, claimed that the vibration produced in the arc lamp mechanism promotes regularity in the feeding, and greater steadiness in the light. It has certainly been demonstrated that the temperature, and light radiating from the pulsating arc lamp varies greatly during the pulsations, being lower and therefore less efficient at the moment of commutation and zero current; but this variation of temperature of the positive electrode with the pulsating current can be nothing like so great as in the electrodes of the alternating current arc lamp, in which each electrode in turn is radiating heat and light without generation for more than half of each complete period. It may be that the total illumination emitted from the pulsating arc lamp is subject to no less fluctuation than that from the alternating arc; this is however a different matter to the fluctuation of temperature of the electrode; the source of radiation in the alternating arc is constantly shifting from one electrode to the other, and the heat energy stored up during the time either is the positive is radiated with a smaller proportion of light radiation during the time it is cooling down as the negative. With the pulsating current the period of cooling of the positive electrode is much shorter, and the radiation proceeds from this electrode without much loss in efficiency. Furthermore, the advantage of better distribution of light remains with the pulsating as with the continuous current.

A more complete discussion of the subject of the luminous efficiency of the arc lamp, complicated as it is by the variation of the radiation in different directions, and the practical question as to the advantages or disadvantages of greater uniformity, will be given in the chapter on arc lamps. It is the opinion of many that the advantages of the continuous current arc lamp over the alternating current for street lighting has been much exaggerated, and at least does not compensate for the cost of the rectifying machinery, and the cost in skilled attendance that it inevitably demands. If this be so the rectifier itself may be omitted from the system, and all the advantages of the high efficiency of distribution, and combination of the series-arc with the alternating-current generating plant with constant potential maintained by the use of the above-described constant potential to constant current transformer, giving a series system with alternating current.

A branch series circuit from an alternating-current system for a few lamps only requires the employment of a simpler transformer adapted to give a constant current in the secondary coil when constant E.M.F. is maintained in the primary. Such a transformer has been devised by the Thomson-Houston Company, which regulates the constancy of the current in the secondary circuit with sufficient exactness for the purpose without moving coils, as in the transformer for Ferranti's rectifying system. The primary and secondary coils are wound on separate limbs of the magnetic circuit, and the magnetic leakage is enormously increased by a large magnetic by-pass across a short air-gap. The passage of a large current through the secondary coil increases the magnetic leakage, and thus lowers the E.M.F. which is generated in it. The simple form of constant potential to constant current transformer can be easily regulated by a sliding laminated slab slipped into the air-gap, so as to vary the reluctance of the by-pass, and therefore the leakage.

For alternating-current arc lamps a series arrangement of transformers has been employed, the primary coils forming the series circuit, and the secondary coil, similar to the primary in the number of turns, connected to the single arc lamp. The current in the secondary coil is in general equal to and cannot exceed that sent through the primary circuit, even if the arc lamp be short-circuited. An automatic short-circuit is combined with the arc lamp mechanism, and, in the event of the lamp failing, the corresponding transformer will offer very little opposition to the passage of the primary current, and will absorb very little power. By this means the advantages of series distribution are secured without the difficulties arising from high electric pressure on the lamps. A small transformer is fixed in the base of each lamp-post. The alternator to supply the series alternating current circuit should have an armature with very great self-induction, in order that the current output may be limited, and the alternator short-circuited with impunity. The characteristic of the alternator may be made rapidly "falling," and a fairly constant current may be produced without further regulation, the conditions being similar to that of the shunt-wound dynamo near the critical point, but without the low efficiency and danger of demagnetisation.

For the lighting of large thoroughfares the use of arc lamps taking currents of from 9 to 12 ampères, with a series distribution, is eminently a satisfactory and efficient system. For minor thoroughfares a further subdivision of the light is advisable, and the demand for this further subdivision will increase as the employment of electric lighting extends. If the electric arc be still used as the illuminant a reduction of the current is necessary, for the electromotive force of each lamp cannot be reduced much below fifty volts. We are therefore limited, in series distribution, with regard to the number of lamps that can be placed upon the same circuit, the practical limit being about 60 lamps, giving a total electromotive force of 3000 volts, which cannot conveniently be exceeded. The only way to further subdivide the electromotive force is to employ incandescent lamps, which are not similarly limited in electromotive force, but which can be constructed with short thick filaments of carbon so as to use a large current of, say, 10 ampères, with electromotive forces of from 6 volts upwards. The use of low voltage incandescent lamps in series has not as yet found much favour in this country, but proved very successful in America. The multiplication of the lights necessitates a multiplication of cut-outs, or short-circuiting devices, in order to complete the circuit in the event of the failure of any lamp, and for this reason some very simple automatic device is required.

The Thomson-Houston Company insert a very thin film of paper between the terminals of the lamp, which is capable of resisting the normal electromotive force of the lamp, but of which the dielectric strength at once gives way before the full electromotive force of the dynamo which is applied in the event of the lamp circuit breaking. The arc produced fuses the terminals together and maintains the circuit.

The Westinghouse Company use an alternating current, placing an impedance coil in parallel with each lamp. Very little energy is absorbed by the resistance of this coil and the hysteresis of the core, and the passage of a small diverted current raises the electromotive force of the lamp to its normal amount. If the lamp breaks all the current passes through the impedance coil, raising the difference of potential by only a little, owing to the saturation of the core, but not absorbing energy in proportion owing to the phase difference.

The Parfitt system, recently adopted for street lighting in several minor English towns, is at present the only extensively used series incandescent system in England. The lamps are connected in pairs, each pair consisting of two lamps in parallel, the pairs of lamps being connected up in a series circuit. Several circuits may be connected in parallel to the same dynamo, which may be regulated either for constant electromotive force or constant current, the resistance of each circuit remaining constant. Each lamp has a small electromagnet in series with it which, in the event of an excessive rise in the current through that lamp, attracts an armature which throws into parallel a resistance equal to that of the lamp. Now in the event of the failure of any lamp, a double current passes through the lamp in parallel with it, but no injury results, as the electromagnet instantly acts, and the lamp that failed is replaced by an equivalent resistance. If the second lamp of the pair should fail *subsequently*, the parallel resistance is capable of carrying the whole current, though with some extra expenditure of power.

Bernstein has designed a form of incandescent lamp intended for series working, in which a straight carbon tube takes the place of the ordinary fine filament. This tube is woven of silk, or some textile fabric, which is then saturated with syrup and carbonised. It is supported by hardened iron wires, bent so as to make contact in the middle of their lengths, at which point platinum contact-pieces are fused on to the wires. The carbon tube is held horizontally between the extremities, and is of sufficient rigidity to bend the wires apart and break their contact, but in the event of a fracture a short-circuiting contact is at once made. The lamp was intended for internal as well as external working, and made in small sizes of 16 to 50 candle power, with 4 to 15 volts. It was held in an ingeniously constructed holder, from which it could not be removed without turning a short-circuiting switch.

Bernstein also designed a chemical short-circuiting plug, consisting of an oxide of mercury combined with carbon, which, placed in parallel with the lamp, gave a resistance of about 200 ohms. But when, owing to the failure of the lamp circuit, the full electromotive force of the dynamo was applied to its terminals, the resistance was speedily reduced by electrolytic action to a very small amount.

Goldston has designed another purely mechanical method of maintaining the circuit in the event of the fracture of the filament, or glass bulb of an incandescent lamp. The contact is made externally instead of internally, as in the Bernstein lamp. Two contact pieces, with broad surfaces, are supported on levers which give a parallel motion, and are forced into contact by powerful springs. The lamp terminals are connected to these, and by means of a screw collar connecting the sealed end of the bulb to the frame of the lamp, a tension is applied through the glass which draws the contact pieces apart. A fracture of the glass will allow the short-circuiting contact

FIG. 46.

Goldston Series Incandescent Lamp.

to be made; and the fracture of the filament will allow an arc to be formed between the supporting iron wires, which will either fuse them together, or cause molten metal to fall and fracture the glass, and thus indirectly cause the short-circuit. Goldston's lamp is adapted to use a current of 10 ampères with an electromotive force of about 11 or 12 volts, and is intended to be used in series with a 10-ampère series arc system for positions where a smaller light is required. The candle power is about 50.

CHAPTER X.

Alternating Currents (Theory).

THE continuous current transformer system, employing secondary batteries and motor dynamos for the transference of power from a high tension circuit to a network of distributing low tension circuits, is probably destined to play a more important part in electric lighting in the future than it does at present, for the principal objection to the system is one which will lose its force as the electric light becomes more universally adopted. This objection is the necessity of constant attendance on the batteries and motor-dynamos, requiring that they should be concentrated at transforming centres, or substations, which feed the surrounding district through a low tension network. Now in entering into competition with older established means of illumination, the first customers of an electric supply system were to be found here and there over the whole area undertaken, and numerous small centres of transformation were necessary to utilise the full advantage of the high tension transmission. The cost of construction and attention at these small centres or substations is relatively much greater than it would be if the number of lamps supplied within the same area were large. Hence it followed that a system which does not render attention at the transforming centres necessary, and allows indefinite subdivision of transformation, obtained and still holds the preference; a system fulfilling the requirement was supplied by alternating current transformation.

Alternating current transformation is effected in a manner analogous or in fact almost identical, to that of continuous currents by the motor-dynamo, the only difference in the principles involved being that mechanical motion (the rotation of the double armature) is replaced by rapid variation, in magnitude and direction of the E.M.F. and current. The result is a more efficient and less expensive transformer, effecting the same purpose, and requiring no attention when in use. And though the alternating-current transformation system will certainly be most efficiently worked when the centres of transformation are concentrated into large substations, and under supervision, as is necessary with continuous current transformater, it has hitherto been applied most frequently with a separate transformer on the premises of each consumer, an expedient acknowledged to be temporary, and destined to be replaced by a more satisfactory arrangement, when the "density" of the supply, that is the number of consumers within a fixed area, is sufficiently increased. The alternating system suffers under the disadvantage that at present no means of storage of the power has been devised, but it is hoped by its advocates that by the utilisation of the generating plant and mains to supply motive power during the daytime, the load on the former may be made more uniform, and the advantage of storage thus rendered of little importance. If this hope be not realised, or a method of storage discovered, the continuous-current transformater system will possess an advantage which may, especially in dense districts, more than compensate for the more costly and inefficient transformation. A combined system, of recent introduction and possessing some of the advantages of each, is already under trial; the main principles of this will be considered when we have described the systems which, after prolonged use, have been acknowledged as effective.

The generation of alternating currents is more simple in theory than that of continuous currents. The E.M.F. produced by the variation of the flux of Magnetic Induction through any closed circuit is necessarily alternating, that is to say, it must change in direction periodically, and the E.M.F. can only be maintained in a uniform direction in a part of the circuit by some interchange of the connections. In a continuous current dynamo the E.M.F. and current in any turn of the armature are alternating, and it is only in the external circuit that they are made continuous by the constant change of the connections at the commutator. The flux of Magnetic Induction through a coil cannot increase or decrease indefinitely, so that when the variation changes in sign, the E.M.F. also changes in direction. In a single coil rotating with uniform speed in a uniform magnetic field about an axis in its own plane, and perpendicular to the direction of the lines of force, the direction of the E.M.F. is reversed twice in every revolution, and the magnitude of the E.M.F. being proportional to the cosine of the angle of inclination of the plane of the coil to the direction of the lines of force, varies gradually between its extreme values in either direction, repeating the cycle of variation with every revolution of the coil.

The alternating E.M.F. produced by the rotation of a coil in a field which is not uniform, may differ greatly as to the law of variation in magnitude of the E.M.F. produced. For some purposes a very different law of variation is purposely effected. In the well-known induction coil, for example, an alternating E.M.F. of high intensity is produced in the secondary coil by the magnetisation and demagnetisation of the bundle of iron wires which form the core. The magnetisation by the current in the primary coil is relatively slow, resulting in a relatively small E.M.F. in one direction: the demagnetisation is effected by the self-demagnetising force of the poles of the short core, and is much more rapid, producing an E.M.F. of much higher intensity and shorter duration than that produced by magnetisation. The current produced across the spark gap will be only in one direction unless the electrodes be brought close together, the direction being that given by the demagnetisation E.M.F. In a form of electromagnetic generator adapted to medical purposes a high E.M.F. is periodically produced in a circuit which bridges a gap suddenly opened in a self-inductive circuit carrying a current, the E.M.F. being alternating in direction with intervals of rest; attaining high values momentarily, such as may be called electric impulses, but a very moderate average value.

For the generation and transformation of considerable electric power, it is advisable that the variation of the alternating E.M.F. should be fairly gradual, at least avoiding the sudden changes described above. That obtained by the uniform revolution of a coil in a uniform magnetic field, commonly known as the "harmonic" or "sine" law of variation, is most commonly purposely secured by the design of generators. It is most convenient for mathematical analysis to assume the sine law, though, as will be seen later the variable permeability of iron will much modify the law of variation in actual practice. Whether the sine law gives the most efficient results remains a matter for discussion. A cycle of variation, corresponding to a single revolution of a coil in a uniform field is known as a *complete alternation, or period,* the number of complete alternations per second is termed the *frequency* of alteration. It is the universal practice to use the symbol $\sim$ for the frequency of an alternating E.M.F. or current; in mathematical investigations, however, this quantity is almost always combined with a multiplier 2π, and we shall use the letter p for the product $2\pi \sim$.

An alternating E.M.F. will produce an alternating current in any complete circuit, and if the circuit be non-self-inductive, as for example, a bank of incandescent lamps, and if its resistance remain practically constant during the alternations, the current will at all times be proportional to the E.M.F., being determinable by Ohm's law, and will therefore follow the same law of variation, arriving at its maxima and zero values at the same moment. In self-inductive circuits, however, that is to say whenever the current can create a magnetic field of its own, the variations of the latter field with the current will introduce a further E.M.F. into the circuit, which will modify the relation between the current and the original or impressed E.M.F. But before considering this modification we must understand the principle upon which alternating currents and E.M.F. are to be measured.

With the frequency commonly employed for electric lighting (from 50 to 150 complete alternations per second), an alternating current would not deflect a galvanometer, as the motion of the needle (or moving coil) would be far too slow to follow the current through its rapid changes, and a position would be taken up measuring the average (algebraic) value of the current, which if produced by electromagnetic changes in a generator whose total or average value is zero, must also be zero. With such instruments as the Siemens Dynamometer, or Kelvin Current Balance, where the current is measured by the attraction of two coils in each of which the current is made to flow, the direction of the current is immaterial, and the instrument may be used to measure either continuous or alternating currents. Now in such instruments the attracting or deflecting force on the moving coil is necessarily proportional to the square of the current passing, and provision for this is made in the calibration for continuous currents. When used to measure alternating currents the attracting or deflecting force is proportional to the average square of the current as it passes rapidly through its cycle of values; with the same calibration as was used for continuous currents the measurement given is of the number of ampères whose square is the average square of the number of ampères of current at all times.

Now the power expended in the generation of heat by a continuous current of C ampères, flowing in a circuit of resistance R ohms, is C^2R watts. An alternating current flowing in the same circuit would involve the expenditure in heat generation of the power measured in watts by the average value of the square of the number of ampères multiplied by R. Hence, if the continuous current and the alternating current are to generate heat at equal rates, and represent the absorption of an equal amount of power in this way, the measure of the former in ampères should be the *square root of the mean square* of the variable measurements of the latter, an infinite number of measurements being supposed taken at equal but infinitesimal intervals so as to obtain a true time-average. This measurement of the alternating current is given directly by the dynamometer or current balance, calibrated for continuous currents, and is that of the continuous current that will have an equivalent effect in heating the conductor. A hot-wire ampère-meter will also give a similar relation between its measurements of continuous and alternating currents. For the sake of distinction the unit of measurements of alternating currents taken in this way, is termed the "virtual ampère."

Alternating E.M.F. is measured by the number of virtual ampères of the alternating current it would produce in a non-self-inductive circuit of resistance equal to one ohm, the unit being termed the "virtual volt." The same measurement will also be given with electrostatic instruments calibrated for continuous electromotive forces, since in these instruments the electrostatic forces of attraction are proportional to the square of the difference of potential between the fixed and moving parts. An equivalent term, less frequently used, is that of "effective" in the place of "virtual."

If the alternating current or E.M.F. follow the harmonic or sine law of variation the relation between its measurement in virtual ampères or volts and the maximum values reached every alternation may be found as follows. Let E be the maximum E.M.F. attained; the E.M.F. at any moment, e, is given by $e = E\sin\theta$, where to θ is given all possible values (in the case of the generation of E.M.F. by the rotation at uniform speed of a coil in a uniform magnetic field, θ is the angle between the axis of the coil and the direction of the lines of force). Now the average value of $\sin^2\theta$ is one-half, since for every value of θ there is another value (the complementary angle) such that the sum of the squares of their two sines is unity, and therefore the sum of a large number of values of $\sin^2\theta$ taken at small uniform intervals is one-half of the number taken. Therefore the average value of e^2 is $\frac{1}{2}E^2$, and the measure of the E.M.F. in virtual volts is $\frac{1}{\sqrt{2}}E$. A similar relation connects the measurement of the current in virtual ampères with the maximum current reached.

Subject to other laws of variation than the harmonic the relation between the virtual and maximum measurements will be different. For example, with a uniform rate of increase and decrease from a maximum in one direction to a maximum in the other, the ratio of the maximum to the virtual measurements is that of the square root of three to unity.

The power absorbed in heat generation by the conducting circuit may be in all cases obtained in watts by multiplying the square of the measure of the current in virtual ampères by the resistance of the circuit in ohms. But Ohm's law will not be applicable to give the relation between the measurements of the E.M.F. and current in virtual volts and ampères, except for circuits free from self-inductance, and, therefore, it is only for the latter circuits that the power may be measured by the product of these measurements. The actual number of watts supplied to the circuit from the generating source will lie between $C^2.R$ and E.C. The former, being the lower value, will be correct when the power is wholly spent in heating the conductor itself, as it will be in a coil of wire without an iron core which does not induce currents in any other coil. In general some of the power supplied is transferred to another circuit in which currents are induced, or converted into mechanical power directly, and this transferred power is less than the difference between E.C and $C^2.R$. In the armature of the continuous current motor, it will be remembered, we have a similar formula, the difference between the above quantities being the product of the measures of the current and the "back" E.M.F. of the motor, in this case representing, without reduction, the power transferred from the armature circuit, for the most part (less the minor electrical losses in hysteresis and eddy-currents) reappearing as mechanical power.

We have now to consider the modification of Ohm's law mentioned above, applicable to self-inductive circuits.

Suppose the electric circuit external to the generator of an alternating E.M.F. to consist of a coil of wire wound round a laminated electromagnet, which we will for simplicity suppose to have a closed magnetic circuit of uniform section embraced by the coil. We will further suppose that the magnetism of the iron be never carried to saturation, and that the permeability of the iron may be taken as approximately constant through the range of magnetic variation that will ensue. If c be the current that at any time passes through the coil, n the number of turns, and A and l the cross-sectional area and length respectively of the magnetic circuit, the magnetic flux of induction will be given in c.g.s. units by,

$$N = \frac{\frac{4\pi}{10} nc}{\frac{l}{A\mu}}.$$

The variation of the magnetic flux will produce an E.M.F. in the coil which will oppose the impressed E.M.F. of the generator, this opposing or "back E.M.F." being $\frac{n}{10^8} \cdot \frac{dN}{dt}$ volts, so that if e be the value of the E.M.F. of the generator at any moment the current will be given by,

$$c . R = e - \frac{n}{10^8} \cdot \frac{dN}{dt} = e - \frac{\frac{4\pi}{10} n^2}{\frac{l}{A\mu}} \cdot \frac{dc}{dt}.$$

The expression $\frac{\frac{4\pi}{10} n^2}{\frac{l}{A\mu}}$ in this equation is termed the "coefficient of self-induction," or "self-inductance," or briefly the "inductance" of the circuit, and is commonly denoted by the letter L. In any electric circuit we may define the inductance by stating that the back E.M.F. in the circuit is measured in volts by the rate of change of the current in ampères multiplied by the inductance. The unit of inductance is that of a circuit in which the change of one ampère per second results on the back E.M.F. of one volt, and is termed the "henry," or "secohm."

Every electric circuit, even a straight wire, possesses some inductance, since a magnetic field is produced in the neighbourhood. For coils of wire the inductance is proportional to the square of the number of turns, and inversely proportional to the reluctance of the magnetic circuit. The inductance may be predicted from the measurements of the circuit, as in the simple case given, or may be measured by laboratory methods. When iron is present in the magnetic field the inductance is not a constant quantity but varies according to the intensity of magnetisation at any moment, and in general gives different values according to whether the current is increasing or diminishing. We may, however, consider, at least for the elementary investigation of the action of alternating currents, that the inductance is constant for the coils of electromagnets as long as the magnetism does not approach saturation, postponing the modifications that will be introduced by the considerations of variable permeability and coercive force.

We may now write the equation for the current,

$$R.c + L.\frac{dc}{dt} = e.$$

If the variation of the E.M.F. follows the harmonic law, we may write,

$$e = E \sin pt$$

where E is maximum E.M.F. attained during the alternations, and $\frac{p}{2\pi}$ is the frequency, or number of complete alternations per second. The solution of the above differential equation may then be written,

$$c = C \sin (pt - \theta).$$

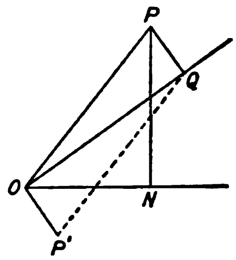
Where $C = \frac{E}{\sqrt{R^2 + p^2L^2}}$ and is the maximum current (in ampères) attained during the alternations; and $\tan\theta = \frac{pL}{R}$, θ being termed the "lag" or difference in "phase" between the current and the E.M.F. The quantity $\sqrt{R^2+p^2L^2}$ is called the "impedance" of the circuit, or sometimes the "virtual resistance," and may be denoted by the letter I. So that $\sin\theta = \frac{pL}{I}$, and $\cos\theta = \frac{R}{I}$. Denoting by E' and C' the measurements of the E.M.F. and current in virtual volts and virtual ampères respectively, the relation between them is the same as that between the maximum values, namely $C' = \frac{E'}{I}$.

The energy stored up in the magnetic field when a current c is passing through the coil is $\frac{1}{2}$ L.c² watt-seconds, or $\frac{1}{2}$ L.c². 10⁷ ergs.

Graphical Methods.

Two distinct graphical methods are in vogue for the illustration of the phenomena of alternating currents. The first is known as the clock-diagram, in which the maxima values of the current or E.M.F. are represented by vectors, or lines of fixed length drawn radially from a central point. Supposing the figure to revolve uniformly about the central point once during a complete alternation, the actual values of the current or E.M.F. would be given by the horizontal or vertical projection of these lines. The rotation is generally supposed to be in the opposite direction to that of the hands of the clock, and drawing one of the vectors in any direction such that the vertical projection represents any instantaneous value, the direction of any other vector, representing similarly another current or E.M.F. will be determined by the phase relation between it and the former.

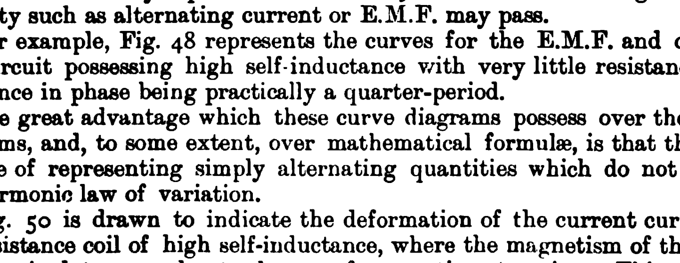
FIG. 47.



For example, in Fig. 47, OP may be drawn to represent the maximum value of the E.M.F. in any circuit, PN its instantaneous value. Let C be the maximum value of resulting current, somewhat lagging in phase (given by the angle POQ). If OQ is drawn to represent CR, the product of the number of ampères and numbers of ohms, it can be shown that PQ is perpendicular to OQ, and in magnitude is equal to pLC, where p is 2π times the frequency. For, completing the parallelogram $OPQP'$, it will be seen that since OQ is the diagonal of the parallelogram, by a well-known geometrical theorem familiar to students of mechanics, its vertical projection is the *algebraic* sum (in the figure the projection of P' is negative) of OP and OP'. Now OP' is a right angle, or a quarter-phase, behind OQ, and represents the back E.M.F. due to Inductance in the circuit at any moment. This subtracted from the instantaneous value of the E.M.F. should give the value required by Ohm's law, which is the projection of OQ.

The second method is to represent the instantaneous values of any quantity by ordinates drawn upwards or downwards from a horizontal zero line. The time is here represented by the position on the zero line at which the ordinate is drawn, any convenient length representing a complete period. The extremities of these ordinates, representing a recurring quantity, will be on an undulating curve repeating with each period. The

FIG. 48.



curves so drawn may represent conveniently all the values through which a quantity such as alternating current or E.M.F. may pass.

For example, Fig. 48 represents the curves for the E.M.F. and current in a circuit possessing high self-inductance with very little resistance, the difference in phase being practically a quarter-period.

The great advantage which these curve diagrams possess over the clock diagrams, and, to some extent, over mathematical formulæ, is that they are capable of representing simply alternating quantities which do not follow the harmonic law of variation.

Fig. 50 is drawn to indicate the deformation of the current curve in a low-resistance coil of high self-inductance, where the magnetism of the iron-core is raised to a moderate degree of magnetic saturation. This current curve is traced from purely theoretic considerations from the cyclic curves of Fig. 49. The E.M.F. in the circuit being represented by the harmonic curve having the smaller ordinates, the curve for the Magnetic Induction must be similar to that having the larger ordinates (the magnitudes of the ordinates depending on the scales chosen for each). For the variations of the Magnetic Induction, there being negligible resistance, are such that its variations balance the E.M.F. in the circuit, and therefore follow a harmonic

FIG. 49.

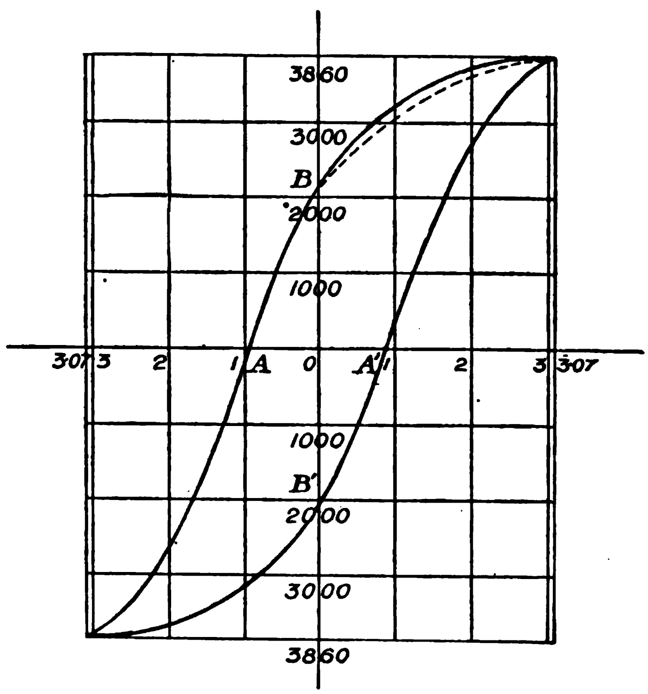
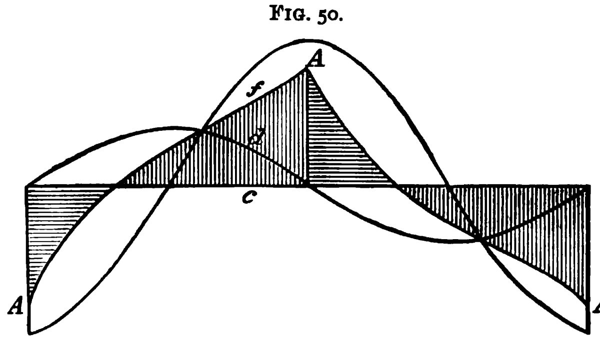


FIG. 50.



law, with a quarter period phase-retardation behind the E.M.F. The current is at any moment such as will give the Magnetic Induction, whether rising or falling, at the corresponding points on the cyclic curve. The maxima values of Current and Induction will occur simultaneously, but the current curve will fall more rapidly to give the corresponding values of the Induction which is "retained" when the magnetic circuit is complete, and will reach the zero value at the point corresponding to residual Magnetic Induction.

The current must also reach, when the Induction is zero, a value corresponding to the Coercive Force. The shaded curve *AA* thus represents the actual current curve, very much distorted from the true harmonic law, which is only approximated to when very low magnetisation is given by the alternating current, or when the magnetic circuit is incomplete.

The actual tracing of the curves for E.M.F. and current is exceedingly interesting and instructive, and in some cases of definite practical utility. This has been done directly for currents with an instrument termed the oscillograph, which is practically an instantaneous reflecting ammeter, recording on a moving photographic film. The instrument is, however, far too delicate when the errors of natural oscillation are sufficiently reduced for the measurements to be exact. The more practical "point-to-point" method is now used in every experimental laboratory, in which readings are taken upon an electrostatic instrument arranged to be switched on only at certain definite instants taken in succession through a complete period. A revolving switch upon the axle of the generator, or synchronous motor, is used, and many practical forms have been devised. A condenser charged through the revolving switch every revolution of the generator will maintain the difference of potential the same as at the moment of contact throughout the revolution, and this may be read with the electrostatic voltmeter, quadrant electrometer. The writer has a preference for a delicate moving coil galvanometer, with an immensely high resistance in series with it, to all intents and purposes equivalent to an electrostatic voltmeter, but much wider in range and quicker in reading. With the latter it is possible to trace the curves for currents also, by introducing an additional resistance of very small value, and without self-inductance, into the circuit; the fractional differences of potential between its terminals are then readable, and give the true instantaneous current values when multiplied by the resistance in ohms.

Most alternating-current dynamos give curves of alternating E.M.F. differing appreciably from the harmonic law. The current curve will in general follow that of the E.M.F in non-inductive circuits, Ohm's law being applicable for all instantaneous values, but self-inductance, and, still more, the variable permeability of iron, causes modification. The assumption of the harmonic law is generally sufficient for all purposes of calculation relative to design, but the deformation of curves has more effect on efficiencies than is at present recognised. It appears that a modification of the harmonic law for the electromotive force in the direction of a more "peaked" curve, that is a more rapid rise at the maximum and less near the zero value, would give less iron-core losses in transformers; while, on the other hand, arc lamps and motors would be more efficiently served by a blunt or flattened curve. The former is accounted for by the fact that a peaked curve for the E.M.F. results in a flattened curve for the Magnetic Induction, avoiding the hysteresis loss which mainly depends on the maximum value reached. Steinmetz has reported a test upon a 200-kilowatt transformer where the loss was reduced 13 per cent. by the substitution of a peaked E.M.F. curve for one following the harmonic law.

The power absorbed in the circuit by the resistance, and thus converted into heat, is measured in watts by C'^2R or $\frac{1}{2}C^2R$. This may also be written in either of the forms—

$$\frac{R}{R^2+p^2L^2}E'^2,\quad \frac{R}{L^2}\cdot E'^2,\quad \frac{R}{I}E'C',\quad E'C'\cos\theta.$$

The product $E'C'$, multiplying the readings of voltmeter and ampèremeter, is often called the number of "apparent" watts, and the correcting factor, the cosine of the angle of lag, is necessary to obtain the real value of the power absorbed.

The expression E'C' cos θ for the true number of watts supplied to a coil from a generator remains true under all conditions, and even when the harmonic law is not followed by the current or E.M.F. there still remains a factor equivalent to cos θ, which may be measured experimentally and is called the "power factor." But the great value of alternating-current employment consists in the fact that the power is not necessarily absorbed as heat in the coil, but may be transferred to another coil in its neighbourhood by induced currents through the medium of a magnetic field common to both. Generally the coils carrying the inducing and induced currents are named primary and secondary, and the combination is termed a "transformer" or "converter." The current in the primary coil is largely modified by that in the secondary, and it is necessary to enter into a short theoretic investigation of this influence as the foundation of the practical discussion of alternating-current systems of distribution.

Suppose, for example, the secondary coil to consist of n_2 turns, wound so as to include the whole magnetic flux through the primary of n_1 turns. Let the primary, as before, be wound round a laminated iron ring, or be of the form of a long solenoid or complete ring, so that the magnetic field is uniform. In this case it is possible to calculate the flux of magnetic induction through the coils as before, and the E.M.F. produced in the secondary coil by change of the current in the primary will be

$$\frac{\frac{4\pi}{10} \cdot n_1 n_2}{\frac{l}{A\mu}} \cdot \frac{dc}{dt}.$$

The co-efficient of $\frac{dc}{dt}$ is called the "co-efficient of mutual induction" or "mutual inductance" of the two coils. In all cases, for any pair of coils, the mutual inductance is a measurable quantity, and is the same whichever coil be taken as the primary, and which as secondary. As with self-inductance, it is difficult to calculate mathematically from measurements except in the example given above, nor is it a constant quantity when an iron core is used and a high degree of magnetisation permitted. The letter M is commonly employed to represent the measures of mutual inductance, and the same units as for self-inductance, the "henry" or "secohm," is used, as the quantities are of a similar nature.

The graphic representation of the power supplied to the circuit is indicated in Fig. 51, where the thick line represents the curve for E.M.F., the thin line the current; and the shaded curve, whose ordinates are proportional at each point to the product of the number of volts and ampères at each instant, represents the curve of power supply. The shaded portions represent by their area the total energy delivered to the circuit during any corresponding period, the part below the zero line indicating energy returned from the magnetic circuit to the generator. It may be easily shown that the power curve also follows the harmonic law, with twice the periodicity of the E.M.F. and current curves, and preserves its own dimensions exactly so long as the maxima values of the E.M.F. and current remain the same. Its central line is, however, raised somewhat above the zero line of the diagram, by an amount dependent upon the phase difference. When the E.M.F. and current are co-phasal the power curve is raised wholly above the zero line, touching it at every zero value of the former curves. As the phase-difference is increased the power curve sinks down, indicating a smaller and smaller amount of *average* power delivered to the circuit; until with a phase-difference of a quarter period the power curve is equally above and below the zero line, indicating that the energy oscillates without loss, an ideal case, between the generator and the circuit.

It will be noticed that Fig. 50 given above to illustrate the deformation of the current-curve due to intense magnification shows that power is really delivered to the circuit. For, on the whole, the current-curve is dragged forward so as to give an *equivalent* lag somewhat less than a quarter-period. The power-curve may easily be traced to show this more clearly, and obviously represents the power absorbed by the hysteresis of the iron.

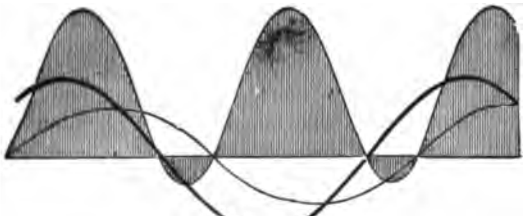
Calling the circuit connected to the generator the *primary*, and the other the *secondary* coil, we will suppose the latter to have a self-inductance L_2, and a resistance R_2, and a current c_2 to flow in the secondary circuit, while we shall now use the symbols c_1, R_1, L_1 for the current, &c., in the primary circuit. The equations for c_1 and c_2 may be written:

$$R_1 . c_1 + L_1 \frac{dc_1}{dt} + M . \frac{dc_2}{dt} = E . \sin pt.$$

$$R_2 c_2 + M . \frac{dc_1}{dt} + L_2 \frac{dc_2}{dt} = 0.$$

The complete solution of these simultaneous differential equations give

FIG. 51.



the magnitudes and phases of the currents in the primary and secondary coils. It may be shown that

$$c_1 = \frac{E}{\sqrt{R'^2_1 + p^2 L'^2_1}} \sin (pt - \phi)$$

Where

$$R'_1 = R_1 + \frac{p^2 M^2}{R_2^2 + p^2 L_2^2} . R_2$$

$$L'_1 = L_1 - \frac{p^2 M^2}{R_2^2 + p^2 L_2^2} . L_2$$

$$\tan \phi = \frac{pL'_1}{R'_1}.$$

That is to say, the current flows as if in a circuit of equivalent resistance and inductance given by R_1' and L_1'.

For the secondary circuit the conditions may similarly be shown to be fulfilled by supposing an equivalent electromotive force in the coil equal to that in the primary circuit multiplied by

$$\frac{pM}{\sqrt{R_2^2 + p^2 L_2^2}}$$

with a lag of

$$90^\circ + \tan^{-1} \frac{pL'_1}{R'_1}$$

behind it; and with an equivalent resistance and inductance respectively given by

$$R_2 + \frac{R_2^2 + p^2L_2^2}{p^2M^2} . R_1 \text{ and } L_2 - \frac{R_2^2 + p^2L_2^2}{p^2M^2} . L_1 .$$

It has been thought advisable thus to write down the complete solution without pursuing the intervening steps. For, though in the actual transformer as commonly constructed a simpler investigation would serve the purpose, there are often cases in which a modification is necessary; for example, when the coils are wound on opposite limbs of a laminated electromagnet, and the magnetic flux is by no means common to both. It is then convenient to refer to the complete solution to explain practical variations from the commonly accepted formulæ, which suggest the explanation even when the quantities involved are not known or measurable.

In the transformer as used for power distribution the problem is very much simplified by the use of a high value of the frequency; further, by the use of transformers with little or no magnetic leakage between the coils (except under conditions to be described); and thirdly, in systems intended for electric lighting and not for motive power, by the reduction of the inductance of both primary and secondary to a very small amount above and beyond that of the coils themselves. Except when these conditions are fulfilled, the engineer must be very wary in the use of the simpler formulæ now to be deduced.

If the frequency be very great, so that R_2 may be neglected in comparison with pL_2, we shall have approximately,

$$\frac{C_2}{C_1} = \frac{M}{L_2} .$$

If, moreover, there be no self-inductance in the secondary circuit except that of the coil which is wound with n_2 turns so as to include the identical flux of Magnetic Induction that passes through the primary coil of n_1 turns, the ratio of the co-efficient of mutual inductance to the self-inductance of the secondary will be $\frac{n_1}{n_2}$, so that $C_1 n_1 = C_2 n_2$.

Further, if the primary circuit have no additional self-inductance, or if by the alternating E.M.F. we mean the alternating difference of potential between the terminals of the coil, we shall have,

$$L_1 : M : L_2 \text{ as } n_1^2 : n_1 n_2 : n_2^2$$

and, therefore,

$$R'_1 = R_1 + \frac{n_1^2}{n_2^2} . R_2 \quad L'_1 = 0$$

$$R'_2 = R_2 + \frac{n_2^2}{n_1^2} R_1 \quad L'_2 = 0$$

$$E_2 = \frac{n_2}{n_1} E.$$

The current in the primary coil will be cophasal with the E.M.F., that in the secondary will lag 180° (since $\frac{pL_2}{R_2}$ is taken as infinity), or, in other words, flow in exact opposition.

If R_2 cannot be neglected in comparison with pL_2, that is, if the resistance of the secondary circuit be very great, the current in both the primary and secondary coils are extremely small, and no longer in a fixed ratio. If the secondary circuit be broken, or R_2 infinity, and $C_2 = 0$, we shall have

$$C_1 = \frac{E_1}{\sqrt{R_1^2 + p^2L_1^2}} = \frac{E}{pL_1} \text{ approximately.}$$

This is called the *magnetising* current of the transformer, and were it not for hysteresis and eddy-currents in the iron core would lag behind the E.M.F. of the generator 90° or a quarter-period. When the frequency and the self-inductance of the primary coil are great, the magnetising current becomes very small. The quantity pL_1, being analogous to the resistance in a non-inductive circuit, is sometimes termed the *re-actance* of the coil.

The above investigation has shown how an electric current may be produced in a secondary circuit, having no electric connection with the primary circuit connected to the generator of alternating E.M.F., the sole requirement being that the coils forming part of each circuit should be wound so as to embrace the same magnetic circuit. Such an arrangement is known as an alternating current "transformer," or "converter." The general investigation shows that—

(1) The currents in the primary and secondary coils are in the ratio of the coefficient of mutual inductance to the impedance in the secondary coil.

(2) With a high frequency, and no further self-inductance in the secondary circuit beyond that due to the magnetic circuit of the transformer, the ratio between the currents in the primary and secondary circuits is inversely as the number of turns in the respective coils (to a close approximation except in the case in which the resistance of the secondary circuit is very high).

(3) If the resistances of the coils of the transformer are small, the current will be determined by the external resistance of the secondary circuit, the difference of potential between the terminals of the secondary coil being to that between the terminals of the primary coil in the direct ratio of the numbers of turns (which is therefore called the *ratio of transformation*). The effect of resistances R_1 and R_2 in the primary and secondary coils respectively of the transformer will be equivalent to an additional resistance added to the external resistance of the secondary of $R_2 + \frac{n_2^2}{n_1^2} R_1$, so that if E be the difference of potential (maximum) between the terminals of the primary coil, that between the terminals of the secondary will be

$$\frac{n^2}{n_1} E - \left(R_2 + \frac{n_2^2}{n_1^2} R_1\right) C_2.$$

(4) When the secondary circuit is broken, a small *magnetising* current flows in the primary coil, determined by the frequency and self-induction, if its resistance be comparatively small. This current lags something less than quarter-period behind the E.M.F. of the generator. In the intermediate case, when the secondary circuit is complete and of "pure" resistance, the primary current becomes more and more nearly co-phasal with the E.M.F. of the generator as this resistance is reduced; the secondary current is given by Ohm's law, the E.M.F. being $\frac{n_2}{n_1} E$, applied to the "pure" resistance circuit. The ratio of the currents in the primary and secondary circuits approaches that of $\frac{n_2}{n_1}$, as the resistance of the secondary circuit is reduced.

In the use of the alternating-current transformer for electric lighting, whether for incandescent or arc lamps, there will be little or no self-inductance in the secondary circuit, to which the lamps are connected. The regulating solenoids of arc lamps introduce a small amount of self-inductance, but insignificant in comparison with that of the coils of the transformers. The purpose of the transforming system will be, as already described in the chapter on continuous-current transformation, to utilise a high constant

E.M.F. in the distributing mains, and obtain a lower E.M.F. in the various circuits to which the lamps are connected in parallel. For regulation it is required that the reducing ratio of transformation should be constant, that is to say, independent of the currents flowing, so that the lamps may be connected in parallel between conductors joined to the terminals of the secondary coil, the primary coils of the various transformers in parallel between conductors connected to the terminals of the generator of alternating E.M.F.; constancy of E.M.F. between the lamp terminals may then be secured by regulation of constant E.M.F. between the terminals of the generator, and the currents in both primary and secondary circuits determined by the resistance of the secondary. The requisite conditions have been shown to be, firstly, that the self-inductance of the transformer coils and the frequency of alternation should be as high as possible, and secondly that the resistance of the primary and secondary coils of the transformer should be low in comparison. The resistance of the primary coil (and distributing mains) is, however, only equivalent to an addition to the secondary resistance of its measure multiplied by the square of the transforming ratio of reduction.

Analogy to Continuous Current Transformer.

The alternating current transformer may be considered as analogous to the continuous current transformer or dynamotor. The motor armature corresponds to the primary, the dynamo armature to the secondary. The driving current with zero load in the armature is analogous to the magnetising current. Again we have a certain definite ratio between the number of turns, producing an equal ratio between the primary and secondary electromotive forces. Also this ratio is modified in a similar way by the resistances of the armature and coils, the falling off of the potential between the terminals of the dynamo armature or secondary coils being equivalent to that given by the secondary current passing through a resistance

$$R_1 + \left(\frac{n_2}{n_1}\right)^2 R_2$$

where R_1 and R_2 are the respective resistances. The formulæ for calculating the dimensions and number of turns is also analogous in the two cases; that for the dynamo or motor being

$$E = \frac{nNV}{10^8}$$

while for either primary or secondary coil of the transformer we shall use

$$E = \sqrt{2}\pi . \frac{nN\sim}{10^8}$$

where N is the maximum flux of Induction through the coils; $\sim$ the frequency, and n the number of turns. The numerical factor $\sqrt{2}\pi$ is nearly 4·4, and to compare the formulæ we may note that E is doubled owing to each turn of the coil being equivalent to two bars on the armature; again doubled because all the turns are in series, not forming two parallel circuits as in the closed-coil armature; and finally increased by about ten per cent. owing to the necessity of taking the square root of the average square of all values (following the harmonic law), instead of the average values for all the bars, as in the theory of the armature.

As soon as the secondary armature or coil, in either the continuous or alternating current transformer, is connected to an external circuit a current not only flows in the secondary, but an additional current in the primary armature or coil. Again the ratio of the two currents is in inverse proportion to the number of turns in the windings, that is to say, to the E.M.F. generated in them. But the analogy needs an important modification for the alternating current transformer. The additional current is not generally co-phasal with the magnetising current, but in advance, being, if the self-inductance of both circuits is practically confined to the transformer coils, co-phasal with the E.M.F. The two currents are combined, not by direct addition, but more nearly by taking the square root of the sum of their squared values. Using the clock diagram we may combine them by taking the resultant of the two vectors, the diagonal of the parallelogram, as with vectors representing mechanical forces, representing in magnitude and direction the combined alternating current. Algebraically, if c and C represent the two currents, with a phase difference ϕ, the resulting current is the square root of

$$C^2 + c^2 + 2Cc\cos\phi.$$

Experience is wanted to determine whether alternating or continuous current requires higher insulation. It has been pointed out that it is not so much the question of the leakage current, but the prevention of the disruptive sparking, that has to be dealt with. An alternating electromotive force of 100 virtual volts reaches a maximum of 141.4 volts when the sine law of variation is followed, so that to avoid the possibility of a "disruptive discharge" it would seem that the insulation thickness for alternating currents should be about half as great again as for continuous currents of the same standard electromotive force. 50 or even 100 per cent. extra is frequently specified by insurance companies, etc., for there is no guarantee whatever that the sine law will be maintained, in fact, it is most common for the maximum value of the electromotive force to exceed the virtual by a great deal more than 50 per cent.

Material subjected to rapid alterations of mechanical stress undergoes "fatigue," and often gives way ultimately to stresses far below the ultimate strength or elastic limit of the material, through the degeneration of its mechanical structure. By analogy it would be reasonable to expect insulating material, subjected for many years to electrical stresses which are reversed from 100 to 300 times per second, would ultimately break down though the stress may be far below that which they could bear if the stress were uniform, so that a larger factor of safety should be required for alternating currents than continuous.

On the other hand it appears that a certain time is required to establish the condition of electric strain in india-rubber, gutta-percha, or other insulating material which exhibits the phenomenon of "residual discharge," and it may be maintained that in the case of rapidly alternating currents the stress is reversed before the material has had time to be appreciably strained, and that consequently not greater, but less insulation is required for alternating than for continuous currents.

Since, however, a safety factor of at least 10 is used in calculating the necessary insulation, this important point may still be left undecided, until prolonged experience with high tension alternating currents has given sufficient data for a satisfactory decision. At the time of writing the matter is receiving great attention from leading engineers connected with electrical distribution of power. In view of the excessively high E.M.F. demanded by long distance transmission, and losses due to electrostatic hysteresis which are no longer negligible with high E.M.F., considerable improvements are to be looked for in cable manufacture in the near future.

CHAPTER XI.

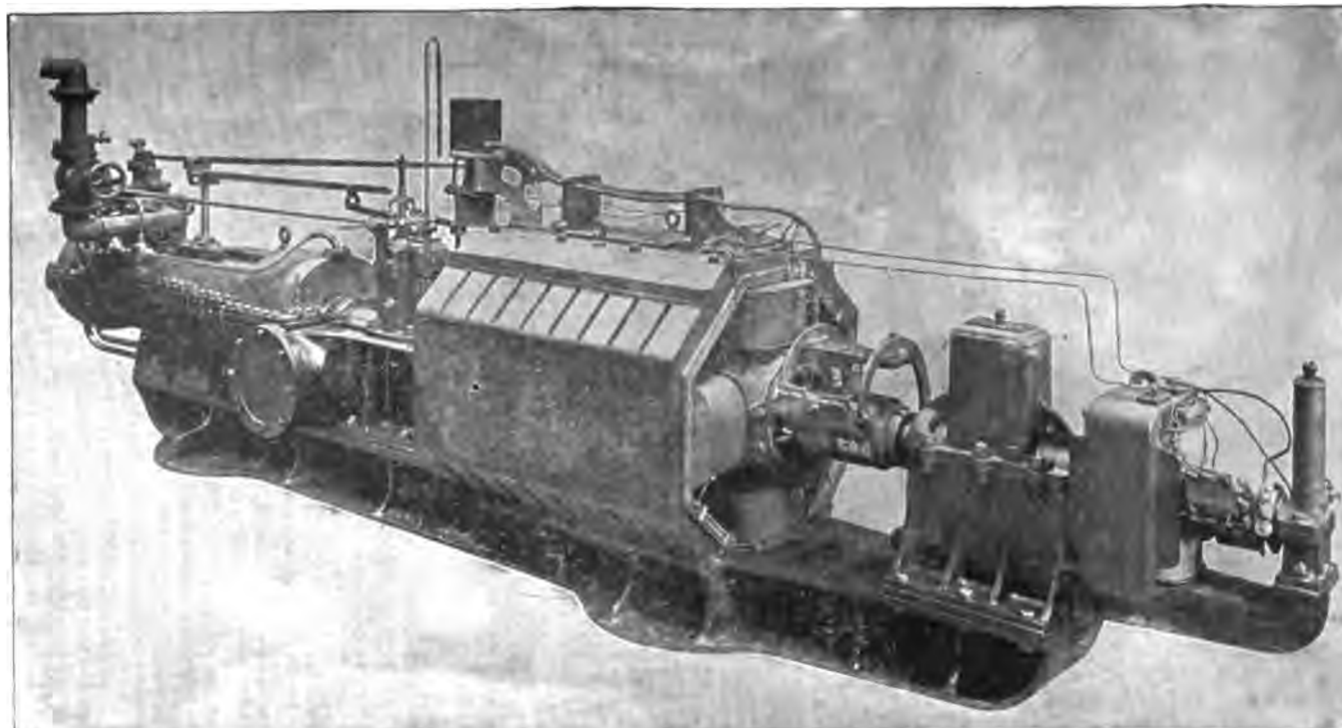
Alternating Currents (Machinery).

The shuttle-wound armature may be looked upon as the starting-point in the evolution of the alternator, or alternating current dynamo, as it is of the continuous current dynamo. Connecting the extremities of the single coil to two separate insulated rings mounted on the shaft, with which two brushes make sliding contacts, and form the terminals of the external circuit, we shall have an alternating E.M.F. generated between these terminals, giving one complete alternation per revolution of the armature. But the variation of the magnetic field, owing to the revolution of the shuttle-shaped core, will give rise to wasteful eddy-currents in the poles of the field-magnets, which could not be tolerated in a large machine.

Parsons alternator is only a step removed from this simple form. A cylindrical core or framework is adopted as for the closed-coil dynamo, and long flat coils, wound round an oblong disc of wood fibre, are placed on the surface, and firmly bound with steel wire wound spirally round the cylinder. In a later form the coils are "tunnel-wound" beneath the surface of the cylindrical iron framework, so that the air-gap is reduced to the necessary clearance for rotation. In the two-pole form each of these coils covers one-half the surface of the cylinder, and they are connected in series or parallel to the two connecting rings. The frequency of alternation is the number of revolutions of the armature per second, and a very high speed of revolution is required to give sufficiently high frequency for alternating current transformation, without making the transformers of excessive dimensions. A frequency of 50 to 150 alternations per second is usually employed for lighting purposes, the higher rate being preferable if the power is to be used for lighting purposes only owing to the smaller size of the transformers, but the lower being more suitable if alternating current motors are to be employed in connection with the distributing system, as is very desirable for commercial economy. These frequencies will require a rate of revolution of 3000 to 9000 revolutions per minute with a two-pole alternator. Parsons alternator is intended to be driven by the steam turbine designed by the same inventor, and is therefore suited to these high speeds, which with the ordinary reciprocating engine would be impossible, except with a high rate of speed multiplication by belt or rope driving. Fig. 52 shows a four-pole Parsons alternator directly driven by a steam turbine, the whole generating plant occupying a very small space indeed. The field-magnets are of the "ironclad" type, giving no external leakage field. Similar poles are opposed to one another, and four armature coils are required, which may be connected in series to give the high E.M.F., the connections being such that the armature circuit reverses in direction with consecutive coils since the E.M.F. is at any moment the same in magnitude, but in an opposite direction. The frequency of alternation is that of twice the number of revolutions per second. The field-magnets are excited by coils in which a continuous current is caused to flow, generated by a small closed-coil dynamo on the same shaft as the alternator itself.

The electrical efficiency of the alternator is very high, there being little opportunity for waste of power by hysteresis, &c. Also the small amount of friction in the whole combined plant renders a very high mechanical efficiency possible at all loads. The steam turbine is however of high efficiency only when condensation is available, and a good vacuum obtained in the condenser. A very ingenious electrical governor is employed with this combined plant to maintain constancy of E.M.F. at all loads between

FIG. 52

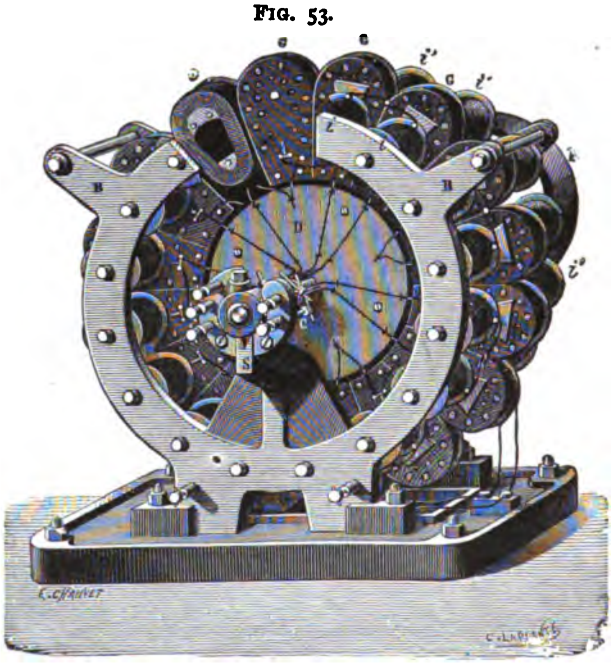


350-unit "Parsons" Turbo-Alternator.

the terminals of the alternator. The E.M.F. generated in the armature with a constant speed and constant magnetic field would be constant, but a reduction in proportion to the current flowing due to the resistance and self-induction of the armature would require to be subtracted to give the alternating difference of potential between the terminals, that absorbed in sending the current through the armature being given in vertical volts by the number of virtual ampères multiplied by the impedance of the armature.

The speed of a steam turbine may be regulated by the opening and closing of a throttle-valve. so as to control the steam admission with a reduced pressure. A better efficiency is obtained by an intermittent admission at the full pressure, for which purpose the throttle-valve is opened and closed every 14 revolutions of the turbine by a steam relay, the valves

FIG. 53.



Siemens Alternator.

of which are operated by the raising and lowering of a lever which is jointed to an eccentric rod moving on an axle pinion-geared to the main shaft of the turbine. The duration of the opening of the throttle-valve is regulated by a compound solenoid, or two solenoids, attracting a core attached to a distant end of the lever controlling the steam relay. A solenoid conveying the magnetising current controls the speed of the turbine so as to maintain this constant when the alternator is on open circuit; this solenoid is opposed by a solenoid carrying the output current of the alternator, so as to give an increased speed and higher E.M.F. in the armature when the load is heavy.

For alternators to be driven at the speeds more common in engineering practice, it will be necessary, in order to obtain the required frequency, to employ a multipolar field, the number of poles depending upon the speed at which the alternator is to be driven. The armature will consist of a number of similar coils, so arranged that at any moment the rate of change of flux of Magnetic Induction through all of them is the same in magnitude, and these coils will in general be connected in series, as a high E.M.F. is commonly desired for alternators, the connections of the coils being made so that the E.M.F. produced by the variation of the flux of Magnetic Induction is for all the coils in the same sense when considered as a single circuit embracing the magnetic field, though not necessarily in the same sense with regard to the symmetry of their position on the armature. The number of complete alternations per revolution of the E.M.F. generated in the armature will be equal to the number of positions of maximum flux in the same sense through which any coil passes. The E.M.F. generated in the armature will be the sum of that in all the coils (if in series); or if m be the number of coils, N the maximum flux through any coil, n the number of turns in each, and the harmonic law of variation be followed, we shall have for the E.M.F. at any moment,

$$e = \frac{m.n.}{10^8} \frac{d}{dt} (N.\sin.pt) \qquad \text{the frequency being } \frac{p}{2\pi}$$

And therefore the virtual and maximum E.M.F. will be given by E′ and E, where

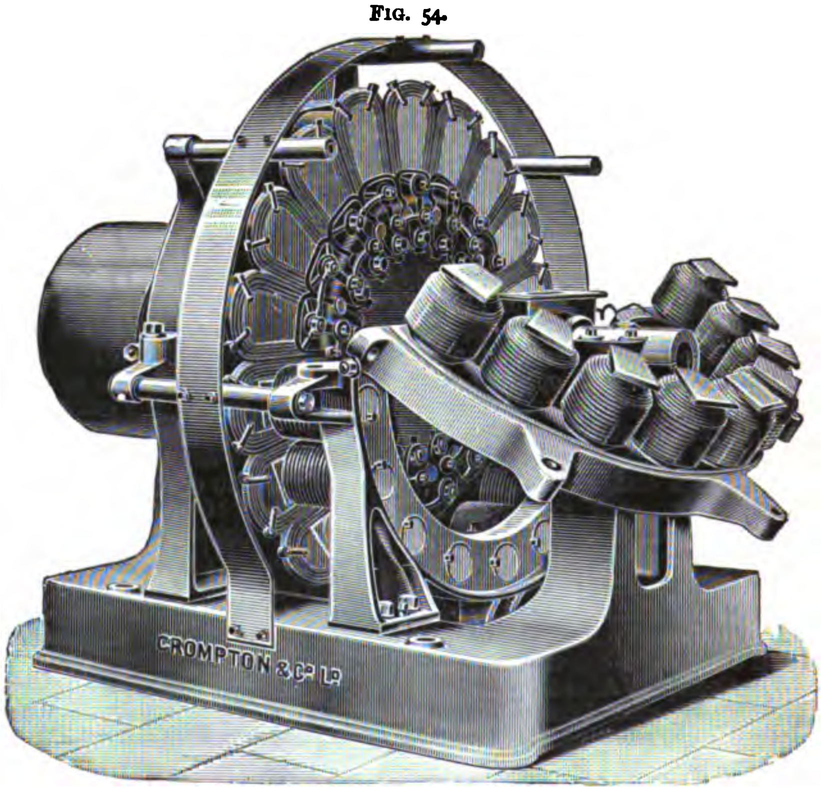
$$E' = \frac{1}{\sqrt{2}} E = \frac{p}{\sqrt{2}} . \frac{m.n.N}{10^8}$$

One of the earliest forms of multipolar alternator was designed by Siemens, and is illustrated in Fig. 53. From a base plate there rise two circular iron frames, which are steadied by tie-bars extending from one frame to the other. On the inner faces of these are fixed two ranges of magnet poles, poles of opposite characters being opposed to one another so that the magnetic induction passes across from one to the other in a direction parallel to that of the shaft. The relative positions of the poles are changed as we pass to a consecutive pair, so that any two consecutive pairs afford a complete magnetic circuit with a section of each supporting frame and two polar gaps. Between the two ranges of poles pass a series of armature coils of oval disc shape, the longest diameter being radial, each wound on a wooden core. These coils are mounted on a framework of german silver, and are generally connected in series, the direction of winding following the armature circuit, being reversed as we pass to a consecutive pair. The closed-coil dynamo supplying the current for the magnetising coils is driven by a belt or ropes from the shaft of the alternator.

The Crompton Alternator in Fig. 54 illustrates a more modern machine, following the same lines of design. The improvements consist in more flattened coils, reducing the magnetic reluctance, and easy accessibility to the armature.

A more widely used type of alternator has been designed by Ferranti with a similar arrangement of the magnetic field and armature coils, though with considerable modification of the mechanical details. This type is employed at Deptford in very large units to generate electric power at an E.M.F. of 10,000 virtual volts directly, in order to transmit it to a distance of upwards of seven miles for the lighting of London. It has been found more convenient, however, to generate an E.M.F. of 2400 virtual volts, and to multiply this by transformation to the higher value for transmission. The following details concerning an alternator generating 625 electrical horse-power, 35 ampère at 2400 volts may be of interest. The copper ribbon forming the armature conductor is 12.5 millimetres in width, and 0.75 millimetre thick, each coil consisting of 25 turns wound over a brass core (laminated at right angles to the direction of rotation, and insulated with asbestos), the copper strip being bare, and the successive turns insulated from one another by means of a continuous strip of fibre, 0.5 millimetre thick, wound between them. The inner end of the coil is connected to the brass core, which is also connected to a consecutive core, while the outer end of the coil is connected to that of the previous coil, so that the direction of winding is reversed in passing from one coil to the next. The coils are not all connected in series, as this would involve the maximum difference of potential existing between the first and last coils, which would be adjacent; instead of this the armature is divided into two semi-circular ranges of coils in series, the ranges being connected in parallel, and the connections to the collecting rings taken from opposite sides of the armature. The number of coils in the armature is 40, joined in two sets of 20, and the diameter of

FIG. 54.



Crompton Alternator.

the armature 7 feet. The current density in the armature conductor is thus nearly 1200 ampères per square inch, and the number of alternations per revolution of the armature, 20, giving a frequency of 88 complete alternations per second, with a speed of 264 revolutions per minute. The peripheral velocity being nearly 6000 feet per minute, special attention has to be paid to prevent the coils flying off through the great strain due to centrifugal force. Each of the laminated brass cores is solid at the inner end, nearest the driving shaft, and an insulated bolt passed through a hole drilled in this solid portion parallel to the shaft secures the core and coil to the revolving framework. The internal resistance of the whole armature is 0.176 ohm, the clearance between the pole-pieces is 0.875 inch, the power absorbed in the magnetising coils about 12 electrical horse-power.

An external view of the alternator designed by Mordey, for the Brush

Company, is given in Fig. 55. This type preserves the same arrangement and connection of the armature coils as in the Siemens and Ferranti types, but the armature is stationary, while the variation of the flux of Magnetic Induction through the coils is effected by the rotation of the field-magnets.

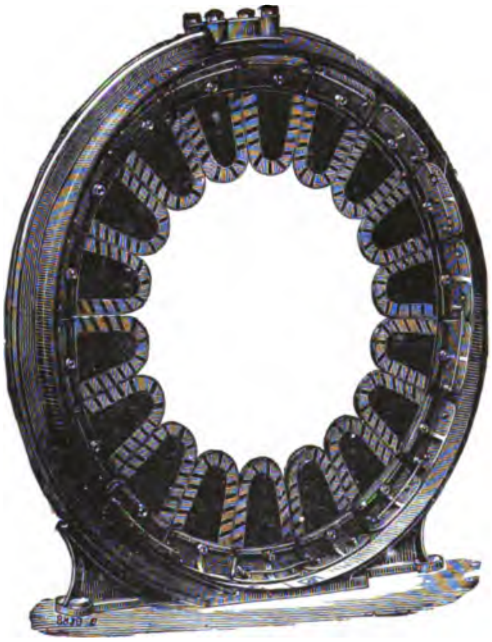
FIG. 55.

Mordey Alternator.

The armature is shown separately in Fig. 56. It consists of a number of flat pear-shaped coils of copper ribbon, wound on cores of paraffined wood or porcelain. The outer broad end of each coil is clamped between a pair of german-silver plates, carefully insulated from the coil by strips of ebonite, and through these plates and the core of the coil a bolt passes which fixes the coil firmly in position on the interior of a gun-metal ring. The armature ring is constructed in two portions, bolted together at the top and bottom, so that it can be divided, and either portion easily withdrawn to obtain access to the armature for repairs; and any coil can be removed and replaced in a few minutes if found faulty.

In order to simplify the field-magnets, and use but a single magnetising coil, it is arranged to employ only north poles on one side of the armature, and only south poles on the other, so that the flux of Magnetic Induction through the coils of the armature is always in one direction. The number of poles on either side is therefore made only one-half of the number of coils in the armature, so that the flux through any coil fluctuates between a zero and a maximum value, any coil reaching the zero position when the adjacent coils are at a maximum value, the interconnections being made so

FIG. 56.

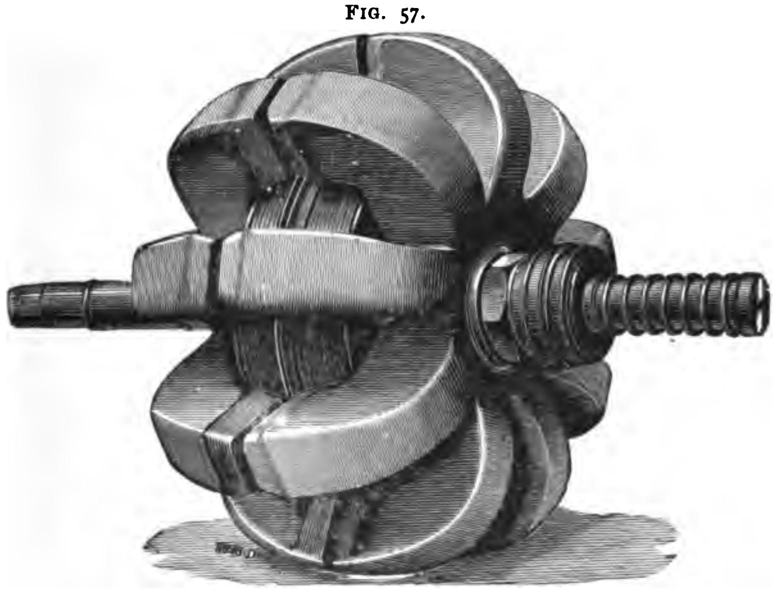


Armature of Mordey Alternator.

as to reverse the direction of the winding in successive coils, as in the types of alternator previously described. The field-magnets are shown separated from the armature in Fig. 57. They consist of two massive iron castings, with a number of horns or claws, bent as shown, so as to face one another at a short distance apart, and form the poles which embrace the armature. The magetic circuits are completed by a short cylindrical casting, through which the shaft passes, and round which the single magnetising coil is wound with numerous turns. These massive iron castings can of course be rotated at very high speeds without fear of flying to pieces, and their great moment of inertia produces the greater steadiness of running. A thrust bearing as shown is necessary to prevent the slightest traverse of the rotating field-magnets, which, since the minimum clearance is allowed for the coils in order to reduce the reluctance of the magnetic circuit, might bring them into contact with the coils. The magnetising current is generated by a small "Victoria" closed-coil dynamo on the same shaft as the alternator, and conveyed to the magnetising coil through brushes touching insulated brass rings on the shaft, which form the terminals of the coil. The number of complete alternations per revolution of the field-magnets is that of the poles on one side only, or one-half the number of the coils. A frequency of 100 complete alternations per second is generally employed with this type of alternator.

In the types we have so far described, the coils are made as flat as possible, in order to reduce the necessary clearance between the field-magnet poles. Iron cores could not be employed, as they would involve considerable variations of the strength of the magnetic field, causing heating of the pole-pieces by eddy-currents, and objectionable noise and vibration. Owing to their flatness the armature coils are with difficulty made sufficiently strong to bear the great mechanical stress to which they are constantly subjected. In order to increase the mechanical strength of the armature, a different arrangement of the magnetic field is preferred by some, in which

FIG. 57.



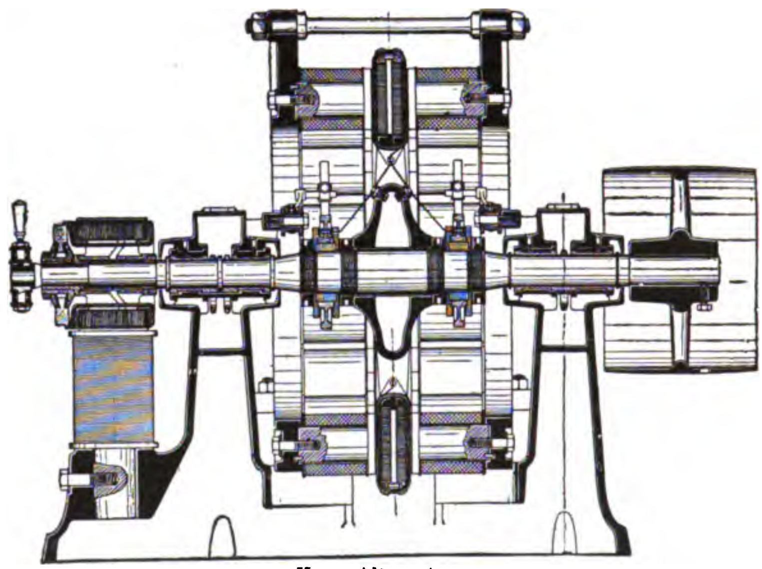
Field-Magnets of Mordey Alternator.

the coils can be wound on a laminated iron framework which will support them and render buckling impossible. To compensate for the mechanical superiority, a waste of power will in general ensue owing to hysteresis in the core; and with constant speed and magnetisation there will in general be a greater fall of potential as the current output is increased, owing to the greater self-inductance of the armature. The latter will not, however, imply a waste of power, but will demand more attention to the regulation of constant E.M.F., which is generally effected by rheostatic adjustment of the magnetising current under the control of the attendant.

An alternator designed by Kapp, and illustrated in Figs. 58 and 59, was probably the earliest of the iron-cored armature types. The alternator illustrated is one made at the Oerlikon works, and largely used in Continental Lighting and Power stations. The field-magnet system consists of two sets of magnet poles, on either side of the armature as in the Siemens alternator, but having the opposing poles of similar nature, with rectangular pole-faces and circular yokes on which the magnetising coils are wound.

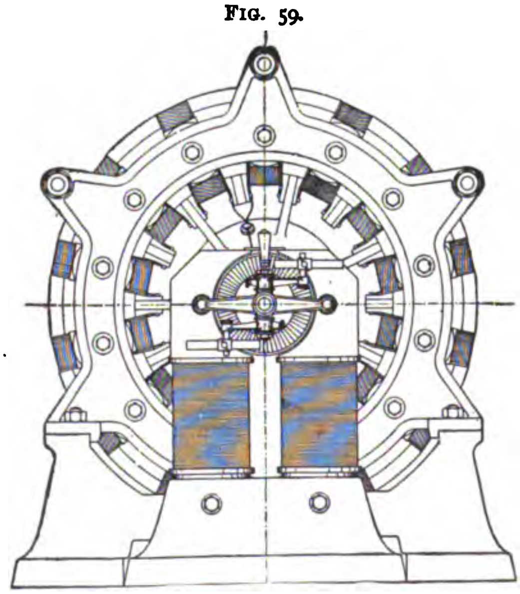
The armature-core is composed of charcoal iron strip coiled up with paper insulation over a gun-metal supporting wheel, to form a narrow and deep ring to which lateral strength is given by steel bolts inserted radially

FIG. 58.



Kapp Alternator.

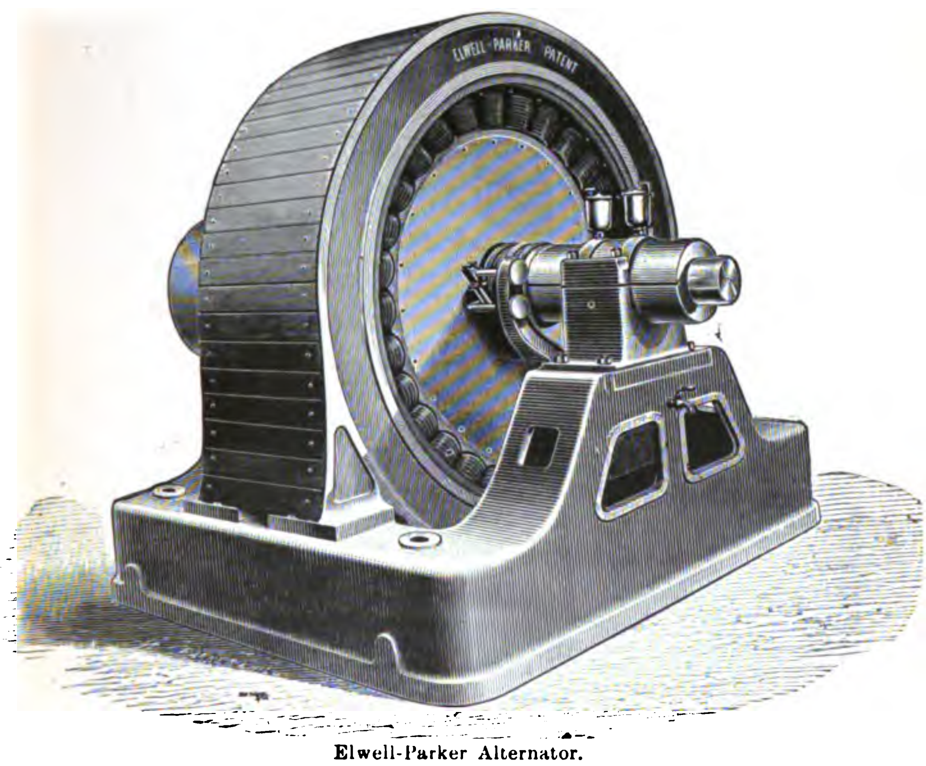
FIG. 59.



Kapp Alternator.

as shown. The magnetic circuits are completed through sections of this ring, passing from one pair of poles to the next adjacent pairs along the ring. The armature coils are wound round the ring, carefully insulated from the ring with mica strips. In a later form designed by Kapp, and manufactured by Johnson and Phillips, the field-magnet system is made similar to that in the Mordey alternator, and forms the revolving part, while the iron-cored armature is retained as above. A few details of an alternator of the original form are given as follows: The pole-pieces are of wrought iron, $4\frac{1}{8}$ inches in diameter, and 14 in number on each side. The magnetising coils are each wound with 186 turns of wire, and the total resistance in series is 1.76 ohms: the magnetising current is 21 ampères, requiring an E.M.F. of 37 volts nearly, and the expenditure of power of a little more than 1 E.H.P., or 1.3 per cent. of the maximum output. The

FIG. 60.

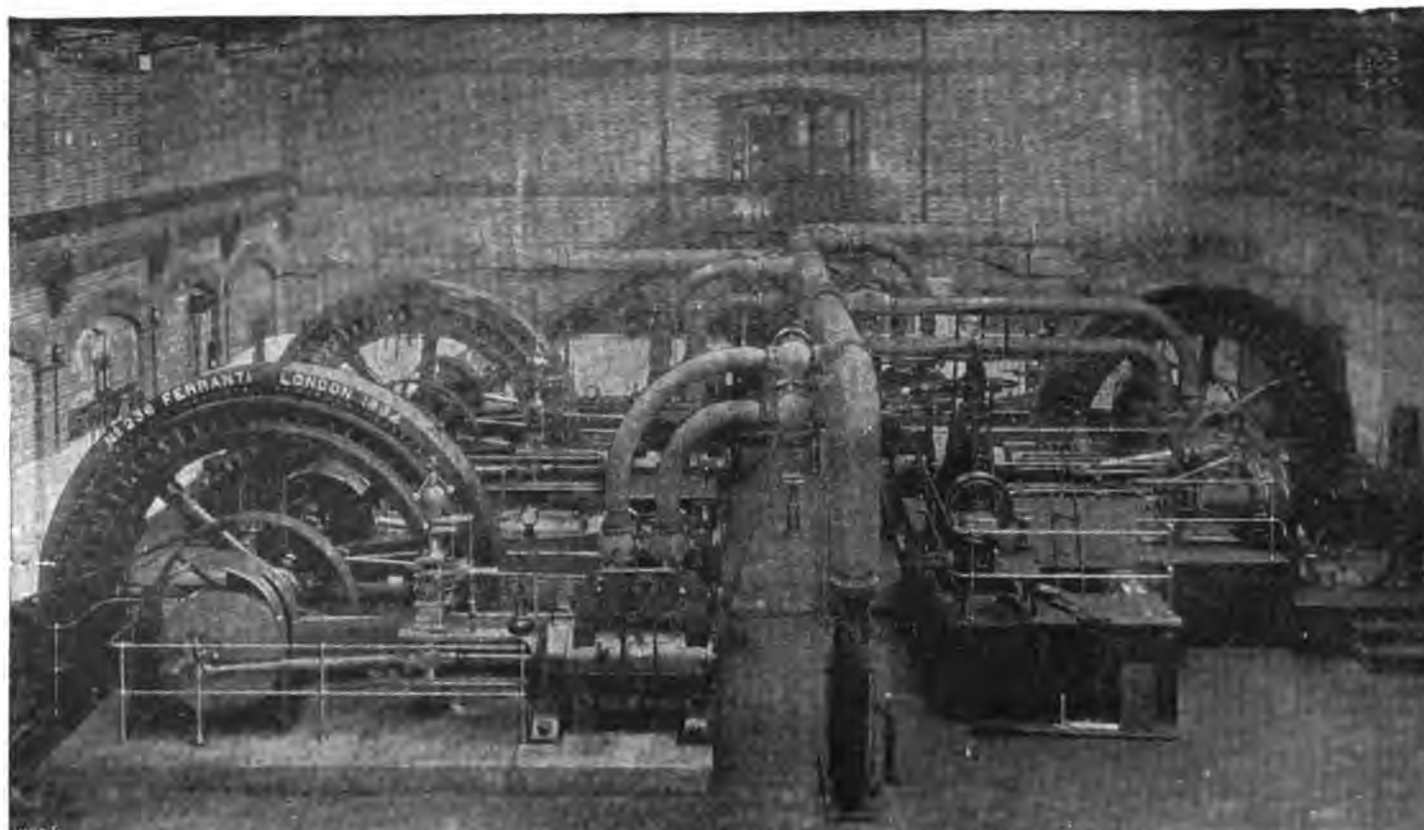


Elwell-Parker Alternator.

armature coils are also 14 in number, each consisting of 80 turns of wire 120 mil. diameter, wound in two layers on the iron core-ring, and connected in series giving a total resistance of 1.8 ohms. At 600 revolutions the armature gives 2000 virtual volts, with a frequency of 70 complete alternations per second, and the maximum current is 30 virtual ampères. The loss of power due to armature resistance is thus 2.7 per cent. at full load.

The Elwell-Parker Alternator (Fig. 60) of the Electric Construction Co., illustrates a different type of iron-core armature greatly favoured in England and America. The revolving field-magnets have in this case numerous poles radiating outward, the magnetic field being completed through an external laminated iron ring. Against the inner face of this ring the coils are laid flat, facing the poles and equal in number. In more recent practice the coils are tunnel- or groove-wound to reduce the magnetic reluctance.

FIG. 61.



Portsmouth Electric Lighting Station with Ferranti Alternator.

The more common American practice is to invert this arrangement, the pole-pieces being attached to the external ring and pointing inwards, the coils groove-wound on an inner cylindrical armature.

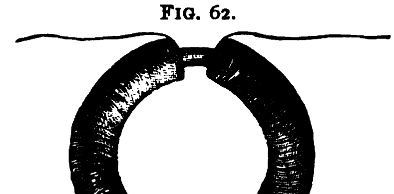
Recognising that the use of rope or belt driving in order to obtain the requisite multiplication of speed for the employment of slow-speed horizontal engines in conjunction with high speed alternators is a source of considerable waste of power, as well as a frequent cause of accident or failure, it has lately been the endeavour of the manufacturers of large alternators to adapt their designs to direct driving with slow speeds of under 100 revolutions per minute, in order that the moving parts of the alternator may be direct-driven, taking the place of the fly-wheel of a slow-speed engine. This requires an alternator of very large size, though certainly occupying less space than the combined plant with belt or rope driving, and encourages the employment of the heavier field-magnets as the rotating part rather than the armature of the alternator. For this purpose also a radial clearance between the armature and field-magnet poles would seem the most suitable design, as with the large diameter and the irregular strains of the engine cranks it will be more difficult to maintain a small horizontal clearance. In Fig. 61 the engine-room of the Portsmouth Electric Lighting Station is illustrated, showing three direct-driven Ferranti alternators, of design totally different to the Ferranti moving armature alternator previously described. The engines are of the slow-speed horizontal type, with Corliss valve-gear, making 95 revolutions per minute. The fly-wheel of the engine carries the field-magnets, and is surrounded by a laminated core-ring in which the armature coils are wound.

There are numerous other types of alternator of which we cannot afford space for more than a summary reference. The iron-cored armature designs last described have been modified so as to use only one magnetising coil for the field-magnets. This has been effected by arranging two sets of inward or outward pointing poles, facing two parallel rows of coils round the ring, the north poles on one side and the south poles on the other. This is equivalent to a number of horse-shoe magnets, and a single coil wound round in a radial plane, between the two rows of poles suffices. Again the poles have been bent in alternately so as to face a single row of coils. Another group of designs, termed Inductor alternators, follow the same winding arrangement, but both the armature and field coils remain stationary, while the poles alone rotate. The difficulties, however, of collecting alternating currents, or the continuous currents for magnetisation, by sliding contact have been so completely eliminated that Inductor dynamos are in no way more efficient or economic. Other designers have returned, mainly for small alternators, to a very similar arrangement to that of ring-wound armatures for continuous currents, or to multipolar drum-armatures with wave winding.

Alternating Current Transformers.

The starting-point in the evolution of the alternating current transformer was Faraday's anchor-ring, Fig. 62. Coils of thick and thin insulated wire were wound round an anchor-ring of soft wrought iron, each coil occupying nearly one-half of the ring. The thick wire was connected with a battery through a key, by which contact could be rapidly made or broken. The long thin wire was connected with a galvanometer. On starting the battery current there was a transitory current in the secondary wire, and on stopping the battery current there was again a transitory current in the secondary wire, but in an opposite direction to the previous current. With a "reversing key" the primary current may be reversed, and the secondary current is then found to be about double what it was when the contact in the primary circuit was simply made, and considerably more than double of that when it was broken. This was the first transformer, and involved the principle of the closed magnetic circuit. It shortly developed into the Ruhmkorff coil, or induction coil, an instrument too well known to need description, in which a backward step was taken by the omission of the closed magnetic circuit and its replacement by the straight core. This incomplete iron circuit is essential when the induced current is due simply to the make and break, and not to the reversal of the primary current; for in this case the residual magnetism of a closed magnetic circuit would be so great that the induced current due to the simple make and break would be very much enfeebled. In the anchor-ring, as in the Ruhmkorff coil, the transformation was from low tension to high tension. When the current is started or stopped on reversal by hand the charges are so slow that the primary current is flowing steadily for a great portion of the time, and while so flowing it is doing work in generating heat, but producing no secondary current. The efficiency of such an arrangement must necessarily be insignificantly low, and to obtain high efficiency the charges must be so rapid that the current has not nearly time to reach its maximum value. As an instrument for laboratory research, and as an electro-medical appliance, the Ruhmkorff coil is still extremely valuable.

FIG. 62.



The first tranformers for the distribution of power by means of alternating currents for electric lighting purposes were constructed by Messrs. Gaulard and Gibbs, and in principle were precisely the same as Faraday's anchor-ring. At first these transformers were used in series, the high tension alternating current being sent through the primary coils of a series of transformers in succession, while the secondary coils of each provided current for a group of lamps. This was the original arrangement on the Metropolitan Railway. As the primary current traversed a number of transformers in succession, the wire employed in winding them did not require to be very fine; in fact, the primary and secondary windings might be made of a precisely equal number of turns, in which case, supposing the efficiency perfect, the primary and secondary currents would be equal, and the electromotive force in the primary circuit would be equal to that in the secondary circuit, multiplied by the number of transformers, together with that necessary to maintain the primary current against the resistance of the circuit. The transformer arranged in series worked satisfactorily so long as the load on each remained steady, but any alteration of the load on one changed the electromotive force upon all the others. This method of using the alternating current transformer is still employed occasionally for supplying a system of arc lamps, each having its own transformer at the base of the standard. Such a system avoids many difficulties as to the use of high tension, and sub-division of the power, but makes no use of the valuable regulative property of the transformer. Alternating current transformers are now almost universally arranged in parallel circuit, so that except for a minute loss in the mains, the primary of each transformer takes the whole electromotive force of the alternator, but, as described above, only such portion of the current as may be required by the secondary load.

We have seen that it is necessary that all iron which is subject to rapid magnetic changes should be laminated, so that the eddy-currents induced may be as far as possible eliminated. The object of lamination is not solely the attainment of efficiency by the removal of a source of dissipation of energy, but is an essential condition in order that the magnetic qualities of the iron should be utilised. With the usual frequency of alternation the magnetism will not penetrate into solid soft iron to the depth of more than a fraction of a millimetre, the eddy-currents tending to set up a counter magnetisation. In fact, the solid iron of an electromagnet will act similarly to a closed electric circuit, and render the self-inductance less than it would be if the iron were removed and the magnetic field existed in air. The following experiment once performed by the writer forms a remarkable illustration of this fact. The armature of an Elwell-Barker alternator was placed in series with twelve hundred-candle-power lamps, the current being supplied at 100 volts from a transformer connected to a similar alternator. The former alternator was at rest, and its field-magnets unexcited, its armature simply acting as a choking coil, and causing the lamps to burn at about half their normal voltage. On slowly rotating the field-magnets it was found that the current rose and fell as the cores of the field-magnets passed in front of the coils of the armature, the lamps varying very greatly in brightness. But it was observed that the largest current and the greatest brightness were obtained when the cores were opposite the coils, that is, when the magnetic circuit was completed through the solid wrought-iron cores. These cores therefore acted as a closed secondary, and their presence diminished the self-inductance of the armature. With small machines the reverse of this result is obtained, unless the frequency of alternation be very high.

There are therefore two matters to be considered in dealing with the requisite thickness of the plates, strips or wires of which the iron core of transformers must be built, viz., the degree of lamination necessary that the whole of the iron may be efficiently magnetised by the rapidly alternating magnetising force, and the degree of lamination necessary that the waste of energy of eddy-currents may be reduced to within permissible limits.

A very complete mathematical investigation of the magnetisation of iron plates by rapidly alternating magnetising forces following the harmonic law was made by Professors J. J. Thomson and Ewing in 1892, which served to confirm the already established practice of transformer builders in using plates of about .014 inch or .35 millimetre thickness with the common frequencies of alternation; and also indicated how this thickness should be varied according to the frequency employed, and other conditions of the transformer. These investigations were published in papers in the *Electrician* for April 8 and 15, 1895, of which we give the following summary:

First, with regard to the magnetic screening, it was shown that: "The magnetisation is substantially the same as if the plate consisted of two skins, each a quarter of a millimetre thick, with an empty space between. It is only when we make this total thickness less than the sum of two such skins (one millimetre) that any marked falling off begins to be seen in the *total quantity* of magnetisation of the plate." This result, which insists on the reduction of the thickness of the plates to less than a millimetre if the diamagnetic properties of the whole of the iron are to be brought into action, was calculated on the assumption of a frequency of 100 complete alternations per second, and a permeability of 2000. The general formula for the "equivalent depth of uniform magnetisation" on either side of a plate of thickness 2h centimetres is given as

$$\frac{1}{m\sqrt{2}}\left\{\frac{\cosh 2mh - \cos 2mh}{\cosh 2mh + \cos 2mh}\right\}$$

where

$$m^2 = \frac{2\pi\mu p}{\sigma}$$

μ and σ being the permeability and specific electrical conductivity (c.g.s. units $\frac{1}{10^9}$ ohm) of the iron, and $\frac{p}{2\pi}$ the frequency of alternation.

By the "equivalent depth of uniform magnetisation" is meant the depth of an imaginary skin which, if magnetised uniformly with the given magnetising force, would contain the same total number of lines of force as the actual plate, with its varying distribution, does contain at that instant of each period in which the number is a maximum. For a thick plate this becomes $\frac{1}{m\sqrt{2}}$ or $\frac{1}{2}\sqrt{\frac{\sigma}{\pi\mu p}}$, and therefore varies inversely as the square root of the permeability, or of the frequency. The following table may be deduced from the general formula giving the equivalent depth (in millimetres) of uniform magnetisation for different frequencies and thicknesses of the plate. We may take $\mu = 2000$ $\sigma = 10{,}000$ as approximate values in transformer iron.

Thickness of plates in millimetres.	Frequency 50.	Frequency 100.	Frequency 150.
∞	.356	.252	.205
2	.362	.250	.204
1	.399	.282	.217
.75	.355	.285	.233
.5	.2475	.233	.216
.25	.1243	.1245	.1245

Whence it will be seen that little is gained by reducing the thickness of the plates below half a millimetre, except with high frequency, as far as the magnetic screening of the interior of the plate is concerned. Consideration of the loss of power owing to the eddy-currents, however, imposes a further limitation on the thickness.

The energy absorbed in ergs per second *per square centimetre* of the plate by the eddy-currents, when the plate is subjected to an alternating Magnetising Force, whose variation follows the harmonic law, and whose maximum value at the surface of the plate is H_0, is given by the expression

$$\frac{\sigma m}{16\pi^2} \cdot H_0^2 \cdot \frac{\sinh 2mh - \sin 2mh}{\cosh 2mh + \cos 2mh}.$$

With thick plates this expression becomes (the last fraction being unity)

$$\frac{\sigma m}{16\pi^2} \cdot H_0^2 \text{ or } \frac{\sqrt{2\pi\mu p\sigma}}{16\pi^2} \cdot H_0^2$$

With thin plates (expanding the last fraction)

$$\frac{1}{3\sigma} \cdot \mu^2 p^2 h^3 \cdot H_0^2 \left\{1 - \frac{17}{2520}(2mh)^4 + \ldots\right\}$$

With a frequency of 100 complete alternations per second, we may take $m = 28.1$; so that 2mh becomes unity, when the thickness of the plate is

.356 millimetre. Therefore, as long as the plates do not greatly exceed this thickness, which is about the value employed in common practice, we may omit the second term in the bracket, and write for the energy absorbed per square centimetre of the plate in ergs per second,

$$\frac{1}{3\sigma} . \mu^2 p^2 h^3 H_0^2 \text{ or } \frac{1}{3\sigma} p^2 h^3 . B^2$$

And, therefore, per cubic centimetre of iron employed

$$\frac{1}{6\sigma} \mu^2 p^2 h^2 H_0^2 \text{ or } \frac{1}{6\sigma} p^2 h^2 . B^2$$

The energy absorbed in thin plates per cubic centimetre therefore varies as the square of the thickness. Taking $H_0 = 2$, corresponding to about $B = 4000$ in the iron, the energy absorbed per cubic centimetre when the plates are one-quarter of a millimetre thick, and the frequency 100, is 16,500 ergs per second (.00165 watts). This loss will be quite insignificant in comparison with the power absorbed in hysteresis with this maximum value of Magnetic Induction.

Ewing found the absorption of power by hysteresis by the iron, when the maximum intensity of Magnetic Induction was between 2000 and 8000 units was given very approximately by the expression $1340 H - 1610$, where H is the maximum value of the Magnetising Force. Except in the thinner plates, in which the magnetic screening is insignificant, there exists a considerable difference between the maximum Magnetising Force at the surface of the plate and the mean maximum value of the Magnetising Force from one side of the plate to the other. Calling the former H_0, and the latter H_1, Ewing calculates the following values of these and for the absorption of power by eddy-currents and hysteresis for different thicknesses of plates, to produce a mean maximum Magnetic Induction $B = 4000$ throughout the plate:

Thickness of plate. Millimetres.	H_0	H_1	Power absorbed by eddy-currents. Ergs per second.	Power absorbed by hysteresis. Ergs per second.	Total.
2	8	2.74	569,000	206,000	775,000
1.5	5.87	2.46	427,000	169,000	596,000
1	3.55	2.23	241,000	138,000	378,000
.5	2.15	2.02	66,000	110,000	176,000
.25	2.01	2.00	16,500	107,000	123,500

Also for other values of the mean maximum magnetic induction in plates of one-quarter and one-half a millimetre thick.

Thickness of plate. Millimetres.	B	Power absorbed by eddy-currents. Ergs per second.	Power absorbed by hysteresis. Ergs per second.	Total.
.25	4000	16,500	107,000	123,500
.25	6000	37,000	241,000	278,000
.25	8000	66,000	375,000	441,000
.5	4000	66,000	110,000	176,000
.5	6000	147,000	245,000	392,000
.5	8000	262,000	379,000	641,000

It appears, therefore, that the reduction of the thickness of the plates to one-quarter of a millimetre will reduce the absorption of power by the eddy-currents in the iron to less than one-sixth of that due to hysteresis, when the frequency of alternation does not exceed 100; moreover, when the iron grows hot owing to the conversion of this power into heat, the specific resistance of the iron will rise, and so also will the permeability, so that the absorption of power will be less. The common practice of using plates of about .35 millimetre thick, insulated from one another by the thinnest possible paper, will therefore reduce the eddy-current loss to insignificance, and justify calculations made on the assumption of uniform Magnetising Force and Magnetic Induction throughout the whole of the iron with the usual formulæ for the reluctance of the magnetic circuit.

Dr. Fleming gives the following formula for the absorption of power in watts per cubic centimetre of iron

$$W = \frac{.0032}{10^7} \, n \, B^{1.55} + \left(\frac{tnB}{10^8}\right)^2,$$

the first term referring to the hysteresis, and the second to the eddy-current losses; n being the frequency of alternation; t the thickness of the plates in *mils.* or thousandths of an inch. This is a "hybrid" formula, utilising two different units of linear measurement, but has the merit of simplicity. The first term assumes a law of variation of hysteresis loss with the Magnetic Induction which is approximate through a wider range of the latter than is common with transformer cores, for which a somewhat lower power of B seems nearer the results obtained by tracing the complete cycles of magnetisation.

While the hysteresis and eddy-current losses will both be diminished by the rise in the temperature of the transformer iron when the transformer is active, this rise in temperature exercises a deteriorating influence on the iron which causes an increase of the hysteresis loss after the transformer has been in use for some time. This deterioration has been carefully investigated by Mordey, and the causes described in a paper read before the Royal Society, December 19, 1894. He found that in six months' intermittent use upon an alternating current the hysteresis absorption of energy rose nearly 75 per cent. The magnetising current only rose about 50 per cent., the extra increase in hysteresis-loss being due to the increase of the power-factor, or cosine of the equivalent lag, pointing to a considerable increase in the Coercive Force of the iron. With a transformer in which the value of the maximum Magnetic Induction was 2500 units, and the value of iron 49.7 sq. cms., the following measurements were taken (amongst others):

Magnetising current.	Power factor.	Watts absorbed.	Date.
.41	.74	16.54	Aug. 27.*
.50	.75	20.76	Sept. 20.
.53	.87	20.65	Sept. 27.
.60	.81	26.71	Nov. 27.
.62	.85	26.96	Feb. 7.

Mordey's experiments gave rise to the following conclusions:

(1) The effect is not fatigue of the iron caused directly by repeated magnetic reversals—it is not "progressive magnetic fatigue."

* Commencement of test.

(2) Neither magnetic nor electric action is necessary to its production.

(3) It is a physical change resulting from a long-continued heating at a very moderate temperature.

(4) It appears to be greater if pressure is applied during heating.

(5) It is not produced when the iron is not allowed to rise more than a few degrees above the ordinary atmosphere.

(6) It is similar to the effect produced by hammering, rolling, or by heating to redness and cooling quickly.

(7) The iron returns to its original condition on re-annealing.

(8) It does not return to its original condition if kept unused and at ordinary atmospheric temperatures, whether the periods of rest are short or long.

The cost of transformers is a fairly large item in the capital expenditure attendant upon a light tension system of electric supply. As a large number are generally necessary, it is advisable that the labour required in their construction should be as small as possible. Designers have attended nearly as much to this as to the attainment of high efficiency. If the iron core forms a complete magnetic circuit, as is almost universally the case, it is necessary either that the coils should be wound tediously by hand, being passed through the core at each turn; or else that the coils should first be constructed and the core built up round it, or at least completed after the coils are in position: the latter method is far preferable and generally adopted.

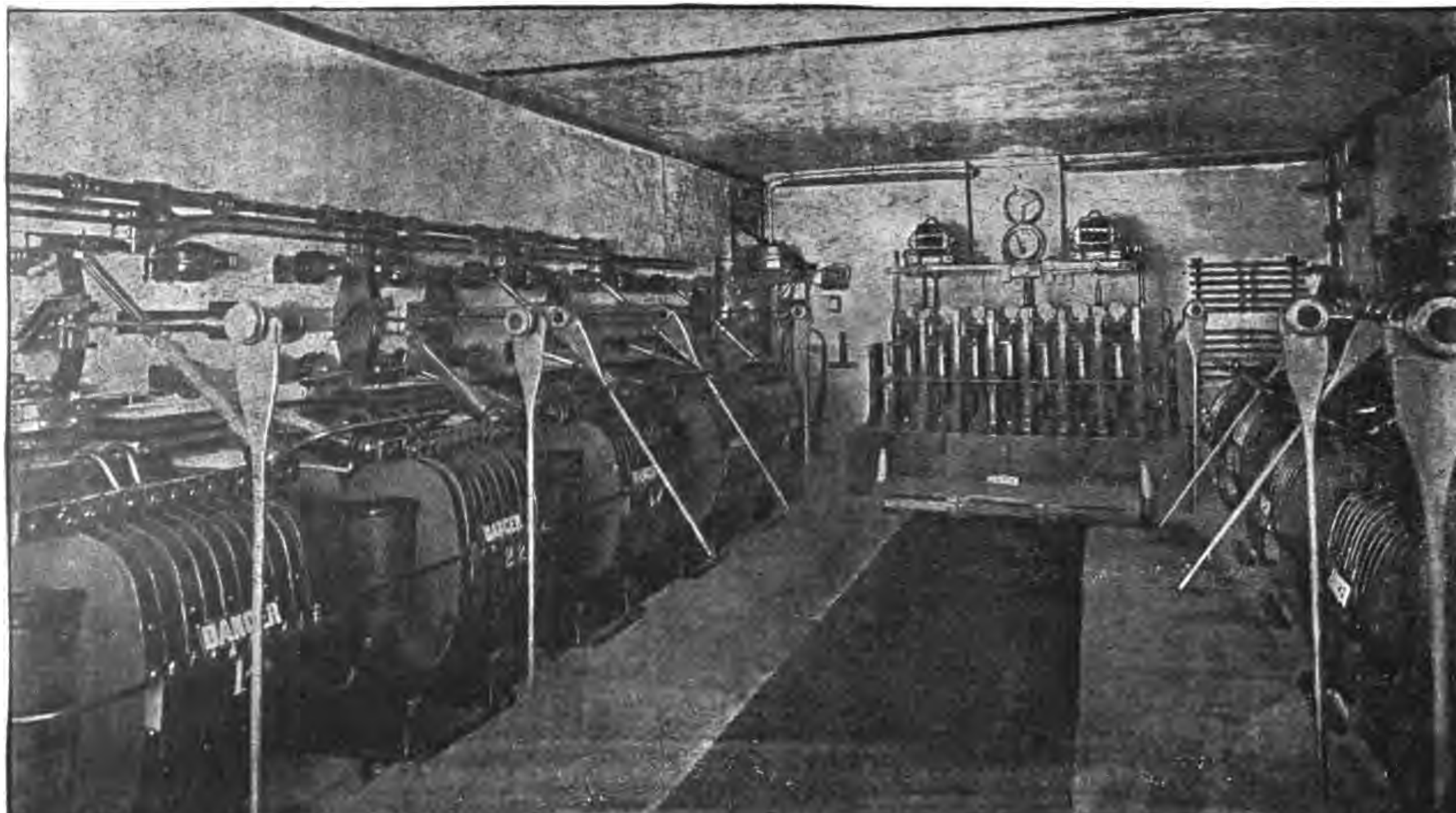
Another matter to be considered is economy in material; much can be saved if the iron stampings are of such a shape that they can be stamped out of a large sheet without leaving much waste.

The early forms of Gaulard and Gibbs' transformer were constructed with the intention of being employed in series on a constant current primary circuit, and so to generate in the secondary currents exactly equal to that in the primary. The primary and secondary windings were, therefore, exactly similar. They were constructed of perforated copper disks slit along one radius and soldered together so as to form a helix, the two helices being interlaced like the threads on a double-threaded screw. The copper disks were insulated by similar disks of varnished cardboard. The iron wire core was slipped through the perforations of the disks, being insulated from the copper by an ebonite tube.

In more recent forms of Gaulard and Gibbs transformers the iron core forms a closed magnetic circuit resembling a nearly rectangular chain link, around the two longer sides of which the conductors are wound, the primary being wound in separate sections, each provided with its own terminals by which the several sections can be coupled in series or parallel, according to the electromotive force available in the primary circuit, and that required in the secondary.

The first step towards the more convenient method of completing the iron circuits after the coils are placed in position was made by Zipernowsky and Déry, who wound the primary and secondary conductors in two large flat coils, each of hemispherical section, so that when placed together their section was circular, and then overwound them with iron wire. In this type of transformer the copper conductors have taken the place of the anchor ring, and the iron wire that of the copper conductors in Faraday's Transformer. The closed magnetic circuit is, of course, preserved. The two transformers are geometrically similar, but the magnetic and electric circuits are interchanged. Elihu Thomson's welding transformer is constructed in precisely the same way, but in this case the secondary conductor consists of less than a turn (a horse-shoe) of very stout copper bar, in which enormous currents of very low tension are generated. The chief objection to this design is the great labour expended in winding the iron wire around the copper, and the

FIG. 63.



Sub-station of Electric Supply Corporation (Ferranti Transformers).

necessity of unwinding it all if a fault should appear in the insulation of the conductor.

Swinburne employed a cylindrical coil, with a core made up of iron wires which were considerably longer than the coils. The ends of these wires as they project from the coils are bent round in all directions, forming a bunch at each end by which the lines of Magnetic Induction are distributed through a great section of air, the external appearance suggesting the name "Hedgehog," by which it is known.

It will be noticed that in the Hedgehog transformer the magnetic circuit is not closed in iron, and in this respect it differs from all other types now in common use. It however possesses a distinct advantage over the early forms of Gaulard and Gibbs' open circuit tranformers in that the section of the air through which the Magnetic Induction passes is always much greater than that of the iron core. The spreading of the ends of the wires enables the Magnetic Induction to remain in the iron until it can utilise an air section of something like a hundred times as great as the section of the iron core. Even this does not compensate for the great difference between the magnetic permeability of iron and of air, the value of μ in the softest iron being 2000 or more with such low Induction as should be used in transformers, the system appears to introduce unnecessary magnetic leakage. An open-circuit transformer will generally not maintain its electromotive force in the secondary as nearly uniform with great variations of load as is the case with transformers possessing closed iron circuits, and much greater mass of iron in their constitution. While possessing the advantage of dissipating little energy by hysteresis, it unquestionably demands a very great magnetising current, the self-inductance of the primary circuit being low. This magnetising current, however, does not represent a proportionate load upon the generator, as it will be in a different phase to the electromotive force.

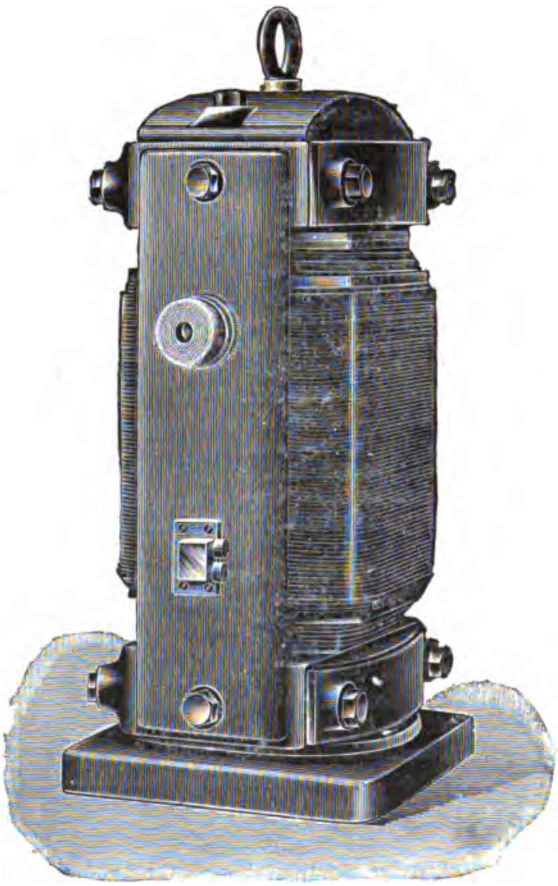
In the Ferranti transformer the iron wires in the core are replaced by hoop iron. Strips of hoop iron insulated by paper from one another are laid one above the other, and six such bundles are placed side by side. The central portion, for about one-third of the length of the strips is overwound with the secondary conductor, which consists of copper strip, cotton insulated; and over this the primary coils, wound in sections, and carefully insulated, are slipped. One half of the strips of hoop iron are then bent upwards, and the other half downwards, and their ends brought together above and below, overlapping some distance. The apparatus is then placed in a cast iron frame, the upper and lower parts of which are bolted together, the ends of the coils being protected by suitable shields, which form part of the castings of the frame. Spaces are left between the bundles of hoop iron which greatly facilitate the escape of heat.

Fig. 63 shows one of the sub-stations of the London Electric Supply Corporation, in which a number of 150 h.-p. Ferranti Transformers are employed in parallel to transform the Electric Power transmitted from Deptford at 10,000 volts, to 2400 volts suitable for the distributing mains locally, whence it is again transformed to 100 volts by smaller transformers on each consumer's premises.

The Lowrie-Hall transformer (Fig. 64) constructed by the Electrical Construction Corporation is somewhat similar. Both the primary and secondary coils are divided into two sections, one of each being placed upon a limb of a single magnetic circuit. Sheets of wrought iron are used which are made to bend over and overlap at the top only, the whole being held in a cast-iron frame.

A very large number of transformer designs employ flat wrought-iron plates, stamped out in various shapes, but with suitable perforations through which the limbs of the transformer coils are threaded, so that each plate forms two complete magnetic circuits in its own plane. The plates are placed side by side, separated by thin paper insulation, so that the completed iron core takes the shape of an elongated prism, twelve inches or more in length, with two (generally rectangular) perforations extending

Fig. 64.

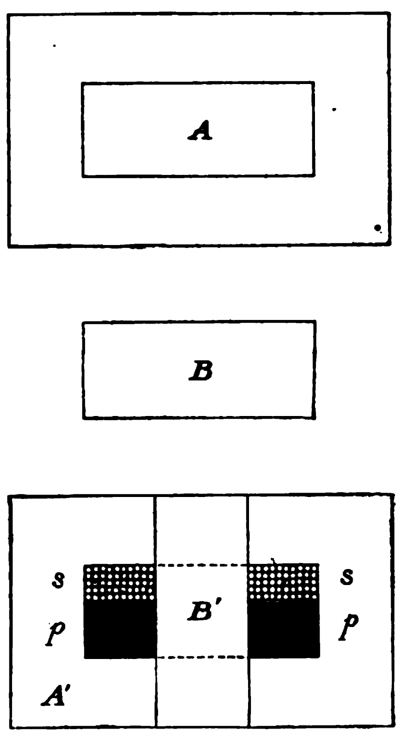


Lowrie-Hall Transformer.

throughout the whole length through which the limbs of the coils pass. It would not, of course, be possible to thread the conductors through these long tunnels so as to form a compact coil, the general method of procedure being to wind the two coils in an oblong shape on formers, and subsequently to build up the magnetic circuits around and through them. The following are a few of the contrivances adopted for the purpose.

In the Mordey (Brush) transformer (Fig. 65) a rectangular plate, *A*, is stamped out with a perforation in the middle, whose length is equal to the breadth of the plate *A*, and whose breadth is half that of the breadth of the plate, and equal to the difference of the lengths of the plate and the perforation. The portion *B*, stamped out of the middle of the plate, is preserved and subsequently laid across the plate so as to complete the magnetic circuit through the coils as shown at *A'*, *B'*, the return magnetic circuit being double, but of the same total sectional area throughout. The primary and secondary coils are of oblong shape, the limbs fitting easily into the perforations, with ample insulation, in the positions shown. The external iron rings are slipped over the coils, and the central pieces through them alternately. When complete the prism of iron discs is pressed together by the ends of the frame in which they are held, being drawn together by screwed longitudinal stays and nuts. The transformer is admirably ventilated by the air spaces between the external rings, and

FIG. 65.



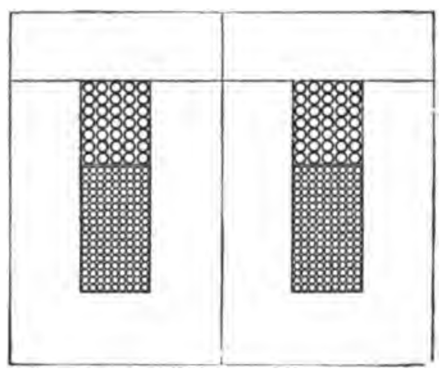
The Brush Transformer.

the necessity of the lines of force having to pass from a central strip to the adjacent external rings twice in a complete circuit, across the intervening paper insulation, introduces little extra magnetic reluctance. But the total sectional area of the actual iron is less than half that of the available space between the coils. The primary and secondary coils are wound with approximately the same amount of copper, but owing to the extra insulation required for the former it occupies somewhat the larger space.

The iron discs in the transformer, designed by Kapp and Snell, are illustrated in Fig. 66. Each plate is made in four pieces, the portions stamped out to make room for the coils being employed to complete the iron circuit on one side.

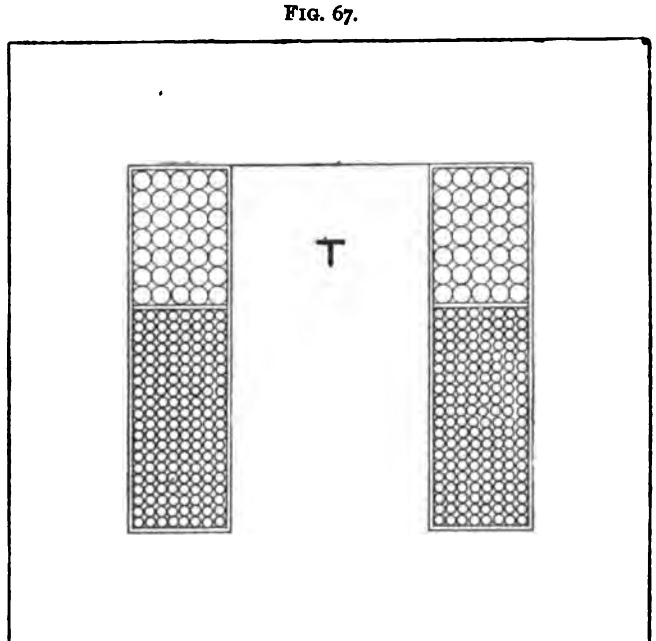
In the Weston type of transformer (Fig 67) there is only one joint in the magnetic circuit of each plate, but the form of the stamping involves a further waste of material. The central portion, T, forms a tongue, which is bent upwards so as to allow of the disc being placed over the coils, after which the tongue is bent back into its position, forming a central core through the interior of the coils. By reversing the direction of the tongues in the alternate plates it is rendered impossible for them to be

FIG. 66.



Kapp and Snell Transformer.

FIG. 67.



Weston Transformer.

deflected out of their respective planes, so as to fail to make contact with their proper discs.

In any well-designed transformer it is essential that the resistance of the coils should be so low that when the transformer is working "on open circuit," the electromotive force required to maintain the current in the primary coil against the "ohmic" resistance may be quite negligible. That is to say, the impedance must be almost entirely due to the inductance, otherwise the transformer will fail to "regulate," and the electromotive force upon the lamps will be much greater when the load is light than at full load, the E.M.F. in the primary circuit being regulated for constancy, but the transforming ratio not maintained.

Consider, for example, a transformer capable of transforming 2500 watts from a pressure of 1000 volts to 100 volts, and suppose, as is the common practice, that the same weight of copper is used in the primary and secondary coils. Neglecting the small excess of current in the primary required to produce the magnetisation, we may assume that the secondary current is exactly ten times that of the primary; and with one tenth the number of turns, the same weight of copper would make the resistance of the secondary one hundredth of that of the primary coil, the watts dissipated in heat will be the same, and the resistance of each coil will produce the same effect in lowering the electromotive force at the terminals of the secondary.

Suppose we fix a loss of 3 volts as the maximum permissible at full load. This will mean a loss of 1.5 volts in the secondary, and with a current of 25 ampères will correspond to a resistance of .06 ohm. The resistance of the primary will be 6 ohms, and with a current of 2.5 ampères there would be a loss of 38.5 watts, the same as in the secondary, therefore necessarily producing a similar loss of potential difference between the secondary terminals, viz., 1.5 volts. At full load this transformer will give 97 volts between the secondary terminal, while on open circuit it gives 100 volts, the potential difference between the primary terminals being supposed to be kept uniform at 1000 volts. This is certainly the greatest loss which can be permitted, and consequently for a transformer with this output the resistances should not exceed the figures mentioned.

In a transformer recently tested by the writer, the coils of which had the above-mentioned resistances, the current in the primary when the secondary circuit was left open was shown by the electro-dynamometer to be .179 virtual ampère, corresponding to a copper loss (C^2R) of .191 watts only. Compared with the current which would be produced in a circuit of 6 ohms resistance by an impressed electromotive force of 1000 virtual volts, this magnetising current is barely $\frac{1}{10}$ per cent. It follows, therefore, that the impedance is almost entirely due to the self-inductance of the coil, and the ohmic resistance may be safely neglected when considering the magnetising current. It then follows that on open circuit the rate of change of Magnetic Induction in the iron must balance the electromotive force applied to the terminals of the primary coil.

The induced electromotive force in any circuit is measured by the rate of change of Magnetic Induction through the circuit. If the electromotive force follows the harmonic or sine law (as it does very approximately in most types of alternators, except with those of very self-inductive armatures when heavily loaded), the rate of change of the Magnetic Induction must also follow the harmonic law, and hence the Magnetic Induction itself must also follow the harmonic law, but there must be a difference of a quarter period between the phase of the Magnetic Induction and that of the electromotive force, so that the Induction must be just changing its direction when the electromotive force is at its maximum, and the magnetism will be at its maximum intensity when the electromotive force is changing sign and has its zero value.

Let n_1 denote the number of turns of the primary conductor; A the total cross-section of the iron core in square centimetres, B the magnetic induction per square centimetre at any time, e the corresponding value of the electromotive force at the terminals in volts. The total magnetic flux through the circuit is n_1A.B, and the rate of charge of this quantity must be equal to 10^8e, or with the notation of the differential calculus:

$$n_1 A \frac{dB}{dt} = 10^8 e$$

If there are $\frac{p}{2\pi}$ complete alternations per second, and if E be the maximum value of the electromotive force, the harmonic law being followed,

$$e = E \sin pt$$

Hence

$$n_1 A \frac{dB}{dt} = 10^8 E \sin pt$$

and therefore

$$B = -\frac{10^8 E}{pn_1 A} \cos pt = \frac{10^8 E}{pn_1 A} \sin\left(pt - \frac{\pi}{2}\right).$$

The maximum value of B is $\frac{10^8 E}{pn_1 A}$, and the variation of B is represented by a "sine" curve, the maximum ordinates of which will represent $\frac{10^8 E}{pn_1 A}$ c.g.s lines of Induction per square centimetre.

Take, for example, the transformer above referred to. In this transformer A was 63.36, n_1 was 920, the virtual electromotive force intended to be used was 1000 volts, and therefore E was 1000 $\sqrt{2}$ or 1414; the number of alternations per second was 100, so that p was 2π . 100, or 628, and hence the maximum value of the Magnetic Induction B should be

$$\frac{10^8 \times 1414}{628 \times 920 \times 63.36} = 3860 \text{ nearly.}$$

This intensity of magnetisation would correspond to a loss of about 1200 ergs per cycle per cubic centimetre of iron through hysteresis if the best charcoal iron plate most carefully annealed were used. It would, however, be safer to take the loss at 1500 ergs per cycle per cubic centimetre. The total value of iron in the core was about 4800 cubic centimetres, so that the power dissipated by hysteresis when there was no load on the secondary circuit was about

$$\frac{1560 \times 4800 \times 100}{10^7} \text{ or } 2 \text{ watts.}$$

If the permeability were constant, and the same for increasing and decreasing magnetism, the current would be always strictly proportional to the Magnetic Induction. It would therefore follow the harmonic law, and be represented by a curve which would be a projection of the curve B. In the transformer referred to, the mean length of the magnetic circuit was 68 centimetres. Hence the current would be given in ampères by the equation

$$B = \mu \frac{4\pi n_1 c}{10 \times 68}$$

If we suppose μ constant and equal to 1000, we have, since $n_1 = 920$,

$$c = \frac{10 \times 68}{920 \times 4\pi \times 1000} B$$

And since the maximum value of B is 3860, it follows that the maximum value of c is .227 ampère, and therefore assuming the harmonic law, the measure of the magnetising current in vertical ampères is .16; a result calculated upon data and assumptions that make no pretence to exactitude, but not very greatly different from the observed value of .179 ampere.

To obtain exact agreement between the observed and calculated values of the current it will be necessary to refer back to Figs. 49 and 50. To illustrate the deformation of the current curve we there employed the cyclic curve traced for the iron used in our typical transformer, through the range of magnetisation for which it was designed. (The horizontal scale there indicates ampère turns per centimetre, the magnetising force being $\frac{10}{4\pi}$ of the horizontal readings.) The sine curve is not followed, and therefore the virtual ampèrage is not $\frac{1}{\sqrt{2}}$ of the maximum, but rather greater, as a glance at the curve will show. The correction may accurately be made by plotting a new curve whose ordinates are proportional to the squares on the ordinates of the current curve, and finding the area contained between this curve and the zero line. The ratio between this area and that enclosed between the zero line and a parallel line at a distance equal to the maximum ordinate of the curve will be the square of the reducing factor for obtaining the number of virtual volts from the maximum.

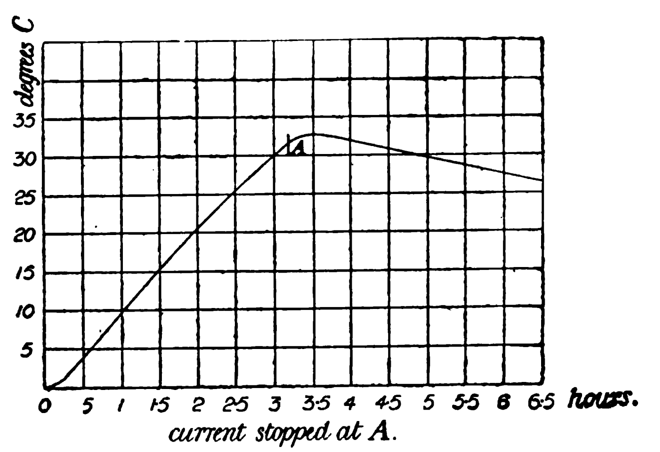
In measuring the power supplied from a generator to one or more transformers under the ordinary conditions of alternating current supply for lighting purposes. the product of the measures in virtual volts and ampères of the E.M.F. and current is generally taken as giving the correct measure of the power in watts; and this is sufficiently approximate except where a very small output indicates that the magnetising current forms a large proportion of the demand. In this case the retardation of the current phase causes a considerable discrepancy to exist between the real and the apparent output thus measured. Also when the load is taken up to any considerable extent by alternating current motors, or in any other way, the circuits either primary or secondary, are affected by self-inductance or perceptible capacity, information concerning the relation between the phases of the electromotive force and current are necessary before the output of power can be correctly measured.

Let this be illustrated by our typical transformer. The magnetising current was measured and found to be .179 virtual ampère, the electromotive force of the generator being 1000 volts, so that the apparent consumption of power when the secondary circuit was open would be 179 watts.

Now the power dissipated in heat through the resistance of the primary coil is quite insignificant, viz., .19 watt, and that dissipated by hysteresis has been estimated at 72 watts. The calorimetric method of measurement, to be described below, enabled us to trace a total expenditure of 91 watts, the additional amount being due for the most part to eddy currents in the iron. The real dissipation was therefore barely one half the apparent, corresponding to an equivalent lag, or retardation in phase, of about 60°. The ratio of the real to the apparent number of watts dissipated in a circuit is commonly termed the *power factor*.

To measure directly the efficiency of a transformer when loaded, we may use a wattmeter to measure the power delivered to the transformer, and measure the power absorbed in the secondary, if the circuit outside the transformer is non-inductive, by multiplying the readings of a voltmeter and ammeter. The power delivered to the transformer by the generator, or by any self-inductive circuit, may also be measured by the "three voltmeter" method devised by Ayrton and Sumpner, and the corresponding "three ammeter" method of Fleming. In the former a known non-inductive resistance R is placed in series with the primary of the transformer, and an alternating current made to flow. Three voltmeter measurements are taken, E_1 between the terminals of the known resistance; E_2 between the terminals of the transformer coils; E between the extreme terminals. E is found not to be the sum of E_1 and E_2 as it would be with two non-inductive resistances in series; nor by the formula $E^2 = E_1^2 + E_2^2$ as it would be if the current in the transformer coils lagged a quarter phase behind the electromotive force between its terminals, giving a "wattless" current. But it may be shown that the expression $\frac{E^2 - E_1^2 - E_2^2}{2E_1E_2}$ is the *power factor* for the self-inductive circuit. In the "three ammeter" method a similar non-inductive resistance is placed in parallel, and measurements are made of the

FIG. 68.



Calorimetric test of Transformer.

currents in the transformer coil, in the resistance, and in the main from the generator; then with similar notation the power-factor in the self-inductive circuit is $\frac{C_1^2 + C_2^2 - C^2}{2C_1C_2}$.

The above methods may be applied to test the transformer at any load. But another method, which is most simple in theory, and with due care most reliable in practice, is the calorimetric method. It simply consists in packing the transformer in some non-conducting material, and observing by thermometers suitably placed the rise of temperature in a given time, while the transformer is at work, or connected to the mains with open secondary circuit. Allowance may easily be made for the heat that is conducted through the packing, by observing the rate of cooling at different temperatures after the current is cut off. If the temperature of the transformer is found to rise at the rate of T^0 Centigrade in one hour, after making the suggested correction, the number of heat units supplied must be

$$\left\{ .113 \cdot M_1 + .95 \cdot M_2 \right\} \frac{T}{3600}$$

where M_1 is the mass of iron in grammes, M_2 of copper; and the watts dissipated can be obtained by multiplying this by 4.2.

The calorimetric method applied to the small transformer mentioned above gave a fairly uniform rise in temperature of about 10° Centigrade per hour, as shown by the plotted curve in Fig. 68, whence the power absorbed by hysteresis was calculated. Correction for the waste heat escaping through the packing was made by observing the law of cooling.

Dr. Fleming has recently made a very laborious and complete series of experiments with alternating current transformers constructed by the leading manufacturers, with a view to a comparison of the relative efficiencies, &c., of the various types. It will appear from these records that a drop of potential difference between the terminals of the secondary coil, due to the resistances of the coils

$$\left(R_2 + \frac{n_2^2}{n_1^2} R_1\right),$$

of from 2 to 2.5 volts is commonly permitted. An absorption of power on open (secondary) circuit, owing to hysteresis and eddy currents in the iron core, of from 1.3 to 2.8 per cent. of the specified maximum output of the transformer, is permitted; the lower percentage being obtained with large transformers with a specified maximum output of about 20 electrical horse-power.

At full load an efficiency of from 96 per cent. upwards is obtained with transformers designed for a maximum output of from 6 E.H.P. upwards. At half load this efficiency is but slightly reduced, the increased percentage of the core losses compensating for the reduction in the loss due to the resistance of the coils. At a load of 10 per cent. of the maximum the efficiency varies from 80 to 85 per cent. The rise in temperature permitted, when the transformer has been working for some time at full load, is from 150 to 212 degrees Fahr.

To estimate the actual diurnal efficiency of a transformer, that is to say, the ratio of the total amount of energy output in the secondary circuit to the total energy absorbed from the generator, when employed in the customary manner for domestic lighting, the primary coil being permanently connected across the high-tension distributing mains, and a varying demand being supplied according to the number of lamps switched on to the secondary conductors, we require a knowledge of the efficiency at all loads, and the variation of the demand throughout the day. As a rough approximation to common conditions of practice, suppose the demand for lighting to be confined to four hours, during which the load is varying, but of sufficient magnitude to give an average efficiency of 94 per cent.: and during the remaining twenty hours of the day the output to be insignificant, while a uniform core loss of 2 per cent. of the maximum proceeds. Suppose, also, that the total secondary output of energy be equivalent to that given by a uniform maximum output for three hours, or 12.5 per cent. of the total possible output for the twenty-four hours. The energy absorbed by the transformer during the continuation of the supply will be six per cent. for four hours, or one per cent. of the total possible output during the day; the energy absorbed during the remaining twenty hours will be two per cent., or 1.66 of the total possible; the total loss will be thus 2.66 of the total possible output, or 21.3 per cent. of the actual output. Thus the diurnal efficiency of the transformer will be 78.7 per cent.

SUMMARY OF DR. FLEMING'S TRANSFORMER TESTS.

	Loss on open circuit. Per cent. of full load.	Efficiencies at various loads. 5 per cent.	10 per cent.	Half-load.	80 per cent.	Full load.	Fall of secondary E.M.F. at full load.	Resistance of primary ohms.	Resistance of secondary ohms.
15 K. W. Ferranti . .	1.3	65.4	86.5	96.1	96.8	96.6	2.1	2.75	.0061
11 K. W. Ferranti . .	1.3	79.0	88.1	96.0	96.1	95.5	2.2	3.77	.0092
6½ K. W. Westinghouse .	1.46	75.9	85.7	96.0	96.8	96.9	2.4	5.95	.0108
4½ K. W. Thomson Houston	1.6	76.6	78.8	93.8	95	94.7	2.3	19.68	.019
6 K. W. Brush (Mordey)	1.82	67.6	67.6	93.7	94.9	95.4	2.25	7.73	.0163
4 K. W. Kapp . . .	2.8	56.5	72.3	91.9	93.8	94.2	2	11.38	.024
6 K. W. Hedgehog . .	2.6	65.2	79.0	94.8	96.1	96.1	3	7.93	.01512

Experimenting with an open circuit "Hedgehog" transformer, designed for a maximum output of 3000 watts, Dr. Fleming found that the magnetising current was nearly half that of full load, instead of barely three per cent., as would be obtained with a closed circuit transformer designed for a similar output. The power factor, or cosine of the equivalent angle of lag, was, however, very small, reducing the measurement of the actual loss to about 112 watts. Even the latter (3.7 per cent. of the maximum output) was greatly in excess of that found with closed magnetic circuit transformers, but the excess was probably due to eddy currents in the large secondary conductors, which were wound inside the primary coil. The total volume of the iron was only 856 cubic centimetres (weighing 5982 grammes), consisting of wires 18 inches in length and .0225 in. in diameter; thus, in spite of a somewhat high intensity of Magnetic Induction, amounting to 10,000 lines per square centimetre in the middle of the core, Dr. Fleming estimated that the hysteresis loss could not be greater than 20 to 30 watts, and the eddy current 10 to 15 watts. In testing a larger six-kilowatt transformer, transforming from 2400 to 100 volts, having a laminated secondary conductor, the magnetising current was found to be 1.194 ampères, whereas in a closed circuit transformer for corresponding output .07 ampère would be enough, and the power absorbed on open secondary circuit was reduced to 2.6 per cent. (156 watts), not greatly in excess of that obtained with closed magnetic circuits. The excessive magnetising currents necessary with this type of transformer, although not representing a corresponding waste of power, still remain a great objection to their employment as these currents mean a waste of power in the distributing mains, and no corresponding advantage, unless it be in the saving of weight in the transformer, seems to be obtained. By the employment of a condenser connected across the terminals of the primary coils, the "wattless" magnetising current can be maintained by an interchange of potential energy between the magnetic field and the condenser which reduces the necessary magnetising current flowing from the generator in the distributing mains, but it is improbable that this device, if perfectly satisfactory, will allow an open circuit transformer to compete in commercial efficiency with the closed circuit, owing to the extra cost of the conednser.

Having designed a transformer for the conversion of a given electric power from one electromotive force to another, it will be easily seen that the only alteration required to adapt the same design to different electromotive forces is a corresponding multiplication or division of the number of turns in either coil, the magnetic circuit remaining the same, and the capacity and efficiency remaining the same if the sectional area of the wire is only limited by the total sectional area allowed in the design. This statement makes no allowance for the extra insulation which is required as the electromotive force, and the number of turns are increased. In short, the capacity of the transformer, that is the total power convertible with a given percentage loss, is a function of the size of the transformer, and independent of the electromotive forces in the primary and secondary, except for certain practical modifications.

We must now investigate the relation between the size and the capacity for a given type of transformer; we shall suppose that the linear dimensions of all the parts in a given type are multiplied in a given ratio, call it x, and investigate the variation in capacity and efficiency; from this investigation we shall be able to decide whether it will be advisable to alter the ratio of the parts in increasing or diminishing the size.

The variations are identical with those previously discussed in the theory of dynamo design, save that there need be no reservation corresponding to the speed of the dynamo. The linear dimensions being multiplied by x, the area of the magnetic circuit, and therefore with the same induction density, the total number of lines of force is multiplied by x^2. The number of turns in either primary or secondary is therefore divided by x^2. The total area available for the coils is multiplied by x^2, and therefore for each wire by x^4. The length of each turn is multiplied by x, and therefore the total length of either coil is divided by x. Hence the resistance of either coil is divided by x^5.

It follows that for the same percentage of loss in copper resistance, and fall of pressure in secondary at full load, the capacity is multiplied by x^5; but if we are limited by the current density in the conductors the capacity is only multiplied by x^4. The hysteresis and eddy current losses are multiplied by x^3, the increase in the mass of the iron, but the percentage loss is divided by x^2 or by x in the two cases. It will follow that if the balance between these losses is to be preserved a slightly smaller proportion of iron would be used in larger transformers, and the density of Magnetic Induction increased. But on the other hand, we must remember that the surface of the transformer is only increased in the ratio of x^2, so that an increase in the quantity of iron instead of a decrease will be necessary, if the same limiting temperature is to be reached.

An increase in the size of the transformer should therefore be designed with a somewhat lower density of Magnetic Induction. The capacity may be specified to increase at a greater rate than the weight, and the efficiency, both in respect of the iron and copper losses, must necessarily be improved, or the temperature of the transformer will be higher than in the smaller sizes.

Ewing has given empirical formulæ for the hysteresis loss in iron per cubic centimetre during a complete alternation, from which it appears that

$$.01B^{1.475}$$

gives a very close approximation to the loss in ergs per cubic centimetre, when B, the maximum value of the Induction, is between 2000 and 8000. It appears that the rate of variation is the same as $B^{1.4}$ between $B = 2000$ and 5000 and $B^{1.5}$ from 5000 to 10,000, so that we shall be very close to the truth in taking Ewing's formula as representing the variation at the intensity most commonly used in transformers. The eddy-current losses should vary as B^2, and these should be almost negligible in comparison; still the combined loss would be most approximately and simply represented by a variation in proportion to $B^{1.5}$. Upon this assumption, let us find the effect upon the efficiency of increasing all the linear dimensions of a transformer in the ratio x, but decreasing the induction so that the same power may be converted with the same loss in copper resistance.

If the number of turns in either the primary or secondary be multiplied by y, the sectional area of the conductors will be multiplied by $\frac{x^2}{y}$, and the length multiplied by xy; the resistance of either coil must be multiplied by $\frac{y^2}{x}$, and if this is to remain the same, $y^2 = x$. The total number of lines of force throughout the core must be divided by y, and since the area is multiplied by x^2 the intensity of induction, that is the maximum value of B, must be divided by x^2y or by $x^{2.5}$. The loss by hysteresis per cubic centimetre will therefore be divided by $x^{3.75}$, and since the mass of iron is increased in the ratio x^3, the total loss will be divided by $x^{.75}$. Or if W be the weight of the transformer, the iron losses will vary as $W^{\frac{1}{4}}$. If we had assumed that the loss varied as $B^{1.4}$, they would have been found to vary as $W^{\frac{1}{6}}$. The efficiency, therefore, improves very shortly with size at moderate intensities of Induction, but at very high or low Inductions, where the loss varies as a higher power of B up to the second, the rate of improvement with size is more rapid.

The effect of varying frequency on the iron core losses of a transformer was investigated practically by Mordey for his own design by the calorimetric method. He found that the rate of rise in temperature reached a minimum with a certain rate of alternation, about 100 complete periods in the transformer tested being greater with 75 and 125 periods. In any case the best frequency will depend on many conditions, chiefly the quality of the iron and proportion of eddy current to hysteresis losses; but it will follow that a wide range of frequency will be possible without much variation in the loss, according to the universal law that the variation of any quantity near its maximum or minimum values is slow. A simple test, measuring the power with a wattmeter at various frequencies, is sufficient to indicate without much error the best frequency to employ.

The reason for the small variation can be seen by consideration of the fundamental equations. If the frequency be increased the maximum Magnetic Induction is correspondingly reduced. The loss per alternation is therefore reduced according to some power, about 1.5, of the frequency; the loss per second is then reduced according to the .5 power, or square root, of the frequency. The net advantage is therefore somewhat in favour of the higher frequency if an effective lamination is secured. The loss by eddy currents is, though it should be very small, much increased; the magnetic screening causes irregular density of Magnetic Induction in the iron; and other increased losses occur through eddy currents and skin effects in the copper conductors; these accumulate till the small gain owing to reduced Magnetic Induction is more than neutralised.

CHAPTER XII.

Alternating Current Distribution.

THE most common British practice in Alternating Current Distribution employs a parallel constant potential system for the distributing mains, at 2000 virtual volts, with secondary two-wire systems at 100 volts. There is much, however, to be said for the reduction of the distributing E.M.F. to 1000 virtual volts, as adopted in a few instances, the avoidance of the difficulties and dangers introduced by the higher E.M.F. possibly more than compensating for the extra sectional area of the distributing mains. The gradual concentration of the transforming centres may also render a three-wire secondary system more common in the immediate future. With a current density of 1000 ampères per square inch, the fall of E.M.F. at the distance of one mile from the generating station, considering the resistance of both the go and return conductors, will be about 90 volts, if the copper be of standard conductivity. This is a drop of only 4½ per cent. of a distributing E.M.F. of 2000 volts, with a corresponding percentage waste of power. Within this distance, therefore, it will be possible to arrange that the variation of the pressure at different points of the system should not exceed 2½ volts, and it would be easy to arrange for a still smaller variation by compensating for the extra fall at the extreme distances by a few extra turns of the secondary coils of the transformers there employed. Further, by a system of feeder mains, in which a greater fall of potential is permissible, it will be possible to reduce the variation at different points of the distributing system, while allowing a somewhat greater percentage waste of power, which will still be within very moderate limits. There will be a still further drop of potential to be allowed for in the transformers and secondary mains; but since the demand all over an extensive system will, as a rule, rise and fall with approximate uniformity, a corresponding increase and decrease of the E.M.F. of the generators, according to the total demand, may be made to partly compensate for this variation. We have therefore to deal with three causes of fall of potential and corresponding sources of waste power, the drop owing to the resistance of the high and low pressure distributing mains, and the variation of the transforming ratios between zero and full load. Each of these may conveniently be reduced within 2½ per cent. The variation of the transforming ratios may be entirely compensated for by the variation of the E.M.F. at the generating station according to the total load, if the demand over the system is at all times similarly proportioned to the maximum. The variation at different points according to the length of the primary and secondary conducting mains leading to them can similarly be reduced to 2½ volts in excess or deficit of that specified. As a variation of 4 per cent. is permitted by the Board of Trade regulations, this is well within the limit, allowing for further variation by imperfect regulation, &c.; but we may still further approach uniformity by overwinding the secondary coils of the transformers where the fall is great, using lower current density for the conductors leading to more distant lamps, and other similar devices.

For widely distributed systems, extending upwards of a mile from the generating station, it may be advisable to use a current density of less than 1000 ampères per square inch in the distributing mains. Remembering that, with an E.M.F. of 2000 volts, every ampère represents 2.77 electrical horse power, and will supply 30 sixty-watt lamps (with a loss of ten per cent.), it will be seen that a conductor of $\frac{1}{10}$ sq. inch section, carrying a current of 100 ampères, will supply 3000 sixty-watt lamps. The extra expense of a further increase of the section of such a conductor, so as to diminish the current density, and corresponding fall of E.M.F. and power absorbed, will be far less in proportion to the cost of the generating and transforming plant than a corresponding increase in low pressure systems for the same purpose. With a current density of 500 ampères per square inch at 2000 volts, the system may be carried to upwards of two miles from the generating station without experiencing any difficulty in maintaining uniformity over the whole system.

The alternating current transformer system possesses this advantage over the continuous current, in addition to the higher efficiency of transformation possible, that the centres of transformation can be in practice indefinitely sub-divided, and no attention whatever need be given to the transforming plant. But, as has also been shown, the concentration of the transforming plant in large units offers possibilities of greatly raising the efficiency of distribution, owing to the fact that the larger sizes of transformers may be at the same time much cheaper in first cost, and of much higher efficiency than the small. Nor is this the only advantage gained by concentration, for it may be practicable, when large transformers are grouped together in a sub-station, greatly to reduce the daily loss of power in the magnetising current by adjusting the capacity of the plant to the ever-varying demand, this being done either by a sub-station attendant or by some automatic device which switches out some of the transformers at times of light load.

It is now universally recognised that the concentration of the transforming plant, and the use of a secondary network supplying many consumers, is the best method of applying the alternating current system. The method which has hitherto been most common, that of supplying each consumer with a separate transformer, having been intended only as a temporary expedient, necessary while consumers were only to be obtained here and there over a wide area, and the minimising of capital expenditure was advisable before the commercial value of the system had been thoroughly demonstrated. In the place of this scattered system the sub-station or concentrated system is being rapidly introduced, with a secondary network, preferably using a three-wire system, or direct employment of 200 volts.

For the house transformer method branches are taken from street mains to a transformer in the basement. Concentric cables are inconvenient with this system, owing to the numerous joints that must be made. The branch conductors leading into the house should not be of less size than 7/18, giving ample mechanical strength, although the current could be carried on wire of much smaller cross-section. The transformer should be contained in a fire-proof chamber, or cast-iron case, and double pole fuses used on both primary and secondary mains.

When the mains are drawn into conduits, a few feet of slack should be left in each "drawing-in" box for convenience in making the joints for the branch conductors. Moreover, the joints should be V-joints, made at such points that they can be drawn back at the service boxes a few feet into the conduits, always in a uniform direction, say towards the generating station. This, when worked systematically, enables a large number of branches to be made from a pair of cables with the minimum amount of slack. The Metropolitan Company, which is the largest supply company in London, have improved upon the branch conductor system by drawing in the cables in short lengths from one consumer to the next, so that the main circuit can be broken in the transformer chamber of each consumer, and joints in the street culverts are thus almost entirely avoided. Ring-mains are completed wherever possible, so that each consumer may be supplied from two directions, and any small section of the mains separated for testing without stopping the supply.

As the number of consumers increases, or to use an expressive phrase, the lamp "density" in any area increases, the advantage of the concentration of transformer plant becomes obvious. At present the tendency is towards transformer-pits sunk under the pavement, feeding a secondary network laid parallel, but of course in separate conduits, to the primary or high-tension mains. It is, of course, vitally necessary that such transformer pits should be well drained, or else hermetically sealed. Moisture is fatal in any high tension system, and far greater care must be taken than with low tension work. On the cables themselves, with high rubber insulation and impermeable covering, the presence of water in the culverts is probably rather beneficial than otherwise. The transformer coils are proof against creeping moisture when worked continuously, and therefore always at a moderately high temperature—the danger comes in restarting after a period of rest. It has been attempted to protect transformers from moisture by completely sinking them in a thick oil, of greater density than water, supposing that the water would not sink to the fibrous insulation of the coils. At the cost of dear experience this device has been proved worse than useless. For underground cables a fibrous insulation impregnated with oil is the safest of all systems, owing to the self-restoring properties of the insulation; but where there is circulation and oil-surface exposed to deposit of moisture the insulation sooner or later breaks down. In the oil-sunk transformer a circulation in the heavy oil is at once set up by the heat generated, and a thin film of the water floating on the surface is carried round with it. This moisture is at once taken up by the cotton or other fibrous insulation, actually taking the place of the oil in it, and refusing to be expelled by heat, until the cotton is absolutely saturated, takes a leakage current, carbonises, and a short circuit results. Hermetic sealing will alone prevent this happening, and then the oil is probably superfluous.

In the Deptford "extra high tension" system, the transformation from 10,000 volts to the intermediate 2400 volts is effected in several sub-stations. The transformers have a capacity of 150 h.p., and a number are placed in parallel. These are kept under constant supervision, and the number in use is varied according to the demand. By this means the immense loss due to the magnetising current is greatly reduced. In the transformer pits the same efficiency could be secured by an automatic switch, or the employment of an attendant to visit the transformer at stated periods. Several attempts, more or less successful, have been made to design an effective automatic switch. But the action must be absolutely certain, and the switch-break very sudden for such to be effective. A design by Ferranti employs a small motor, which attains a certain speed before the switch acts, so that it may be thrown over suddenly when the load reaches or falls below a certain amount. The primary and secondary are each wound as two separate and similar coils, which are placed in series for small loads and parallel for large. The capacity, when the coils are in parallel, is four times as great as when they are in series, but the loss in hysteresis would be between three and four times as great, as the Magnetic Induction in the transformer core is carried to twice the maximum value.

The secondary network may be arranged so as to be fed from several transforming centres. A fairly uniform distribution of electromotive force in the secondary may thus be secured, but unless a number of transformers be thus connected, and the fuses be very heavy, a breakdown in one transformer will cause the fuses of the others to be blown. If, however, a sufficient excess of current can be drawn from the remaining transformers to blow the fuse of the one that has broken down, the lighting will be continued, though perhaps with an undue fall of pressure at certain points on the network. In the borough of Portsmouth the following system was initiated, and since adopted elsewhere. A secondary network of uniform size is used throughout the whole system. This secondary network consists of three pairs of No. 19/18 cables, or a total sectional area of only just over a tenth of a square inch for the three conductors, connected to one pole. Running parallel to the high tension mains in adjacent conduits, it is fed by transformers at convenient intervals, the positions of the transformers being preferentially chosen so that the conductors for a large installation may be led off at once from the junction-box. It is initially arranged that the transforming centres should not be more than about 300 yards apart. In the event of a heavy demand along the intervening gap, the secondary mains are not increased, but an intermediate transforming centre is laid down and connected to the same secondary network. Concentric cables are universally preferred to pairs of cables for sub-station transformer systems, the advantages being the slightly reduced cost, the smaller space occupied, the greater immunity from risk of injury, and the total absence of inductive effects upon telephone wires, &c. There are now no longer numerous branch joints to make, as the transforming centres are few in number, and some convenient form of junction-box, in which the branch of the transformer may be disconnected, takes the place of the joint. The insulation between the inner and outer mains is alone of vital importance; the external insulation need only be sufficient to prevent a leakage which, by joining a partial earth return, may affect neighbouring telegraph and telephone lines. It is customary to earth the conductor at the distributing station, so that all parts of this conductor may only vary slightly from the zero potential. Thus, if the output be such that the maximum fall of potential at any point of the system be 4 per cent., in a 2000 volt distribution, or a total of 80 volts, the difference of potential between the outer conductor and the earth at that point is only 40 volts, so that the electrical strain is insignificant.

In connecting alternating current transformers in parallel so as to supply the same secondary system, dividing the load between them, care has of course to be taken that the transforming ratios are identical, or at least very approximately identical; and also that the terminals are so connected that the secondary coils are in parallel, and not in series, with regard to the phase of the E.M.F. generated in them. When joined in parallel, the division of the load will depend on the fall of potential in the transformers, owing to the primary and secondary resistances, each taking such currents as will lower the transforming ratio so as to bring the difference of potential between the secondary terminals down to that between the main conductors to which they are connected. In other words, if the transforming ratios at zero load are identical, the proportion of the current supplied by each transformer will be inversely proportional to the resistances either of the secondary or of the primary coils; for the ratio of the resistance of the secondary to that of the primary coil in any well designed transformer should be the square of the transforming ratio, and therefore the same in each transformer (otherwise the division of the current will be inversely proportional to $R_1 + \frac{n_2^2}{n_1^2} R_2$ in each transformer). Provided, therefore, that the transformers are designed for the same transforming ratio, and the same fall of secondary E.M.F. at full load, transformers of different sizes, joined in parallel, will divide any load in the proportions of their specified maximum output; but if any transformer give a higher secondary E.M.F. at zero load than another, it will take a larger proportion of the load when they are joined in parallel, so that an extra fall in the former may equalise the difference of potential between the secondary terminals.

To supply a secondary three-wire network two transformers, or sets of transformers, may be joined with their primary coils in parallel across the high pressure distributing mains and secondary coils in series. Again, however, care must be taken that the secondary coils are correctly in series, their E.M.F. at any moment being in the same direction through the series circuit, and not in opposition; otherwise the middle wire will take the sum, instead of the difference, of the currents in the two sections of the system. Multiple wire systems have been employed by the Thompson-Houston Company in America with alternating currents for incandescent street lighting, employing a "compensator," or "equaliser" to maintain equality of potential difference between the different sections of the system. The principle of this apparatus is similar to that of the equaliser employed for continuous currents, save that mechanical motion is now no longer necessary. In place of the motor-dynamo armatures, similar coils are wound round the same laminated magnetic circuit. The self-inductance of these coils prevents anything more than the minute magnetising current from passing through them; but in the event of the difference of potential between the terminals of one coil rising above that of another, a current will pass through the former conditional upon a current in the reverse direction passing through the latter. Thus, if the current through the lamps be reduced in any section, tending to raise the E.M.F. between the corresponding conductors, and lower than in the other sections, a current will flow in the corresponding coil of the compensator, and acting as the primary of a transformer, generate higher E.M.F. in the remaining coils, and once more equalising the difference of potential between each adjacent pair of conductors.

In dealing with the size of conductors required to carry alternating currents, a modification is introduced by the fact that, since a magnetic field is created even by a straight wire carrying a current, the alternations of this magnetic field will introduce further impedance, and increase the fall of potential along the conductor above that given by the application of Ohm's law. This modification will be partly equivalent to a co-efficient of self-inductance, which, as previously shown, modifies Ohm's law so that the relation between the virtual ampères and volts is given by

$$C = \frac{E}{\sqrt{R^2 + p^2L^2}},$$

where R is the resistance of the conductor, $\frac{p}{2\pi}$ the frequency, causing the current to lag in phase $\tan^{-1}\frac{pL}{R}$, and the power dissipated to remain C^2R watts as before, except for hysteresis loss, etc.; but in addition to this, the alternating magnetic field created within the conductor itself will cause the self-inductance of the interior of the conductor to be greater than that on the surface, causing a varying distribution of current density throughout the conductor, larger upon the surface and diminishing towards the interior, the conductor being thus equivalent to one of smaller section and greater resistance, with further dissipation of energy than would be given by a continuous current of the same number of virtual ampères flowing in the same conductor. This phenomenon, known as the "skin effect," was first observed by Prof. Hughes in 1883.

The fall of potential due to self-inductance owing to the alternations of the magnetic field external to the conductor itself, so far as it does not affect the distribution of current density, would be very great in the case of a single conductor drawn into an iron conduit, but is rendered very small if the return conductor is drawn into the same conduit and lie in close proximity, thus neutralising its magnetic field. With a concentric cable the effect would be still less. Taking the precaution mentioned, we may neglect, except for very long mains, consideration of the fall of potential and retardation due to self-inductance alone, but with conductors of large section the varying current density, which also increases the absorption of power, becomes of great importance.

Lord Rayleigh has shown (*Phil. Mag.* May 1886 "On the Self-induction and Resistance of Straight Conductors") that the "virtual resistance" R′ and co-efficient of self-induction L of a long straight wire of length l and permeability μ may be given in absolute units by the formulæ

$$R' = R\left[1 + \frac{1}{12}\frac{p^2 l^2 \mu^2}{R^2} - \frac{1}{180}\frac{p^4 l^4 \mu^4}{R^4} + \ldots\ldots\right]$$

$$L' = l\left[A + \mu\left(\frac{1}{2} - \frac{1}{48}\frac{p^2 l^2 \mu^2}{R^2} + \frac{13}{8640}\frac{p^4 l^4 \mu^4}{R^4}\ldots\right)\right]$$

A being some constant depending upon the position of the return wire, and R the ohmic resistance of the conductor, measured in absolute electromagnetic units $\left(\frac{1}{10^9}\text{ ohm}\right)$. With a copper wire or rod one centimetre in radius, carrying an alternating current of frequency 100 (the permeability being unity), we have

$$R = \frac{1616}{\pi} l$$

and therefore

$$R' = R\left\{1 + \frac{\pi^4}{13}\frac{10{,}000}{(1616)^2}\ldots\right\}$$
$$= 1.128\ R.$$

Or the virtual resistance is about one eighth more that the actual for a copper wire of one centimetre in radius. For an iron wire the resistance would be enormously increased, the increment being multiplied by μ^2, which, even for the low magnetisation involved, would probably be several thousands. The increment to the resistance varies as the square of the frequency, and the fourth power of the diameter or radius. The building up of the conductor with stranded wires of small section, at least by the common method in which the internal and external wires maintain their relative positions throughout the length of the cable, does not prevent this augmentation of virtual resistance. What is needed is a method of stranding in which all the strands are brought in succession to the exterior of the cable every few feet, so that the self-inductance of each strand may, in a reasonable length, be the same, and the current uniformly distributed.

The following table, calculated by Mordey, will give the relation of virtual resistances to the actual resistance of solid round wires or rods of copper of various diameters, carrying currents of various frequencies of alternation. For stranded cables the increment may approximately be taken as the same as for a solid conductor of equal diameter.

Diameter of Copper.		Area of Cross-Section.		Increase over Ordinary Resistance.	Current at 450 Ampères per Square Inch.	Watts at 2000 Volts.	Watts at 100 Volts.	Frequency.
Milli-metres.	Inches.	Square Milli-metres.	Square Inches.					
10	0.3937	78.54	0.12	less than $\frac{1}{100}$ %	55	110,000	5,500	80
15	0.5907	176.7	0.274	$2\frac{1}{2}$ "	133	266,000	13,300	
20	0.7874	314.16	0.487	8 "	220	444,000	22,000	
25	0.9842	490.8	0.760	$17\frac{1}{2}$ "	—	—	—	
40	1.575	1,256	1.95	68 "	—	—	—	
100	3.3937	7,854	12.17	3.8 times	—	—	—	
1000	39.37	785,400	1,217	35 "	—	—	—	
9	0.3543	63.62	0.098	less than $\frac{1}{100}$ %	45	90,000	4,500	100
13.4	0.5280	141.3	0.218	$2\frac{1}{2}$ "	98.5	197,000	9,850	
18	0.7086	254.4	0.394	8 "	178	356,000	17,800	
22.4	0.8826	394.0	0.611	$17\frac{1}{2}$ "	—	—	—	
7.75	0.3013	47.2	0.071	less than $\frac{1}{100}$ %	32	64,000	3,200	133
12.61	0.4570	106.0	0.164	$2\frac{1}{2}$ "	74	148,000	7,400	
15.5	0.6102	189.0	0.292	8 "	131.4	263,000	13,140	
19.36	0.7622	294.0	0.456	$17\frac{1}{2}$ "	—	—	—	

The Board of Trade Regulations insist that "A high pressure electric line shall not be used for the transmission of more than 300,000 watts, or in the case of an aerial line 50,000 watts," so that we see from the above table that, as long as this Regulation is adhered to, the increment of the resistance owing to the skin-effect will not be a serious matter, amounting to only a little over 8 per cent. with the maximum size and high frequency of alternation. With the low pressure mains lighting a large building, the skin-effect becomes more serious, especially as the fall in E.M.F. is generally as great as is permissible. A subdivision of these large conductors, limiting the carrying capacity to about 100 ampères for each cable, is advisable from other considerations; for example, to diminish the rise in temperature, by which means the skin-effect is rendered inconsiderable.

Some of the typical systems of underground mains have been described in a previous chapter, and, except the bare copper systems, these are all applicable to high tension distribution with some extra care as to insulation. The concentric vulcanised-rubber insulated cable drawn into some form of conduit is likely to remain the favourite method, especially where a secondary network is combined, though the buried armoured concentric main is less expensive. For the latter the Ferranti main is the most famous example. The inner conductor is a copper tube $\frac{1}{8}$ inch thick, having an internal diameter of $\frac{9}{16}$ inch, and an external diameter of $\frac{13}{16}$ inch, and therefore a sectional area of slightly over $\frac{1}{4}$ square inch. The external conductor is another tube of $\frac{3}{64}$ inch thickness, with an outer diameter of $1\frac{15}{16}$ inch, and the same sectional area. The insulation between the tubes, as nearly as possible $\frac{1}{2}$ inch thick, is made up of layers of brown paper soaked in black mineral wax or ozokerit, and the whole is drawn through a taper die which compresses the insulating material into a solid mass. The external insulation is of similar material but only $\frac{1}{8}$ inch in thickness. Over the whole is drawn a thin wrought-iron tube. The conductor is made in lengths of 20 feet, which are laid in wooden troughs filled with pitch. The joints are made in position, and in spite of their number add very little to the resistance of the main. The copper tubes are turned at one end into a long cone, which fits exactly a hollow cone in the next length. These are hammered together and soldered. Four trunk mains thus constructed carry the power from a generating station at Deptford to the distributing stations in the Metropolis. The capacity of these cables is great, about .367 microfarads per mile, and with a frequency of 67 alternations per second, and an electromotive force of 10,000 volts, the condenser current is nearly 1½ ampères per mile of cable. This great capacity has the effect of raising the electromotive force at the sub-stations above that of the generating station at light load, owing to the oscillating interchange of potential energy between the magnetism of the transformers and the static charge of the cables, an effect which has to be allowed for at the generating station. A full account of the theory and experimental investigation of this phenomenon will be found in Dr. Fleming's Alternate Current Transformer, vol. ii.

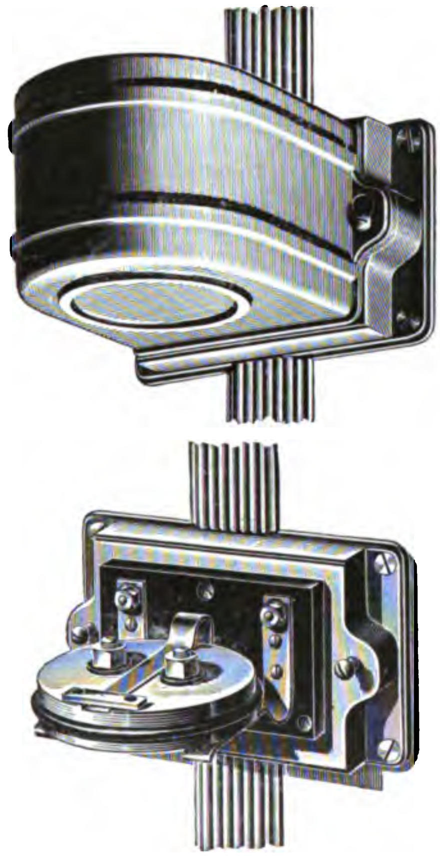
A word should here be said concerning the fuses to be used on high-tension circuits. It has been stated elsewhere that the fuse break should not be less than one inch for every 100 volts, and this length should be increased for very large currents. This rule gives a great length of fuse for high-tension work, and ingenuity has been brought to bear upon designing a fuse of shorter length with some means of extinguishing the arc. A design of Ferranti is most effective, the fuse being only about two inches in length, consisting of several strands of No. 30 copper wire. An earthenware vessel is used, divided by a diaphragm into two troughs, which are filled with thick resin oil. The ends of the fuse terminate in two rings, which are slipped over the ends of two spring rods, one in each trough, which keep it in tension over the diaphragm. These rods are connected to brass blocks, which pass through the earthenware and form contact pieces with the main terminals. In the event of a fuse melting, the spring rods plunge into the oil and extinguish the arc.

An important safety Regulation issued by the Board of Trade is as follows (Regulation 12):

"In every case where a high pressure supply is transformed for the purpose of supply to one or more consumers, some suitable automatic and quick-acting means shall be provided to protect the consumer's wires from any accidental contact with, or leakage from, the high pressure system, either within or without the transforming apparatus."

The sole point of danger in a carefully supervised transforming system is in the transformer itself, where the primary and secondary coils are necessarily in close proximity, and the most perfect insulation is liable to break down in the presence of damp, or through mechanical injury. The most effective safeguard is probably the separation of the coils by strips of metal, effectively earthed, which, in the event of any considerable leakage from the primary coil, would cause the protecting fuses on the primary circuit to cut out the transformer immediately. This arrangement is, however, inconvenient, and an automatic device to connect the secondary conductors, or at least one of them, close to the transformer to earth, immediately the potential rises above a permissible limit (400 volts) is commonly preferred. This may, or may not, result in the blowing of the high-tension fuse protecting the transformer, according to the resistance of the leak; but the occurrence of such an event will be recognised at the Supply Station by the fall in the insulation resistance of the distributing mains. A thin film separating a point on the secondary conductor from an earthed conductor, the insulation of which will be destroyed by a disruptive spark when the potential rises, has been employed for the purpose. An "earthing device" designed by Major Cardew, and approved by the Board of Trade, depends on the principle of electrostatic attraction. This apparatus is shown in Fig. 69, with and without the protecting cover. It consists of two metal discs insulated from one another, the lower supporting a thin strip of aluminium foil so as to bring it very close to the upper disc. The upper disc is connected to the secondary or house circuit, close to one of the terminals of the transformer, and the lower, by a wire not less than No. 18 S.W.G. to the nearest gas or water pipe. Should the insulation of the primary coil of the transformer fail at any time, causing a leakage into the

FIG. 69.



Cardew Earthing Device.

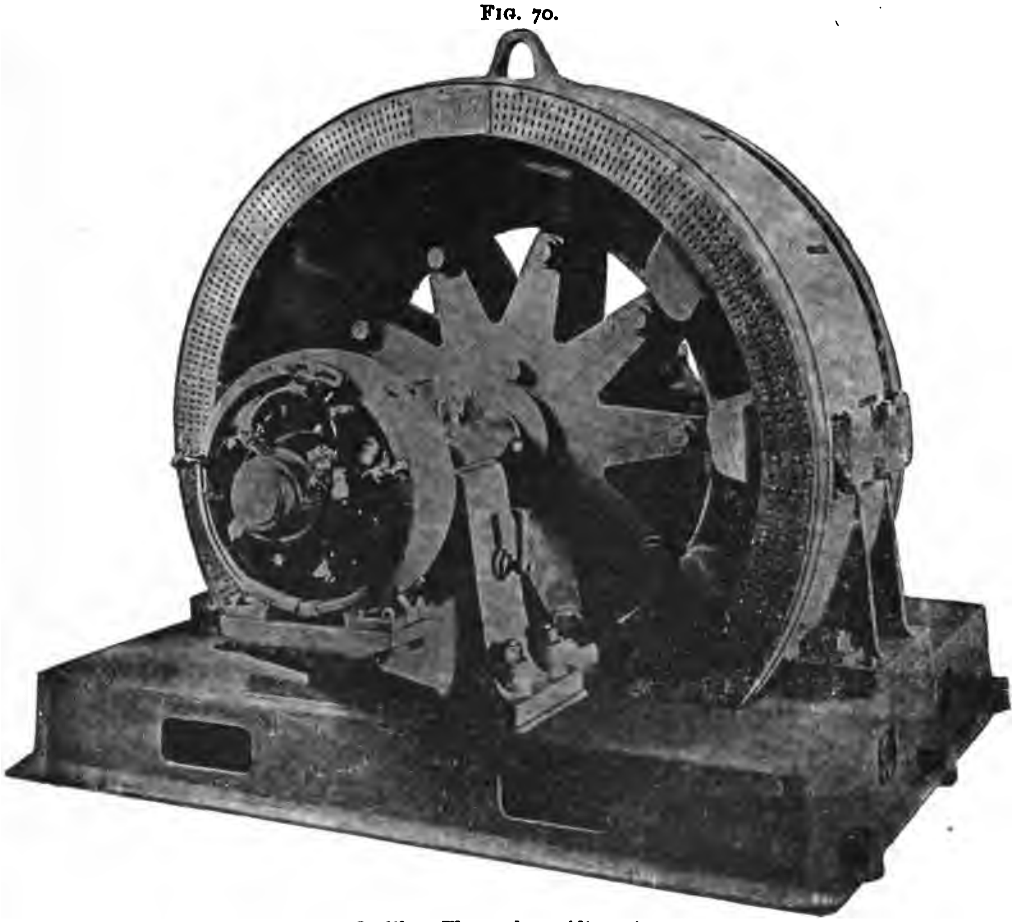
secondary, and thus the potential of the latter rise above 400 volts, the static charge developed on the upper disc attracts one end of the strip of aluminium foil and thus puts the circuit to earth.

Polyphase Currents.

Instituting a general comparison between alternating current and continuous current dynamos with respect to efficiency and output, it will be seen at once that a considerable advantage must inevitably lie with the latter, from which the complication of winding and commutator difficulties will subtract but little. The higher rate of magnetic variation, owing to the rapid alternation generally demanded has already been noted as requiring a lower induction and therefore larger size or lower efficiency in alternators. Another disadvantage is the less economic use of the interpolar space, or surface of armature-core, which is only partly filled in by conductors; so that for a given size of machine, and involving given mechanical and magnetic losses, approximately only one half the space can be utilised, and the output for the same efficiency correspondingly reduced.

This immense waste of space and consequent inefficiency can immediately be removed by utilising the space devoted to the core of the coils for the

FIG. 70.



Oerlikon Three-phase Alternator.

winding of other coils, and forming a second armature of an equal number overlapping the former and utilising the same magnetic field. In this second armature the phase of the electromotive force is a quarter-period, or right-angle, in advance or in retard of that in the former armature; and except for the heat to be removed, we may consider the output of the alternator to have been doubled by this means, with the slight inconvenience that two separate circuits must be employed for the distribution of power.

An alternator such as described is known as a "two-phase" alternator, and for lighting purposes alone may be looked upon as a generator suitable to systems already described, simply requiring a division into two circuits.

For some purposes it is advisable to go even further and construct a triple armature of symmetrically overlapping coils, generating electromotive forces with phases at equal intervals, sixth periods, or 60 degrees, in difference. Three independent circuits could in this way be supplied, but if, as, with the two-phase system, the circuits be totally independent with six conductors, we shall only succeed in increasing the elaboration, and secure no further advantage beyond that obtained by the two-phase system.

Should it however be found possible to arrange that the demand in three different circuits should be approximately equal, and fairly evenly distributed, the three-phase system presents a considerable advantage. A moment's consideration will show that at any moment whatever the sum of the electromotive force in the three different circuits is zero, or in other words, the greatest of the three is in opposition and equal in magnitude to the sum of the other two electromotive forces. It is easy to show this from either of the graphical methods in vogue, or from the simple trigonometrical identity

$$\sin \theta + \sin (\theta + 60^\circ) + \sin (\theta + 120^\circ) = 0.$$

If the resistances, then also the currents will in non-inductive circuits follow a similar law, and it will be possible to reduce the number of conductors in the system from six to three, the circuits being between any pair. At any instant one of the three conductors may be looked upon as the return wire for the currents flowing in or out in the other two.

The "Three-phase" System, as the arrangement thus briefly explained is termed, presents certain difficulties in direct application to lighting which has prevented its adoption except to a very limited extent. Theoretically it may be worked in a similar way to the three-wire system with continuous currents, except that lamps must be connected with approximate equality in load between each pair of wires, the effective difference of potential being the same for any pair. The weight of copper will then be about 25 per cent. less than for a single-phase system, but the difficulty in maintaining a sufficient approximation to equality in load in the three circuits, and the variation of potential difference arising from irregularity, is almost prohibitive in practical work. Incandescent lamps have been constructed with triple filaments so that the load for each is equally partitioned, but this is scarcely likely to prove a practical solution of the difficulty. It is more likely that when the three-phase system is used for distribution a transformation to direct current will be employed for lighting purposes.

We have shown that the two- and three-phase, or to use an inclusive term, the *polyphase* systems, have a distinct advantage over the single-phase system in the larger output and higher efficiency of generators having the same dimensions. Still greater advantages are to be found in the fact that self-starting efficient motors can be employed in either system, and that transformation to continuous currents can be effected with great facility.

Motor supply is very closely connected with the economic question of electric lighting, but a complete account of the "rotary field" or "polyphase" motor would involve a long chapter on the general theory of polyphase systems, and for this, not directly bearing on the subject to which we have carefully limited ourselves, we must refer to one of the many specialist text-books recently published. It must be noted, however, that the polyphase motor is better supplied where possible by a separate system of mains to those used for lighting, though the same generator may be used. For the large currents with low power-factor employed in starting them is likely to cause a heavy drop of potential along the mains, temporarily affecting the lighting supplied from the same mains; the effect on the generator is less marked with separate circuits for lighting and motor supply as the real load at starting is comparatively small. The polyphase motor is conveniently used to drive a separate arc lighting plant, a continuous current dynamo of the open-coil type supplying a long series circuit, or a closed-coil dynamo supplying several shorter series circuits in parallel, as the conditions may determine.

For continuous currents of lower potential as required for incandescent lamps a similar arrangement may be used, but a much more efficient and satisfactory means of transformation to continuous currents is supplied by the "rotary converter." This really amounts to a synchronous polyphase motor and closed-coil armature combined in one machine. An ordinary closed-coil armature is supplied with "slip-rings" and brushes by means of which connections may be made permanently to fixed points of the armature. For the transformation of two-phase currents four slip-rings are provided, one pair connected to two points on the closed coil in simultaneous contact with the commutator brushes, the other pair to similar points which reach the positions of commutation at intervals midway between those of the former pair. Driven by an engine, this machine can supply either continuous currents from the commutator, or two-phase alternating currents from the slip-rings; it can also act as a transformer from continuous to two-phase, or *vice versâ*. In transforming to continuous currents it is, however, necessary to rotate the armature until synchronism is obtained, before connecting to the two-phase mains. This is easily effected when a secondary battery is worked upon the continuous current side, which may be employed by discharge to start the converter, and be subsequently charged. A system worked out on these lines goes some way to solving the question of the storage of power hitherto impossible with alternating current systems.

The rotary converter for three-phase currents is exactly similar, save that the three slip-ring contacts are made to points on the closed coil at equal intervals (120° apart on bipolar dynamos). The great advantage of the converter over a motor-driven dynamo lies in the compactness and reduced cost owing to the same armature and magnets being used for both alternating and continuous currents, and still more to the fact that for the most part the current passes directly from one circuit to the other through a portion only of the armature, with little loss due to resistance of the coils. The current is in fact only redistributed, and not regenerated in the closed coil, the greater part passing to the nearer brush; the distribution in the armature at any moment of the alternating currents is such as to produce the normal distribution in the closed coil.

Supposing the E.M.F. produced in any turn of the closed coil during rotation followed the sine law there would be a definite ratio between the effective E.M.F. in the alternating circuits and in the continuous current circuit. This would be $\frac{1}{\sqrt{2}}$ or .707 for the two-phase and $\frac{2\sqrt{2}}{\sqrt{3}}$ or .613 for the three-phase. The practical divergence from the theoretic ratio is seldom more than 5 per cent., and we may assume that to produce 100 volts between the commutator brushes will require 71 volts between either pair of mains in the two-phase system, and 61 volts between either of the three mains of the three-phase. It will be necessary to transform the alternating currents to these voltages, or other necessary values, before conversion to continuous currents.

With polyphase systems it has been found advisable to reduce the value of the frequency to 50 or even a smaller number of periods. This low frequency is to suit the convenience of motor construction; and where the use of large motors for mechanical power is the principal purpose of the system, a frequency as low as 25 has found favour, as in the two-phase system supplied by the generators at the Niagara Falls. The rotary converters must run at a corresponding speed, being synchronous motors: with a frequency of 50 complete periods a speed of 3000 revolutions per minute would be necessary with a two-polar machine, and 1500 revolutions with a four-polar machine. The latter is of course the more convenient, and within the practical limits for a converter of very large output, since, owing to the reason explained above, the size of the converter is very small as compared with a dynamo of similar output.

Without altering the E.M.F. between the mains of the alternating current circuits it is possible by varied excitation to modify to some small extent the E.M.F. in the continuous current circuit, sufficient at least to compound the machine so as to compensate for the fall of potential at heavy loads. The speed being simply dependent upon the frequency, the E.M.F. in the continuous current circuit must necessarily be raised, when the excitation is increased by hand regulation in a shunt circuit, or automatically by series coils, the magnetisation being of course supplied by the continuous current. The result in the alternating current circuits is to produce a higher E.M.F. between the slip-rings than between the terminals of the generator, but a reference to the theory of the parallel running of alternators will show that this is not impossible, but only involves a variation in the phase relation of the generator and converter. Power is still transferred from the former to the latter, but the power-factor in the alternating current circuit is reduced.

Two-phase and three-phase circuits may be with facility connected together for the conversion of power from the one to the other. Suppose two transformers be wound on similar cores with an equal number of turns in the primaries, which are to be connected to the two-phase circuits, but with the secondaries in the ratio of $\frac{2}{\sqrt{3}}$ or 100 : 86.7. Let the latter secondary coil have one terminal connected to the middle point of the former secondary coil, its other terminal to one of the three-phase mains, the two free terminals of the first secondary to the other three-phase mains. In this way the transformation may be effected from two- to three-phase or *vice versâ*.

The theory of this transformation is as follows: Calling the effective electromotive forces in the secondaries 100 and 86.7 volts respectively, it will be noticed that the difference of potential between the free terminal of the latter and either of the former is the resultant of 86.7 volts, and 50 volts with a phase difference of 90°. The resultant is in magnitude $\sqrt{(86.7)^2 + (50)^2}$ or 100 volts, and its phase difference from that of the 100-volt transformer $\tan^{-1} \frac{86.7}{50}$ or 60°. In actual practice the ratio of the secondary windings is made 10 : 9 to compensate for the somewhat longer transformer circuit. The length of wire through which the three-phase current has to pass in one of the coils is only about $\frac{10}{14}$ of that in the other two, and the lower resistance would give this a higher difference of potential.

With somewhat less practical efficiency, three-phase currents may be directly converted to single phase. For this purpose three separate transformers are used, the primaries connected to the three-phase mains, the secondaries in series, in such a way, by the reversion of the normal sequence of one coil, that their electromotive forces do not neutralise one another, but give an electromotive force in the phase of the reversed coil. By this means, while equal currents are still obtained in each of the three-phase circuits, a single-phase alternating current represents the whole power. Owing, however, to the partial opposition of two of the secondaries, the efficiency is not as good as is to be desired; unfortunately the conversion is not reversible, from single to three-phase.

On the whole the two-phase system is likely to be preferred, as more "flexible," for systems mainly devoted to electric lighting. The two circuits are practically independent, and may be used in exactly the same way as in the single-phase distribution already detailed. But the great value will lie in the manner it will link with the many systems now in use, and probably solve the problem of concentrating the source of generation when various lighting and power stations now established under different systems in one city desire to unite. This problem must inevitably be dealt with within a short time in London. In dealing with future possibilities it must not be forgotten that we are dealing with a youthful science which is advancing even more rapidly than the industry which it controls; another decade of similar advance as the last may as completely upset our predictions as those of ten years ago.

Present conditions would be best suited by the establishment of one or more large generating stations at some distance from the centre of a city, where every advantage of natural power, or condensing water, cheapness of land, and carriage of fuel, might be obtained. A three-phase, or two-phase with three wires, system of transmitting mains at extreme high pressure, would connect the generating station with many sub-stations, for which the present generating stations could conveniently be modified. A transformation to lower tension, single or two-phase could then be effected, the latter where motive power is required. Motor driven arc-light generators would supply the public lighting locally on the series, or multiple series system. Rotary converters might be combined with large secondary batteries, the continuous current with a three-wire distribution and storage for safety and uniformity of load still being unsurpassed for the denser areas of supply. More scattered areas would still prefer alternating current, with grouped or separate transformers, according to the density of supply. Large rotary converter sub-stations would be established for the working of electric traction, railways and tramways, since at present alternating motors cannot compare with continuous current motors for variable speed.

CHAPTER XIII.

The Coupling Together of Generators.

In the supply of electric power from central stations it is very often absolutely necessary, and always a matter of great convenience, if the various units of plant, that is to say, combinations of dynamo and engine, can be made to assist one another by dividing up among themselves the load that is demanded. If no arrangement is made for such coupling it will be necessary to divide the supply mains into a number of different circuits, in each of which the maximum load must not rise above the output of one of the units of plant; and a great complication of switches will be necessary in order that any one of the dynamos may be readily switched on or off from any one of the circuits. In addition to this complication of switches, it will generally be found difficult to arrange the working so that the minimum number of units are at work, and some loss in efficiency results. Also, and this is most important of all, a momentary extinction of the lights accompanies switching over of circuits from one dynamo to another, and even if the switching be done so rapidly as not to be noticeable, yet the sudden diminution or accession of load to any unit of plant will, unless the government of the engine and regulation of the dynamo be exceptionally good, result in an oscillation or "hunting" of governor or regulator, and consequent variation in the lights for several seconds.

There will be a vital difference between the conditions necessary for the connection of various classes of dynamo in series and in parallel, especially between the conditions for alternating and continuous current dynamos. The safety and smoothness of running will depend at least as much upon the government of the source of mechanical power, steam-engine, turbine, or other, as upon the dynamo itself. In this chapter we shall discuss the various classes of dynamo *seriatim*, and in most cases assume that they are driven by a steam-engine with the ordinary type of centrifugal governor, being thereby maintained at a speed which is approximately constant.

Two series wound continuous-current dynamos, giving of course the same current, may be connected *in series* without any further precautions, each supplying the same electromotive force as it would if run separately, and the two dynamos together will give the sum of the two electromotive forces. There is, however, seldom a demand for such connection in practical working. Nor should any great difficulty arise in connecting shunt or compound dynamos in series; this arrangement is frequently required for systems of parallel distribution with multiple mains. In such cases secondary batteries are frequently connected between the mains to ensure equality of potential difference when the number of lamps in the different sections varies. But in the case of two dynamos connected in series, of the same design and size, equality in the division of the electromotive force between the two may be further secured by connecting the shunt coils in series as a separate circuit between the external terminals, and removing their contacts with the intermediate terminals, so that the same current must inevitably flow through each shunt coil. The strengths of the magnetic fields being thus made identical, equality of electromotive force is secured in the armatures if the speeds are identical.

The coupling of continuous current dynamos in *parallel* is a matter of much greater practical importance, and more consideration and care is required. Two dynamos giving the same electromotive force may of course be thrown into parallel upon the same circuit without interference as long as equality of electromotive force is maintained. But the variation of the current in the armatures causes variations in the electromotive force, and in certain cases the equilibrium is *unstable* so that the slightest variation may cause a complete upsetting of the conditions.

The criterion of satisfactory stability is simply this: *that the characteristic curves of both units of plant should be falling at the points at which they are working.* By the characteristic curve is meant, not merely the curve giving the relation between the current output by the dynamo and the difference of potential between the terminals *at a constant speed*, but the curve giving the actual relations between these when driven by its steam-engine, or other source of power, the government of which inevitably causes a slight decrease in speed as the load increases. By the characteristic *falling* is meant that an increase in the current-output causes a decrease in the difference of potential between the terminals.

A very little consideration will demonstrate the truth of this simple criterion. For the two dynamos will so determine and divide the current in the external resistance that the difference of potential between their terminals may be the same; and then, in the case of both characteristic curves being "falling," if a variation of this balance occurs, the dynamo which obtains an increase of current will also obtain a decrease of electromotive force, and *vice versâ*, so that the combination will tend at once to return to its former condition of equilibrium. Even with dynamos compounded for constant electromotive force at constant speed, satisfactory stability may be possible owing to the decrease of speed as the current in the armature and therefore the load of either unit is increased; thus the characteristics may be really falling. If one characteristic is falling and the other rising stability probably depends upon whether the rise in one is more rapid than the fall in the other or not; but in practice it is necessary that the stability should be unquestionable and maintained through a wide range of load, so that it is advisable to remove any uncertainty by the precaution which will be explained directly. Series-wound dynamos cannot be run in parallel except when both are supplying a larger current than that which gives the maximum electromotive force. Should an attempt be made to couple them in parallel with smaller currents the result of a decrease in the current in either dynamo will be a fall in its E.M.F., a still further decrease ensuing, and ultimate reversal of its magnetisation and of E.M.F., the two dynamos becoming really arranged in series; and unless the armature-resistance or armature reaction on the magnetisation be very great, the fuses will be blown, the engines be pulled up, or the armatures destroyed by a huge current. It is erroneous to state that one will be driven as a motor by the other, the converse being true as long as the dynamos continue to run in the same direction, for the current and E.M.F. will be reversed together in one of them, its engine being still loaded, and the electromotive forces will assist one another to send a current through the two armatures. Shunt-wound dynamos work without difficulty in parallel, for their characteristics are necessarily falling. It is also very easy to divide at pleasure the load by an adjustable resistance in the shunt circuit, or by increasing or reducing the speed of the engine, provided, of course, that the dynamos are designed to give similar differences of potential between the terminals with their suitable loads. As with the charging of secondary batteries, the worst that can happen is that one will be driven as a motor by the other to maintain the requisite speed.

With compound dynamos there is generally an uncertainty as to whether parallel running is possible. With over-compounded dynamos particularly it is necessary to adopt the following precaution which cannot fail to secure perfect stability. When exactly similar compound-wound dynamos are to be coupled those brushes which are not connected to the mains directly, but from which the series coils proceed, should be also joined together by a short thick piece of cable of negligible resistance. This will ensure that the whole outgoing current shall in all cases be divided equally between the two series coils, whatever currents flow in the armatures of the dynamos respectively. With dynamos of different sizes the resistances of the series coils should be carefully balanced so that the current may be divided in the right proportion. It is customary to arrange that the aforesaid brushes should be invariably the negative brushes of the dynamos, and then the greatest care should be taken that the positive terminal should be the last to be connected to the positive "omnibus bar" or massive copper bar upon the switch board to which the positive terminals of all the dynamos are switched. This precaution tends to safety because the previous division of the current in the series coils when the negative switch is on prevents the possibility of the dynamo which is to be switched into parallel attaining with the normal speed its full electromotive force in the opposite direction to that of the other dynamo or dynamos, an event which might occur if the initial magnetisation were reversed before starting. Before a dynamo is switched into parallel its electromotive force should be tested and made equal to a volt or so in excess of that between the "omnibus bars," so that it will immediately take a small portion of the load, and not be driven as a motor by the dynamo or dynamos with which it is placed in parallel.

Coupling of Alternators.

The theory of the coupling together of alternating current dynamos is entirely different from that of continuous current dynamos. For it is evident that if two alternators are to work together upon the same circuit so as to divide the power by combining their currents or electromotive forces, the frequency of the alternations in the two alternators must be identical, and therefore the speed of the alternators must be the same in each if the machines are similar, or if dissimilar their speeds must bear a certain fixed relation to one another.

Now supposing two alternators are driven by engines each governed to maintain a constant speed, it is evident that either the speeds for which the engines are governed must be absolutely identical (or in a fixed ratio giving the same frequency for the alternators), or else subject to slight variations within such limits that the speeds may be made identical by some electrical control tending to keep the speeds identical when the armatures are connected. We shall show that the alternators themselves supply this control, but it must first be noted that with an engine governed in the usual manner to maintain constant speed, the factor which determines the power supplied by that engine can be nothing else than the variation of its speed, or rather, the decrease in speed below that which it will acquire when running freely with no load. For example, in the ordinary steam-engine the power depends upon the admission of the steam, and this depends simply upon the position of the governor, and therefore upon the speed of the engine. Thus, when two alternators driven by separately governed steam-engines are connected together so as to divide an electrical load the combination runs as a rigid system as if mechanically coupled, whatever be the speed of the system the governor balls take up a relative position according to their adjustment, so that the amount of steam admitted to each, and therefore the power supplied by each is fixed, and quite independent of the electrical conditions of the alternators. Of course, it is not meant that the ratio of the horse-power of the two engines remains the same for different total loads, for neither is the power necessarily proportional to, though determined by, the steam admission, nor is the steam admission in any way proportional to, though determined by, the variation from any speed; also the slipping of belts and ropes may affect the relative speed of the engines at different loads. But this all-important statement is unquestionable: given a fixed output in power from the combined plant, no alteration of the excitation of the field-magnets or other interference with the alternators themselves, so long as it does not alter the total load, and their combined speed remains the same, can affect the division of the load between them; for this is entirely determined by the positions taken up by the governors at the speed with which the engines are running.

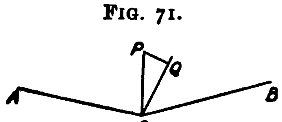
The property which renders the parallel running of alternators possible was discovered by Wilde, and his experimental results published in the *Phil. Mag.* for January 1869. The importance of the discovery was not recognised, as the demand for its application did not exist, until in 1883 it was re-discovered by Dr. Hopkinson, who also gave the theoretical explanation, and the results of practical experiments upon the large De Meritens alternators used to supply the arc lamp in the lighthouse at South Foreland.

The property, possessed by all types of alternator in a greater or less degree, is simply this: that when alternators, running at approximately the same speed, and excited to give approximately the same electromotive force, nave their terminals connected in pairs, a current passes through both armatures which tends constantly to pull them into such a position that the total electromotive force in the circuit through both armatures and therefore the current is a minimum; and therefore into such a position that the alternating electromotive forces are in opposition as regards the circuit through the armatures, and in parallel as regards any external circuit joining the pairs of terminals. Unless, therefore, a difference of speed be enforced by a power greater than this control, the alternators will be constrained to maintain the same frequency, and to remain in a position favourable for parallel working. The alternators are then said to remain "in step" or "in synchronism."

In following out the line of argument used by Dr. Hopkinson, by which he deduced the existence of this control, before applying his theory to practice, we prefer to adopt the clock-diagram method, in preference to the current curve or the algebraic methods; and in the first place we shall deal with two alternators with their terminals connected together, so that there is no external circuit, but only one circuit through the armatures; then we shall show that the alternators will be constrained by the current to move relatively towards such a position that their electromotive forces are in opposition.

In Fig. 71 let the vectors OA, OB represent in magnitude and relative phase the (maximum) electromotive force of the two alternators at any moment. Their resultant OP (the diagonal of a parallelogram) represents the resultant electromotive force in the circuit of the armatures. There will be considerable self-inductance in this circuit, and the current will lag behind OP in phase, so that in the right-angled triangle OPQ, where $\tan POQ = \frac{p\text{L}}{\text{R}}$, OQ may represent $\text{C} \times \text{R}$.

FIG. 71.



Supposing the electromotive forces OA, OB to be very nearly equal, the products of these and the current (the "apparent watts") are the same for each alternator, and OP bisects AOB. But the true load is obtained by multiplying the products respectively by $\frac{1}{2} \cos AOQ$ and $\frac{1}{2} \cos BOQ$, and the latter angle being the smaller the load upon the corresponding alternator is greater; in many cases the angle AOQ will be obtuse, and then the alternator whose electromotive force is OA will be motor driven.

In any relative position of OA, OB, the load will always be heaviest upon the alternator which is in advance of the phase of opposition to the other, and lightest upon that behind. And unless the separating force is great, or the charge of relative phase is so rapid that the retardation or propulsion changes from one to the other too rapidly to have any effect in bringing the alternators into step, they will take up a position of relative equilibrium not far from that of exact opposition.

The existence of a controlling force tending to bring and to keep the alternators in step, and in the correct relative position for parallel working, being thus demonstrated under the simplest conditions, let us suppose the opposite terminals connected through an external resistance. For the sake of simplicity, let us suppose the alternators similar in design, and that the external resistance is not self-inductive, and also, as will generally be the case, that the resistance of the armatures of the alternators is negligible in comparison with their self-inductance (that is, the number of ohms much fewer than the number of secohms L multiplied by the periodicity p). Let ON in the clock-diagram, Fig. 72, represent the product of the ampères C (maximum) and ohms R in the external circuit, and therefore the maximum value (in volts) of the difference of potential between the terminals. The division of the power between the alternators is determined solely by the balance of the governors of the driving engines. If OA represents the impressed electromotive force in the armature of one alternator, which must be slightly in advance of the phase ON, AN represents the back electromotive force in the armature pLC_1 where C_1 is the maximum current, and the area OAN is equal to pL times the true watts supplied by the alternator. Similarly with regard to OB, the electromotive force in the second alternator. The areas OAN, OBN being thus determined when a certain electromotive force ON is called for between the terminals, it will follow that if the currents C_1 and C_2 in the armatures are to be co-phasal with the external current, OA and OB must be made of different magnitudes according to the division of the load, so that ABN are in one straight line perpendicular to ON, and the alternators take up an equilibrium position with a difference of phase (in the impressed electromotive force) represented by the angle AOB. Then we have simply $C = C_1 + C_2$, or is represented by NC multiplied by $\frac{2}{pL}$.

But if the excitation of the alternators be altered, one may be increased and the other diminished, but yet the difference of potential between the

FIG. 72.

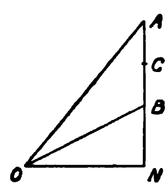
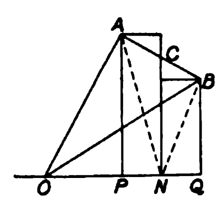


FIG. 73.



terminals maintained the same. The condition is then represented by the clock diagram of Fig. 73. The areas OAN, OBN may be maintained by moving the positions of A and B along lines parallel to ON. Then AN and NB, which give the back electromotive forces in the armatures, must represent in magnitude pLC_1 and pLC_2, and the phases of the currents by vectors perpendicular to these from the point O. The resultant of the armature currents must be of course the current in the external circuit, and represented in magnitude and direction by $\frac{2}{pL} \cdot NC$ (or rather a vector perpendicular to and equal in magnitude to $\frac{2}{pL}NC$), and therefore the line joining N to the middle point C of AB must be perpendicular to ON. It will follow that the horizontal displacements NP, NQ of A and B must be equal, the phase difference of the alternators altered (increased in the special case of Fig. 73, but sometimes decreased), and the current increased in both armatures; for their algebraic sum is now greater than that in the external circuit, even as the sum of NA and NB is greater than their resultant $2NC$. It may be easily shown that the control still exists since a relative advance in phase of either throws a heavier load upon it.

We have simplified this discussion as much as possible, considering it already sufficiently intricate for the scope of this work. The more complete problem in which the resistance of the armature, and the self-inductance of the external circuit is taken into account may be easily treated by inclining the lines CN, NO, &c., in the figure at certain fixed angles, and the laws governing the parallel running of different sizes of alternators, &c., may be deduced. Our chief object is to point out the method of obtaining the most efficient results in practical working. The load can only be adjusted by attention to the engine governors, "speeding" the engine to obtain a greater share of the load. And in order to obtain the minimum current in either armature, which is obviously the most efficient condition, the excitation should be increased as a heavier load is given to it, its impressed electromotive force being the same as it should have if it were supplying its portion of the load upon a separate circuit, with the specified difference of potential between the terminals. The same argument that shows that parallel working of alternators is possible, shows that series working is impossible except with a mechanical coupling, but happily the demand for this practice does not exist. Parallel running, on the other hand, is now the rule in nearly all stations using alternating currents.

The mistake has often been made of supposing that, since the mutual control of alternators depends upon the existence of self-inductance in the armature, those which have no iron core, and therefore small self-inductance, such as the Mordey or Ferranti (Deptford type), are unsuitable for this purpose. As a matter of fact, some of the first and best results in parallel running were obtained by these types, the control being more and not less powerful. The reason is not far to seek. Although with the same controlling current the synchronising force is smaller, yet with the same variation from the true phase difference, the current changes are so much the greater. Furthermore, with iron core armatures lines of force may be created by the armature current which cause self-inductance, but do not pass through field-magnets and have no motor power to produce control. So that in reality the control is more *rigid* in alternators that have no armature-core. This is partly an advantage and partly a disadvantage. An advantage in respect of more powerful electrical coupling, a disadvantage in respect of danger from the huge current that will pass in the event of a breakdown of the existing current, or the engine driving one of the alternators, and the inferior strength of the armatures themselves. The excess of readings of the sum of the alternator ammeters over the circuit ammeters, $C_1 + C_2 - C$, is sometimes incorrectly called the "synchronising" current. A better name is the "equalising" current, since it compensates for defects in the regulation of the excitation.

For any advantage to accrue from parallel working it is necessary that the range of speed through which the governors work should overlap. Otherwise it must either happen that the slower alternator and engine will be driven as a motor at the speed of the faster, or if the load is too heavy for this, the two will work together within the range of the slower and the faster will be ungoverned and take the maximum amount of steam possible. Some adjustability is advisable, but many prefer to work with an equality of normal speed, and to vary the distribution of the load in switching on or off by closing the stop-valve. By one means or the other the load may be removed previous to switching one of the alternators off the supply circuit; or the speed of an engine reduced to equality with a loaded engine just before switching in. But not only is it necessary that the speeds of two alternators should be almost exactly identical before switching on in order to prevent the sudden strain on the armatures which drags them into synchronism, but it is advisable to switch on at the moment when the two alternators are exactly in phase. The first condition, of equal speed, might be told with considerable accuracy by the musical notes emitted by the two alternators, the well-known effect of "beats" or surgings of the sound indicating approximate equality in frequency of alternation. But to tell when the alternators are in the same phase requires what is known as a "synchronising" arrangement. The following, or some modification of the same principle, is employed. A small transformer is connected to each alternator, transforming the potential down to 50 volts when normally excited. If the secondary coils of these transformers are connected in series and supply a 100-volt lamp, it is easily seen that this lamp will only light up with its full brilliancy when the alternators are exactly in phase, or to speak more correctly, if the differences of potential between the terminals of the two alternators is the same, which is the correct relative position for parallel running. Otherwise the difference of potential between the lamp terminals will be 100 volts multiplied by the cosine of the phase-difference. Full brilliancy will then indicate the correct moment for switching on. A dead-beat voltmeter may be used instead of the lamp; and the transformer secondaries may, in either case, be connected in opposition and the moment for switching on determined by darkness or zero reading. There is, however, more liability to accident, for a lamp filament may break, or other deceptive event happen. On approaching equality of speed the synchronising lamp begins to oscillate slowly between full brightness and darkness, as the relative phase difference slowly changes. Seizing the opportunity of full brightness, the alternators may be placed in parallel when exactly "in step," a load can then be transferred to the incoming alternator by "speeding" its engine; the exciting current should at the same time be increased, while that of the alternator or alternators that were previously supplying the lighting should be reduced to maintain the correct difference of potential between the outgoing mains, and at the same time to retain the minimum current in the armatures.

CHAPTER XIV.

Incandescent Lamps.

THE generation of heat in a conductor by the passage of an electric current owing to its resistance was one of the first observed phenomena in connection with voltaic electricity, and therefore the possibility of using a conductor of high resistance as a source of illumination, by thus raising it to a temperature at which it emits radiation of light as well as of heat, must have been obvious long before it was thought possible that electrical energy could be produced at a cost that would enable it to compete with other sources of illumination. The invention of the incandescent lamp followed naturally upon the development of the dynamo and steam-engine.

The rate at which the temperature of a conductor *begins to rise* when an electric current is started in it depends upon the rate of production of heat units in it, and upon the capacity for heat of the conductor. The capacity for heat depends upon the mass and specific heat of the material of which the conductor is made. The rate of production of heat is $.24C^2R$ calories per second, a calorie being the quantity of heat required to raise one gramme of water one degree Centigrade. Hence if M be the mass, h the specific heat of the conductor, the temperature will *begin to rise* at the rate of $\frac{.24C^2R}{M.h}$ degrees Centigrade per second. The ultimate temperature reached with a steady current will be independent of the capacity for heat, and will depend upon the facility with which the heat-energy is removed by conduction and radiation from the conductor. Equilibrium will be established when the excess temperature of the conductor over surrounding bodies causes the rate of removal of the heat to be equal to the rate of production.

In the incandescent lamp every means is taken to reduce to a minimum the removal of heat from the electric conductor by heat-conduction, and practically the whole of the heat-energy generated is *radiated* in the form of light or radiant heat. The maximum temperature is then attained when the rate of heat generation is equal to the rate of heat dissipation from the surface. The latter depends upon the temperature, the area of the surface, and some property determining the rate of energy radiation per unit of surface which is called the *emissivity*. Now for the purpose for which the incandescent lamp is primarily intended, that of illumination, the energy which is radiated in the form of the non-luminous heat rays is entirely wasted, and may be considered in most cases positively objectionable, as well as wasteful. One of the greatest benefits attending the use of the electric light is that for a given amount of illumination there is less heat radiated by the lamps than with any other source of illumination, and hence the interior of buildings may, when desired, be kept cooler. But even with the highly efficient arc lamp it appears that of the total energy converted into heat as much as 90 per cent. is dissipated in non-luminous radiation, and with the incandescent lamp a still larger proportion. An enormous improvement in efficiency is therefore theoretically possible. The proportion of *luminous* radiation to the *total* radiation increases with the temperature so that it cannot be expected that the efficiency of the incandescent lamp can be nearly as high as that of the arc lamp as long as the same material, pure carbon, is used for the filament of the one and the electrodes of the other; since in the latter case the material is raised to the highest temperature possible, that of volatilisation, and in the former a much lower temperature must be maintained if the filament is to remain intact for any length of time. Furthermore, even if we could discover and utilise a body much more refractory than carbon, or by some method prevent the volatilisation and so use a much higher temperature, we could increase the proportion of luminous radiation, but it does not follow that the efficiency of illumination will be proportionately increased. The value of the illumination in enabling the eye to distinguish details of shape and colours is not in simple proportion to the energy of the luminous radiation. The more refrangible rays at the "upper" or violet end of the spectrum require a very much larger amount of power to produce a given intensity of illumination measured by its effect on vision than equivalent rays of less refrangibility. The arc lamp, and the "overrun" incandescent lamps are disproportionately rich in the former rays. The ideally efficient source of illumination, if the distinguishing of shape were the only object, would only emit rays of a certain refrangibility and colour. Probably the best source, for all purposes, would be one which would follow the proportion of radiation in the different parts of the visible spectrum exhibited by daylight, to which the eye is accustomed, but omit the heat radiation as far as possible.

The proportion of the various rays of different refrangibilities emitted by different materials at the same temperature depends upon the nature of their surfaces. This property, called "selective radiation," must not be confused with the emissivity, which is a measurement of the total rate of energy dissipation at any temperature. Certain metallic oxides—magnesia, lime, &c.—will at a high temperature emit a very much larger proportion of luminous radiation than will carbon at the same temperature. The whole question is too wide to be dealt with in this place; it is largely physiological, depending not only on the relative sensibility of the eye to illumination of different colours, largely modified by the colour of the object to be observed, but also on the adjustability of the pupil of the eye, whereby the efficiency of illumination is by no means proportionate to the intensity. Attention is called to this in order to qualify apparently dogmatic assertions which will follow in this chapter, and the main question, affecting all sources of illumination alike, left to be dealt with in another section of the series, of which this article forms a part.

The first recorded application of the thin filament in a vacuum as a source of light dates as far back as 1840, when Moleyns, of Cheltenham, employed a thin platinum wire in the very partial vacuum which was the best that could then be obtained. In 1847 Petrie employed iridium in the same way.

In 1845 the use of a carbon filament was patented by Starr and King, of America. Their invention was exhibited in England, and is said to have been seen and admired by Faraday. But the principles of electro-magnetism discovered by the latter philosopher had not yet evolved the dynamo, and electrical power could only be obtained from primary batteries at a totally prohibitive cost.

For nearly thirty years the history of the incandescent lamp is a blank, but in 1873 Lodyguine, a Russian physician, revived the carbon filament in the form of straight needles between blocks of carbon in the best obtainable vacuum.

By this time several forms of passably efficient dynamos had been designed, and the arc lamp had advanced to a practical success. Inventors were striving to find some means of further subdividing the electric light, so as to make the lamps independent of one another, and suitable for interior lighting. Their efforts gave rise to a class of lamps which are sometimes called "semi-incandescent," and may be considered as holding an intermediate position, in principle and history, between the arc and incandescent lamps. Their appearance was partly previous to and partly contemporaneous with the first successful incandescent lamps, and though this class of lamp is practically obsolete, the principles may yet be revived in the future, so that a short review of some of the types may not be amiss.

Semi-incandescent lamps are of two types: The first is the Lampe-Soleil, in which the electrical arc between two carbons is made to heat to incandescence a block of highly refractory material interposed between them. This type seems to have been in its origin a development of the Jablochkoff candle, for the principle is formulated in the specification of a patent taken out by Jablochkoff in May 1877. "The passage of a spark (arc) through a slab of kaolin renders the substance of greater conducting power at all points where it is touched by the spark; in a few seconds the current passes readily, and the kaolin becomes incandescent along the entire path of the current." The invention was worked out by Clerc (engineer to the Jablochkoff Company) and Bureau, and an English patent was taken out in April 1880. "The electrodes are surrounded by a guide-block of refractory material, for instance, marble, which protects the poles from the air, compels the arc to take a prescribed line, and may give a special tint to the light. The block hides the poles from view, and has orifices which serve as a guide for the voltaic arc. It is cut out like a vault for distributing the light in any desired direction. The guide-block is enclosed in a casing (of cast iron). The carbons advance, as they are consumed, by their own weight, or by counter weights and springs. To light the lamp, rods of plumbago, for instance, connect the carbons through the orifices at the top of the vault which communicate with the points of the carbons. One of the carbons may be replaced by a metallic electrode." The carbons were large and burnt extremely slowly. The marble glowed with a golden colour, and became conducting, so that it would relight even if the current should be extinguished for a minute; the intensity of illumination was very steady, the great heat capacity checking irregularities in the supply. These qualities must have been of great value with the generating machinery of 1880.

In the semi-incandescent lamps of Reynier and Werdermann intense heating is produced at a bad contact between a thin carbon pencil and a large block. The local heating raises the extremity and sometimes a considerable length of the former to incandescence. By this means a large current of about 50 ampères with an electromotive force of only about 6 volts will give about 300 candle power, and thus, with a series system of distribution, the question of subdivision of the electric light was first partially solved.

The first English patent is that of Reynier in June 1877. The idea was probably suggested in working out an invention of the preceding year in which an arc was maintained between the edges of two rotating discs, separately driven by small motors, with axes in the same plane inclined at an angle of from 20° to 120°. In the 1878 patent: "A long vertical rod or stick of carbon is guided by an insulator at its lower part and by a 'pivot' or bracket at the top: this bracket, by its weight, presses the carbon downwards. A rack on the bracket rotates a carbon disc by means of a train of gearing of rapidly-increasing speed. The edge of the disc supports the carbon rod, which descends as it consumes by the passage of the electric current through it and through the disc. At the same time the rod acts as a brake to the disc and thus, by friction, regulates its own descent. The conductor to the rod presses laterally upon it, the rod simply gliding past it. The contact is kept constant by the pressure of a spring.

"In another instance the rotation of the disc is obtained by the tangential force of the weight of the rod and its attachments upon the disc, the rod being in a position not normal to the disc. Instead of a disc, a flat or rounded surface roller, or a sliding surface may be used. This apparatus prevents the accumulation of cinder, and presents fresh surfaces to the descending rod."

Werdermann's patent is almost simultaneous. Instead of the rotating disc there is a slightly convex block of carbon, for which copper was afterwards substituted by Joel, and the lamp was inverted so that the pencil was pressed upwards against the block (which was connected to the negative conductor). The pressure of the pencil on the block was maintained by a weight acting through cords which passed over pulleys, and drew upwards the saddle in which the carbon pencil rested. The invention includes an arrangement in parallel circuit, the resistance of the lamps being sufficiently constant, though low. The lamp which is first with regard to its position on the positive main is the last on the negative main, and so on; thus the fall of electromotive force from the dynamo to each lamp is the same. The loss of energy would of course prevent transmission to any distance on this system with the large currents used. Ducretet (Jan. 1879) floated the carbon pencil in a tube of mercury, the electrical connection being made through the mercury; but this was associated with the production of mercury vapour to an extent which could not be permitted indoors, and the pressure between the electrodes alters as the carbon is consumed. Sawyer placed the lamp in an atmosphere of nitrogen and thus greatly lengthened the duration of the carbon pencil. Further development of the semi-incandescent was checked by the appearance of the true incandescent lamp.

In October 1878 Lane-Fox filed a patent for "obtaining light by electricity; and for conveying, distributing, measuring and regulating the electric current for the same." The light was produced by the incandescence of a continuous conductor, made of an alloy of platinum and iridium, surrounded by an atmosphere of nitrogen gas. The lamps were to be arranged in parallel with a network of single conductors, and an "earth" return. The engines driving the generators were to be regulated electrically, and the regulation assisted by placing a battery of Planté secondary cells in parallel with the lamps. A further invention provides for the covering of the metal filaments with finely-divided asbestos or some other refractory material. And again in March 1879, it is proposed to use a mixture of plumbago with some refractory non-conducting substance for the conducting "bridge."

In November 1878, Sawyer revived the use of carbon rods, again in an atmosphere of nitrogen, preparing the carbons by "flashing," that is heating electrically in a hydrocarbon gas or liquid, as will shortly be described. Edison in America was meanwhile working with filaments of platinum, ruthenium, and other metals. In Oct. 1878, several arrangements were patented by which the metal may be prevented from fusing by an excess of current. "The heat evolved in the light expands a wire or other body, either by the passage of electricity through it, or by its proximity to the source of light: the expansion acts through a lever, or similar device, to shunt or short circuit more or less of the current, or throw a resistance into the circuit." Later the wire is "pyro-insulated" by a coating of some refractory metallic oxide such as lime or magnesia.

The next year 1879, Edison used a carbon filament in a nearly perfect vacuum. The filament was made of carbonised cotton or paper covered with a plastic compound of lamp black and tar. Carbonised paper without further treatment was subsequently used, and in the following year (Sept. 1880) fibres of bamboo, stamped out and shaved down to the proper thickness by special machinery, were used. The inventor aimed at preserving the structural character of the bamboo fibres, and obtaining a filament of high resistance in order to use a parallel distribution. The preservation of organic structures in the filaments is now believed to be a mistake, but still this bamboo fibre lamp must be looked upon as the first really successful form of incandescent lamp.

Various patents were taken out in 1880 by Swan, of Newcastle-on-Tyne, for obtaining greater durability in the carbon filament. He appears to have made attempts as early as 1860 to produce an efficient lamp, but the vacuum that could then be obtained was insufficient. The development of the Sprengel mercury pump had now made a high state of exhaustion possible, and by raising the filament to incandescence during the exhaustion, the gas occluded in the carbon was driven out. Cotton thread was the carbonising material preferred, the organic structure being destroyed by parchmentising. Swan exhibited his lamps before the Newcastle Literary and Philosophic Society in October 1880. The resistance of the lamps for the same candle-power was lower than that of Edison's lamp, and it appears to have been intended to use a series system of distribution.

The exhibition of the incandescent lamps of Swan at Newcastle was an anticipation of the master-patent of Edison, but only carried the right of manufacture of lamps with filaments of a greater diameter than $\frac{1}{32}$ in.

We shall not attempt to follow further the history of the incandescent lamp; it is by no means easy to give due credit to the multitude of inventors who have contributed to its development. The amalgamation of the Edison and Swan Companies in 1883, gave the "Ediswan" Company control of sufficient patents to monopolise the manufacture of incandescent lamps in this country up to the autumn of 1894.

The qualities of carbon which render it entirely without competitor as the material for the construction of the incandescent filament are as follows:

(1) Its resistance is suitable, requiring for the consumption of power required for small lamps a conducting filament of sufficient thickness to give good mechanical strength with the electromotive forces suitable for parallel distribution. Metal filaments, of platinum or iridium, require to be very long and thin to give the right resistance and radiating surface. The specific resistance of pure carbon is sufficient, though it might with advantage for this purpose, be higher.

(2) Its emissivity is very much superior to that of metals, so that at the same temperature the candle power per square millimetre is much higher. With regard to "selective radiation," it is as stated above much inferior to certain "earths," or metallic oxides, such as zirconia, &c., which emit at the same temperature a larger proportion of luminous rays. These oxides are, however, very partial conductors only at high temperatures, and non-conducting when cold. Efforts have been made to combine these substances with carbon, or to cover the carbon filament with them, but have failed owing to the variation of expansion when heated, which causes the oxide to break away. It seems preferable to strive to obtain the purest carbon and increase the efficiency of radiation by the higher temperature which can thus be permitted.

(3) Carbon is much more refractory than any of the metals. At the temperature of incandescence it retains its rigidity, and is still far from its melting or volatilisation point. Platinum or iridium are near their melting-point when incandescent, and become very soft.

(4) The conductivity for heat is very low, and therefore very little of the heat-energy escapes by conduction through the terminals.

Poullet has given the following summary of the relative incandescence of a carbon filament at different temperatures, showing the colour of the luminous radiation from the surface:

Degrees Centigrade.	
525	Incipient redness.
700	Dull red.
800	Incipient cherry redness.
1000	Full cherry redness.
1100	Yellowish-green.
1200	Bright yellow.
1300	White heat.
1400	White heat (strong).
1500	Dazzling whiteness.

The first carbonising substance used by Edison in 1879 was parchmentised paper, which he replaced the following year by fine strips of bamboo, stamped out by special machinery. Swan also used both parchmentised paper and cotton. The latter substances, paper and cotton, still remain the favourite raw material from which the carbon filament is manufactured. Cotton is almost exclusively used in England except for special "focusing" lamps, where filaments with a flat, or oblong, cross-section are required, but there are various methods of preparing the filament for carbonisation. The older established process consists in "parchmentising" by the action of sulphuric acid, and then drawing through die-plates till it is shaved down to perfect uniformity of the required section. The parchmentising process destroys the organic structure of the thread, reducing it to a semi-transparent gelatinous, or "amyloid," state, but retaining the same chemical composition ($C_6H_{10}O_5$). The thread (of loose knitting or crochet cotton) is drawn slowly through an acid solution (of specific gravity 1.64), and thence through a large basin of water. The thread thus remains soaked in the strong acid for from 4 to 5 seconds only, and the acid must be entirely removed in the water bath.

After drying the thread is found to be in a tough, horny state, and can be shaved down to the required uniform section by drawing through successive jewelled wire draw-plates with very sharp cutting edges.

The latter operation is expensive and difficult, but most essential in order to obtain the perfect uniformity required. Other less expensive methods, giving a similar result from the same raw material have lately come into extensive use. The cotton material may be completely dissolved in chloride of zinc, and the resulting viscous fluid squirted through a small hole into a vessel containing alcohol, which causes it to set and harden immediately. A difficulty arises, however, in obtaining uniform viscosity, and preventing the formation of air bubbles, so that the squirted thread may be perfectly uniform. There are other methods of converting cotton into a fluid mass, which may then be either squirted or squeezed into a flat sheet between glass plates, dried, and cut into strips.

Next comes the carbonising process. As this will destroy the flexibility of the thread, it is necessary previously to wind it upon carbon frames, which will maintain the shape which is ultimately required, before placing in the carbonising furnace. For low voltage lamps the short filament required may be of a simple horse-shoe shape, but for the longer filaments required for higher voltage a looped form is more convenient. Two carbon

FIG. 74.

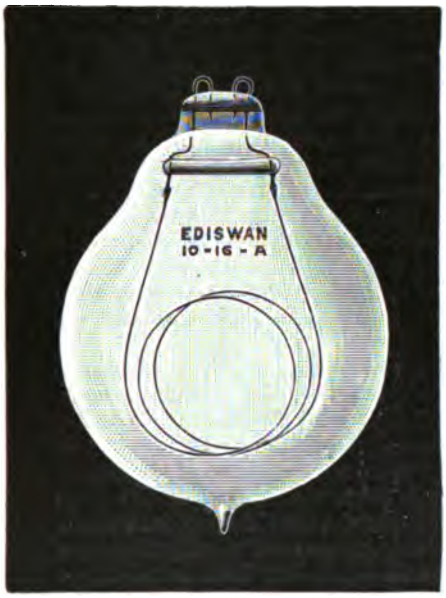


FIG. 75.

High and Low Voltage Lamps.

cylinders held apart by wooden struts will constitute a framework upon which the thread can be wound continuously, so that it can be cut after carbonisation into either required shape. For the horse-shoe form the thread must be wound continuously round the two cylinders together; for the looped form an intermediate turn must be taken round the cylinders separately. The thread shrinks considerably in carbonising, and for this allowance may be made by separating the carbon cylinders with wooden struts, which in also carbonising shrink proportionally. For looped filaments it will be necessary to split the cylinders in the direction of their length and separate by similar short wooden struts. The frames are then placed in plumbago crucibles, and raised gradually to an exceedingly high temperature in a reverberatory furnace. A carbon box containing about ten of these frames is placed in the crucible and the intervening space between the box and the crucible filled up with powdered charcoal. The small amount of air left in the box cannot cause the thread to burn while carbonising. The temperature must be both raised and lowered very gradually, and the subsequent duration of the filament will depend largely upon the highest temperature reached. If the carbonisation is not complete, the resistance of the filament is high, and the subsequent carbonisation when incandescent will cause rapid disintegration by the gases produced in the interior of the filament. The carbonisation process, formerly a matter of several days, is now abridged to a few hours, a temperature of something like 2000 degrees Centigrade being attained for a short period at about half-time.

The next process is that of "mounting," or connection to the "leading in" wires. These wires have to pass through the glass bulb into which the filament is subsequently inserted. The wires must be sealed into the bulb, and must be capable of withstanding the many changes of temperature to which they will be subject, both during the sealing with the blow pipe, and subsequent incandescence of the lamp, without either melting or cracking the glass. We need therefore a metal having a high fusing-point, and a coefficient of expansion identical, or nearly identical, with that of glass. Platinum fulfils the conditions excellently, the only objection being its expense, but this is after all a very small proportion of the cost of the lamp. Certain alloys of silicon and iron or nickel have been designed to meet the requirements, but these are liable to injury in "sealing in," and the extra skill in manipulation costs as much as the extra expense of platinum. The coefficient of expansion of platinum is .0000088, which is sufficiently near the average for various kinds of glass. In lamps of high candle power, where the stouter filaments would allow of a perceptible conduction of heat to the wires, and injury as well as a slight inefficiency might result, short lengths of iron wire, which is a worse conductor of heat as well as cheaper than platinum are sometimes interposed between the leading in wires and the filament itself.

A good joint, both electrically and mechanically sound, is of course essential. Edison in his first lamps made a socket for the carbon filament, by twisting the platinum wire into a spiral; the joint was then made secure and electrically perfect by an electro-deposit of copper. The objection to this joint is that with the high temperature of incandescence some of the copper is inevitably volatilised and forms a deposit upon the interior of the glass bulb. Swan and Lane Fox used small jointing tubes of carbon, into which the wires and the filament ends were pushed, and secured by a little carbon paste. Maxim flattened the ends of the filament, and used a miniature platinum bolt and nut.

The best joints were till recently after Edison's method, but with a dense carbon deposit produced by the decomposition of a hydrocarbon gas or fluid when the joint is heated to a high temperature, instead of the electro deposit. The socket is made with less waste of platinum by flattening the ends of the wire for about one eighth of an inch and bending round so as to form a tube. The filament-ends are then inserted in these sockets and placed in the hydrocarbon gas or fluid. A current many times larger than that which will subsequently pass through the joints is now made to flow through them, the rest of the filament being meanwhile short-circuited. The heating at the joints decreases as carbon is deposited, and the joint becomes sound.

Ordinary coal gas may be used, but the deposit from fluids is more rapid. The mineral oils, kerosene or pure petroleum, are the best, but care must be taken to prevent ignition. A mixture of four parts of kerosene to one of turpentine is recommended by Ram as giving a rapid and hard deposit.

More recently, with the keen competition in price arising from lapse of the master patents, this somewhat difficult process has been abridged by the use of a suitable cement, applied directly. The composition of the various cements is generally a secret, and a weak joint is a common fault in some of the cheaper lamps, resulting in a speedy fracture.

The process of carbon deposition mentioned above for the purpose of perfecting the joint must not be confused with the next operation which is similar, but introduced for the purpose of improving the filament itself. The deposition by "flashing" takes place over the whole surface of the filament, but must be conducted with much greater care. The objects of flashing are threefold: (1) To secure perfect uniformity in the filament. This was the primary object for which it was introduced by Weston. Any parts of the original filament which happen to be of reduced sectional area are heated to a higher temperature, and the deposit there proceeds more rapidly till the incandescence is uniform. Filaments can now be made by the process of drawing through die-plates with a uniformity which is practically perfect; but even thus there will generally be a slight difference in incandescence owing to the slightly freer radiation from the limbs than from the loop. The loop requires, for uniform incandescence, to be of slightly lower resistance than the limbs, and the requisite variation in different parts is effected by the flashing process.

(2) The deposited carbon may be made far more durable, and capable of bearing a higher temperature of incandescence than the original filament. The surface has, after a slow deposit, a silver-grey appearance, and the emissivity is considerably reduced. It does not follow, however, that the efficiency, which depends upon the ratio of the luminous to the total radiation, is correspondingly lowered, but simply that a larger surface is required for the same amount of illumination. Higher efficiency may certainly be attained with flashed filaments since a higher temperature of incandescence may be used.

(3) Flashing gives a method of exactly adjusting filaments for different lamps so as to give the same temperature of incandescence with the same electromotive force, or of using the same size of unflashed filament for several slightly varying candle powers, by giving deposits of various thickness.

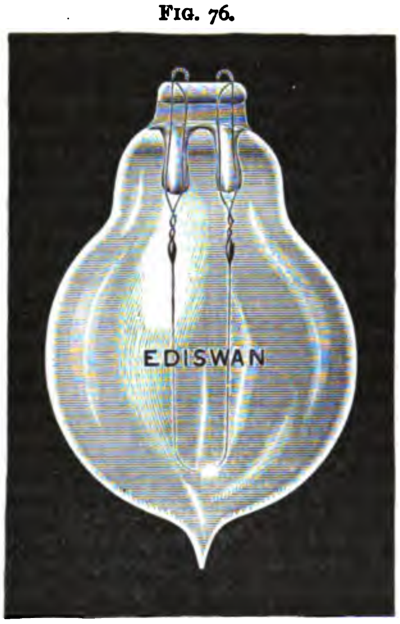
The adjustment of the filament so as to obtain the required temperature of incandescence with the appropriate electromotive force is very important. From a commercial point of view this equality of the temperature of incandescence is more important than equality of candle power in different lamps which are to be sold as similar; for the eye is a very good judge of the colour of the light (its comparative whiteness), which depends upon the intensity of illumination, but is less critical of the actual candle power of the lamp. Now an error of 1 per cent. in the length of the filament will make considerable difference to the temperature attained by the filament and therefore to the intensity of illumination, but will affect the total candle power to a far less degree. By the process of flashing any such error may be corrected very simply and effectively.

The deposit may be obtained either from a hydro-carbon gas or fluid. The process is really the same in each case, since even in the fluid the filament, when raised to incandescence by the electric current, is surrounded by a gaseous envelope. Ordinary coal gas, or vapour of benzine, ether, or other volatile hydro-carbons may be used at ordinary atmospheric pressure. But the deposit will be rapid, and a rapid deposit cannot be very dense, nor does it allow time for the careful regulation of the resistance and temperature of the filament, which is the chief advantage to be attained by the process. It is advisable to use a gas whose consistency is exactly known, and to perform the flashing in a closed vessel in which the gas is kept at a fixed pressure considerably below that of the atmosphere. Pentane, or purified gasolene, as used for the Harcourt standard gas flame, is recommended.

Having thus arranged a system by which the deposit may be slow and dense, and at the same time the conditions of pressure and composition of the hydro-carbon gas the same, the flashing current may be applied. This current may be many times larger than that which will be subsequently carried by the filament in its exhausted bulb, owing to the rapid convection of heat by the surrounding vapour. The resistance of the filament rapidly decreases as the deposit thickens, since the specific resistance of the deposited carbon is often about one tenth of that of the original carbonised thread.

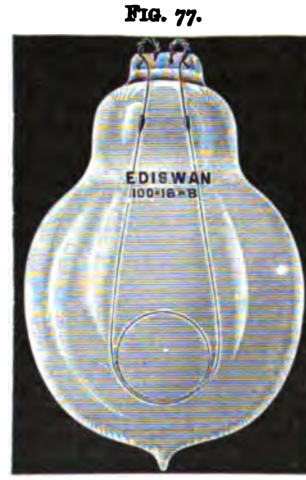
Flashing is generally effected by using an electromotive force about twice that for which the lamp is ultimately intended. At first the current is small, as the resistance of the unflashed filament is about twice as great as it will be after the deposit, and is cold. As the deposit proceeds the resistance decreases, both by the rise in temperature and increasing section, until the current has reached about double the amount intended for the lamp, with which current only about the normal incandescence is reached, owing to

FIG. 76.



Seal for Large Lamp (" Bottom Loop ").

FIG. 77.



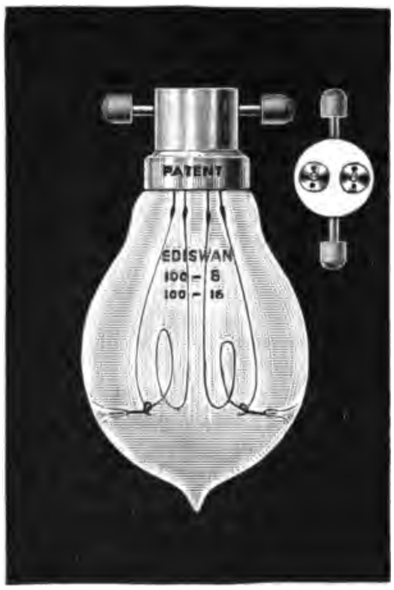
Short Seal for Small Lamp.

convection currents in the gas. An automatic switch at this point breaks the circuit, and the filament is taken out ready for insertion in the glass bulb.

The familiar pear-shaped glass bulbs are blown with the best flint glass containing a large quantity of lead, either direct from the crucible, or from glass tubing. The construction and the sealing in with the blowpipe of the platinum wires need not be described here, though it requires considerable mechanical skill. Owing to the difficulty in obtaining efficient glass-workers, it was necessary for the first lamp manufacturers to make very long seal, with a great waste in platinum wire. A short seal can now be made very dependable, but care must be taken to cool the glass very slowly, or cracking may ensue. A long, thin tube is left projecting at the further end through which the air has to be exhausted.

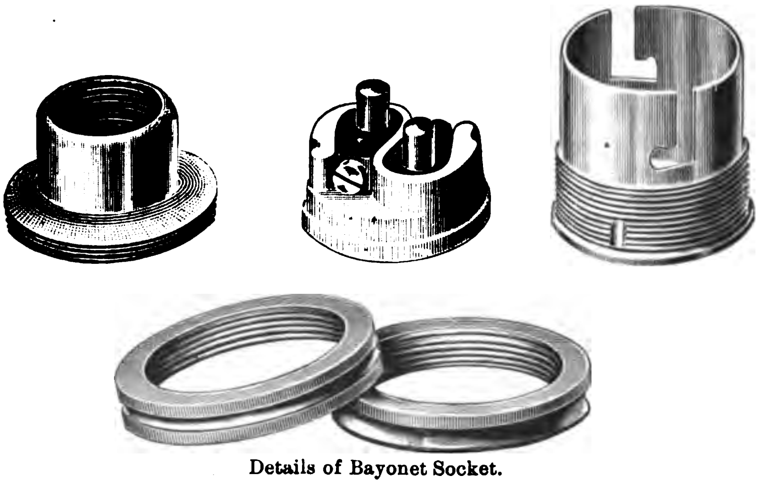
It is not only in order to prevent the consumption of the carbon by combination with the oxygen of the air at the high temperature of incandescence that the vacuum needs to be as perfect as possible. The prevention of conduction of heat away from the filaments by convection currents of any air or gas contained in the bulb is a matter of scarcely less importance. Sawyer in 1879 employed a bulb filled with nitrogen, the oxygen of the air being

FIG. 78.



Lamp with Parallel Filaments ("Ship Side-light") for Bayonet Sockets.

FIG. 79.



Details of Bayonet Socket.

removed by burning phosphorus in the bulb; but even with nitrogen the carbon can, at the high temperature used, combine to form cyanogen. Further patents have been taken out to avoid the necessity of high exhaustion, the most expensive process in incandescent lamp manufacture, by previously removing the oxygen with burning phosphorus, and leaving a very attenuated atmosphere of nitrogen. A vacuum of at least $\frac{1}{3000}$ of atmospheric pressure is the minimum necessary to make the incandescent lamp serviceable. The convection currents decrease the efficiency of the lamp, the heat removed being so much wasted energy, and moreover they cause the glass bulbs to become heated unpleasantly, if not dangerously.

The development of the mercury pump has made the incandescent lamp a practical possibility. The original designs of Sprengel and Geissler have been enormously improved by Swinburne, Stearne and others, so as to produce a pump which will exhaust the air with considerable rapidity, and attain a vacuum which is practically perfect. A difficulty arises in removing the thin film of air which tends to cling to the inner surface of the glass bulb and the occluded air in the filament itself. The glass bulb requires to be gently heated with a blow-pipe, or other convenient means, and the filament should be raised to incandescence by the passage of the full current for which it is designed during the last stages of the exhaustion.

Space cannot be afforded for descriptions of the many forms of mercury pumps used. Fairly complete descriptions may be found in Ram's "Incandescent Lamp and its Manufacture," or Slingo and Brooker's "Electrical Engineering." Until quite recently the mercury pump was believed indispensable to the incandescent lamp, the discovery of the former having made the latter possible. At the same time it was known to be, at its best, defective, slow in its action, and imperfect in its results since mercury vapour must be left behind, and it has been strongly suspected that the latter is mischievous in more than one way. Attempts to construct an efficient mechanical pump have been made continuously since the incandescent lamp has been in use. Recently by perfect fitting of the cylinders, and the device of distributing the vacuum through a gradation of chambers, Berrenberg has succeeded in producing an exceedingly good vacuum, but mercury exhausted lamps are still generally considered the highest class. The vacuum should certainly not be less than about $\frac{1}{20000}$ of atmospheric pressure and as much nearer perfection as can be obtained. It may be tested by the glow produced in it by an induction coil, but perhaps the most practical as well as simple criterion of the vacuum would be the temperature of the glass bulb when the lamp has been burning for a short time.

Candle Power and Efficiency.

In the modern incandescent lamp with long fine filament, and its vacuum to all intents and purposes perfect, the heat generated by the electric current is almost entirely removed by radiation; the only two possible sources of conduction, by the leading in wires and by convection currents in any enclosed gas are now almost entirely eliminated.

The filament therefore attains the temperature at which the radiation from the surface is equal to the rate of production of heat in the mass of the filament. The former depends upon the temperature, the area of the surface, and the emissivity. The latter upon the current and resistance.

Heat is generated in the filament at the rate of .24EC calories per second; or we may write this $.24\frac{E^2}{R}$ or $.24\ C^2.R$ calories, according as the known factor of the power is E or C With constant electromotive force the rate of heat production varies inversely as the resistance of the filament. The total capacity for heat of the filament is of no importance, only affecting the rapidity with which the lamp answers to the switch, and perhaps tending to compensate for rapid variations in the current or electromotive force, acting as a sort of "thermal fly-wheel."

The absolute efficiency of the lamp is the ratio of the useful luminous radiation to the total radiation from the surface, and this is found to increase rapidly with the temperature which the filament maintains. The efficiency depends upon, and is commonly expressed as, the number of watts dissipated per candle power, since it is most difficult to determine the absolute efficiency, that is the ratio of the energy radiated as light, to the total energy absorbed. This expression "watts per candle power" should be more correctly termed the *inefficiency* of the lamp, as the number of watts per candle power should decrease as the efficiency improves. The measure of the candle power per watt dissipated would be a more correct method of measuring the efficiency, but would be subject to the disadvantage of being in almost all cases a fraction.

Accepting, however, the expression established by custom, it is necessary to define further the meaning of "candle power." The illumination of the incandescent lamp, though more uniformly distributed than that of the arc lamp, is by no means uniform in all directions. Suppose the lamp suspended, as is most usual, with the exhausting seal downwards, the best illumination is to be found in a horizontal plane through the lamps. But even in this plane it is far from uniform, especially in the looped filament types, but varies with the visible area of the filament. At right angles to the plane of the filament the visible area is practically given by the product of the length and diameter; but from a direction at right angles to this, that is in the plane of the filament, the apparent area is distinctly less, that of the looped part being reduced in the ratio of $2 : \pi$. Underneath the lamp the apparent area is much reduced, especially with "horse-shoe" filaments. In fact the surface of which the radii vectores from the lamp express the illumination in any direction would be approximately an ellipsoid of three unequal axes. By the candle power of the lamp is to be understood, not the maximum, but the "mean horizontal" candle power, that is, the average ratio of the illumination in all directions in the horizontal plane through the suspended lamp to that of the standard candle.

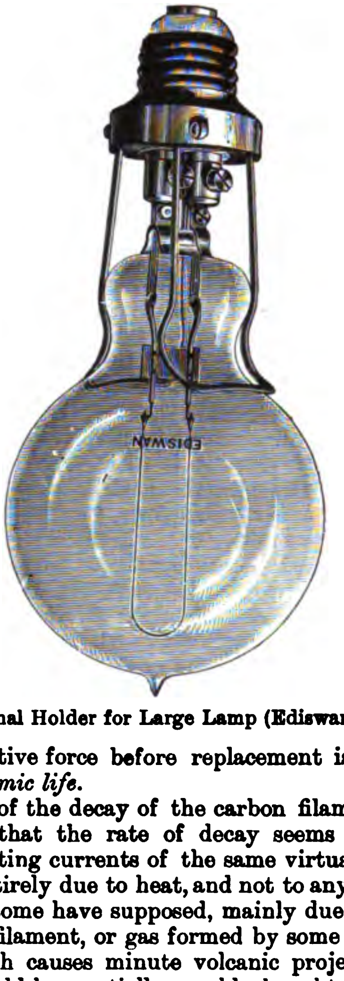
The variation of the illumination in different directions might well be considered somewhat more than it is in arranging incandescent lamps to obtain the best effect. The "mean spherical" candle power, that is to say, the average candle power in all directions, would be in some cases a more satisfactory method of measurement. More especially would this be the case with large lamps, which are commonly suspended at a considerable height in halls or large rooms. With such the "horse-shoe" shaped filament is preferable, in order that the light may be better distributed, there being then no bright patch underneath the lamp. The light under the lamp is also weakened by the dispersion due to the sealed end of the glass globe.

The efficiency of the incandescent lamp must necessarily be lower than the nominal efficiency of the arc lamp, about $\frac{1}{2}$ watt per candle power. The efficiency may, however, be raised to very nearly this amount by an increase of electromotive force, producing a temperature which almost immediately volatilises the carbon and so destroys the filament. Even at a temperature which gives an efficiency of 1 watt per candle power, the carbon filament rapidly disintegrates, and is destroyed in a few minutes.

A gradual decay of the filaments takes place with greater or less rapidity, according to the temperature of incandescence, and finally results in the rupture of the filament at its weakest point. The time which a lamp may be allowed to burn with a given electromotive force before this rupture is called its *life*. The life will be shortened as the electromotive force and therefore the temperature and efficiency are increased. In improving the efficiency of radiation we therefore require more frequently to replace the lamp by a new one. The electromotive force which, for a given type of lamp, gives the best commercial efficiency, that is, the minimum total cost per candle power per hour will be called the *best* electromotive force for that type of lamp, and will be said to give the *best* efficiency and *best* life. It will, of course, depend upon the relation between the costs of power and the prime cost of the lamp, as well as the law of dependence of the life upon the electromotive force, &c.

But with large lamps having coarser filaments it will be found sometimes advisable to replace a lamp before its "life" is ended, that is before the filament breaks. For the disintegrated particles of carbon are deposited upon the interior surface of the globe, and cause great obscuration of the light, and hence decreasing efficiency as time goes on. The time of burning

FIG. 80.



Screw Terminal Holder for Large Lamp (Ediswan Sunlight).

with a given electromotive force before replacement is rendered advisable will be called the *economic life*.

The physical cause of the decay of the carbon filament is not yet fully understood. The fact that the rate of decay seems to be identical with continuous and alternating currents of the same virtual magnitude assures us that the effect is entirely due to heat, and not to any extraneous electrical effect. It may be, as some have supposed, mainly due to minute quantities of occluded gas in the filament, or gas formed by some chemical reaction at high temperature, which causes minute volcanic projections of the carbon particles. If so it should be partially curable by obtaining perfectly pure carbon. Or it may be premature volatilisation, which may proceed slowly in the vacuum before the temperature of volatilisation at atmospheric pressure is reached. It is at once evident that the "best" efficiency will depend upon the size of the lamp, since the prime cost does not increase at anything like the same rate as the candle power, and for this reason alone it will be more economical to use lamps of higher efficiency allowing more frequent renewals. For example, the prices of lamps up to 25 candle power are generally the same, the cost of manufacture being probably even greater for the smaller, fine filament, lamps. While the price of a 1000 candle power lamp is only between 16 and 17 times as great instead of upwards of 40 times. Moreover, supposing the decay of the filament to proceed at the same rate per square millimetre of surface, as it may be reasonably supposed to do at the same temperature, the life of the larger lamp will be longer in proportion to the increase in diameter of the filament. It is therefore possible to use a higher temperature and efficiency, and retain the same length of life. The economic life may be somewhat shortened, since the surface area of the bulb will not increase in proportion to the candle power, and the lamp will blacken faster, but it is still commercially advisable to allow a higher efficiency. Postponing further discussion on this point, we may state that at the present cost of power, and of lamp manufacture, the efficiency considered most advisable is that of 3 to 4 watts per candle, according to the voltage for lamps of less than 16 candle power; from 2.5 to 3.5 for lamps from 16 to 100 candle power; and for larger lamps the efficiency may be improved to the limit of 2 watts per candle power.

Having decided the efficiency which is advisable for a lamp of a certain candle power, the next thing is to calculate the requisite dimensions of the filament. For this calculation we shall have two simultaneous equations for the length and diameter of the filament given by the following conditions:

(1) The resistance of the filament must be such that the power dissipated with the given electromotive force or current must be the product of the candle power and the watts per candle.

(2) The area of the surface must be such that the requisite radiation is obtained at the temperature that corresponds to the specified efficiency. For the first formula we need experimental data concerning the specific resistance of the carbon; for the second experimental data concerning the relation between the candle power per square millimetre (ϵ), and the watts per candle power. We shall treat solely of the case of a filament of circular cross-section. Let P be the total candle power required ("mean horizontal"); the candle power calculated on the assumption of a straight filament would be somewhat greater than this according to the shape of the filament, say κ P. Let E be the candle power per square millimetre of the surface. Then since ld is the apparent area viewed from a point at which it is a maximum, the second condition gives us

$$\kappa P = \epsilon ld.$$

If ρ be the specific resistance; W the watts per candle power, the first condition gives us

$$W.\,P = \frac{E^2}{R} = \frac{E^2}{\rho \frac{4l}{\pi d^2}}$$

Whence for lamps of various candle power intended for the same electromotive force we shall have

$$d \propto P^{\frac{2}{3}} \qquad l \propto P^{\frac{1}{3}},$$

and for lamps of the same candle power intended for various electromotive forces we shall have

$$d \propto E^{-\frac{2}{3}} \quad l \propto E^{\frac{2}{3}}$$

Exact determination of the dimensions of the filament can scarcely be made owing to the difficulty of determining the properties of the carbon denoted above by the symbols ϵ and ρ. And even if such determinations could be made it would be hard to carry them into practice with any certainty in the manufacture of fine filaments. The flashing process however gives us a means of correcting small variations, and obtaining lamps giving exactly the required candle power. It is, however, far more important to ensure that the lamps when placed upon the same circuit should glow with equal brilliancy, reaching the same temperature of incandescence, than that their actual candle power should be identical. The eye soon detects this variation in brilliancy, while it judges badly of the actual candle power. Such equality can easily be attained by carefully regulating the time and conditions of flashing.

The preliminary determinations must be based upon careful measurements with the material used in any lamp factory. In order to get some idea of the requisite sizes of filament, we shall give some calculations based upon certain average properties of carbon filaments. With regard to the quantity ϵ, we may assume that with a temperature of 4 watts per candle, the candle power per square millimetre is about $\frac{1}{2}$ for unflashed filaments; but according to Ram the radiation is reduced in the ratio of 10 : 14 by the denser deposit after flashing.

The specific resistance of the unflashed amyloid carbon filament is about .035 ohms per cubic millimetre at the temperature of incandescence, and of the deposited carbon about $\frac{1}{10}$ of this. The resistance does not appear to vary greatly with the temperature throughout the range of incandescence from 2 to 6 watts per candle power; but when cold the resistance of an unflashed filament is about $1\frac{1}{2}$ times as great; and the specific resistance of the deposited carbon about $2\frac{1}{2}$ times as great. Hence the resistance of a lamp may be in general taken roughly as about twice as much cold as hot.

Suppose we require the dimensions of a 16 candle power lamp intended for an electromotive force of 100 volts, with an efficiency of 4 watts per candle power (somewhat low in view of recent developments), and therefore requiring 64 watts. The ratio of the maximum to the mean horizontal candle power will depend upon the shape of the filament; with a looped filament of the common shape the maximum would be about 18—that is the coiled filament will give a mean horizontal intensity of illumination of about $\frac{8}{9}$ that it would give when straightened out.

Then for an unflashed amyloid filament

$$ld = 36$$

$$.035 \times \frac{4}{\pi}\frac{l}{d^2} = R = 156.25$$

whence

$$d^3 = \frac{4}{\pi} \cdot \frac{36 \times .035}{156.25}$$

giving approximately d = .217 mm.; l = 160 mm.

The effect of flashing is to reduce ϵ in the ratio of 10 : 14, so that for a very thin coating

$$l\,d = 50.4$$

and

$$d^3 = \frac{4}{\pi} \cdot \frac{50.4 \times .035}{156.25}$$

whence d = .243 mm.; l = 207 mm.

When, however, the deposited coating is of appreciable thickness, the mean specific resistance of the filament is considerably reduced, owing to the fact that the specific resistance of the deposited carbon is only about

$\frac{1}{10}$th of the amyloid variety, so that a smaller diameter, and greater length, are required for a lamp of the same candle power. For example, if the flashing be continued until the surrounding tube of deposited carbon is one tenth of the sectional area of the unflashed filament, so that the resistance is reduced by flashing to one half, the mean specific resistance will be $\frac{11}{20}$ (.035) ohms per cubic millimetre; hence the diameter will have to be increased in the ratio of $(.55)^{\frac{1}{3}} : 1$, and the length correspondingly increased, giving (approximately)

$$d = .2 \text{ mm.} \quad l = 250 \text{ mm.}$$

For lamps of other sizes intended for the same electromotive force, and the same efficiency (4 watts per candle), we have $d \propto P^{\frac{2}{3}}$, $l \propto P^{\frac{1}{3}}$. Thus for a 100 candle power lamp the diameter will be increased in the ratio 3.39, and the length in the ratio 1.84.

But for lamps of this size a higher temperature and efficiency may be used with advantage. Now we shall give directly the results of experiments showing that the candle power of the same lamp varies approximately, taking the average through a considerable range of variation, as the 5.5 power of the electromotive force. This will give us a means of calculating how the radiation per square millimetre will vary with the efficiency, by considering the variations in the same lamp.

The resistance varies but slightly with the temperature when the filament is incandescent, and therefore the total radiation, being the number of watts absorbed, varies as the square of the electromotive force. Hence W, the number of watts per candle power, varies inversely as the 3.5 power of the electromotive force. For

$$P \propto E^{5.5}$$
$$\epsilon \propto P.W \propto E^2$$

whence

$$W \propto E^{-3.5}$$

and therefore

$$\epsilon \propto E^2 \propto W^{-\frac{2}{3.5}} \propto W^{-\frac{4}{7}}$$

That is to say, the candle power per square millimetre varies inversely as the $\frac{4}{7}$th power of the watts per candle power.

The same law must apply to lamps of various sizes. Therefore, since $l\,d \propto \frac{P}{\epsilon}$ and $\frac{d^3}{l} \propto PW$ for lamps intended for the same electromotive force

$$d^3 \propto \frac{P^2 W}{\epsilon} \propto P^2.W^{\frac{11}{7}} \text{ or } d \propto P^{\frac{2}{3}}\ W^{\frac{11}{21}}$$

and

$$l^3 \propto \frac{P}{\epsilon^2 W} \propto PW^{\frac{1}{7}} \text{ or } l \propto P^{\frac{1}{3}}\ W^{\frac{1}{21}}$$

For a lamp of 100 candle power, with an efficiency of 2.5 watts per candle power, we should therefore require to multiply the dimensions of the filament given above for a 16 candle power lamp, with an efficiency of 4 watts per candle power, by 2.65 and 1.80 for the diameter and length respectively.

It is inevitable that the glass globe should arrest a certain amount of the radiation from the filament, but when it is clean the loss in the luminous radiation must be very small. Any defect in the vacuum speedily shows itself in the conduction of heat to the glass, but a properly exhausted lamp of small candle power should remain quite cool, and may be safely placed amidst highly inflammable material. In the event of the lamp breaking, the filament of such a lamp will be consumed almost instantly.

Not so, however, with large lamps; they must be suspended at a considerable distance from combustible material. For the mass of incandescent filament is greater in proportion to the surface, and a perceptible time must elapse before the filament is consumed after the fracture of the bulb. Also the normal temperature of the bulb is higher, since the area of the globe must be smaller in proportion to the total radiation from the lamp.

To see this clearly, notice that with the same temperature of incandescence the length of the filament must be proportional (with the same E.M.F.) only to the cube-root of the candle power. And therefore if the other linear dimensions follow the same law of variation, the area of the surface of the globe varies as the $\frac{2}{3}$ power of the candle power of the lamp, that is to say, increases in a smaller proportion. But more than this; if the efficiency is improved in the larger lamps, the length of the filament and the area of the glass will be increased still less. The pear-shaped globe of an 8 or 16 candle power Ediswan lamp measures about $3\frac{1}{4}$ in. by $2\frac{1}{4}$ in., and of a 100 candle power 5 in. by $3\frac{1}{4}$ in. (not including the sealing ends), so that the areas of the surfaces are about in the ratio of 1 to 2.2, while the candle powers are in the ratio of 1 : 12.5 or 1 : 6.2. The large multifilament lamps will be constructed upon a still more deficient scale, and will be raised to a very high temperature.

Jamieson in 1882 first gave the sixth power of the electromotive force as the law of variation of the candle power of a lamp. Some tests by Ayrton in 1892 gave, with 100 volt 8 candle power lamps, a somewhat more rapid variation through a short range when the lamps were new, approaching more nearly the seventh power. But with lamps which had burnt for some time (two or three hundred hours) the following formulæ are given for the variations of candle power P, total watts EC, and watts per candle power W.

$$P \propto E^{5.91} \propto (EC)^{2.9}$$

and therefore

$$E \propto W^{-.358}$$

G. S. Ram has observed the law of variation through a much wider range, testing two lamps intended for very low electromotive force, which was more than doubled before the filament gave way. Expressions of the form aE^n gave an exceedingly close approximation to the observed candle power up to the point where the efficiency is about one watt per candle. The values of a and n for the first lamp were 7.76×10^{-8} and 5.35 respectively, and the expression aE^n gave a very close approximation up to .65 watts per candle. The discrepancy from this point was no doubt due to the rapid disintegration of the filament, which broke down at .6 watts per candle power. The other lamp gave $a = 1.695 \times 10^{-8}$; $n = 5.51$, the expression giving the correct candle power approximately up to 1.25 watts per candle power. The filament gave way at 8.5 watts per candle power.

The measurements on the opposite page were taken of the two lamps, and are placed side by side with the calculated value of the candle power by the formula.

The nominal efficiencies of the arc lamp and incandescent lamp are for the former about $\frac{1}{4}$ to $\frac{1}{5}$ watts per candle power in the best direction and for the latter 2 to 4 watts. The real illuminating efficiencies would, however, be more satisfactorily compared by taking the number of watts to the "mean spherical candle power" which would reduce the former to about $\frac{1}{2}$ watt per candle power. The efficiency of the incandescent lamp may, as shown above, be improved to nearly the same limit, $\frac{1}{2}$ watt per candle power, but the filament will then be raised to a temperature that it will be destroyed in a few seconds.

Still more recently Dujon, in investigating the law of variation of the candle power with the E.M.F. adopted an empiric formula of the form

$$P = K(E - a)^n$$

which he found to express the law of variation very closely through an extensive range, K depending upon the resistance of the filament when cold, a and n constants depending upon the physical conditions of the carbon, &c. For lamps manufactured by three leading companies the following values of a and n were found to agree with the experimental results:

Ediswan (110 volt lamps) . . .	a = 9.75	n = 6
Kohtinsky (105 volt lamps) . . .	a = 46	n = 3.5
Cie. Francaise (110 volt lamps) . .	a = 9.8	n = 5.7

This law of variation shows a more rapid increase of illumination with the E.M.F. than was given by the experiments of Ram, which were conducted with lamps suited to a much lower E.M.F.

C.-P.	Volts.	Amp.	Watts.	Ohms.	aE^n.	C.-P.	Volts.	Amp.	Watts.	Ohms.	aE^n.
5.3	29	1.13	32.6	25.7	5.15	2	30	1.03	30.9	29.1	2.33
6.2	30	1.15	34.5	26.1	6.2	3	32	1.1	35.2	29.1	3.22
8.8	32.5	1.23	40.0	26.4	9.52	4	33	1.15	37.9	28.7	3.92
10.6	33	1.28	42.2	25.8	10.3	5	34.5	1.2	41.4	28.8	5.05
12.5	34	1.31	44.5	26.0	12.07	6	36	1.24	44.7	29.0	6.34
14.2	35	1.34	46.9	26.1	14.18	7	37	1.27	47	29.2	7.4
16.0	36	1.36	48.9	26.5	16.4	8	37.5	1.3	48.7	28.9	7.97
17.7	36.5	1.39	50.7	26.3	17.65	9	38	1.33	50.5	28.6	8.5
22.2	38	1.45	55.1	26.2	22.0	10	39	1.36	53.0	28.7	10.0
26.5	39.5	1.49	58.8	26.5	26.8	12.5	40.2	1.4	56.3	28.7	11.68
35.4	42	1.58	66.4	26.6	37.4	15	41.8	1.45	60.5	28.6	14.5
44.0	43.5	1.66	72.1	26.2	45.0	20	43.7	1.51	66.0	29.0	18.4
53.0	45	1.7	76.5	26.4	51.4	25	45.5	1.58	72.0	28.8	24.0
62.0	46	1.75	80.5	26.4	61.3	30	47	1.62	76.3	29.0	27.6
71.0	46.8	1.78	83.5	26.4	66.8	35	48.5	1.68	81.5	28.9	32.6
80.0	47.8	1.81	86.5	26.4	74.6	45	51.2	1.77	90.5	28.9	44.2
106.0	50.5	1.9	96.0	26.6	100.0	50	52.2	1.85	94.5	28.2	48.9
124.0	52	1.94	101.0	26.8	117.8	60	54.2	1.88	102.0	27.8	60.7
142.0	53	1.98	105.0	26.8	130.0	70	55.4	1.92	106.2	28.8	68.0
159.0	54	2.05	112.8	26.8	159.0	80	57	1.98	113.0	28.8	80.0
177.0	56	2.07	116.0	27.0	174.5	90	57.8	2.01	116.3	28.8	86.5
195.0	58	2.13	123.6	27.2	210.0	100	59.6	2.08	124.0	28.8	102
212.0	60	2.2	132.0	27.3	252.0	120	62	2.17	134.5	28.6	127
230.0	61.8	2.22	137.2	27.8	296.0	140	64.8	2.25	145.0	28.8	166
248.0	65	2.3	149.5	28.3	389.0	160	68	2.35	160.0	28.4	211
						180	69	2.38	164.0	28.9	230
						200	72.5	2.49	181.0	29.1	300
						250	80	2.7	216.0	29.6	518
						295	90	2.8	252.0	32.2	1000

The commercial efficiency (or rather *inefficiency*) may be expressed as the cost per candle power per hour. This will depend upon the costs of the energy per unit, the prime cost of the lamp, and the relation between the life of the lamp and the illuminating efficiency (watts per candle power). Let p be the prime cast of the lamp; h the cost of one watt hour; L the life in hours; P the candle power; W the watts per candle power; the cost per candle power per hour may be written

$$\frac{p}{L\,P} + h\,W$$

This self-evident formula was employed by Professor Perry in 1885 to determine the electromotive force, which reduced the cost to a minimum with certain types of lamps then manufactured, L, P and W being determined empirically as functions of the electromotive force E. The expression found for certain small lamps was reduced to

$$p \cdot 10^{.07545\,E\,-\,11.697} + h\left\{3.7 + 10^{8.007\,-\,.07667\,E}\right\}$$

and by either an algebraic or graphical method the value of E giving a minimum cost per candle hour was thus determined.

Shortly afterwards Professor Fleming expressed the relation between L, P, W, and E, by the formulæ

$$L = \frac{A}{W^{\alpha}} = \frac{B}{P^{\beta}} = \frac{1}{E^{\gamma}}.$$

From which it follows that for maximum economy

$$\frac{h}{p} = \alpha \cdot \frac{\beta - 1}{\beta}$$

For certain Edison lamps it was found that $\alpha = 6\frac{1}{4}$, $\beta = 4\frac{1}{8}$, from which it follows that of the whole cost of lighting the cost of renewals should be about 17 per cent. This result is of course dependent simply upon the durability and efficiency of the lamps, and not on the costs of lamps and energy, and is probably approximately true for *small* lamps as at present constructed. But with larger sizes of lamps the deterioration of the efficiency due to the blackening of the globes greatly affects the average cost per candle hour. The blackening is practically insignificant in really good lamps of 16 candle power or less, and it has been found that the candle power of the lamp will actually increase for the first hundred hours. This increase may be due partly to an improvement in the vacuum, and partly to a decrease in the resistance of the filament itself, allowing a larger current to pass.

Perry's expression for the cost per candle hour must now be corrected by P and W, their mean values, and for L the economic life, or the number of hours of burning up to the time at which it is advisable to renew the lamp. It may sometimes be necessary to renew a lamp owing to the

Table showing average Candle power (per cent.) and Efficiency of Incandescent Lamps at various periods of their Lives.

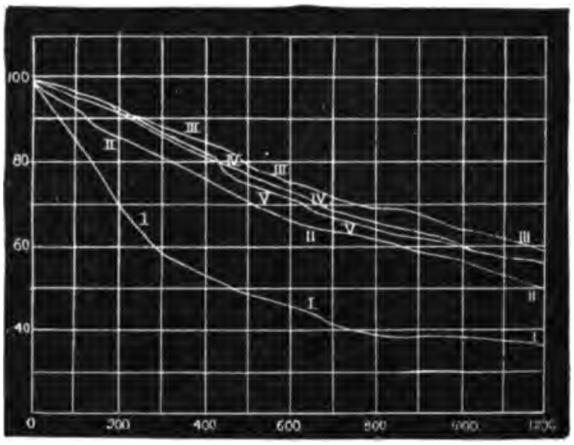
Class I. having initial efficiency of 2 to 2.5 watts per candle power; Class II., 2.5 to 3; Class III., 3 to 3.5; Class IV., 3.5 to 4; Class V., more than 4.

Time in Hours.	I.		II.		III.		IV.		V.	
	P.	W.	P.	W.	P.	W.	P.	W.	P.	W.
0 .	100	2.4	100	2.9	100	3.3	100	3.8	100	4.5
100 .	84	2.8	93	3.0	95	3.4	96	4.1	96	4.7
200 .	70	3.3	85	3.3	91	3.5	91	4.3	92	4.9
300 .	59	3.7	81	3.5	88	3.6	86	4.5	87	5.2
400 .	53	4.2	76	3.8	84	3.7	81	4.7	82	5.4
500 .	48	4.6	71	4.0	79	3.9	77	5.0	75	5.8
600 .	45	4.8	69	4.2	76	4.1	73	5.3	72	6.1
700 .	41	5.2	64	4.4	72	4.2	69	5.6	68	6.4
800 .	39	5.3	62	4.7	69	4.4	66	5.9	65	6.8
900 .	38	5.5	59	5.0	69	4.7	63	6.1	62	6.9
1000 .	37	5.7	56	5.3	64	5.0	60	6.3	60	7.0
1100 .	36	5.7	53	6.0	62	5.4	58	6.5	58	7.1
1200 .	35	5.8	50	6.3	59	5.6	56	6.7	56	7.1

fall of its candle power, even before such a course may be rendered advisable by the lessening efficiency. The same lamp may then still be used with advantage in a position where less candle power is required.

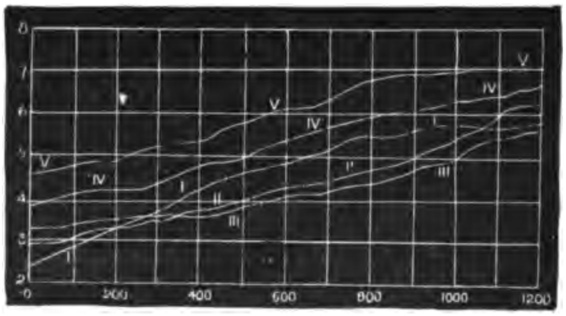
One of the most complete sets of experiments were made by Feldmann, giving the mean of the results for 500 lamps made in twenty-eight different factories, American and European. The table on previous page gives the law of deterioration of P and W, with electromotive forces which gave various initial efficiencies.

FIG. 81.



Variation in Candle power during Life of Incandescent Lamps.

FIG. 82.



Variation of Efficiency (Watts per Candle) during Life of Incandescent Lamps.

The same results are shown graphically in Figs. 81 and 82.

It will be seen that the deterioration appears to increase less rapidly in proportion to the efficiency than might have been expected, except perhaps with the lamps of very high efficiency. In fact, the lamps of the class V., giving low efficiency, are evidently of inferior make and deteriorate more rapidly than those of II., III., IV.

For the life of the incandescent lamp up to "smashing" point (the average time of burning till the filament breaks) the tests require to be applied to a very large number of lamps, in order to obtain a satisfactory average, and the electromotive force must be maintained with scrupulous exactness. The relation between the life and the efficiency candle power, or electromotive force, will of course vary very greatly according to the size of the lamp, that is, the sectional area of the filament; but the law of variation of length of life with the same size of lamp subjected to different electromotive forces, and therefore giving different initial candle power and efficiency, should be determinable and approximately constant.

The following table gives the average life of Ediswan lamps of a normal 16 candle power, when the electromotive force is varied, for various initial candle powers.

Candle power.	Life in Hours.	Candle power.	Life in Hours.
10	5,550	19	534
11	3,963	20	443
12	2,857	21	371
13	2,134	22	312
14	1,628	23	266
15	1,292	24	228
16	1,000	25	196
17	802	30	163
18	651		

From which we find that the law $L \propto P^{-3.6}$ expresses the variation very closely indeed.

Now, taking the law of variation of the candle power with the electromotive force as $P \propto E^{5.5}$, and remembering $P.W \propto E^2$ when the resistance of the filament is constant, we get $L \propto E^{-19.8}$ and $W \propto E^{-3.5}$ and therefore $L \propto W^{5.6}$.

Let us apply this law to the case of a lamp which, with an efficiency of 3.5 watts per candle power, is found to have a life averaging 1000 hours.

Watts per Candle power.	Life $= 1000 \left(\frac{W}{3.5}\right)^{5.6}$
1.5	8.6
2	43
2.5	151
3	421
3.5	1000
4	2120

Supposing that the lamp is to be used until the filament breaks, it is now easy to construct a curve giving the relation between the total cost per candle hour and the "life," the latter depending as above on the initial efficiency. Perry's expression for the cost per hour may be written

$$\frac{p}{\text{total candle hours}} + h \text{ average watts per candle,}$$

p being the prime cost of the lamp; h the cost of power per watt hour.

Fig. 83 shows three curves traced by Prof. Ayrton from experiments with 8 candle power Ediswan lamps, to show the total cost per candle hour with three different prices of energy and of lamps, according to the probable lives that are determined by the efficiency chosen. The data for the respective curves are

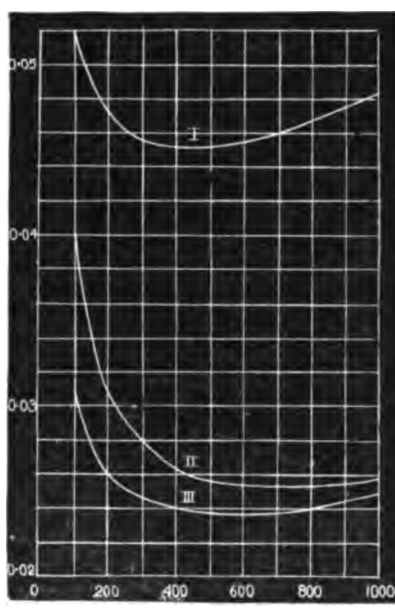
I.	Cost price of lamp	1*s.*	energy	.009*d.*	per hour, or	9*d.*	per unit.
II.	"	2*s.*	"	.0045*d.*	"	4½*d.*	"
III.	"	1*s.*	"	.0045*d.*	"	4½*d.*	"

Whence for these three places, taking lowest point on curve to determine the most economic conditions, we determine

I. Best life, 400 hours, minimum cost .045*d.* per candle hour.
II. „ 650 „ „ .025*d.* „
III. „ 600 „ „ .0235*d.* „

Professor Ayrton also finds for these lamps that it is not advisable to replace till the filament breaks, and no marked economy is gained by over-running even at these low prices. To determine at what point it is advisable to replace a large lamp owing to the decreasing efficiency a curve might be traced *for any given initial efficiency*, showing the cost per candle hour upon

FIG. 83.



Curves showing Total Cost per Candle hour for Lamps of various "Lives."

the assumption that it is regularly replaced after a certain length of time, the ordinates of the curve giving the cost, and the abscissæ the life allowed. This curve would begin to rise at the point determining the "economic" life of the lamp.

The Nernst Lamp.

Only recently a new form of lamp has entered into competition with the carbon filament, which may still be classed as an *incandescent* lamp, though the term "electrolytic" proposed by the inventor, Prof. Walther Nernst of Göttingen, suggests a distinguishing characteristic. In some respects it is a revival of the extinct Jablochkoff candle, and the "Sun" light, in which the kaolin or marble became fused by the arc, and subsequently self-conducting and luminous.

The glower is composed of sticks or tubes of what are commonly called rare earths, the principal one being zirconia. The tube or stick of zirconia is a non-conductor of electricity when cold, but when it is heated it allows the current of electricity to pass. The lamp, therefore, contains the necessary arrangement for the preliminary heating of the glower. In the lamp as now made by the Nernst Electric Light, Limited, Fig. 84, the heater consists of a porcelain spiral upon which is wound fine platinum wire. As soon as the current is switched on to the lamp the heater becomes red-hot, and in a space of time varying from 10 seconds to 40 seconds, according to the size, the glower lights up. In circuit with the glower is the magnetising coil of a cut out in the heater circuit. As soon, therefore, as the current passes through the glower the heater circuit is broken, so that the heater is only in use for the short time while the lamp is lighting. As the resistance of the glower falls rapidly as the current passing through it and the temperature increase, it is necessary to have a balancing resistance in the glower circuit. This resistance is preferably made of iron wire, owing to its very high temperature coefficient. The iron wire is protected against oxidation by being enclosed in a glass bulb containing hydrogen. Resistances of platinum wire may also be used under certain conditions.

FIG. 84.

The Nernst Lamp.

The lamp is arranged with a detachable replacement piece containing the heater and the glower, which can be renewed at a slight cost if either the heater or glower fails. The cut-out and balancing resistance are contained in the case of the lamp. The large lamps are made to hang up like small arc lamps; the smaller sizes are made to fit into ordinary lamp-holders like the usual incandescent lamps. The glowers are made in sizes of ¼, ½, and 1 ampère. These are cut in lengths according to the voltage required, and the candle power consequently varies according to the voltage. The 1 ampère lamp, for instance, at 200 volts, is double length of glower and double the candle power of a lamp at 100 volts.

Owing to the high temperature at which the glower can be worked, the efficiency of the lamp is very great, and may be taken as from 1.5 to 1.75 watts per candle.

The light is of an exceedingly white colour, with a large proportion of ultra-violet rays. The efficiency does not seem to improve much with an increase in the electromotive force, or "overrunning," as with the carbon filament, while the life is greatly shortened thereby. There appears inevitably to be a slight falling off in the quantity and efficiency during the first few hours of burning, but subsequently, at least with the lamps by the best makers, the efficiency is maintained well for about 400 hours, when the falling off is rapid, and the glower should be replaced.

It does not appear possible to enclose the Nernst glowers in a vacuum, though unquestionably great gain would ensue if convection currents of air did not remove the heat-energy. Happily the glowers are so small that the escape of heat is far less than it would be from a carbon filament giving an equal amount of light. The access of air appears to be an essential condition for the electrolytic conduction in the glower. Another curious fact, of which at present no adequate explanation can be given, is the polarisation of the glower adapted for continuous currents, which renders it essential that the direction of the current should remain unchanged throughout the life of a glower, or speedy destruction will ensue. The glower can be adapted to alternating currents. The details of the composition are at present kept as trade secrets by the various manufacturers who have acquired rights, some being more successful with continuous and others with alternating currents.

There appears also to be a difficulty in constructing glowers for currents larger than 1 ampère, which gives upwards of 60 candle power with 100 volts, and 130 candle power with 200 volts. Unless, therefore, multiple glowers are to be employed, the introduction of the Nernst lamp will favour the use of high electromotive forces when large lamps are to be used.

CHAPTER XV.

Arc Lamps.

UNDER ordinary conditions of atmospheric pressure, and with electromotive forces such as are commonly used for electric lighting, air and all other gaseous media may be considered as of infinite specific resistance. Absolute contact of the metallic or other solid or fluid conductors to complete any circuit is necessary before any current will flow, and the circuit is effectively insulated by an extremely thin surrounding of air, no appreciable current escaping over a large area by conduction through the gaseous envelope, and no further insulation would be necessary if we could ensure that the separation from other conductors at all points was complete. There are, however, certain abnormal conditions under which an electric current can cross a gap in an incomplete metallic circuit. These conditions will now be very briefly described. The manner in which the conduction takes place, and the attendant phenomena, differ very widely under the different conditions, and from the manner of conduction by metals and fluids.

With very high electromotive forces, such as are obtained by influence machines or induction coils, air or gas at ordinary temperatures and pressures will allow the passage of a small current of electricity. The terminals of the metallic circuit, or "electrodes," are observed to glow with a faint bluish light; this electric conduction, which is known as the "glow discharge," is in all probability of the nature of convection by charged particles of metal, extremely minute, disintegrated and repelled from the surface of the electrodes, conduction by the gas itself taking no part in the phenomenon.

The "spark," or "disruptive discharge," takes place when the electrodes are brought within a certain distance dependent on the nature, pressure, and temperature of the gas, and the shape of the electrodes. The property of a gas by which it resists the passage of a disruptive spark has been termed by Maxwell the "electric strength" of the gas. It appears that in air at atmospheric pressure there is a minimum electromotive force of between 300 and 400 volts, with which a disruptive spark can be obtained between two electrodes of any shape or material, and however closely approached short of absolute contact. This minimum electromotive force for a disruptive discharge is not reduced by decreasing the pressure of the air, but a longer spark may be obtained with the same electromotive force. To produce a spark of a millimetre in length at atmospheric pressure requires an electromotive force of about 4000 volts, one centimetre about 20,000 volts, the electrodes being planes or spheres of moderate curvature.

Hot gases appear to conduct electricity with varying degrees of facility. According to J. J. Thomson, "Gases, such as air, nitrogen, or hydrogen, which do not experience any chemical change when heated conduct electricity only to a very small extent when hot, and in this case the conduction appears to be, as Blondlot supposed, convective. Gases, however, which dissociate at high temperatures, that is, gases such as iodine, hydriodic gas, &c., whose molecules split up into atoms, conduct with very much greater facility, and the conduction does not exhibit that dependence on the material of which the electrodes are made, which is found when the electricity is transmitted by convection."

With the non-dissociable gases are to be included those whose dissociation consists in the splitting up of the molecules of the gas into simpler molecules, but *not into atoms*, as when a molecule of steam splits up into molecules of hydrogen and oxygen, these gases giving very low conductivity. Thomson concludes that "the molecules even of a hot gas do not get charged, it is the *atoms* and not the molecules which are instrumental in carrying the discharge . . . The small amount of conductivity which hot gases, which are not decomposed by heat, possess, seems to be due to a convective discharge carried perhaps by dust produced by the decomposition of the electrodes; in some cases perhaps the electricity may be carried by atoms produced by the chemical action of the electrodes on the adjacent gas."

Gases in a state of high rarefaction become very passable conductors of electricity, and induced currents may be produced with electromotive forces of a few volts. The conduction is in this case also due to dissociation of the atoms and not to convection by the molecules. The electromotive force required when the current passes from the gas to metallic electrodes is much higher, and is always accompanied by disintegration of the latter. The phenomena produced by conduction through "vacuum tubes" are too elaborate for discussion in this article, since up to the present time the luminous radiation obtained in this way has not approached the conditions necessary for it to become a practical means of illumination.

With differences of potential between the electrodes of less than 300 volts, a disruptive discharge is probably impossible in air at ordinary temperatures and pressure. If, however, a current be once started between the electrodes, as when they are separated from contact, or an initial disruptive discharge is caused with a higher difference of potential, the current can be *maintained* across a gap of considerable length with a comparatively low difference of potential between the electrodes. This phenomenon is known as the electric "arc."

A current of considerable magnitude, and therefore a considerable absorption of power and production of heat, are necessary accompaniments of the electric arc. The material of which the electrodes are composed is rapidly consumed, being melted, vaporised, and oxidised owing to the high temperature. It is still uncertain by what operation the conduction takes place, whether by the statical charges of minute particles thrown off from the electrodes and traversing the gas, or direct conduction by the intensely heated gases, accompanied by molecular dissociation; it is almost certain that both operations take place to some extent, but in proportions hitherto undetermined.

A certain minimum difference of potential between the electrodes is necessary to maintain an electric arc, even of infinitesimal length, the difference depending on the material of which the electrodes are composed; also a certain minimum current seems to be necessary, and the difference of potential may be somewhat, but very slightly, decreased when a larger current is allowed to pass. An excess difference of potential above the minimum proportional to the length of arc-gap between the electrodes will be necessary, the excess difference being less when a large current passes. In other words, if E be the difference of potential between the electrodes, L the length of the arc-gap (in millimetres), we may write

$$E = a + b \cdot L$$

where a is a number depending on the material of the electrodes, very slightly, if at all, modified by the current passing; b is a function of the current, and does not seem to be dependent on the material of the electrodes to anything like the same extent as a.

Lecher gave the following results of measurements of a and b with different materials, the variation of which with the current in the particular case of carbon electrodes will be considered later at some length:

Horizontal carbon electrodes	$E = 33 + 4.5$ L.
Vertical "	$E = 35.5 + 5.7$ L.
Platinum (5 mm. diameter)	$E = 28 + 4.1$ L.
Iron (5.5 mm. diameter)	$E = 20 + 5$ L.
Silver (4.9 mm. diameter)	$E = 8 + 6$ L.

There seems to be some relation between the first term, the minimum difference of potential that can maintain an arc with the given material for the electrodes, and the temperature at which that material melts, these being:

For platinum	3,080 deg. Fahr.
For iron	2,786 "
For silver	1,873 "

that of carbon being too high to be satisfactorily determined. As the arc, or at least the extremity of the positive electrode which is the point where the greatest heat is always found, seems always to attain a certain fixed temperature depending only on the material of which it is made, it has generally been assumed that this temperature is that of the *boiling*-point of the material. The necessity of a minimum difference of potential is then very simply explained by supposing that this difference corresponds to the power that must be supplied to evaporate the material at the rate required for one ampère of current, supplying the latent heat of evaporation, assuming that the rate at which the material is volatilised is proportional to the current. It has been objected that, taking the case of carbon electrodes for example, it would be necessary to assume an enormous value of the latent heat of evaporation as compared with metals which boil at a lower temperature (such as mercury), if the energy supplied is to be thus accounted for by the volatilisation. But it must be understood that by far the greater portion of the material volatilised is re-condensed as it cools on leaving the positive electrode, and has to be re-evaporated; the actual consumption of material bearing no relation to the volatilisation in the arc itself, but depending upon oxidisation or other chemical combination at the high temperature. Violle succeeded in approximating to the temperature of the extremity of a positive carbon electrode in the following manner: A 400 ampère arc was used, and the end of the positive carbon was isolated from the rest by a narrow isthmus. When the arc had caused this to be heated throughout to a nearly uniform temperature, the luminous button was struck off into a calorimeter, consisting of a copper tube containing a number of pieces of graphite, and sunk in a suspended water vessel. It was found that a gramme of carbon thus heated in the arc possessed 1300 units of heat (gramme-degrees Centigrade) above what it possessed at zero Centigrade. Now it requires 300 units to raise the temperature of a gramme of carbon 1000 degrees, so that there remained 1300 to be accounted for. Violle estimated the specific heat of the carbon throughout the higher ranges of temperature leading up to that of the arc as .52, this giving a rise of an additional 2500 degrees, so that the probable ultimate temperature was about 3500 degrees Centigrade.

In using the electric arc as a means of illumination, electrodes made of some form of carbon are alone practically possible, for the following requirements are essential:

(1) In extremely high temperature of volatilisation. The high temperature is demanded by the consideration of efficiency, since the proportion of light radiation to the total radiation increases rapidly with the temperature.

(2) A moderately good conductivity for electric currents.

(3) A low heat conductivity, in order that the heat may not be conducted away, but escape, as far as possible, solely by radiation.

(4) The oxide of the material must be a gas, otherwise it will be deposited in the neighbourhood of the electrodes, with obvious attendant inconveniences.

(5) A high selective emissivity for luminous radiation (see the discussion in the chapter on Incandescent Lamps).

The discovery of the electric arc is generally attributed to Davy, who in 1810 first obtained the phenomenon in experimenting with 2000 large primary cells connected in series. Two pieces of wood charcoal were used as electrodes, and after contact the electrodes were separated horizontally to a distance of over four inches; a brilliant "arch" of light was formed, the upward current of heated air causing the shape which gave rise to the term "arc." Davy's apparatus was, of course, most inefficient both as regards generation of power, and its conversion into light, and no expectation was entertained at the time that the electric arc could become a practical source of illumination. From the arc itself a very small proportion of the heat generated is radiated as light, the heated electrodes themselves radiating light infinitely better, and the high E.M.F. required for a long arc corresponds to a large expenditure of power which is converted mainly into heat radiation and not luminous radiation, or heat carried away by currents of air.

As soon as the development of the dynamo had caused it to supersede the primary battery, coal replacing zinc as fuel, and the cost of the production of electrical energy immensely reduced, the possibilities of the electric arc for lighting purposes were recognised, and it soon became a practical success. The first carbons used as electrodes were made of hard gas-retort carbon cut into suitable shapes, round, straight rods placed in the same line replacing all other forms, though revolving discs, and rods inclined to one another were fully considered. The electrical resistance of gas-retort carbon is very much higher than that of modern artificial carbons, and the necessary uniformity in its composition would not be obtainable. Finely pulverised coke is generally the basis of the improved material, this being mixed with pure carbon powder to improve the conductivity, and some adhesive paste, such as syrup of cane sugar or gum, cements the combination together. This is either squeezed into a mould, or through a die of the proper size, and cut into the requisite lengths (from 8 to 14 inches). The materials and method of manufacture are very varied, and in many cases are held as trade secrets. The chief requirements are that it should be perfectly homogeneous, of the lowest resistance possible, free from extraneous matter of a less refractory nature, and as mechanically strong and dense as possible to diminish the rate of consumption. The carbons intended for the positive electrode are somewhat longer or else of larger diameter as the rate of consumption is generally twice as great, and should be "cored." In moulding, or as it passes through the die, a central hole is made throughout its length, which is subsequently filled with a core of carbon in the soft graphitic form, which, being of higher conductivity and more easily volatilised than the remainder of the rod, causes the arc to spring from the centre of the rod, and assists the formation of the "crater" as will be described.

The diameter of the carbon rods vary according to the current they have to carry: for the most common current employed, that of ten ampères, they require to be from twelve to eighteen millimetres. It used to be a common practice to cover the surface, especially of the negative carbon, with a thin layer of copper or nickel, electrolytically deposited, in order to improve the conductivity, and ensure good contact with the carbon-holders; but this is now generally abandoned, as the volatilised metal entering the arc reduces and varies the intensity of the light, and befouls the globe and regulating mechanism.

The following is a list of the various diameters of the carbon rods supplied by three leading arc lamp manufacturing firms in England, the diameters being given in millimetres:

Nominal Candle power.	Current.	Electric Construction Co.		Brush.		Crompton.	
		+	−	+	−	+	−
1000	5	13	8	11	8	13	8
1500	7½	16	9	13	11	16	9
2000	10	18	12	15	12	18	12
4000	20	—	—	18	15	25	18

Viewed through deeply tinted glasses, or better still by projecting with a lens a much enlarged image upon a white screen, the general appearance of the arc between two carbon electrodes may be studied. Owing to the great changes in appearance according to the length of the arc, the magnitude of the current, &c., and the utter failure of any uncoloured illustration to represent anything except the shape of the electrodes (which is subject to extreme variation), it is preferable to adhere to a purely verbal description. The illumination proceeds almost entirely from the ends of the carbon electrodes, a small area on each of which is raised to an intense white heat. On the positive electrode the area of this bright surface is far the greater, and somewhat the more brilliant, and is responsible for at least 80 per cent. of the light. The area of the bright surface of the negative carbon may be responsible for about 10 per cent. of the light, with short arcs, while not more than 5 per cent. comes from the intermediate gap, or the arc itself. The latter appears a bright violet ball, shading off into green, and surrounded by a golden aureole. The bright surfaces of the electrodes are likewise surrounded by yellow and yellowish-red belts, darkening rapidly into black.

With a long arc, upwards of about 5 millimetres, or about half the diameter of the carbon rods, the carbon ends are both flattened, becoming more and more rounded as they are brought nearer. With less than 5 millimetres gap the positive begins to hollow out into a "crater," and the negative to become pointed. Shortening the arc still further, to less than 2 millimetres, the point of the negative carbon develops into a knob, or mushroom, especially when a cored positive carbon is used, the crater becoming very deep. The knob seems to be formed by a deposit of graphitic carbon thrown off from the positive, piling itself up on the negative point, finally breaking off and causing "hissing." On the fringe of the bright surfaces there generally appear a number of bright balls or nodules, which are more easily seen on the negative than on the positive electrode owing to the light thrown on them by the former from the crater, and which are probably boiling syrup or the adhesive paste which is used in the manufacture of the carbon.

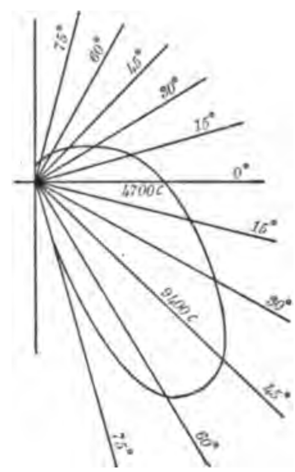
The shapes assumed by the carbons confirm the statement already made that the consumption of the material is due less to the volatilisation in the arc, than to the oxidisation, or burning, of the material at the high temperature, and this takes place from the heated surface surrounding the bright parts. The conical or pointed shape of the negative carbon, which is more marked as the arc is shortened, is to be explained by supposing that it receives its heat entirely by radiation and conduction from the crater and arc, thus being consumed more rapidly with the shorter arc; except at the centre, when it is in an atmosphere of volatilised carbon, and carbon gas so that the oxygen has no access to permit burning. With long arcs the consumption of the negative carbon is greatly reduced. The positive carbon, on the other hand, is heated in the neighbourhood of the bright surface by conduction, and the shortening of the arc allows this to be better protected from the oxygen by the carbon gas, and thus avoiding being consumed, forms the rim of the crater. With long arcs the brilliant spot of intense heat wanders uncontrolled over a flat area of positive carbon, volatilising and burning it away uniformly; with shorter arcs it becomes stationary, throws up a surrounding ridge where burning is prevented by absence of oxygen, and burns by conduction a surrounding cone.

When the current is increased beyond a certain strength, depending upon the sectional area of the carbons and the length of the arc, the difference of potential between the electrodes falls considerably, and the arc assumes an unstable state, the carbon breaking off in lumps, accompanied by a hissing sound. This hissing is probably due to a state of the arc which is similar to that known as "priming" in a boiler, the bright surface being too small for steady and complete volatilisation of the requisite amount of carbon, and is a sign of too short an arc, or a too heavy current for carbon electrodes of the section used.

The highest temperature, as well as the source of by far the larger amount of light radiation, is to be found at the bright surface of the positive carbon. It may therefore be expected that the energy supplied will be largely absorbed at this point, and converted into heat. Dr. Fleming has shown this experimentally by introducing the extremity of a well insulated third carbon into the arc, and measuring with an electrostatic voltmeter the difference of potential between it and the electrodes. It will be found by this method that a considerable difference of potential is obtained between the positive electrode and a point in the arc very close to its surface, in fact probably that minimum electromotive force 33 to 39 volts which is necessary to produce the shortest arc. The bright surface of the positive carbon is therefore the place where the energy corresponding to this E.M.F. is absorbed and partly radiated as light. An additional E.M.F. of about 30 volts or so per centimetre (this additional E.M.F. varying greatly according to the current) is necessary to overcome the resistance of the arc-gap, but of the energy absorbed to which it corresponds a very much smaller proportion is radiated as light. The highest efficiency of the arc as a means of illumination will be obtained by reducing the length of the arc as far as is consistent with steady burning, avoidance of "hissing" through incomplete volatilisation, and with free radiation from the positive electrode without eclipse from the negative. The use of a smaller diameter for the negative carbon, now the almost universal practice, allows much freer radiation from the positive carbon extremity, and it also has the advantage of equalising the rates of consumption in the electrodes, thus simplifying some arrangements in their regulating mechanism. A ratio of diameters of about 3 to 2 secures this equality of rate of consumption with ordinary lengths of arc; with longer arcs the negative may be further reduced in diameter.

The luminous intensity of the bright surface of the positive carbon reaches according to the best determinations, about 170 candle power per square millimetre. This luminous intensity is obtained only when hard and fairly pure carbon is used, and reduces very considerably, to about 130 candle power per square millimetre, when a soft graphite core, more easily volatilised, allows a lower temperature. As, however, the latter is soon consumed to some depth in forming the crater, the luminous intensity is restored to the higher value after a short time of burning. The luminous intensity of 170 candle power per square millimetre to a temperature of about 3500 degrees Centigrade, which is maintained, without much variation, whatever current flows through the arc. The area of the bright surface is, roughly, proportional to the current, but measurement of this area is not easily or satisfactorily made owing to its irregular shape, and the gradual shading off of the luminosity round the edge. With a ten-ampère arc the

FIG. 85.



Illumination of Continuous Current Arc Lamp in differently inclined Directions.

area of the brightest surface is about twelve square millimetres, so that in a direction normal to the surface the luminous radiation should be about 2000 candle power.

The luminous radiation in different directions from an electric arc of the common type will be found to vary very greatly. The greatest illumination will be found in the direction in which the whole of the positive bright surface is visible, as near as possible normal to the surface, but just avoiding eclipse by the negative electrode. This maximum value is known as the *nominal* candle power of the arc lamp. With the common arrangement, vertical carbons, the upper being the positive, the maximum illumination will be found in a direction inclined at an angle of about sixty degrees to the vertical: with shorter arcs the inclination to the vertical giving maximum illumination will be greater, with longer arcs less. In other directions the illumination will vary in proportion to the apparent area of the bright positive surface viewed from that direction, somewhat modified by the illumination from the negative carbon end and the arc itself. The distribution will depend very greatly on the shape of the electrodes and the length of the arc, but Fig. 85 will illustrate a typical relative distribution in various directions in one vertical plane (given by an arc of 10,000 nominal candle power). The illumination in any direction is shown by the corresponding radius vector of a curve.

The total illumination emitted by the arc may be calculated from this curve, and compared with the total illumination from a standard candle emitting light equally in all directions. To perform the calculation the mean candle power for every five degrees or so may be multiplied by the solid angle generated by its revolution about the middle line of the carbons, and the sum of the products divided by 4π. This will give what is known as the *mean spherical* candle power, and will generally be about one-third of the nominal. The mean spherical candle power of the arc lamp would be a very fair measure of its value as a means of illumination if the light in all directions were equally valuable. As a rule, however, the arc lamp is placed in an elevated position, and only the light projected downwards is of any use. When a hood reflector is placed over the arc lamp, or, as is often preferred, a white screen, eighty per cent. or more of the light thrown upwards is reflected, and the mean spherical candle power may be considered the best criterion of the illumination. The same may be said of an arc lamp used for interior lighting of large halls or factories when the ceiling and walls are white; and even for exterior lighting when the light is thoroughly diffused by an opal or dioptric globe. One of the most effective methods of interior lighting with arc lamps is to invert the positions of the carbons, and place a reflector under the arc to throw all the light upwards towards a white ceiling. A perfectly diffused light is thus obtained without shadows, and as the diffusing globe, which would otherwise be necessary and absorb probably half the light, is dispensed with, the system is highly efficient.

When the light thrown upwards is wasted, the *mean hemispherical* candle power, calculated as before but taking account only of the light thrown downwards in the lower hemisphere, is often preferred as the measure of illumination. This is generally about half the nominal candle power. It may be noted however that when using a few widely scattered lights, in elevated positions, the difficulty of maintaining uniform illumination over the ground may be partly met if the increased illumination in directions considerably inclined to the vertical be made to compensate for the increased distance. With a short arc and thinly opalescent globes it may be arranged that the illumination on the ground level given by any lamp should be fairly constant within a distance from the foot of the support equal to the height of the arc, and beyond this decreases slowly till the point intermediate between this lamp and the next is reached. The best criterion of the illuminating power would be the measurement of the illumination in the direction of this intermediate or darkest spot. With closely set lamps this criterion may not be far different from the nominal candle power.

When an opal or other diffusing globe is used, it is advisable to place the arc somewhat above its central point, so that the light thrown downwards from the arc may illuminate the globe with a broad equatorial belt of light, and not the lower hemisphere alone. The light is more evenly diffused, or in other words the mean spherical is more nearly equal to the mean hemispherical candle power, than with the naked arc. This even diffusion, lessening the proportion thrown downwards, is a disadvantage in itself with the usual methods of outdoor lighting, but an unavoidable necessity if we wish to eliminate the dazzling effect, and heavy shadows cast by the naked arc. The following figures were given by Guthrie and Redhead showing the *relative* value of the two measurements when different diffusing globes were used:

—	Naked Arc.	Clear Glass.	Rough Glass.	Opal.
Mean spherical candle power .	319	235	160	144
Mean hemispherical candle power	450	326	215	138

From the arc itself a large proportion of the heat generated is carried away by currents of air, but that generated at the bright surface of the positive carbon is almost entirely removed by radiation. The best determinations of the energy thus radiated give from 27 to 30 watts per square millimetre. Of this the greater amount is heat radiation, probably about 90 per cent., but even with this great loss the proportion of the luminous to the total radiation is far higher than can be obtained by any other artificial means. Many attempts have been made to incorporate with carbon some other substance which, by its properties of selective radiation, should give a higher proportion of luminous rays. But the lower temperature resulting from any impurity in the carbons has prevented success in this direction, as it has with incandescent lamps.

As with the incandescent lamp, we may express the efficiency (or inefficiency) by the number of watts absorbed per candle power, using for the latter either the nominal, mean spherical, or mean hemispherical. From every square mm. of the bright surface of the positive carbon the luminous radiation in the direction normal to the surface is 170 candle power, and the total radiation the equivalent of 27 to 30 watts, the efficiency is that of one sixth of a watt per candle power. This may be compared with the corresponding figures for the filament-surface of an incandescent lamp; for example, at a temperature commonly used for small lamps, the luminous radiation may be $\frac{1}{2}$ candle power in a direction normal to the surface, the total radiation $\frac{1}{2}$ watt per square mm., and thus the luminous efficiency 1 watt per candle power. As, however, with a filament of circular section the apparent area viewed from any point is, as a maximum, $\frac{1}{\pi}$ of the actual surface, the illumination in that direction will be $\frac{1}{2\pi}$ candle power for every millimetre of the whole surface, and thus the luminous efficiency is 3.14 watts per candle power in the direction of maximum illumination, which will be reduced to about 4 watts per candle power if we took the mean spherical value, or about $3\frac{1}{2}$ watts per candle power if the mean horizontal.

The luminous efficiency of the bright surface of the positive electrode thus seems to be about 6 times as great as that of the incandescent lamp filament, a comparison which need not be greatly modified whether we compare the normal radiation from a square millimetre of bright surface, that is, the radiation in the direction of the greatest illumination, or the mean radiation in all directions. This comparison is, however, considerably modified in favour of the incandescent lamp when we take into account the energy wasted in the arc itself, from which very little light is radiated, and the waste in producing the necessary diffusion of the light, when we desire to compare the relative efficiencies of the arc and incandescent lamps as means of illumination.

The luminous intensity of the surface of the sun is, according to calculations made by Prof. Young, about 1000 candle power per square millimetre, or about 6 times that of the bright surface of the positive electrode in the electric arc, and about 2000 times that of the incandescent lamp filament at the most common temperature employed. This corresponds to a temperature of about 8000 degrees Centigrade. The power dissipated by radiation of heat and light is about 100 watts per square millimetre, giving an efficiency of about one tenth watt per candle power.

The electric arc may also be maintained by an alternating current. The illumination is emitted equally from both electrodes, and each is flattened or hollowed out slightly into a crater. The electromotive force, that is to say, the "virtual" electromotive force, measured as will be described in the proper place, is less than that required for the same length of arc with continuous currents, since the maximum E.M.F. attained during the alternations considerably exceeds the virtual (generally by 40 to 50 per cent.). A virtual E.M.F. of about 30 volts is most commonly used, so that three arc lamps may be connected in series across mains having a constant difference of potential of 100 volts, a small regulating resistance, or choking coil, absorbing the remaining 10 volts. With solid carbons the arc is liable to become very unsteady, wandering round the edges, but with both carbons cored this wandering may be prevented. Any regulating mechanism suitable to continuous currents can be used for alternating currents, save that the solenoid cores require to be laminated, and a different adjustment made.

The luminous intensity varies very greatly during an alternation as the E.M.F. and current vary in magnitude. This variation will be quite imperceptible to the eye, owing to the extreme rapidity, but it may be shown and measured by causing a screen to revolve synchronously with the alternator supplying the arc, in such a manner as to cut off the light except at regular periods, corresponding to various phases of the alternations. The heat of the arc is, however, not radiated with sufficient rapidity for it to cool and break during the short periods while the E.M.F. is lower than that required to maintain it.

Dr. Fleming, in the course of an investigation of the effect of the shape of the alternating current curve on the variation of luminosity and efficiency of the arc gave the following figures, which will show the relative efficiencies of the continuous and alternating current arcs.

I. *Continuous Current Arc.*

	Carbons {positive 15 mm. diam. cored. nevative 9 mm. diam. solid.				both 15 mm. cored.	
Power in watts	582	380	299	215	607	313
Mean spherical c.-p.	675	455	372	181	562	344
E.M.F.	56	44	36	26	60	40
Current	10.6	8.7	8.1	8.2	10.0	8
Length of arc (mm.)	7.15	2.5	7.	0.	8.07	.61

II. *Alternating Current Arc.*

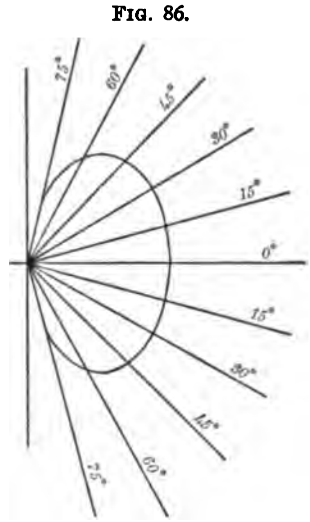
	Carbons 15 mm. diam. both cored. Frequency 83 alternations per sec.					50 alternations.		
Power in watts	601	501	404	305	233	596	459	307
Mean spherical c.-p.	307	274	256	250	144	526	322	254
E.M.F.	35.5	34	28	21	15.3	39	31	22
Current	16.2	15.1	15.1	15.1	15.4	16	15.1	14.6
Length of arc	6.28	—	1.25	.16	.01	.7	—	—

From these figures it may be deduced that the efficiency of the alternating current arc is much lower than that of the continuous current. With long arcs the mean spherical candle power for the same number of watts absorbed is only about half as great in the former, with a high rate of alternation, but with a shorter arc the difference is not so great. With a slower rate of alternation the efficiency appears much higher, and compares well with that of continuous currents.

The distribution of the light is much more uniform, as shown in Fig. 86 the light sent in a horizontal direction being not far from the maximum. For this reason alternating currents are commonly preferred for search-lights, lighthouses, and like purposes.

The relations between the E.M.F., current, and length of the electric arc, or in other words the modification of Ohm's Law applicable to the electric arc, are naturally complicated by the fact that the conducting belt of volatilised carbon is created and maintained by the current itself, and therefore varies in sectional area according to the current. The equivalent resistance of the arc gap depends on the material of which the carbon elec-

FIG. 86.



Distribution of Illumination with an Alternating Current Arc.

trodes are made, their size and shape, and also to some extent on the current already established in the arc. Exact measurements of the simultaneous values of the E.M.F. current and arc-length require to be made with extreme care in order to obtain consistent results, and properly to investigate the laws of their variation.

A comprehensive series of such measurements have been published and discussed by Mrs. Ayrton in the *Electrician*, vol. xxxiv. (January 11, 1895, and succeeding numbers), to which reference may be made for more complete information on this part of the subject. The current was supplied from a secondary battery, and the current and length of arc kept constant for a considerable period before measurements were taken, in order that the carbon ends might have time to assume a shape appropriate to the length of arc. Without this precaution the results were most inconsistent, and different simultaneous values of the E.M.F. and current could be obtained for the same length of arc immediately after being changed in value. The difference of potential was measured between carbon contacts touching the carbon electrodes close to the arc, and the length of the arc itself measured by means of the magnified image thrown on a white screen. In measuring the length of arc the vertical distance between the lowest point of the positive and the peak of the negative carbon was taken, so that, owing to the formation of the crater in the former, the true length of the arc-gap slightly exceeded the measurement, and an arc of zero length represented, not contact of the carbons, but the condition that the peak of the negative was on a level with the edge of the crater in the positive carbon.

Different sizes of carbons such as are used in common practice were tested in this manner, and the results illustrated by curves drawn to show the relation between the current and E.M.F. for fixed lengths of the arc. It would appear that the law of variation differs in some important respects according as a cored or solid carbon is used as the positive electrode. In the latter case a comparatively simple algebraic formula of the form

$$E = a + bL + \frac{c + dL}{C}$$

may be made to represent to a close degree of approximation the relations between E the potential difference between the electrodes measured in volts, C the current in ampères, and L the length of the arc-gap in millimetres (measured as described above), a, b, c and d being constants determined by experiment. For example with carbons 11 and 9 millimetres in diameter respectively, both solid, the following formula is given to express the triple variation,

$$E = 38.88 + 2.074.L + \frac{11.66 + 10.54.L}{C}$$

Under these conditions supposing the current to be maintained constant, say at 10 ampères, the difference of potential will rise uniformly as the length of the arc increases, the formula reducing to

$$E = 40.54 + 3.128.L$$

or an increase of over 3 volts per millimetre with this current, and a greater rate of increase with a smaller current. This will be seen later to be the required condition for regulation with a shunt solenoid.

If the conditions of supply be that a constant difference of potential be maintained between the electrodes, say 50 volts, the current will be given by

$$C = \frac{c + d.L}{E - a - b.L} = \frac{11.66 + 10.54.L}{8.12 - 2.047.L}$$

a length of a little over 3 millimetres giving a current of 10 ampères, and in all cases the current will increase when the arc increases in length. This is the very opposite to the condition required for regulation by means of a solenoid in series with the arc, a decrease of the current as the carbons are consumed being necessary in practice. A constant difference of potential between the electrodes is therefore inconvenient, but with a supply at constant E.M.F. we can still obtain the required condition of a falling current as the arc increases in length by the insertion of a small "regulating" resistance in series with the arc. This additional resistance would be necessary to prevent the rush of current which would take place when the lamp was first switched on while the carbons are still in contact, and is partly supplied by the series solenoid and the carbon rods themselves. Suppose that some additional resistance be added, making the total added to that of the arc itself about one ohm. The E.M.F. in the circuit will be required to be raised about 10 volts (for a 10-ampère lamp), with a corresponding waste of power, to allow for the fall of potential in the added resistance, but an increase in the current can now no longer follow upon an increased length of arc, for the former would involve a greater fall of potential in the added resistance, and therefore a lower difference between the electrodes.

To see that the inverse effect, a fall of the current as the length of the arc-gap increases, is actually produced, we must notice that the difference of potential between the electrodes is E − C.R, where E is the E.M.F. of the circuit, and R the added resistance. The current will be given by the quadratic equation

$$C^2R - C(E - a - b.L) + c + d.L = 0$$

giving two possible values for the current, the greater of which will be established when the carbons are separated from contact. Taking the same values of the constants as above, and the E.M.F. in the circuit as 60 volts, the quadratic becomes (when R = 1)

$$C^2 - C(21.12 - 2.074.L) + 11.66 + 10.54.L = 0$$

which gives us for L = 2 the values 14.7 and 2.3, for L = 2.5 the values 13 and 3, and for L = 3 the values 11 and 4 very nearly. Since the higher values in each case will be assumed by the current, as the arc burns away the carbons the current decreases under these conditions. With this E.M.F. in circuit, and resistance of one ohm added, the maximum length of arc possible is about 3½ millimetres.

The effect of using a cored carbon for the positive electrode is to reduce the difference of potential between the electrodes by 5 or 6 volts, at any rate for the longer arcs. With a constant current the difference of potential between the electrodes increases with the length of arc, and for arcs longer than about 2 millimetres, or about a tenth of the diameter of the carbons, a smaller difference is, as with solid carbons, necessary with a larger current. For shorter arcs the difference of potential seems to rise with the current, but this is very probably due to the greater hollowing out of the crater in the soft core, which makes the true length of the arc somewhat longer than is given by the method of measurement employed. With difference of potential less than about 42 or 43 volts, and an arc length always less than the critical value of about 2 millimetres, it seems that the current will decrease as the arc lengthens, but these lengths would be inadvisable in practice, and the arc subject to extinction on a slight fall in the E.M.F. supplied, or over extension of the arc. For greater length the conditions are as before, and an added "regulating" resistance is necessary for parallel working.

From measurements taken with carbons 13 and 11 millimetres in diameter respectively, the former, or positive, being cored, the following values of the current are deduced. With an E.M.F. of 55 volts in the circuit, and a resistance of one ohm added to that of the arc, a length of 2 millimetres should give a current of about 14 ampères, of 2.6 a current of 10 ampères; and the maximum possible length of arc should be about 3 millimetres. With an E.M.F. of 60 volts, and the same added resistance, the currents should be 15 ampères with a length of 3 millimetres, 12.5 ampères with 4 millimetres, 10 ampères with 4.7 millimetres; and the maximum length of arc about 5 millimetres.

Regulating Mechanism.

Before the regulating mechanism of arc lamps had been developed so as to give satisfactory results, efforts were made to do away altogether with the necessity for such mechanism, or at least to simplify the motion of the electrodes, by placing the carbons otherwise than in the same line. The first of these was known as the Jablochkoff "candle," invented by M. Jablochkoff in 1876. The two carbon rods were placed side by side, and separated by a thin layer of insulating material which burnt away with the carbons. For the latter purpose kaolin was at first employed, but this was found to melt and form a liquid conductor between the two carbon points, which carried the current so that a true electric arc was not maintained; the luminosity of the kaolin under these conditions suggested the semi-incandescent Lampe-Soleil which has been described in the chapter on Incandescent Lamps. Subsequently a mixture of equal parts of sulphate of calcium and sulphate of barium, was employed, which was found to volatilise more completely at the high temperature of the arc. A fine strip of plumbago connected the extremities of the carbon, allowing an initial current to be started, the arc being formed as soon as this was burnt away; subsequent lighting in the event of extinction of the arc being effected by touching the extremity of the candle with a piece of carbon or wire. When continuous currents were used it was necessary to use a larger carbon rod for the positive electrode to equalise the rate of consumption, but more satisfactory results were obtained by the use of alternating currents with carbons of equal section. The diameter of the carbon rods employed was four millimetres, the length twenty-five to thirty centimetres, and thickness of the separating material three millimetres. Several candles were arranged in the same lamp with an automatic or hand switch so that they might be consumed in succession, each lasting from an hour and a half to two hours.

Wilde produced a more efficient electric candle by doing away with the intervening strip which separated the carbons, placing them side by side at a distance of three millimetres, but balancing the holder of one of the carbons on a pivot so that it became inclined till in contact with the other carbon, unless held apart by the attraction of an electromagnet with a magnetising coil in series with the arc. The necessary initial contact of the carbons was thus automatic, and as the carbons were vertical, the heat of the arc as well as the magnetic field created by the current flowing up and down the carbons prevented the arc from descending from the upper extremity of the candle. In order to invert the candle, obtaining the arc at the lower extremity of the carbon rods, Jamin surrounded the whole lamp with a coil wound in a vertical plane, the magnetic field of which caused the arc to be impelled downwards, according to the principle that a conductor carrying a current tends to move transversally to the lines of force. Debrun improved on the starting device of Wilde, that of inclining one of the carbons to obtain initial contact, by making an automatic short circuit between the carbons near the holders, thus starting an arc which was immediately carried to the extremity by heat and magnetic impulsion.

Rapieff in 1878 devised an extremely simple means of maintaining the requisite length of arc by duplicating both positive and negative carbons, and inclining the two positive, and also the two negative, at a slight angle to one another. Each carbon rod being guided in its own line, two similar carbon rods are forced by springs or by their weight to advance towards the point where these directions intersect, and can advance no further, except as they are consumed at this point of intersection. The intersections of the lines of motion of the positive and negative carbons respectively are separated by such a distance as will give the requisite length of arc. The initial contact is made by the descent of the holder of the two positive carbons, and subsequent separation by a series-wound electromagnet. In Rapieff's lamp one pair of carbons was placed vertically above the other pair; in a subsequent improvement by Gerard each pair pointed downwards, being inclined to the vertical, and meeting at a similar angle to that between the two positive, or two negative rods, thus allowing more freedom for the diffusion of the light. Alternating currents were used for both of these types of lamp.

It will be clear from the preceding discussions that the functions of the automatic mechanism of an arc lamp are these: (1) To allow or cause the carbon electrodes to come into contact, either immediately the current through the arc ceases, or directly a difference of potential between is produced; (2) to separate the electrodes from contact a short distance immediately a current passes, or, as it is termed, to "strike" the arc; (3) to maintain the required distance of two or three millimetres between the electrodes by allowing them to slowly approach, or "feed" as their ends are consumed, in general arranging that each electrode should move in proportion to the rate at which it is consumed so that the arc may remain in the same position at all times.

The number of devices employed for securing these ends have been innumerable. Those which have survived and been most extensively used seem to have excelled, not so much in their intrinsic value and ingenuity, as in the care that has been exhibited in their construction. The chief merit of any device is its relative simplicity, which will enable it to be attended to for cleaning or adjustment by unskilled persons, and be worked for long periods with the minimum of attention. Often placed in exposed situations, the works should be such that they are little affected by the inevitable entry of damp and dust, durable, and free from wear in the delicate parts. Perfection in adjustment is in most cases of less importance than certainty of action at all times in spite of unskilled handling.

Time-regulated clockwork might regulate the feed of the electrodes with absolute uniformity, and might be efficient if the exact rate of consumption of the carbon were known. But as the latter would vary with slight variations of the current, some further control would be necessary, and the striking and primary adjustment of the arc-length otherwise effected. Moreover, all clockwork, unless of the most elementary nature, is objectionable owing to the impossibility of excluding dust. Purely mechanical regulation of the feed has been used with arc lamps in lanterns, the striking being effected by hand. For this purpose the carbons are restrained from feeding by steel pointed stops pressing against them near the arc, past which they slip when the carbon has worn away sufficiently owing to the proximity of the arc.

The only satisfactory methods of automatic regulation are those in which the length of the arc affects the motion of the electrodes indirectly through the consequent values of the difference of potential between them and the current through the arc. A coil of thick wire and few turns placed in series with the arc, thus carrying the whole current that passes through it, produces a magnetic field of proportional strength. This magnetic field can be made to produce mechanical effects, the tendency of which must be, directly or indirectly, to separate the electrodes or strike the arc, and to check the motion of feeding. A coil of fine wire, with many turns and a high resistance, connected as a shunt circuit between the electrodes, will carry a current proportional to difference of potential between them, and the mechanical effects produced by its magnetic field must be made to tend, directly or indirectly, to oppose those of the series coil, limiting the striking of the arc and permitting or causing the feeding of the carbons together.

One of these regulating factors, the difference of potential or the current, must be kept constant by the conditions of the supply of power while the lamp is burning. The most satisfactory condition is that of constant current, under which the series coil has no longer any regulating power, its action being unaffected by the length of the arc, and is useful solely as an agency for striking the arc, and sustaining it until the cessation of the current demands a renewed contact. Upon the shunt coil we must depend for the regulation of the feed, and as the difference of potential will rise uniformly with the increasing length of the arc, its action will be effectual if it cause the feeding to commence when the current in it exceeds a certain value.

If the condition of supply be that of constant E.M.F., and the shunt coil were thus connected between mains maintained at a constant difference of potential, its regulative properties would cease to exist, and we must depend solely on the series coil. The latter will be available for striking the arc when the lamp is switched on, but if it be also required to cause or permit the feeding when the arc exceeds the permitted length, the feeding must be consequent upon a decrease in the current. Now it has been shown that with a constant difference of potential between the electrodes, a decrease in the current does not ensue when the length of the arc increases, in fact, the reverse is generally the case; but if a small resistance (of an ohm or so) be placed in series with the arc, and constant E.M.F. maintained in the combined circuit, the current will decrease as required. A shunt coil, though not absolutely necessary, may now be used to assist regulation if connected between the electrodes, that is, not including the additional resistance, for the decrease in the main current will cause a smaller fall of potential in the additional resistance, and therefore higher difference of potential between the electrodes, giving a larger current in the shunt coil, which may thus assist the series coil, if opposed to it, in promoting the feeding.

The simplest method of producing mechanical motion through a limited range by an electric current is to cause it to create a magnetic field varying in intensity at different points, so that a piece of soft wrought iron placed in the field is magnetised by induction, and tends to move towards the stronger part of the field. This is more suitable to our purpose than the attraction of permanently magnetised steel, as is used, for example, in the galvanometer, owing to the possibility of demagnetisation. A coil wound in the form of a solenoid will attract a wrought iron cylinder, sucking it into the interior of the coil. As the cylinder, or "core," enters the coil, the attracting force will increase till it reaches a maximum at some point when the core is half in and half out of the interior of the coil, and thence will decrease until eqilibrium is attained when the core is wholly within the coil. The magnitude of the pull varies roughly as the square of the strength of the current in the coil when it is not sufficient to give saturation of the magnetism of the core, the relation reducing to variation directly as the strength of the current when the magnetism of the core approaches saturation.

Another method adopted in some designs is to use a fixed iron core for the solenoid, which becoming magnetised by induction, attracts a small "armature" or block of iron. This allows more attractive force to be exerted for the same number of ampère turns than the former method, but a smaller range of motion.

A simple form of electric motor has also been used, arranged to drive in one direction when the main current exceeds a normal amount, separating the electrodes, and in the reverse direction with an excess current in the shunt circuit, causing the electrodes to approach or feed. Also reversing gears controlled so as to produce a similar result when driven by a unidirectional motor or clockwork. But these methods involve a departure from simplicity, and therefore certainty and durability, which has prevented any great success.

The simplest form of solenoid-controlled action for the regulation of the length of arc is that in which a movable core is rigidly attached to the upper or positive carbon-holder, and arranged to be lifted by the attraction of the series coil, and depressed by that of the shunt coil. The core and carbon-holder will then be lifted, striking the arc and lengthening it until a balance is obtained between the attractions, except for an excess of the attraction by the series coil sufficient to support the weight lifted. The condition of equilibrium will then be that there should be a certain relation between the currents in the series and the shunt coils, which may be adjusted to correspond to that given by the current and difference of potential with the required length of arc. The difficulty with this simple arrangement is that the position of the core relatively to the solenoids must vary as the carbons are consumed, so that the same currents do not produce the same pull, a different relation between them will be required for equilibrium, and a different length of arc result.

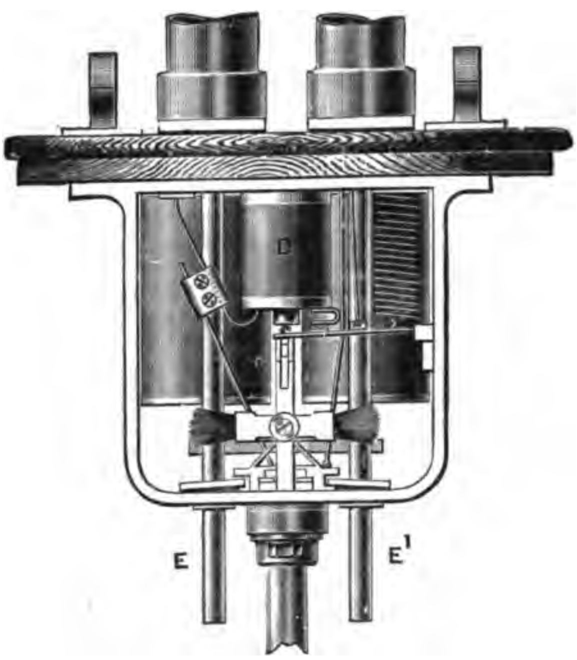
In the Pilsen arc lamp the difficulty is overcome by the use of conical instead of cylindrical cores. The attractive force on a cone of iron entering a solenoid may be made constant throughout a considerable range of motion if the current be unaltered. The two coils may be counterwound on the same bobbin, so that the current in the shunt coil reduces the attraction of that in the series until it is just sufficient to support the weight lifted. Or a double cone (torpedo-shaped) may be used, balanced between an upper series coil and a lower shunt coil, the upward pull of the former being resisted by the downward pull of the latter, equilibrium being obtained by the same currents in all positions of the core, which must necessarily descend if these currents are to remain unaltered as the carbons are consumed, these currents depending on the length of the arc.

To keep the position of the arc constant as the carbons are consumed, it is necessary to permit the lower or negative carbon to ascend as the upper or positive descends. If the sectional area of the latter be half that of the former the rates of consumption will be equal, and the simple device of connecting the holders by a cord passing over a pulley, and allowing both free vertical motions with this sole constraint, will be sufficient, but we must take precaution that the weight of the descending parts should exceed that of the ascending, so that the carbons may fall into contact when the lamp is switched off ready for striking the arc when the supply is renewed. When carbons of equal sectional area are used, some arrangement of pulleys or gearing must be employed giving only one half the rate of movement to the negative carbon-holder that it does to the positive.

In other arc lamp mechanisms the attracted core (or cores) is not connected rigidly to either of the carbon-holders, but by means of a clutch, brake, or other such device, obtains a temporary grip, which it releases and renews at frequent intervals at a slightly different point. Thus, while the series and shunt solenoids attract a core, or pair of cores connected together, so as to permit of only a very limited range of motion, the latter controls the motion of the electrodes through a considerable range. As before, the attraction of the shunt solenoid must oppose or weaken that of the series; an excess of current in the latter must cause the core system to grip the holder system and further separate the electrodes: an excess of current in the latter to cause the electrodes to approach, and a still further excess to release the grip. By their own weight, or a spring, or like means, the electrodes must of themselves tend to approach or feed when the grip is released, a renewed restraining grip being taken by the core system when the length of arc has decreased somewhat during the short period of release. These are the essential principles common to a very great percentage of arc lamp mechanisms, of which a few typical examples will now be selected for description.

One of the simplest as well as the oldest surviving types is the Brush arc lamp, the mechanism of which is illustrated in Figs. 87, 88. The shunt and series coils are counterwound so as to form a pair of solenoids **C**. These attract a pair of cores united by a cross bar **B**, which can move vertically so as to raise or lower a lever to the end of which it is attached. The motion of the lever is steadied by a dash-pot **A**, and the weight of the cores balanced by a spring which adjusts the force of attraction necessary to lift the lever. Near the fulcrum of this lever a link is attached which supports and actuates the clutch. The type shown is the double carbon lamp, having two pairs of carbons, which are consumed in succession, the arc being formed between one pair only at first until they are consumed, and then transferred to the other pair in the manner shown below. The positive carbon-holders alone move, so that the arc is "non-focusing," that is, changes its position as the carbons are consumed. These holders are attached to long vertical rods **E** E^1, which are pushed up into chimneys at the top of the framework when the carbons are inserted, and

FIG. 87.

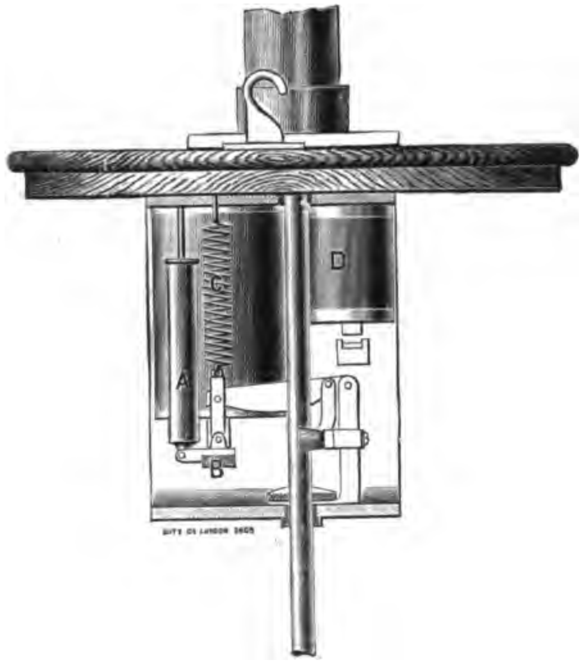


The Brush Arc Lamp.

descend as they are consumed. The current is conveyed to them by fine wire brushes, but as it would be difficult to insulate them from the framework of the lamp, it is customary in this and nearly all types of arc lamps to allow the whole framework of the lamp to remain at the potential of the positive carbon-holder, insulating the terminals and negative holder from them, and to suspend the whole lamp from an insulating support. The negative carbons are supported by the central pillar, of which only the upper part is shown in the figure.

The clutch arrangement consists simply of a fork engaging with a loose ring or washer upon the carbon rod, fairly clearly shown in Fig. 87. The raising of the regulating lever lifts the fork, tilting the washer, and so getting a grip, raises the positive carbon rod and strikes the arc. As the arc lengthens and the pull of the solenoids weakens, the washer is lowered until it comes into contact with the framework, and thereby the tilt is lessened till the rod slides through. The fork clutch is again raised to grip the rod when the arc length has decreased very slightly, and if the action be very quick, there will be no need for the washer to be again raised, as when the carbons are first separated from contact, but with slight variations of the tilt while still in contact with the frame, the rod will be allowed to slip through the washer by frequent and almost imperceptible steps, the consequent variations in the arc length being only detected by close observation. In the double carbon lamp here illustrated the washer on one of the rods is made a trifle looser than the other, the grip on the latter being in consequence effected somewhat earlier than on the former, and thus the corresponding carbons are separated first without forming an arc, and held apart till the other pair are consumed. It is arranged that the positive and negative carbons should be of such relative length and sectional area that

FIG. 88.



The Brush Arc Lamp.

they should be consumed simultaneously to within about an inch of the holder, and then a stop should prevent further descent of the rod, so that the arc lengthens and finally breaks. The second pair then come into contact and an arc is struck between them, which continues until this pair is also consumed. If the arc lamp is burning on a parallel circuit a stop on the second positive carbon rod extinguishes the lamp by breaking the circuit, and the lamp requires "trimming" or insertion of new carbons. But if it be in series with other lamps the circuit must be maintained, or the other lamps will also be extinguished. The circuit is still complete through the shunt-coil, but this being wound with fine wire only calculated to carry a small current of about one-third of an ampère, it will be speedily burnt up. To prevent this happening we require an automatic device which will short-circuit the lamp when the current through the usual path ceases, or if the regulation of the supply would be interfered with by a short-circuit, an equivalent resistance (or about 5 ohms) may be substituted.

Upon the cessation of the current in the arc there will be a rush of current through the shunt-coil, this reversing the magnetism in the cores so that they are pulled up with some violence, and this violent lifting of the cores may be made to strike up the spring-balanced lever shown in Fig. 88, establishing a contact which short-circuits the arc. It is advisable that this short-circuit should be automatically released when the supply is cut off, so that it need not be replaced by hand when the lamp is trimmed. As the current in the shunt coil will cease directly the short-circuit is established, the contact is maintained by the attraction of a small solenoid D in series with the short-circuiting lever, acting on a core attached to its extremity, which allows it to fall away directly the supply ceases. Some arrangement similar to this is necessary for all types of lamps used in series distribution, preventing a break in the circuit, or injury to the lamp, in the event of the arc breaking through the consumption of the carbons, or failure to feed.

The washer-clutch is an exceedingly simple device which works very well as long as the rods are clean, but the rods are rather liable to stick when foul, and when released to slip too rapidly through the washers and "overfeed." Various improved forms of clutch have been designed, but the motion of the rods is so very gradual (at most an inch and a half per hour), that perfect steadiness can scarcely be expected when the clutch is applied direct to the rods. Brockie has succeeded, however, in preventing the possibility of over-feeding by the use of a slightly conical rod, of which the ever-largening diameter at the point where it is gripped requires a still further descent of the cores before the rod can slip more than an extremely minute distance.

In most other forms of arc lamp regulating mechanism the motion of the rods is greatly multiplied by some simple gearing so as to be much more rapid at the point at which the clutch or brake is applied. The favourite form is a large brake-wheel revolving in conjunction with a small pinion which is in gear with a rack rod which is the positive carbon-holder; or else the rods are supported by flexible cords passing round a small pulley revolving with the brake-wheel. The main difference between these types will lie in the different methods adopted to reverse the motion, so as to strike the arc; for this is the main difficulty, the feeding being governed with any degree of steadiness that may be desired by sufficient multiplication of the motion, and the balance between the descending and ascending parts being arranged to ensure feeding, without the possibility of sticking, when the clutch or brake is released.

The latest design of the Brockie-Pell arc lamp mechanism, the same general principle having been employed with numerous changes of detail, is illustrated in Figs. 89 and 90. The coils are wound as separate solenoids, attracting cores on opposite sides of a rocking lever. The carbon rods are suspended by separate flexible cords, wound round pulleys rotating with a large brake-wheel. The brake-wheel has a broad flange on one side, against the inner surface of which a small leathern pad is pressed to check its rotation and thus regulate the feed. This pad is mounted on a short weighty lever, which is pivoted on the extremity of a second longer lever, the other extremity of which is screwed to a flat horizontal spring, which supports it, taking the place of a fulcrum. The weight of the short lever causes the pad to press against the interior of the flange of the brake-wheel when the long lever is slightly raised, but on the descent of the fulcrum the pad is lifted off by an adjustable stop which tilts the short lever. The levers are raised or lowered by a long rod attached to the rocking lever near the fulcrum on the same side as the series coil. When the current is first switched on the carbons being in contact, the connecting rod is lifted

FIG. 89.

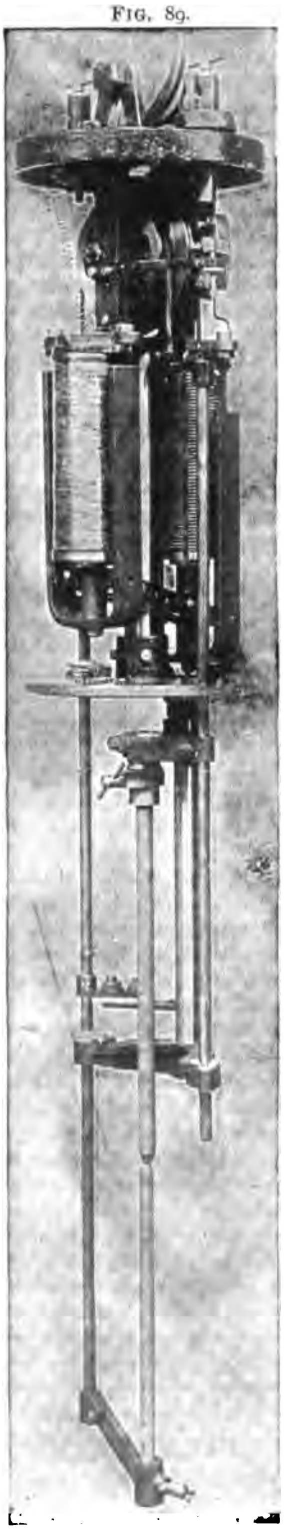
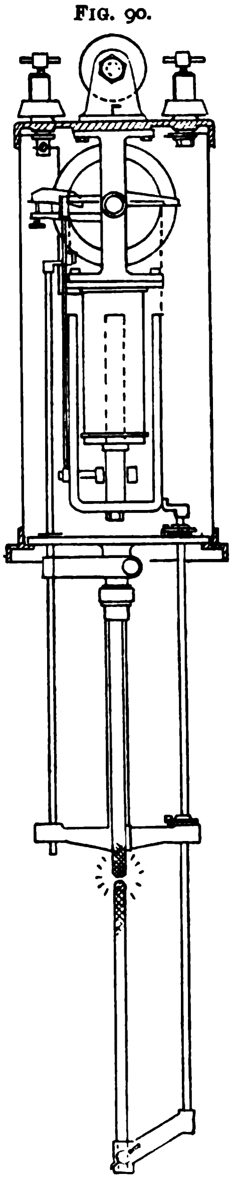


FIG. 90.

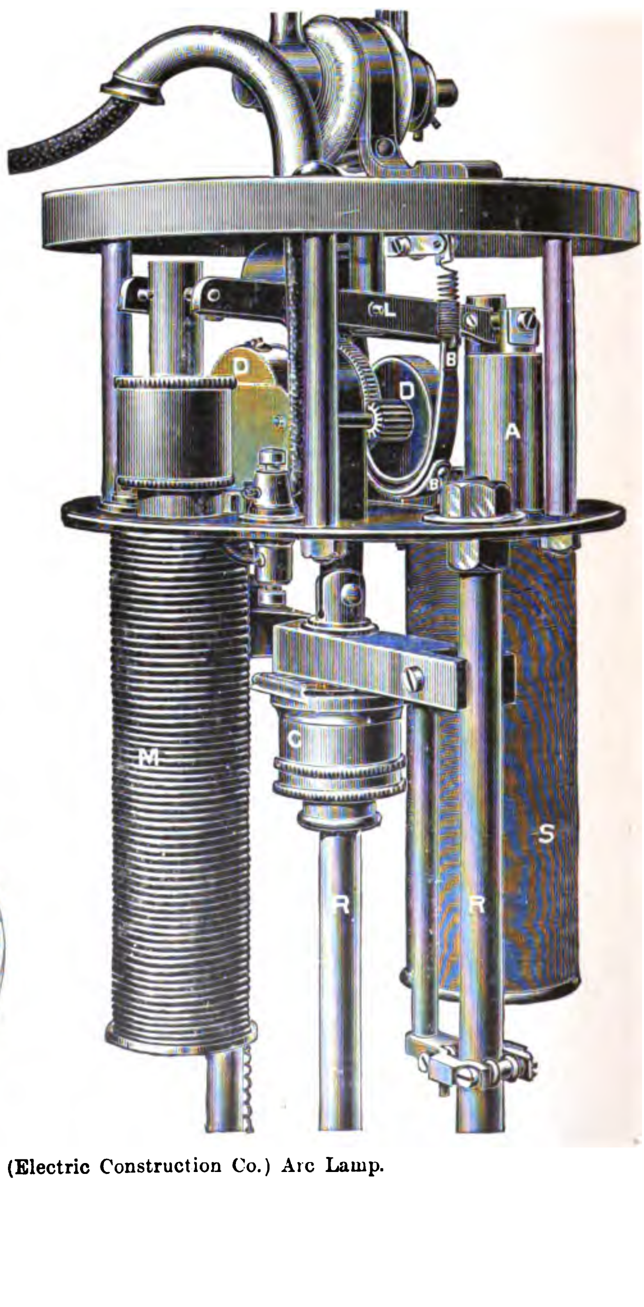


Brockie-Pell Arc Lamp.

until the brake-pad touches the brake-wheel, and then on further rising the short lever is lifted off the stop and carries the brake-wheel round for a short distance till the carbons are separated sufficiently. Only a small motion in this direction would be possible, owing to the limited motion of the solenoid cores and the levers. The motion in the opposite direction, that of feeding, consists in the descent of the levers with the brake-wheel till the stop causes the release of the latter, which slips round allowing the rods to approach by a minute amount before the brake is again applied.

FIG. 91.

FIG 92.



E.C.C. (Electric Construction Co.) Arc Lamp.

The lamp manufactured by the Electrical Construction Company (E.C.C.) is shown in Figs. 91, 92. The solenoids are here inverted, so that the mechanism of the lamp is very compact. The positive carbon-holder is suspended by a double copper tape coiled round a drum **D**. The latter is geared by cogwheels to a more rapidly rotating brake-wheel. Two brake-blocks are applied to the circumference of this, attached to a band, one end of which is supported by a spring and the other by the rocking lever **L** near the fulcrum. The extension of the spring allows a slight rotation to be given after the brake-blocks are applied, thus striking the arc. The subsequent release of the brake allows the rotation of the brake-wheel, and the descent of the positive carbon rod, the negative rod ascending proportionally. The spring also adds to the sensitiveness of the feed. An *inverted* dashpot **A** secures perfect steadiness.

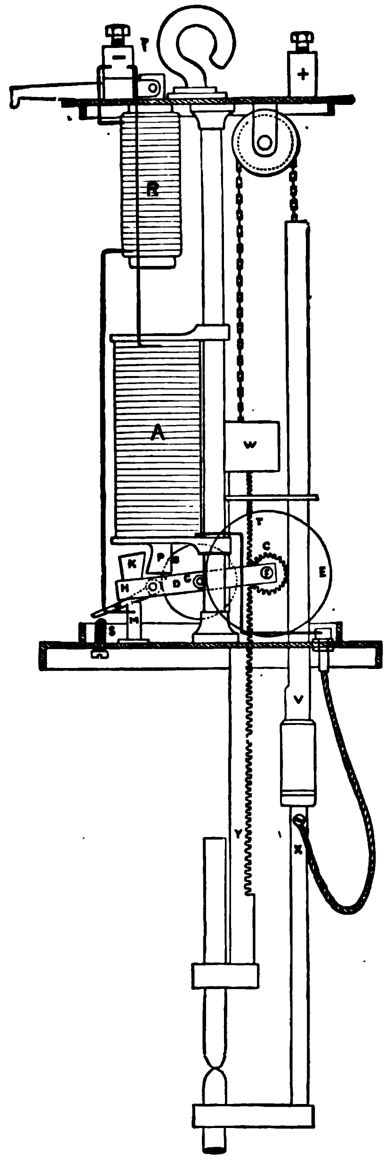
FIG. 93.

Crompton-Pochin Single-carbon Arc Lamp.

The Crompton-Pochin arc lamp (Fig. 93) mechanism resembles the preceding in the arrangement of the solenoids and rocking lever, differing mainly in the manner of striking the arc. The positive carbon rod is a rack-rod gearing with a small pinion rotating with the brake-wheel, to the circumference of which a small brake-pad on the rocking lever is applied from underneath. To strike the arc this brake-pad lifts the brake-wheel, pinion, and rod bodily, rotation of the first-named being of course impossible until it descends once more to the "feeding" pin which supports the axle, and the release of the brake-pad from its periphery allows it to rotate and the carbons to feed. To balance evenly the parts thus lifted, a double brake-wheel is used, as shown in the illustration. In the double-carbon lamp, the "feeding-pin" of the pair intended to be consumed first is set rather higher than that of the other pair, so that the latter may be the first to separate.

The "Phœnix" arc lamp mechanism (Patterson and Cooper) is illustrated in Fig. 94. The shunt and series coils are counter-wound, so as to form one solenoid **A**, and have a fixed soft iron core **P**, which attracts an armature **K** upon the brake-lever **H**. The brake-wheel **B** is pivoted upon this lever, and connected to a small cogwheel **G**, which gears into the large wheel **E**, which acts as an intermediate gear wheel between the brake-wheel and rack-rod, giving a high rate of multiplication for the motion of the former. The revolution of the brake-wheel is checked by the lever **N**, which applies a brake to its circumference when the armature-lever is raised. The brake is released when the armature-lever pulls so that the brake-lever is supported by the screw **S**. The further raising of the armature-lever after the brake is applied strikes the arc; the feeding subsequently proceeds as the brake is released by the fall of the armature-lever. The failure of the circuit through the arc causes the lever **H** to fall sharply upon the block **M**, and short-circuits the lamp through the resistance **R**, which may or may not be sufficient to form an equivalent resistance (5 ohms) to that of the arc, but must be sufficient to allow a large current to pass in preference through the carbons when closed together, so that the lever may be initially lifted and the arc struck when the lamp is trimmed.

FIG. 94.



ne Phœnix Arc Lamp.

The Siemens "Band" arc lamp is illustrated in Figs. 95, 96 and differs from all of the preceding in employing a shunt-wound solenoid only, having a fixed core and attracted armature. The frame *i* which carries the upper positive carbon of the lamp is suspended by a conducting metal "band" *k*, wound round the circumference of the barrel *b* mounted on a horizontal axis *d*, and containing a volute or coiled spring so arranged that the weight of the positive carbon and its frame tends to rotate the barrel

FIG. 95.

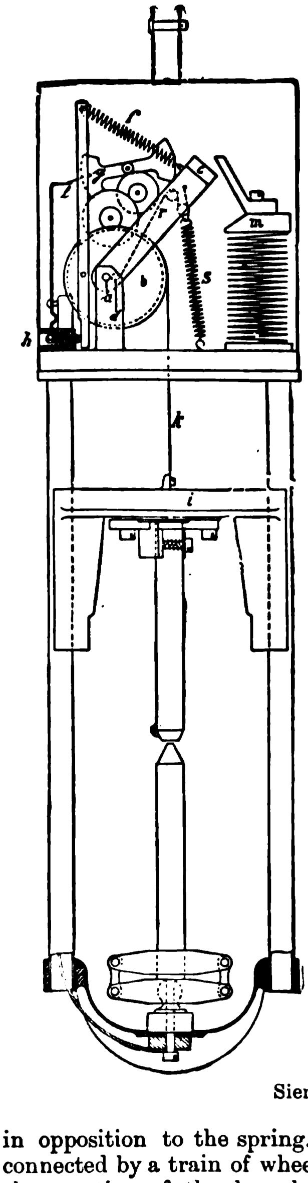
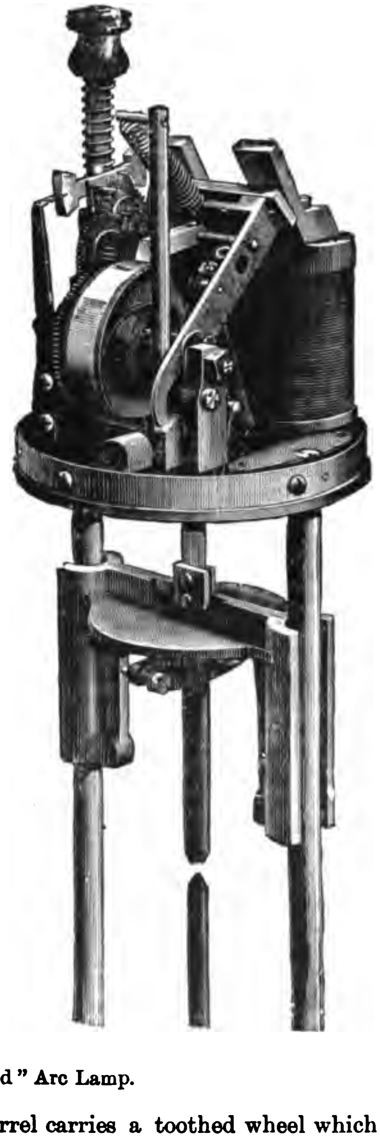


FIG. 96



Siemen's "Band" Arc Lamp.

in opposition to the spring. The barrel carries a toothed wheel which is connected by a train of wheels to an escapement and pendulum *g*, whereby the rotation of the barrel and consequently the descent of the positive carbon due to gravity is allowed to take place at a slow regulated speed. The barrel *b* with its wheelwork and escapement is mounted in a frame *r* pivoted at its lower end at a point *a* (near the axis of the barrel *d*) to standards projecting up from the lamp-base. The upper end of the frame carries an armature *c* facing the pole-piece *m* of an electro-magnet which is connected as a shunt across the terminals of the lamp. When the electro-magnet attracts the armature it draws the frame *r* downwards about its pivots, and thus lowers the barrel carried by it, and also the positive carbon with its frame *i*. The frame *r* is held back at its upper end by a spring *f* (adjustable by a setting-screw *h*), the tension of which is regulated to withstand the pull of the electro-magnet with more or less force, and which when no current is passing through the electro-magnet, holds the frame *r* in such a raised position that the movement of the escapement is arrested by the stop *l*. When the frame *r* is in this position, and the positive carbon is thus raised to such a distance from the lower or negative carbon that no arc is formed, the relatively strong current passing through the coils of the electro-magnet attracts the armature *c*, thus lowering the positive carbon until the escapement is freed from the stop *h*, whereupon the positive carbon and its frame *i* will be free to descend by gravity until it comes in contact with the negative carbon. Owing to the passage of the current through the carbons the current through the electro-magnet will be weakened to such an extent as to allow the spring *f* to raise the frame *r* again so as to arrest the escapement and raise the positive carbon sufficiently to strike the arc. A position of equilibrium is thus established by the increase of the resistance of the arc, and sufficient current passes through the shunt to cause the electro-magnet to balance the pull of the spring *f*.

As the positive carbon burns away, and the resistance of the arc increases beyond this point, the attraction of the electro-magnet overcomes the force of the spring *f* and the frame *r* is attracted, whereby the escapement *g* is released from the fixed stop *l*, and the frame *i* is lowered partly by the descent of the axis of the barrel *b* and partly by the rotation of the barrel on its axis *d*. When the resistance of the arc is thus lessened the electro-magnet becomes correspondingly weakened, and the frame *r* is raised again by the spring *f*, raising the positive carbon frame *i* and engaging the escapment with the stop *l*. In this manner the normal resistance of the arc is re-established, and the regulation of the positive carbon is governed according to the variation in the resistance of the arc itself. For introducing fresh carbons the upper carbon frame *i* is raised by hand, whereupon the volute spring in the barrel is enabled by uncoiling to turn the barrel so as to wind up the suspension band again, the train of wheels being so arranged that this can be done more or less rapidly without actuating the escapement. To compensate for the variation in weight of the positive carbon in burning away, a helical spring *s* strains a cord which is led over a pulley on the frame *r* and becomes wound on the axis *d* of the barrel as the barrel revolves, lowering the positive carbon so as to exert more and more downward strain on the frame *r* the more the carbon is consumed. Thus the spring being strained to the least extent when the carbon has been freshly introduced, its tension and consequently its downward pull upon the frame *r* will increase as the weight of the carbon decreases.

The shunt is permanently connected up to the terminals of the lamp, and, as already described, the regulation is effected by the variation in the strength of the current in it. Messrs. Siemens Brothers and Co. supply lamps of this pattern to burn with currents ranging from three to twenty-five ampères, and can adapt them for working in series of more than two or for alternating currents. The negative carbon is fixed in a holder at the bottom of the lamp framing; as this has no automatic adjustment these lamps have not a fixed focus.

The Luna arc lamp (Figs. 97, 98) is another example of the use of a pendulum escapement to regulate the rapidity of feeding. Two series and two shunt solenoids are wound on separate wrought-iron cores with large square pole-pieces. The armatures are rocking levers mounted on the same spindle at right angles to one another, so that each is normally inclined to the horizontal, but the attraction of the series solenoids and cores tends to bring one armature to the horizontal position, and that of the shunt solenoids and cores the other, thus rotating the spindle in opposite directions. To the aforesaid spindle is fixed a brass lever, which in striking the arc lifts the pendulum escapement and the positive carbon rack-rod with which it is geared. The movement of the escapement is regulated by a fork, an extension from which is free to move upwards, but

FIG. 97.

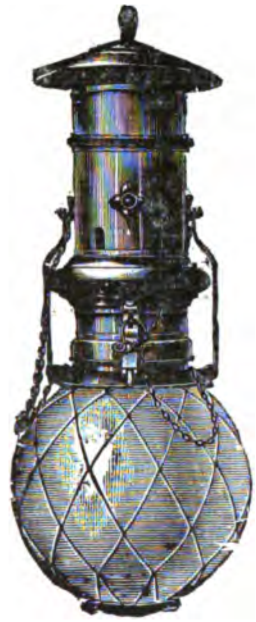
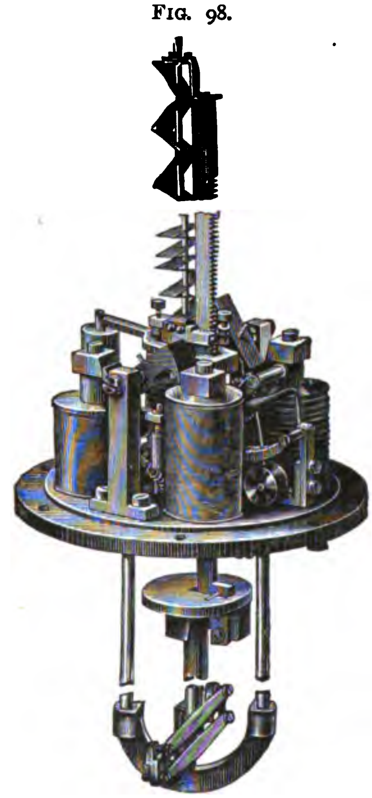


FIG. 98.



The Luna Arc Lamp.

whose downward motion is arrested on its coming into contact with an adjustable stop. In striking the arc the pendulum is locked by being pulled against the movable fork, but released when the latter descends to the regulating stop; the weight of the rack-rod causes the pendulum to swing, and the escapement allows a feed of about 0.2 millimetres for each swing of the pendulum. The connection to the positive carbon rod is made by means of a zig-zag copper strip as shown in the illustration.

There is no doubt whatever that continuous current arc lamps are more efficient than alternating current arc lamps, in whatever way the candle power be measured, whether spherical, hemispherical, or maximum, and that the disposition of the radiation in various directions is more convenient for most purposes. But for detached arc lights on circuits intended primarily for incandescent lighting, the user of alternating currents is met with fewer difficulties. First of all, since the alternating current transformer is much simpler and more efficient than the continuous current transformer, especially with small sizes, it is easy to establish a local circuit with any voltage desired, and use the lamps in series or parallel. The transformer suitable for this purpose will be one allowing a large amount of magnetic leakage, or designed with a comparatively small amount of iron; in transforming from constant potential the transforming ratio will be modified so that that in the arc lamp circuit will fall with an increase of current, and the regulative effect equivalent to the additional resistance required with the constant-potential continuous-current arc lamp.

For a single arc lamp a little over thirty virtual volts is required, and three will work well on a hundred-volt circuit. If incandescent lamps are to be used on the same circuit, instead of the transformer with magnetic leakage, the regulative conditions may be obtained by the use of a choking coil, which is simply a coil wound on an open circuit laminated electromagnet. The self-inductance of this coil takes the place of the regulating resistance with continuous currents, and possesses the advantage that the waste of energy does not correspond to the number of volts "choked-off," as a low power factor may be obtained in a well-designed choking-coil. It is possible to use a single thirty-volt lamp on a hundred-volt circuit, the choking-coil absorbing the remaining volts with little loss; but it must be noted that a supply meter, unless it is an integrating watt meter, will record the apparent, not the actual amount of energy required, and a consumer supplied from public mains may thereby be defrauded.

It will be better for a consumer supplied with, say, 100 volts for incandescent lighting, who wishes to employ one or more independent arc lights, to re-transform in the ratio of 3 : 1. The transformer for this purpose need be very small, as the transformer losses need only exist while the lamp is burning, being designed for a semi-saturated and therefore leaky magnetic circuit. Moreover, there need be but one transformer coil—it will be sufficient to bridge one-third of this coil for the arc lamp connections to obtain the thirty-three volts, and calculate the size of wire for the coil to carry one-third of the current for the arc lamp. This coil may, if desired, be subdivided at two points so as to supply three arc lamps, which will be independent of each other in every way.

Enclosed Arcs.

The cost of the carbons consumed in the electric arc form no inconsiderable part of the total expenditure in producing the illumination. Adding to this the labour and inconvenience of frequent re-trimming, it will be seen that a means of prolonging the life of the carbons is a great desideratum. From the earliest times in the history of electric lighting attempts have been made in this direction by enclosing the arc to keep it from the oxygen of the air, so as to prevent combination and allow the volatilised carbon to re-condense. In 1879 André employed an air-tight globe for this purpose, allowing the volatilised carbon to combine with the oxygen to form CO and CO_2, and thus being enclosed in an atmosphere of nitrogen and carbon gases, the life of the electrodes was greatly prolonged. With a short arc produced by E.M.F. the carbon is thrown off from the arc, and the globe speedily blackens and obstructs the light. With an arc of considerable length, maintained by a high E.M.F., very little blackening ensues, the carbon being consumed with extreme slowness and combining with the limited amount of oxygen admitted. The high potential enclosed arc was developed of recent years independently by Marks and Jandus.

Marks, after experimenting with an air-tight enclosing globe, in which the oxygen combined to form carbon gas, and the heat of the arc caused the pressure to rise within the globe, invented what he called the "ventilated" arc lamp, in which air was admitted only in very limited quantity, thereby prolonging the life of the carbons four or five times. Using E.M.F. of eighty to eighty-five volts, a current of four to five ampères, and a length of arc about one centimetre, he obtained 431 mean hemispherical candle power with 368 watts, or an efficiency of 1.17 watts per candle power. The corresponding maximum candle power was 595, thus the distribution in a downwards direction proved, owing to the free radiation with the long arc, to be much more uniform than with the ordinary arc lamp, in which the mean hemispherical is only about one-half the maximum candle power. If this be a gain, which is doubtful for some purposes, it will partly make up for the waste of power owing to the excessive E.M.F. For the same power the ordinary arc lamp would give a slightly greater value for the mean hemispherical candle power, but would throw much more light in a direction considerably inclined to the vertical, where it is the more needed owing to the greater distance of the objects illuminated.

In the Jandus arc lamp the arc is enclosed in an inner opal globe, and this again within a larger external globe. The former is close-fitting, but not air-tight, admitting air in limited quantity from the surrounding space within the latter, which is closed by a non-admission valve. Thus while the pressure within the globes cannot rise much above the atmospheric pressure, the oxygen within the inner globe combines with the carbon to form carbon monoxide and dioxide, which diffuses slowly into the external space, and is replaced by minute quantities of oxygen necessary to combine with and carry off as gas the carbon as it is slowly consumed. The negative carbon is fixed, the bottom of the inner globe being thus hermetically sealed; the positive carbon passes through a steel cap which covers the inner globe, the whole being just large enough for it to slide freely, and to be controlled by a series, or series and shunt, solenoid, working through a simple form of clutch. Owing to the great length of the arc, about nine to twelve millimetres, the regulation need be far less delicate than with the open arc lamp. The carbons are both solid, one-half inch in diameter, and lengths of 10½ and 6 inches respectively are used. According to tests of the lamp by Houston and Kenelly, the consumption of the carbons was at the rate of .057 inch for the positive, and .015 inch for the negative per hour, the current being 5.6 ampères, and the difference of potential between the electrodes eighty volts. At this rate the positive carbon would be consumed in about 150 hours, only 2½ inches of the negative being consumed in the same time. The use of a non-focusing type having a fixed negative carbon is thus justified, since the position of the arc undergoes little change. The carbon ends become flat, and the light is fairly uniform in the lower hemisphere, the maximum value in the lamp mentioned above being 1295 candle power. The lamp is used with a resistance of about five ohms in series with it, so as to be placed across a 110-volt circuit.

Search Lights.

For the large alternating current arc lamps employed for search lights hand regulation of the length of the arc is commonly preferred; for lighthouses, &c., automatic regulation is of course required, but the conditions are somewhat different from those of the smaller arc lamps for ordinary lighting purposes, in that the lamp must necessarily be under constant supervision for cleaning and correction of adjustment, and the cost of an elaborate regulating mechanism for a single large arc lamp is of comparatively little importance. Clockwork or an electromotor, with a gearing giving a great reduction in the speed of motion, and controlled by a shunt coil, is therefore suitable for the regulation of the feeding; the striking is effected by hand or by the reversal of the motor or gearing effected by the current in a series solenoid.

In the South Foreland lighthouse an alternate current arc is employed with a difference of potential between the electrodes of from 35 to 38 virtual volts. The carbon electrodes are fluted, or of star-shaped section, both cored, a pair having 60 millimetres external diameter being used in stormy weather with a current of 300 virtual ampères; in fine weather a pair having 50 millimetres external diameter are employed with a current of 180 ampères. The object of the star-shaped section is to give a larger surface for the radiation of heat from the carbons, which otherwise are heated throughout a considerable length from the extremities, as well as to centralise the arc. A short arc of one-eighth to a sixteenth of an inch is found to give the best light in a horizontal direction, though in other directions much of the light is screened by the carbons. The rate of consumption of the carbon rods is from 1½ to 2½ inches per hour. With a current of 240 virtual ampères the illumination in a horizontal direction is found to be about 16,000 candle power.

For search lights, or, as they are often called, projectors or holophotes, reflectors are now almost universally employed, having superseded the Fresnel lens, which was at one time largely adopted, the reason for this being that the latter is so liable to be injured by the heat from the arc, and is not so well suited for rough usage as the reflector; and in addition to this, the Fresnel lens could not be protected from external injury, as is the case with the mirror. A serious drawback to the use of the reflector in the first instance was that the parabolic surface, which theoretically gives a perfect result, was so difficult and expensive to manufacture. Colonel Mangin invented a mirror which got over this difficulty by having the two surfaces portions of spheres of different radii, thus making the glass much thicker at the circumference than at the centre. The rays from the arc on striking the inner spherical surface are refracted by the glass, and finally emerge in parallel directions, which renders it possible to direct the beam upon objects at a much greater distance from the light than is the case when a simple spherical surface is employed.

CHAPTER XVI.

Central Station Economy.

In this chapter we shall deal with the various sources of power available for conversion into Electrical Power for lighting purposes, briefly noting their suitability for the purpose and their economic possibilities. The various causes of waste and inefficiency attending the employment of the various sources, and the conversion into the Electrical Power will be investigated, and the directions in which these may be reduced. Thus we shall be able to compare the actual cost in practice of producing the electric light with that theoretically possible.

That the greatest economy in the generation of power is to be obtained where that power is generated upon the largest scale may be considered an axiom. It is true of nearly all undertakings that the larger the scale upon which they are conducted the smaller the percentage in expenses of management, &c. and the higher the possibilities of efficiency. This is peculiarly the case in the supply of power for electric lighting, where attendant labour forms a very large proportion of the current expenditure, and within a certain limit, larger plant gives higher efficiency and entails a great decrease in the proportion of cost in labour and materials. It is therefore quite certain that the highest economy will be attained by concentration of the generating source, and the supply of power from a "central supply station."

The last few years have been a time of great activity for electrical engineers and capitalists in the establishment of such stations. The possibility of supplying energy for electric lighting at a cost which at present competes with and offers possibilities, when conducted upon a larger scale and with improved systems, of eventually underbidding other sources of illumination, has at length been satisfactorily demonstrated. Where such undertakings have been organised by companies, with privately subscribed capital, a few years have, except in a few cases, placed them on a sound dividend-paying basis, and the disasters that arose from premature speculation are now things of the past. The progressive tendency of local governing bodies in the British Isles has, however, fortunately caused them to undertake the supply of electric lighting for the benefit of their respective municipalities in a very large number of cases, and the results have been almost uniformly satisfactory to the consumer and the ratepayer.

In seeking the best system for the supply of electric power over an extensive area, it is the duty of a consulting engineer first to seek for the peculiar advantages, if any, which may be secured by properly choosing the position of the generating-station. It is obvious that for economy in distribution the most central position is the most advantageous. But this advantage will in many cases be counterbalanced by the cost of land, carriage of fuel, and the inconvenience and bad appearance of a lofty chimney in the centre of a town or city. If water-power or any other source of energy be available which does not demand the consumption of fuel, it would be most foolish to neglect its use. Where the distance of the fall from the area of distribution is great, or considerable capital expenditure is demanded for its utilisation, it will be necessary to consider whether the interest on the excess in the capital expenditure over that of a fuel-consuming station would be greater than the corresponding cost of fuel. Even a very limited and irregular source of water-power may be worth securing, to be supplemented by steam-power at such times as it is unable to sustain the required load. Next, if water can be obtained in sufficient quantities as to be available for condensing purposes, such an advantage is worth considerable capital expenditure. With engines running at variable loads as is almost unavoidable in central station practice, the saving in fuel by efficient condensing is found to be considerably greater than in marine practice where a uniform load may be calculated upon, and may rise to as much as thirty or forty per cent. with some steam-engines. When power is to be generated by the consumption of fuel, proximity to a railway or canal is likely to save considerable expense in the carriage of the fuel.

As the subject of fuel has been very fully treated in the first volume of this series, to that volume we must refer for the scientific discussion of the relative values of various classes of fuels, and of their utilisation for evaporation, &c. This discussion must be supplemented by a few remarks concerning certain modifications that arise in the employment of fuel for the generation of electric power as demanded for electric lighting, and then we shall enter into a discussion of the efficiency of the various stages by which the energy of combustion of the fuel is transformed into energy in the form of the electric current. In the term *fuel* we here include all substances, the chemical decomposition of which is used as a source of energy. This is perhaps an extension of the ordinary meaning of the term, as it does not confine us to those which demand the intermediary production of heat in the process of power generation.

There are three methods known to us by which fuel may be consumed so as to produce energy:

(1) The direct method of producing electrical energy by the chemical action in a primary battery.

(2) The utilisation of combustion in a boiler furnace to evaporate water, and employment of the steam-engine.

(3) The direct expansion of the fuel in the form of gas after explosion when mixed with air in the cylinder of a gas or oil engine.

The first method is capable of producing the highest efficiency; that is to say, the electrical energy obtained may be made very nearly equal to the total amount theoretically possible. It is at present, however, only applicable to the chemical action of acids upon metals, such as zinc and iron. The cost of metals as fuel is very much greater than coal or oil, and the energy obtainable per pound of fuel considerably less, in spite of the more efficient method of utilisation. So that the cost is enormously greater, and primary batteries have only been used for electric lighting where expense has been a minor consideration to that of convenience.

Of the second and third methods the former has up to the present been employed universally wherever electric power has been generated upon a large scale; the latter has been considered more convenient in small isolated plants, where gas has been obtainable direct from some neighbouring gas works, or the compactness of oil-engines and the little attention demanded is a great boon. Quite recently the high efficiency of the gas-engine has been more thoroughly recognised, and hopes are entertained of attaining far higher efficiency than is possible with the steam-engine. Several large central stations have been erected having their own gas-generating plant and using large gas-engines in place of the hitherto universal steam-engine plant. A few years experience will show whether, under the conditions of central station supply, the gas-engine will compete with, or excel, the steam-engine.

In considering the financial economy of the production of electrical energy from fuel we have four items to take into account:

(1) The local cost of the fuel per ton.

(2) The calorific value, or the total amount of energy theoretically obtainable per ton of this fuel.

(3) The ratio of the total amount of energy which can actually be obtained in the form of electrical energy to that theoretically obtainable in accordance with the principle of the conservation of energy.

(4) The capital and maintenance costs of the plant and cost of labour necessary for the conversion of the energy from one form to another.

The subject of the calorific value of various kinds of fuels has been treated fully in the first volume of this series, and the results of the most careful experiments given. The total quantity of heat obtainable by combustion may be determined in several ways. Either by direct experiment in boiler furnaces with a careful calculation of the various sources of waste; or by complete combustion on an experimental scale in a calorimeter; or having made careful measurements of the heat developed by the complete combustion of the elements, which will be chiefly carbon and hydrogen, we may make a calculation of the calorific value of the composite fuels from their chemical analyses. Combustion in a furnace when there is sufficient draught of air will always proceed with such a chemical combination that the greatest heat is produced. Having therefore measured the heat obtained by the combustion of hydrogen so as to produce water, and carbon so as to produce carbonic dioxide, these being the combinations which produce the greatest amount of heat, we can find the number of units of heat obtained by the complete combustion of one pound of a compound of these, which may be taken as

$$8080\,C + 34{,}462\left(H - \frac{O}{8}\right)$$

C, H and O being the quantities of carbon, hydrogen, and oxygen in one pound of the fuel, 8080 units being that developed by the combustion of carbon with oxygen to form carbonic dioxide and 34,462 by the combustion of hydrogen to form water, the second term allowing for the oxygen which is already in combination with hydrogen in the form of water. The numerous defects of the above methods of measurement are discussed in the first volume of this series.

There are various ways of expressing the result. The heat unit used above is that required to raise a pound of water from 0° to 1° Centigrade. We can also express the calorific value by the number of pounds of water evaporated from and at 100° Centigrade, by one pound of the fuel, or by the number of foot pounds of energy which could theoretically be developed.

The following table gives the mean of some of the best results obtained for various elements and fuels.

Fuel.	Product of Combustion.	Heat Units per Pound of Fuel.	Pounds of Water Evaporated at 100° C.	Foot Pounds of Energy Theoretically obtainable.
Hydrogen	H_2O	34,462	62.66	47,900,000
Carbon (wood charcoal)	CO_2	8,080	14.69	11.2×10^6
"	CO	2,474	4.5	3.44×10^6
Silicon	SiO_2	7,830	14.24	10.9×10^6
Sulphur	SO_2	2,140	4.09	2.97×10^6
Phosphorus	P_2O_5	5,747	10.45	7.98×10^6
Zinc (primary battery)	$ZnSO_4$	1,670	—	2.32×10^6
Welsh coal	—	8,241	15.37	11.45×10^6
Newcastle coal	—	8,220	15.33	11.42×10^6
Derbyshire coal	—	7,733	14.42	10.77×10^6
Wood (dried)	—	3,547	6.61	4.93×10^6
Crude Petroleum	—	10,190	18.53	14.16×10^6

From this table we gather that it is theoretically possible to evaporate more than 15 lbs. of water per lb. of the best steam coal, the evaporation taking place at atmospheric pressure from water already at boiling-point. Of course in practice the water has to be heated from its normal temperature, and for the highest efficiency it is necessary that the water should be evaporated at high pressure. Under these conditions a much smaller quantity can be evaporated with the same quantity of heat. But we are at present simply using this measure of evaporation as the measure of the total quantity of heat developed, and hereafter when we are measuring the efficiency of the engines by the quantity of steam used to generate a horse-power hour it will be advisable, for the sake of comparison with engines which use a different boiler pressure, in the calculation of the fuel consumption to reduce this measurement to that of the equivalent amount of water evaporated by the same quantity of heat at atmospheric pressure, though it is better practically to use the same quantity of heat to evaporate a smaller quantity of water at a high pressure. To raise water from 15° Centigrade to boiling-point, and evaporate at a pressure of 150 lbs. per square inch, requires about 20 per cent. more heat than to evaporate the same quantity at atmospheric pressure from 100° Centigrade.

The energy which is the theoretical equivalent of the heat produced by the complete combustion of 1 lb. of Welsh coal is given as 11,450,000 foot lbs., or about 6 horse-power hours, or about $4\frac{1}{2}$ Board of Trade units of electrical energy. The generation of this unit would therefore cost, if perfect efficiency were possible, and coal were at 20*s*. per ton, something less than $\frac{1}{40}$*d*. for fuel.

In the London electric supply-stations the cost of fuel varies from $\frac{3}{4}$*d*. to 2*d*. per unit supplied to consumers, and the price charged from 6*d*. to 8*d*. The various losses in the generation, or rather successive transformations of energy from its condition of storage in the coal to the electrical energy delivered to consumers, that give rise to this enormous disparity between the ideal and the actual, must now engage our attention.

From the trials of Lancashire and Galloway boilers, of which the results are given in the first volume of this series, pp. 724-725, it will appear that under test conditions, when the feed-water is supplied from an economiser or condenser at nearly boiling-point, the quantity of water evaporated at atmospheric pressure is from 11 to 12 lbs. per lb. of the best coal consumed. This means that an efficiency of 75 per cent. is about the maximum attainable. In ordinary working conditions it cannot be expected that the efficiency will be maintained as high as this. Even if the boiler be always worked at or near its most efficient rate of steaming, an evaporative efficiency of 9 lbs. of water per lb. of coal, or 60 per cent. of the theoretical maximum will be considered fairly good practice. The skill of the stoker may make considerable difference in the quantity of fuel consumed to produce a given quantity of steam.

But in the steam generation for an electric supply-station a new source of inefficiency arises from the constant variation of the demand, which compels us frequently to employ boilers to generate steam at a rate at which the efficiency of evaporation is very much less than it is under test conditions. As we shall meet with an analogous source of inefficiency in nearly every successive stage of the generation of electric power, it will be well to say a few words upon the effect of this variation in the demand in the case of boilers.

It is not unfrequently maintained that the experience of the marine engineer, who is the largest steam user in the world, is the best guide to the selection of engines and boilers for electric light stations, but there is one very important feature in which the two classes of work differ very essentially. The marine engineer has to deal with a continuous and nearly uniform load, and in the mercantile marine arranges to run at the speed which, taking all expenses and returns into consideration, will prove most profitable. In the Royal Navy the question of economy is of secondary importance, but even there the load is usually steady for long periods except during special manœuvres. But in an electric lighting station the load is exceedingly variable, and is liable to be suddenly increased by very large amounts. A theatre with 1000 lights may be switched on when quite unexpected, perhaps in the middle of the day, and solely for the purpose of exhibiting the lights to a visitor, and thus an extra load of 100 horse-power may be thrown upon the generating-station. Hence it is necessary to maintain an ample margin of power in the running machinery, especially when working at light load, and experience shows that the attendants in charge always like to have plenty of power available at any moment. But even where no single installations exist which, from their magnitude, are liable to put a greatly increased load suddenly upon the generating plant, the demand at different hours of the day is very different. In a provincial town the load may be increased five or six times or even more within an hour of sunset, and three hours afterwards it may again become insignificant. A very large portion of the plant may thus be required for three hours only out of twenty-four, and during the remaining twenty-one hours the plant which is in operation may be loaded with only a small fraction of its most economical load.

Under these circumstances a number of boilers may have to be kept with fires banked for twenty-one hours in order that they may supply steam for three hours, and during a considerable portion of this period they may be working considerably below their best load. It is not, therefore, sufficient to consider what boiler will show the greatest economy when steaming at its best rate, but we must take into account its economy when steaming at a small fraction of its full power, and special attention must be paid to the loss of heat from the boiler when the fires are banked. In this latter relation the amount of surface exposed by the boiler to the air, and the character of its seating, are important considerations.

Suppose, for example, that during the three hours it is at work the boiler consumes 1200 lbs. of coal and produces 10,200 lbs. of steam, and that during the twenty-one hours that the fires are banked it is necessary to burn 30 lbs. of coal per hour to maintain the steam pressure. The total coal consumed during the twenty-four hours is 1830 lbs., while the steam produced is 10,200 lbs., giving an evaporative efficiency for the twenty-four hours of only 5.57 lbs. of steam per lb. of coal, while during the three hours of steaming the evaporative efficiency was 8.5. If another boiler had an evaporative efficiency of only 8 lbs. of steam per pound of coal, but could maintain its temperature with a consumption of only 10 lbs. of coal per hour when no steam was drawn, the total consumption of coal for the production of 10,200 lbs. of steam, under the same conditions as before, would be 1275 + 210, or 1485 lbs. instead of 1830 lbs., and the evaporative efficiency for the twenty-four hours 6.8 instead of 5.57.

It is easy to find results of carefully conducted experiments on the evaporative efficiency of different types of boiler when perfectly clean and steaming under the most favourable conditions, but these are not the average conditions of working in an electric light station, and what is wanted is carefully conducted experiments on the coal consumption in a boiler for every 5 per cent. additional load from zero (*i.e.*, just maintaining constant pressure without any steam being drawn) up to the full power of the boiler, and such results are not usually published.

In a twelve and a half hours test of a Lancashire boiler at an electric lighting station for ten hours the average rate of steaming was about 33 per cent. of the full power of the boiler. For the remaining two and a half hours it varied between 60 and 85 per cent. It was found that with the feed-water at 50° F. the average evaporation throughout the whole trial was 7.78 lbs. of water per pound of coal, the average steam pressure being about 110 lbs. per square inch. This corresponds to the evaporation of 9.4 lbs. of water from and at 212° F. per pound of coal. The boiler was in its ordinary working condition, the flues having been swept a week before the test was made.

To raise the efficiency of steam generation under varying load, as well as to reduce the excessive number of boilers necessary when a heavy load has to be dealt with only for a few hours in the day, various methods of storage have been suggested. A station which uses secondary batteries has a great advantage in this respect, provided the efficiency of the batteries is so high that the loss in them is not greater than the loss through the inefficiency of boilers and engines due to variation in load. A system of thermal storage has been proposed, in which the heat generated is stored in the form of water heated considerably above atmospheric boiling-point, and retained in well-packed steel cylinders, equivalent, in fact, to largely increasing the water capacity of the boilers, and thus enabling them to supply a heavier demand than the normal rate of steaming could supply, for a few hours, without greatly lowering the pressure. According to calculations, the correctness of which is undisputed, this ought to effect a large saving in fuel, and a possible reduction in capital expenditure.

Another method of reducing the loss is to go to the other extreme and use boilers with a very small water capacity, and therefore very rapid in "getting up steam." This obviates the necessity of keeping the boilers banked ready for an emergency, as a new boiler can be brought into action in a short time. The Babcock and Wilcox water-tube boiler is very popular among Electric Central Station engineers, and almost exclusively used in London, both on account of the small ground space occupied and its rapidity of steaming, in view of the sudden demands for power that may occur at unexpected times owing to a fog, which would otherwise require a large number of boilers to be kept banked. Of course this rapidity of steaming has no connection with the efficiency; and though water-tube boilers, owing to the large heating surface in proportion to the grate area, can generally, if the draught be good, be pressed to supply steam in an emergency at a rate much greater than the efficient rate of steaming, yet they have the disadvantage of possessing very little reserve power in the form of water heated above atmospheric boiling-point. A suitable combination of the two types of boilers, say the Lancashire and Babcock and Wilcox, would be the most satisfactory arrangement both as regards prime cost, economy of fuel, and readiness for all emergencies.

A most promising means of reducing the cost of generation of Electric Power has lately been undertaken by several London vestries and provincial Corporations—namely, the combination of refuse destructors with central supply-stations. The heat generated in the furnaces where the town refuse is consumed may be employed wholly or partly in the place of coal. In the attempt to wholly replace coal a difficulty arises, even if the quantity and calorific value of the refuse be sufficient to provide the necessary heat; it is most inexpedient to vary the rate of consumption of refuse, as would be regarded by the variable demand, on account of the enormous size of the furnaces to meet the steam demand at heavy load, and the difficulty in securing perfect consumption of the refuse if the rate be varied. Only by some extensive system of thermal storage, or large secondary batteries, would it be practicable to avoid the employment of coal as supplementary fuel.

But a uniform supply of heat, obtained with very little additional capital expenditure in its application above that which is incurred in effectively disposing of refuse, has a value for the economic generation of electric lighting power which can scarcely be over-estimated, though the actual amount of electrical energy obtained from this heat forms but a small proportion of the total output. It prevents the slow but steady consumption of coal in the banked or slow-steaming boilers during some twenty hours of the day; enables a large number of boilers to be kept ready for action at all times without waste, and thus relieves of all anxiety of failing to meet a sudden increased demand; and renders the low efficiency of the generating plant at reduced load, and the never-ceasing absorption of power by transformers, of little moment. For large towns and cities wasteful transforming systems are rendered necessary by the extensive area of distribution, and dust destructors, more especially needful in large towns, seem the natural antidote.

In the Central Station of the St. Pancras Vestry, eighteen furnaces for dust destruction are placed round the main building, and connected to refuse tanks by iron hoppers, by which the refuse is carried from the tanks to the back of the furnaces. Thence it is gradually carried forward to the front of the furnaces by the motion of the fire-bars. Every alternate bar moves on a cam shaft at the back end, and slides on a dead plate at the other end. Into these bars are coupled, by knuckle-joints, shorter bars at a steeper inclination, and placed at the bottom of the hoppers. The intermediate bars of both the front and back grate do not move. The moving bars, thus effecting mechanical stoking, are operated by shafting from the engine-room, while two small vertical engines operate blowers to effect a heavy forced draught from the ash-pits. Lancashire boilers are used for steam generation, 30 feet in length and 7 feet 6 inches in diameter, with two flues 3 feet in diameter, with six tapering cross tubes in each, designed for a working pressure of 125 lbs. per square inch. They are supported on cast-iron saddles resting on brickwork near the front, and on cross joists at the other, in such a manner that the whole of the outside shell below the water-line is exposed to one large flue, affording considerable heating surface. The large flue carrying the destructor gases to the chimney runs along the back of the row of boilers, and the gases can be diverted into the large outside boiler flue by opening valves at the back end, and through the internal boiler flues, passing out of the furnaces to 15 inches diameter down pipes leading to the chimney. The boiler furnaces and ash-pits are provided with air-tight doors, to be closed when the destructor gases are being used, and the down pipes have valves to be closed when the coal fires are in use. Grid dampers are also provided at the back ends of the internal flues for regulating the draught to the coal fires while the destructor gases are allowed to pass under the boiler only, and another damper to the outlet of the main flue into the chimney. Thus the destructor gases can be employed partly or wholly for steam generation. A Green's economiser is also employed, heated entirely by the destructor gases.

The average efficiency attained in steam generation throughout the whole year in a central electric supply-station will vary considerably according to circumstances. A station using storage batteries, and thus having a fairly equable load upon the engines, should attain a far higher efficiency than can be attained in a station which supplies steam according to the demand. Statistics bearing upon this are not published, though measurements might easily be taken by a water-meter in the supply-main for the feed-water, and would be of great value. In an alternating current station using boilers which gave upon test an evaporative efficiency of nearly 10 lbs. of steam per lb. of coal, the writer found the average efficiency for the winter months alone to be less than 6 lbs. of steam per lb. of coal. Probably the efficiency of steam generation in most central stations is between 30 and 40 per cent. Low as this may seem at first sight, yet as compared with the efficiency of the next process, that of conversion of the heat energy into mechanical energy, it will appear highly creditable.

Efficiency of Machinery.

Under the very best conditions with triple expansion condensing-engines working at their most efficient load the production of a brake horse-power requires per hour at the very least 13 lbs. of steam at high pressure, which is equivalent to about 15 lbs. evaporated at atmospheric pressure. Even this very exceptional practice only represents an engine efficiency of 18 per cent., the horse-power hour being represented in heat energy by the evaporation of as nearly as possible $2\frac{2}{3}$ lbs. of steam from and at 100° Cent. What rates of steam consumption were registered at approximate full-load, half-, quarter-, and zero-loads :

I. *Non-condensing.*

Kilowatts.	Total Weight of Steam per hour. lbs.	Steam per E.H.P. hour. lbs.
219.2	9466	32.22
98.7	5848	44.18
54.5	4330	59.30
0	2092	—

II. *Non-condensing, but superheating* 30° F.

203	8429	30.97
106.1	5287	37.17
0	1402	—

III. *Condensing Vacuum* 25″; *no superheating.*

208	5443	19.51
108.4	3037	20.90
0	531	—

Combined with a 150 KW. alternator, employing helical spur-gearing with a ratio 2 : 1, with a steam pressure of only 70 lbs., superheated, and a condenser vacuum varying from 26½ to 26¾ inches, the following rates of consumption were registered:

Kilowatts.	Total Weight of Steam per hour. lbs.	Steam per E.H.P. hour. lbs.
150.33	3484	17.28
72.84	1950	20
38.97	1150	22.01
.175	437	—

It will be interesting to compare these figures with those for other high-speed engines which will be given later on. They will show, however, that effective steam condensation offers possibilities of reducing steam, and therefore fuel, consumption by nearly 50 per cent., but with reciprocating engines the practical saving will be somewhat less, and the subsidiary waste in the condenser air-pump will lessen the advantage. At reduced loads the gain appears to be still greater than it is at full load, rendering condensation peculiarly desirable for central station practice. In cases where the water available for condensing purposes is limited, it has often been thought advisable to incur considerable expense in cooling tanks and similar means in order to secure these advantages.

As stated above, when dealing with the choice of boilers, the experience of marine and mill engineers, though of the greatest value in connection with an industry of more recent growth, must be greatly qualified if we wish to make the best choice for the special conditions of electric lighting. The peculiarities that must be considered are chiefly the high speed advisable, and the demand for high efficiency at variable loads. To these may be added possibly a natural preference to minimise the prime cost of the machinery at the expense of its durability, in fear lest the advance of the science should render the existing machinery antiquated in a short time. And, moreover, in supply-stations which are most advantageously placed in the midst of congested districts, the saving of space is a matter of at least as much importance as in marine engineering, and, as a rule, of far more importance than in mill engineering.

In industries to which the latter expression applies, almost universal experience has pronounced in favour of large slow-moving engines, generally of the horizontal pattern, with Corliss or other trip-gear, whereby a variable expansion may be obtained with high-pressure steam and efficient governing through a wide range of load. And this experience has been largely followed in alternate current systems, to which some of the above-mentioned peculiarities do not apply so forcibly as with continuous-current systems. The tendency has been lately to construct alternators of very large size to meet the requirements of the slow-moving engine, and thus avoid the inefficient, and sometimes dangerous, use of ropes and belts which were at first, and are still very largely, employed in this class of work.

For continuous-current low-tension systems the necessity of high speed, and the limited space generally at the disposal of the engineer, have caused a strong preference for high-speed vertical engines, and the demand has given an impulse to the design of these types, so that several manufacturers are now producing high-speed engines which not only give great satisfaction when combined with continuous-current dynamos, but endanger the former monopoly of the low-speed mill-engine.

Of these designs for high-speed engines, Willans' central valve, single-acting type is the most popular. It appears that at the beginning of 1895 the total capacity of the engine in electric light stations in Great Britain was 101,390 indicated horse-power, and of this 53,340 horse-power, or more than half, was supplied by Willans' engines, and little more than 4000 by other types of high-speed engines. The chief difficulties in the running of high-speed engines are to secure satisfactory lubrication, the working parts being inaccessible when in motion, and to get rid of the vibration to which high-speed engines are peculiarly subject. Vibration is not only fatal to durability, but cannot be permitted when the station is located in a crowded district on account of the annoyance to neighbours. In the Willans engine the crank chamber is an enclosed oil-bath, the lubrication is perfect when good oil is used, and the engine requires very little attention during running. The vibration is reduced to a minimum by the constant thrust principle.

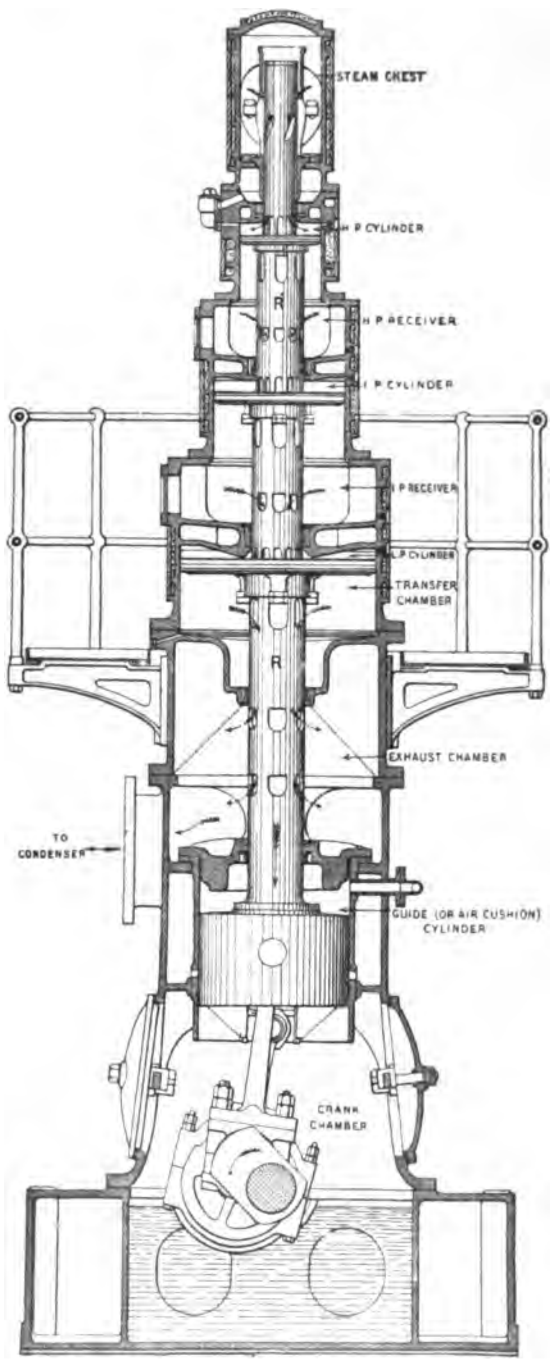
As to the steam consumption of the Willans engine, it appears that upon full-load, non-condensing, test efficiencies of 18.45 lbs. of steam per indicated horse-power per hour have been obtained with an initial pressure of 170 lbs. per square inch (triple expansion being used), and 19.45 lbs. of steam with a pressure of 150 lbs. (compound). And condensing, with a triple-expansion engine of 500 horse-power, 12.48 lbs. of steam per I.H.P. hour has been recorded. Directly coupled with a Crompton dynamo, the following tests are given to show the commercial efficiency of the combination:

Terminal output of dynamo	153 E.H.P.
Indicated H.P. of engine	178 H.P.
Loss in dynamo	7.5 "
" engine friction	17.8 "
Total efficiency	85.8 %
Efficiency of dynamo	95.3 "
" engine	90.0 "

Tests of steam consumption with two such combinations, non-condensing, are given as 19.2 and 18.9 lbs. of steam per I.H.P. hour, and 24.35 and 24.2 lbs. of steam per E.H.P. hour, or 32.63 and 32.44 lbs. of steam per unit respectively.

It appears, however, that the engine losses are practically the same at all loads, owing probably to the fact that the cylinder friction represents much the greatest part of the loss, the lubrication of the bearings being all but perfect. For this reason the efficiency at low loads is comparatively poor, and distinctly inferior to some double-acting types which cannot compete

FIG. 99



Willans Central-Valve Engine.

with it at heavy loads. This fact must be taken into consideration whenever it is intended to run the engine with great variations of load, but is of small importance when an accumulating system is used. With a constant frictional loss a full-load efficiency of the engine of 90 per cent. will give an efficiency of only 81.8 at half- and 69.2 at one-quarter load.

The Bellis double-acting high-speed engine obtains very perfect lubrication by forcing the oil through channels into all working parts. This is effected by a simple pump, without valves or packing, working off the eccentric from a well in the framing, and discharging at a pressure of about 10 lbs. The durability and freedom from breakdown of this engine has caused it to be used largely by the Admiralty for driving ship dynamos. The efficiency claimed at full load is very high, and at low loads is unquestionably maintained better than with single-acting engines, owing to the diminished cylinder friction. Tests of a Bellis-Compton 200 horse-power combination at St. Pancras Central Station, for 6 hours at full load, with a mean steam pressure of 121.75 lbs., non-condensing, give a consumption of 17.58 lbs. of steam per I.H.P. hour, 19.89 lbs. per E.H.P. hour, or a total efficiency of 88.39 per cent.

In the gas-engine which has made marvellous strides lately towards high efficiency, we are not limited to the same extent as in the steam-engine, and there are possibilities of attaining a much higher efficiency. Already it is possible with large gas-engines to rival and even improve upon the steam-engine in efficiency, and if the regulation of speed can be made equally good it is possible that the latter may fail to maintain its pre-eminence. For central electric lighting station work especially the possibilities of the gas-engine are great; for gas can be stored ready for immediate use in the engine without any loss, while, as explained above, it is impossible to do so with steam, and an immense loss results through the constant variation of demand. With gas-engines the only cause of discrepancy between the efficiency under working conditions and under test conditions is the remediable one due to the working of the engines at variable or inefficient loads. The production of gas may be carried on uniformly, and stored without loss.

Gas-engines are open to the following objections for electric light work. They occupy a somewhat larger space than steam-engines of corresponding capacity; they commonly produce greater vibration, and often considerable fluctuations in speed between the explosions; their regulation is seldom as perfect as can be attained with the steam-engine; and the starting of large engines presents certain difficulties.

As to the variation of efficiency at reduced loads the following measurements given by Prof. Unwin as to the gas consumption per brake horse-power per hour may probably be taken as typical of the present practice:

Brake H.P.	Cubic Feet of Gas per B.H.P. hour.
100	21.65
75	23.78
50	28.05
25	40.85
12.5	66.48

For small private installations a gas-engine and dynamo, supplemented by a secondary battery of sufficient capacity to store the whole of the energy required for daily supply, is the most satisfactory arrangement; but a direct supply, employing a smaller secondary battery to restrain the fluctuations of E.M.F., and discharging in parallel with the dynamo at the time of full demand, is often employed. The use of the dynamo as a motor, driven by a discharge current from the secondary battery, affords a convenient means of starting the gas-engine, obtaining the necessary initial compression of the explosive mixture.

For central stations large gas-engines may be built with several cylinders, and steadiness obtained by a suitable arrangement of the order of the explosions, together with great inertia in the fly-wheels and rotating parts of the generators. In the Belfast Central Station, employing a low tension three-wire system with storage, tandem cylinders are employed for the 120 indicated horse-power gas-engines. The explosive impulses occur at each end of either cylinder, following one another in succession—first an explosion in the back end of the back cylinder, then one in the front end of the front cylinder, then one in the back end of the front cylinder, and, finally, one in the front end of the back cylinder. Or, in other words, the four operations of the "Otto cycle" take place in the four cylinder ends successively, admission and compression in one cylinder at the time of expansion, and exhaustion in the other. A uniform speed of 160 revolutions is maintained at all loads, requiring 320 explosions, the speed being regulated by variable admission of explosive gas; this method producing the greatest steadiness in running, but lower possibilities of efficiency at reduced loads than the method of missing explosions. With rope-driven Siemens (60 kilowatt) dynamos, a consumption of 26 cubic feet per E.H.P. is obtained at full load, the gas being supplied from the Corporation gas-works, and consisting of coal-gas admixed with a considerable proportion of enriched water-gas.

It is for alternating current transformer systems that gas-engines possess a special advantage, since, storage batteries being impossible without transformation to continuous currents, and thermal storage difficult, much is lost by irregular steam generation. The great inertia possessed by the moving parts of most types of alternator will help to modify the tendency to fluctuation of speed in gas-engines. In the few central stations where gas-engines have been adopted, some difficulty seems to have been experienced in the parallel running of alternators, and direct coupling has had to be resorted to.

The efficiency of the dynamo, or machinery by which the mechanical power is converted into electrical, although under test conditions at a suitable load much higher than the boiler and the steam-engine, suffers to an equal, and often to a still greater extent from the variation of output. While 95 per cent. is easily attained at full load with closed-coil continuous current dynamos, and 90 per cent. with alternators, some of the causes of the wasted energy, those of mechanical friction, hysteresis, and eddy-currents, and expenditure in the magnetising coils remain constant at all loads, while that due to armature resistance decreases rapidly at low loads (in proportion to the square of the current output). Thus, while attaining the highest efficiency commonly at somewhat less than the maximum output, that at low loads is very poor indeed. The obvious remedy for this source of inefficiency is a proper graduated series of units, engine and dynamo, of various sizes to be employed according to the demand, and adaptability to parallel running of the larger units. A combination of dynamo and engine is much more rapidly brought into action than a boiler, so that the elimination of the loss due to variable demand is far more possible.

Efficiency of Distribution.

The final question, that of efficient distribution, has been the subject of consideration throughout the greater part of this work, only second in importance to that of uniform regulation throughout the area of supply.

To sum up our results we may note that with direct distribution, the simple parallel and multiple wire systems, the wasted energy cannot exceed the proportion to the total output of the maximum drop in potential permitted to the whole E.M.F. With systems of feeder mains it may be possible to extend the supply to such distances that the fall of potential, and consequent absorption of power in transmission, will reach 12 per cent., while the extreme variation with different lamps is kept within half this amount. The total percentage waste *at the time of maximum demand* will thus be less than 12 per cent., and will diminish greatly as the demand reduces, being proportional to the square of the current output. The losses by leakage should of course be insignificant.

When storage is adopted a further loss of at least 20 per cent. must be allowed for, but this, as stated above, is generally far more than compensated for by the increased efficiency of the generating plant supplying a variable demand, and the reduction of labour and other expenses.

With an alternating current transforming system in which the transformers are permanently connected to the distributing mains, a transforming loss of 3 to 4 per cent., and a similar loss in the distributing mains, high and low pressure, may be expected at heavy load. At moderate loads the former percentage remains fairly constant, while the latter rapidly reduces, as with direct supply. With very small or zero loads the efficiency of the transformer becomes exceedingly low, and in cases where the lighting is confined to a few hours in the day, an average diurnal efficiency of barely 70 per cent. may result. In many of the central stations employing small transformers on the consumer's premises the number of units registered by the meters scarcely exceeds, and is often less than, this proportion of the total output of energy during the year. Concentration of the centres of transformation, with secondary distributing systems, so that the transforming capacity may be adjusted to the demand, will reduce this great source of waste to less than 10 per cent., though an increase in the low tension distribution waste may be expected.

With continuous current transforming systems the efficiency of distribution will certainly be lower than with alternating currents, on account of the lower efficiency of rotary transformers; but as concentration of the transforming centres is necessary, it should be higher than a distributed alternating current system, and the possibility of storage will enable a higher efficiency of generation to be attained.

Series distribution being applied almost exclusively in practice to street lighting with arc lamps, is not subject to variable demand, nor need the generating plant be run otherwise than at full load and during the hours of darkness only. An efficiency of 80 per cent. is considered ample with the dynamos employed, and decreased efficiency at light loads does not enter into consideration. The loss in distribution is also extremely small when high E.M.F. is employed; for example, with 3000 volts terminal E.M.F., and a current density of 400 ampères per square inch., the loss is less than 1 per cent. per mile of conductor.

Considerable economy may be effected by a reduction of the street illumination after midnight when the heavy traffic has ceased, and the brilliant light of the arc lamps is somewhat superfluous. For this purpose several supply stations in this country have lately adopted an arrangement whereby the arc lamp is replaced by a pair of incandescent lamps (commonly thirty-two candle power) about midnight, supplied from the distributing mains for interior lighting, these being started by an automatic switch upon the extinction of the arc lamp. A secondary advantage to be obtained from this arrangement is that in the event of an accident to the arc lamp supply generators, or individual lamps, the street is not wholly thrown into darkness, universally or locally. The automatic switch of the incandescent lamps has been also designed to switch off the lamps when required, the incandescent supply being uninterrupted, this being effected by the sending for an instant a current through the series arc system in the direction reverse to the normal direction, the switch gear being of the nature of a polarised relay.

An important economic question arises as to the necessary capacity of the generating and distributing plant for any area of supply, that is to say, its relation to the total number of lamps connected to the system. When the demand is mainly from public halls and theatres, shops and clubs, it may be expected that at times nearly all the lamps will be burning simultaneously, and provision must be made to meet the full demand, or nearly so. Generally, however, this full demand will last for but a short period every evening, and the plant may be overloaded for some time, with probably a somewhat low efficiency and some extra fall at the distant lamps; so that a provision for some 80 per cent. will be ample, running no danger of failure. In the early history of an installation a larger proportion of the maximum demand possible may be expected than will be the case when it is more extensively used in private houses. The latter are generally slower to adopt a new illuminant, for obvious reasons, and the conditions are somewhat different, the demand seldom exceeding half the maximum possible; a much larger number of lamps in private houses may therefore be connected to the supply system than is provided for by the limiting capacity of the plant. This proportion can only be decided by judgment and experience being determined by the habits and customs of the consumers in the district.

A further important question is concerning the extent of reserve generating plant required to prevent failure through accident. In deciding this much will depend on the nature of the plant, the rapidity with which repairs can be executed, &c. Of late, designers of machinery have expended much thought on provision for rapid repair of the parts most subject to injury, such as armature coils, &c., reserve parts being kept in stock. Still it is considered absolutely necessary by most engineers that the capacity of the total generating plant should exceed by that of one of the largest units the total output that must be provided for. A large secondary battery can take the place of this reserve unit only when repairs can be speedily executed. For boilers similar reserve is required.

Since the interest on the capital outlay in generating plant and distributing mains forms in general a large, if not the greater, part of the cost of production, it is evident that the cost per unit of the energy supplied depends largely upon the time during which the lamps are kept alight, and the charge ought to be made to correspond. Generally, the longer the average time of burning, or the larger the total consumption of energy by a lamp of fixed size, the cheaper the total cost of supply, including the necessary capital expenditure. The following methods of charging for electrical energy have been put into practice in place of uniform charges, each of which presents certain advantages:

(1) A fixed charge according to the number of lamps installed, with a small additional charge per unit consumed.

(2) A fixed charge according to the maximum demand with additional charge per unit. The maximum demand at any time is measured by a special indicator. The most successful type has been devised by Mr. Arthur Wright, and is practically a differential air thermometer causing an overflow of liquid, registering the maximum current used at any time. The indicator is slow in action, taking some ten minutes to cause the full overflow, so that an accidental excess current for a few minutes is not registered.

(3) Sliding-scale charges according to load of full installation, or maximum demand. This has the usual objection that applies to all sliding-scale charges.

(4) The use of double circuits, with separate meters, with a two-way switch arranged that one circuit only can be used at a time. On one circuit are connected only such lamps, or electric motors, as are likely to be employed in the daytime; on the other circuit such as will be necessary during evening hours. A smaller charge is made for units registered upon the former circuit.

(5) Meters have been designed with two coils, giving different rates of registration with the same consumption of energy. The coils are alternative, and brought into action, the one during hours of light and the other of heavy load, either by clockwork or a switching gear controlled electrically from the central station.

PHOTOMETRY.

The increase, during the last few years, of the commercial as well as the scientific importance of an exact method of measuring the luminous energy of artificial light has resulted in the establishment of the science of photometry on a definite and precise basis.

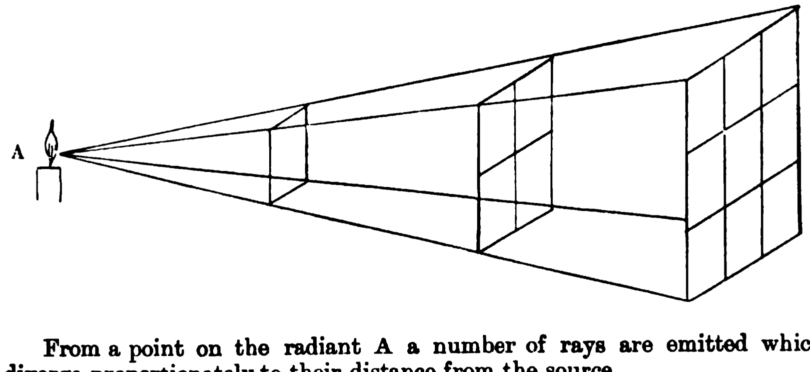
This science has for its object the accurate measurement or comparison of all light sources and the determination of their power to produce a certain amount of illumination on a given object.

The fundamental law of photometry is that the intensity of illumination on any point varies inversely as the square of the distance of the source of light from that point. Hence it is evident that the measurement of a source of light must be made by comparison with another source taken as a standard, so that the two essential requirements are (*a*) a photometer, or the means of comparing lights or degrees of illumination, and (*b*) a light which shall act as a standard of comparison.

An adequate explanation of the law of inverse squares will materially assist in the solution of many problems which will occur, and will show the basis upon which different photometers are constructed.

Light is emitted from a luminous body in all directions in straight lines, and it is therefore evident that if any two rays are taken which radiate from a point in this body, they will diverge in proportion to their distance from that body, and their power of illumination will decrease in the same ratio. The following diagram affords a simple explanation of this point:

FIG. 100.



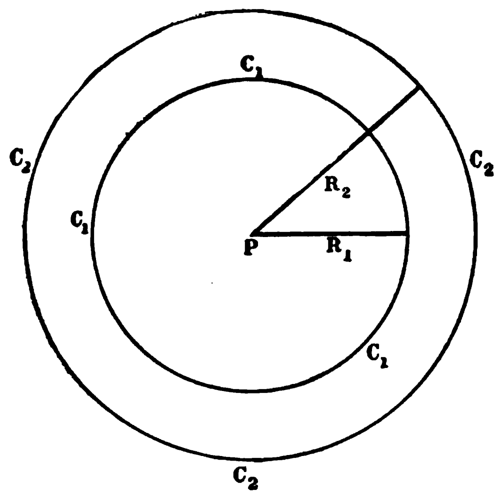
From a point on the radiant A a number of rays are emitted which diverge proportionately to their distance from the source.

Suppose at a distance of 1 foot they illuminate a small screen, at 2 feet—*i.e.*, twice the distance—they will illuminate a screen four times the size, and at 3 feet—*i.e.*, three times the distance—a screen nine times the original size, therefore the light which at one foot was spread over a screen of x area, is at 2 feet spread over $4x$ area, and at 3 feet, $9x$ area; therefore it is evident that the illumination at any point on the screen 2 feet distant can only be one quarter of that on the screen 1 foot distant, and in the same way the light at 3 feet is spread over a screen nine times as large, and therefore can only be at any point on this surface one-ninth the intensity.

This explanation gives a good idea of the meaning of the law of inverse squares, but it is not a mathematical exposition, since it neglects the fact that every point on the screen is not the same distance from the source of light. To obtain such a result the screen would have to be a perfectly circular hollow globe in the centre of which the light source was placed, then the mathematical proof of the law would be as follows:

Let two hollow spheres be represented in section, one inside the other (Fig. 101), and P be the luminous point in the centre; this point will illuminate the whole of the interior of the hollow shell C_1, C_1, C_1, of the radius R_1 equally. If the shell C_1, C_1, C_1 be removed, the light P will illuminate

FIG. 101.



the whole of the interior of the shell C_2, C_2, C_2 equally, but as this shell presents a larger surface to the light P, it is obvious that the intensity per unit surface must be less.

If I represents the intensity of illumination in a sphere, $I = \frac{Q}{4\pi r^2}$ where Q = quantity of light and $4\pi r^2$ = area of the sphere. This applies equally for any sphere, consequently it follows that for C_1, C_1, C_1 of radius R_1, $I_1 = \frac{Q}{4\pi R_1^2}$, and for C_2, C_2, C_2 of radius R_2, $I_2 = \frac{Q}{4\pi R_2^2}$; then,

$$\frac{I_1}{I_2} = \frac{Q}{4\pi R_1^2} \Big/ \frac{Q}{4\pi R_2^2} \therefore \frac{I_1}{I_2} = \frac{R_2^2}{R_1^2}.$$

Thus suppose the shell C_1, C_1, C_1 has a radius R_1 of 12 inches, then the area of the surface of the sphere C_1, C_1, C_1 will be 1809.5 square inches, taking the area of the surface as equal to four times the square of the radius multiplied by 3.14159, and the shell C_2, C_2, C_2 with a radius R_2 of 24 inches, will have an area of 7238 square inches. Now since this area (7238 square inches) is four times the smaller area (1809.5 square inches), it follows that the illumination on every unit area of the interior surface of the larger shell C_2, C_2, C_2 is one-fourth of that on the same area of the interior surface of the smaller shell C_1.

For the purpose of demonstrating this law the source of light has been considered as a point, whilst in practice the source of light is usually a surface of several square inches, and in some cases, such as that of an electric arc, covered with an opal globe, considerably more; this, however, does not vitiate the proof, as a body of light is made up of an innumerable quantity of incandescent particles, each of which may for a theoretical proof be considered as a source of light.

From the law of inverse squares it follows as a corollary that the intensity of the source of light varies directly as the square of the distance.

On these two laws, which are the basis of the science of photometry, the following photometers have been constructed:

Bouguer's Photometer (A.D. 1729) consists of a semi-transparent screen of white tissue paper, ground glass, or thin white porcelain, divided into two parts by an opaque partition at right angles to it, with the two lights under comparison placed one on each side of this partition, so that each illuminates one-half of the transparent screen. The distance of the two lights is adjusted until the two portions of the screen, as seen from the back, appear equally bright. The distances are then measured and the intensity of the two lights calculated in comparison with each other.

Foucault's Photometer (A.D. 1850), much used in France, is a modification of Bouguer's. In place of the fixed partition between the two illuminated halves of the screen, which casts a shadow and renders a comparison somewhat difficult, Foucault introduced a movable partition with an adjusting screw, so that when the partition was moved a certain distance from the screen the two illuminated portions of the screen were contiguous and could be more readily compared.

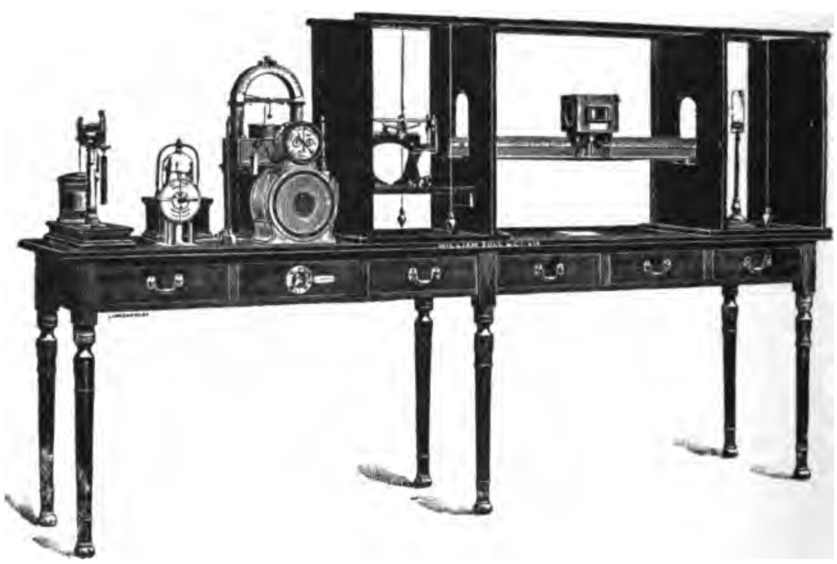
Rumford's Photometer (A.D. 1792).—In this photometer, as in Bouguer's, the two lights to be compared are placed on the same side of the screen, but instead of comparing the illumination of the two halves, the intensities of the shadows cast by an object placed in the path of the rays of light are used as the means of comparison. On two tables, one 12 feet and the other 20 feet long, by 10 inches broad and 35 inches high, the ends of which are fixed at an angle of 60 degrees to each other, the two sources of light, fitted to movable platforms, are placed. By means of endless bands attached to the movable platform the lights are capable of adjustment by the observer whilst taking his observations. The screen on which the shadows are cast is fixed in the back of an open-fronted box, thus excluding the extraneous light as much as possible, and in order to avoid the inconvenience arising from comparing two shadows projected by the same object, shadows which are either too far from each other to be compared with certainty or when they are close enough together are probably obscured by the object itself, two objects are used, and in such a position that the shadows which they cast can be seen between them. The objects used to produce the shadows are narrow cylinders, movable about their axis, each fitted with a vertical wing of the same length as the cylinder and about one half-inch broad; this is necessary to enable the operator to adjust the shadows to the same breadth, as the lights are seldom equi-distant from the screen.

The Bunsen Photometer (A.D. 1843).—Bunsen adopted an entirely different principle for his photometer. A sheet of paper, on which a large grease spot was made, was fixed on one side of a box in which a small gas flame was kept burning. The reverse side of the disc was turned towards one of the lights under comparison, which was then adjusted until the grease spot apparently disappeared, when the distance from the disc to the light was noted and the same procedure adopted with regard to the other light. Thus he obtained the distance at which the two lights gave equal illumination and from it calculated their relative luminosity.

This arrangement had an unfortunate defect: the gas flame in the box was not a constant, so that, although the principle was admirable in every way, it met with but little favour. The idea, however, was communicated by Lyon Playfair to Alfred King, who constructed the modified arrangement now known as the Bunsen open-bar photometer. In this modification King placed the two lights one at each end of a bar 100 inches long, and the grease spot disc in the centre, and by altering the distances of the light from the disc until it was equally illuminated on both sides, obtained a direct comparison.

Letheby considerably improved King's modification by shortening the 100-inch bar to 60 inches, constructing a sighting box for the disc with

FIG. 102.

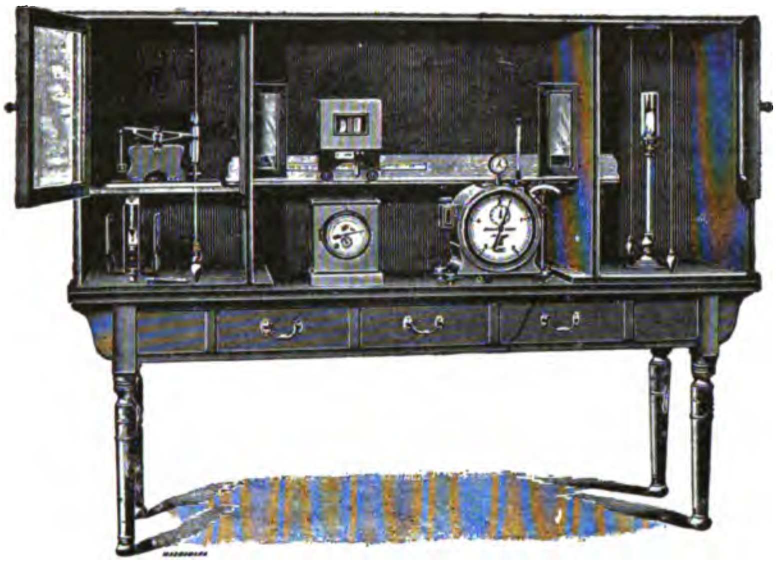


Letheby's Photometer.

mirrors so arranged that reflections of both sides of the disc could be seen simultaneously, and so surrounding the two sources of light with screens that the eyes of the observer were protected from direct light and the flames themselves from draughts. Unfortunately the very trouble that Letheby sought to prevent by boxing up the flames he cultivated. It was found that gas and candle flames in such a photometer were seldom steady, and when a sluggish flame, such as that of the one-candle pentane flame, was used in the photometer, the unequal draughts induced seriously affected the results.

This defect was so marked that it was found necessary during an inquiry on standards of light to somewhat modify Letheby's arrangement in order to obtain a steady flame. This was done by enclosing the top of Letheby's box-ends with flat boards having circular apertures of about 6 inches diameter cut in them. By thus slowing the up-current of air a sufficiently large and steady volume was obtained to produce a practically steady flame. With these modifications this photometer is now largely in use under the name of the Improved Letheby or Tooley Street pattern

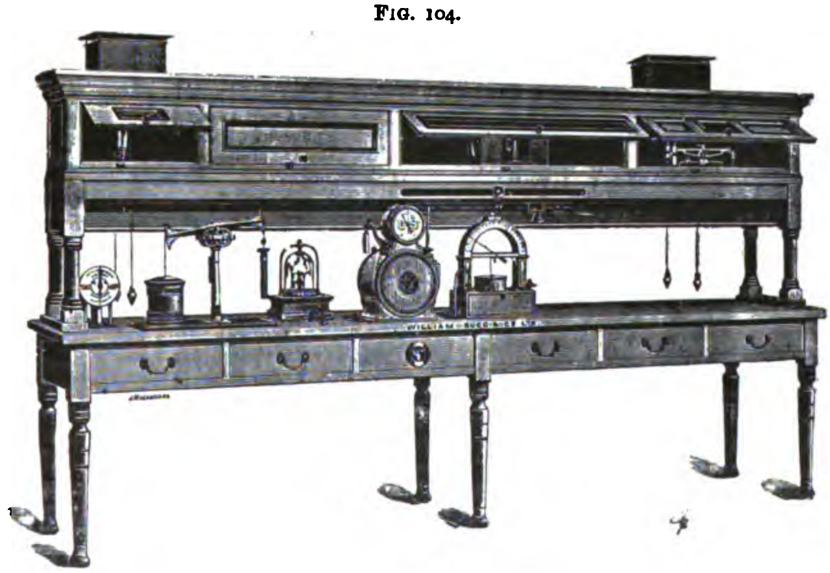
FIG. 103.



Tooley Street Pattern Photometer.

photometer, in consequence of its having been first fitted up at Tooley Street Gas-Testing Station under the Gas Referee's instructions.

FIG. 104.



Evans' Photometer.

Various other modifications of the original Letheby photometer, chiefly as regards its outer casing, have been constructed, such as the Evans, the

Tower, Canadian, &c., but in all of them the above essential features are carefully preserved.

The Evans Photometer, introduced in 1858 for the purpose of testing the illuminating power of street lamps, is a reversion to the 100-inch bar photometer with several modifications. All the essential parts of the photometer are enclosed in a large rectangular box fitted with ventilating tops over the two ends and a series of doors in front to enable the operator to attend to the various parts. The Bunsen disc is clamped in the centre of the bar, with the gas flame fixed at one end 50 inches from it, whilst at the other the standard candles are mounted in a travelling holder. Readings are taken through a glass window in the central door; a winch fixed immediately below and attached to an endless cord enables the operator to alter the position of the candles until the two sides of the disc are illuminated equally.

Harcourt's Table Photometer.—This modification of Foucault's photometer has been recently introduced for the purpose of the official testing of the London gas supply under the direction of the gas referees.

The following is the official description and instructions for its use:

The several parts of the apparatus stand upon a well-made and firm table, 5 feet 6 inches by 3 feet 6 inches, and 2 feet 5 inches high. The upper surface of this table is smooth, level, and dead black. Upon this are placed or clamped in the positions shown in Fig. 105:

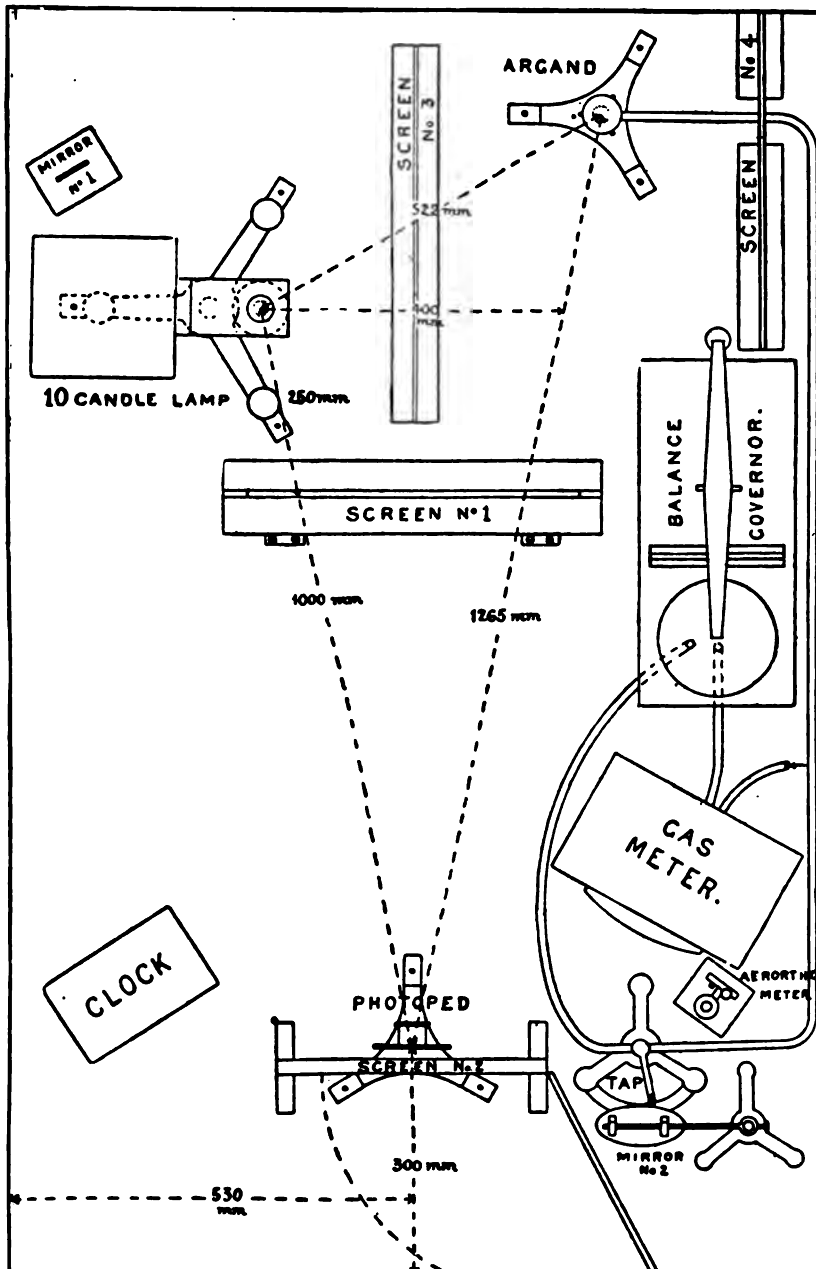
(1) The gas meter;
(2) The gas governor;
(3) The regulating tap;
(4) The "Sugg's London Argand, No. 1" burner;
(5) The connecting pipes;
(6) The Pentane ten-candle lamp;
(7) The photoped;
(8) The ærorthometer;
(9) The stop clock;
(10) Dark screens: mirrors.

The Gas Meter.—The meter is a wet meter, constructed with a measuring drum which allows one-twelfth of a cubic foot to pass for every revolution. A hand is fastened directly to the axle of this drum, and passes over a dial divided into one hundred equal divisions.

The Gas Governor.—The gas governor must be such as will effectually do away with any variation of pressure produced by the working of the meter or other causes. A loose blackened screen, eight and a half inches high by six inches wide, should be placed upon the base of the governor near the tank to prevent heat from the Argand burner from warming the water in the tank.

The Regulating Tap.—This must have a large well-fitting conical plug with a round hole on each side of such a size as to allow gas to pass at the rate of about four cubic feet per hour, under the pressure at the outlet of the governor. In addition there must be narrow saw cuts on opposite sides of the two holes when viewed in plan, which will allow an additional passage of about two cubic feet of gas per hour when the tap is so turned that the holes and the saw cuts are both opposite the orifices of the fixed part of the tap. The construction of the tap is shown in Fig. 106. The index must be secured to the conical plug without any play, and its pointed end must pass over a scale graduated in degrees upon an arc of not less than eighty millimeters radius. The arc is to extend over 90°, and the degrees are to be numbered from 0 to 90. The arc is to be made of white enamel glass, and the divisions are to be etched upon it, and the marks filled in with black. The tap is to be off when the pointer is at one extremity of the arc

FIG. 105.

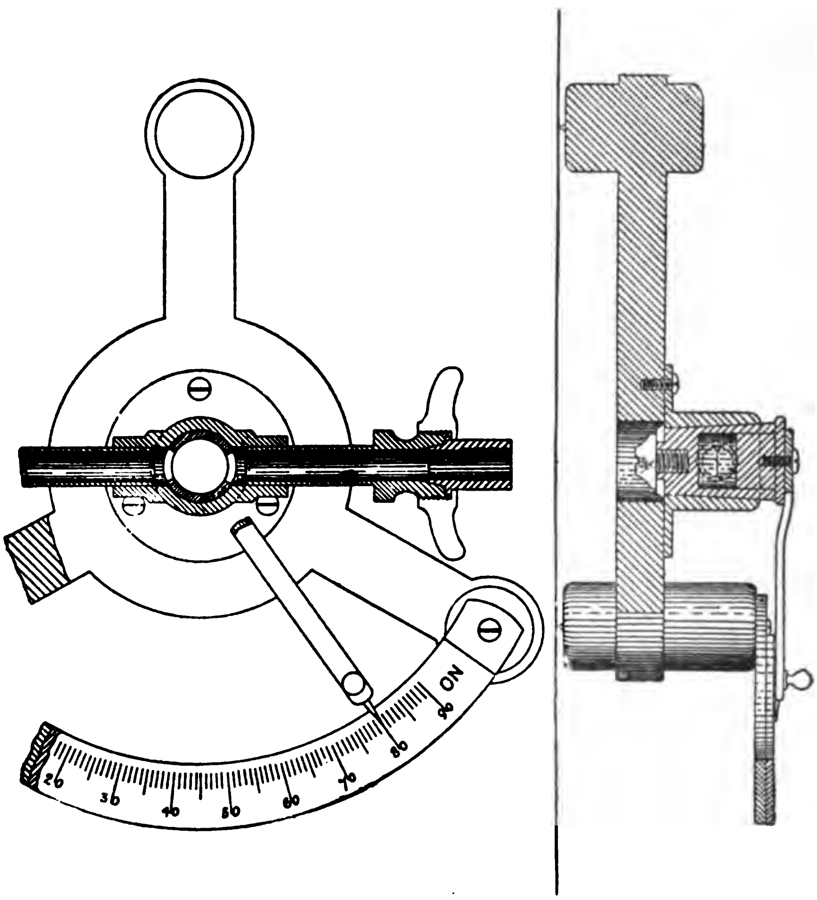


Harcourt's Table Photometer.

at 0°, and fully on when it is at the other extremity at 90°. The small hole should be fully open at about 20°, so that the action of the saw-cuts may extend over the remaining portion of the arc.

The tap must be kept clean and sufficiently lubricated to work easily.

FIG. 106.



The "Suggs London Argand, No. 1" Burner.—This is the burner described in Appendix A. It is to be mounted upon a tripod with flat projecting feet, so that its position upon the table can be adjusted at any time. It may be clamped into position by three ┌-shaped clamps, each made to pinch upon one foot by the action of a single carpenter's screw. The construction of the foot and clamp is shown in Fig. 108. The height of the top of the steatite burner is 353 millimetres above the table. The axis of the burner should be vertical. If it is found to lean in any direction, paper or card should be inserted under one or more of the feet until it is found to be vertical after being clamped in position.

The Connecting Pipes.—These are to be made of half-inch (outside measure) composition piping. They are to be connected with the different pieces of apparatus by three-eighth-inch unions, except in the case of the gas meters, where the unions belonging to the meter may be retained. In all cases the boss of the union is to be attached to the apparatus and the cap and lining to the ends of the connecting pipe. These pipes are to be placed above the table. No grooves, recesses, or holes, other than the screw holes for the screws referred to, are to be made in the table.

The Pentane Ten-Candle Lamp.—This is described under Standards of Light. The lamp need only be placed in position upon the table, but for permanent use clamps corresponding to those used to secure the feet of the London Argand should be employed. The height of the top of the steatite burner is 353 millimetres above the table. The construction of the screw, swivel, plate, and clamp is shown in Fig. 107.

The Photoped.—The photoped is represented in Fig. 108 ; it consists of the following parts : a plate, 100 millimetres square, with a central hole 21 millimetres square. This is held in a vertical position by an upright support so that the centre of the square is 400 millimetres above the table. The upright is carried by a tripod similar to that used for the London Argand and secured in the same way to the table. To one face of the square plate is fastened, by two binding screws, a clamping-plate, 60 by 40 millimetres, also with a central hole 21 millimetres square, so that the two openings are opposite one another. A piece of suitable white paper is pinched between the two plates so as to cover the openings and project a little way below the clamping-

FIG 107.

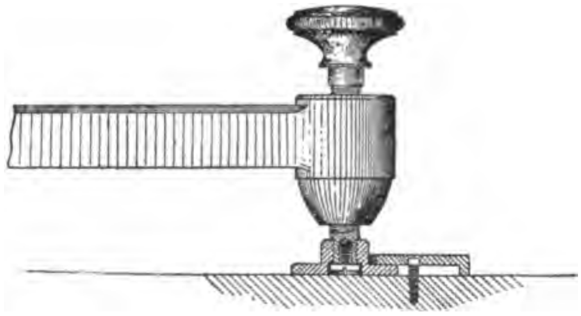


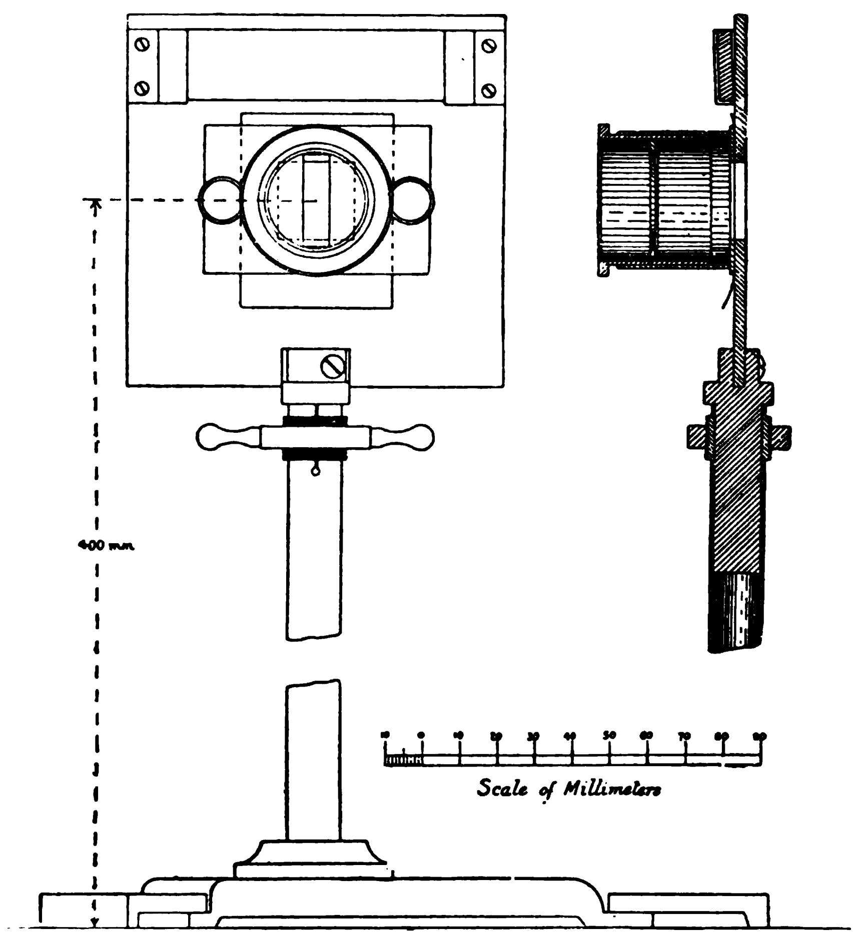
plate. The clamping-plate carries centrally a horizontal tube about 35 millimetres in diameter and 30 in length. In this slides smoothly a smaller tube containing a diaphragm in which a rectangular slit, 25 by 7 millimetres, has been cut. To the upper surface of the larger brass plate, and on the same side as the clamping-plate, is fixed a strip of glass, so that the lower edge is close to, and exactly parallel to, the plate, while the upper edge is so much in advance as will allow the reflection of the flames described on page 289 to be observed.

The photoped should be plumbed vertical. If it is found to lean sensibly towards or away from the lamps, paper or card should be inserted under one or more of the feet until it is found to be vertical after being clamped in position.

Dark Screens, Mirrors, Measuring Rods.—Five dark screens are provided in order to prevent the inaccuracy and inconvenience to which stray light would give rise.

The first is placed between the burners and the photoped in the position shown in Fig. 105. This screen is 500 millimetres square with two rectangular openings. The opening to the left is 40 millimetres wide and 55 high, and its lower edge is 350 millimetres above the table. The opening to the right is 50 millimetres wide, its lower edge is 340 millimetres above the table, and it extends to the top of the screen. The centre is carried by a wooden foot about 500 by 100 millimetres and 30 thick. Care must be taken that it is so adjusted that the whole of the flame under the tube C of the ten-candle lamp and the whole of the chimney and burner of the Argand can be seen through all parts of the slit of the photoped when the paper is removed for that purpose. The foot may then be fastened to the table by means of two hinges, so that the screen may be folded down when the position of the lamp is being verified and may be easily replaced.

FIG. 108.

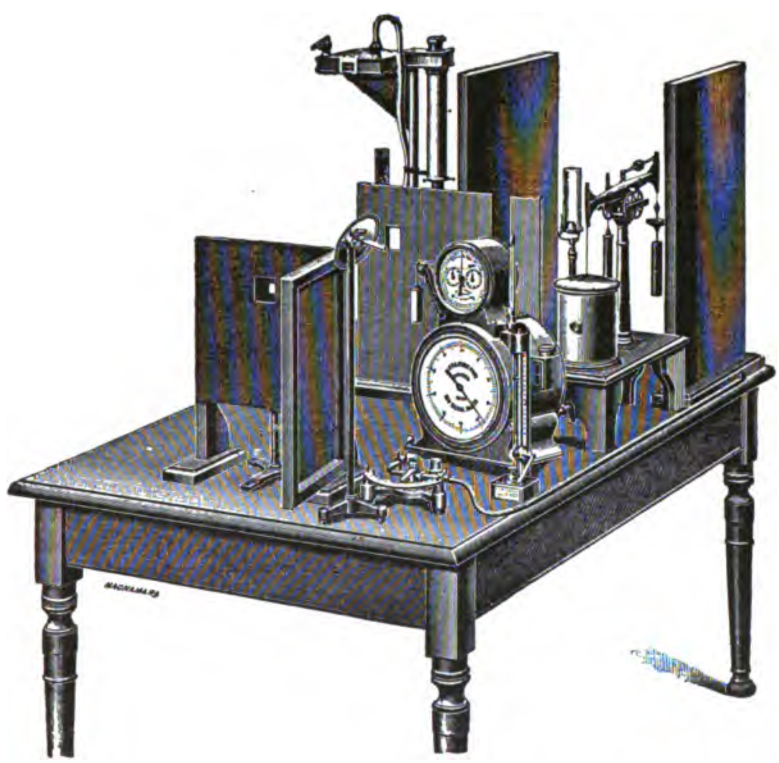


The second dark screen consists of a piece of black velvet or black cloth 350 millimetres square, stretched on a frame and supported so that its lower edge is 150 millimetres above the table. In this is cut a hole 50 millimetres square with its lower edge 380 millimetres above the table. This screen is placed close to the photoped, but on the opposite side to that facing the lamps, and with the square hole opposite the square hole in the plate of the photoped. To the right side of the frame is hinged a light frame 350 millimetres high and 300 wide, with its lower edge 150 millimetres above the table. On this also is stretched black velvet or black cloth. This prevents the illuminated dial of the meter or arc of the regulating tap from interfering with the photometric observations, while at the same time it can be readily moved when these are to be observed.

The third dark screen is about 500 millimetres wide and 570 high. The fourth is about 450 wide and 570 high. These may be card painted dead black, or of thin wood, and may be placed approximately in the positions shown in Fig. 106, and with their lower edge 180 millimetres above the table.

The fifth dark screen consists of a piece of black velvet or cloth large enough to form a black background to the lamps when viewed from the

FIG. 109.



Harcourt's Table Photometer.

photoped. It is best placed upon the wall, but if that is inconvenient, or other objects intervene, it should be supported on a stand, but always so as to be at least 300 millimetres behind the flames of the lamps.

Two small mirrors are carried on light stands. One of these, made of ordinary flat silvered glass, is vertical, and is so placed as to enable the gas examiner, when seated at the photoped end of the table, on moving his head to the left of the second dark screen, to see by reflection the tip of the flame of the ten-candle lamp through the mica window in the tube C.

The other, which should be about 120 millimetres in diameter, is convex, and should have a radius of curvature of about 400 millimetres. It is placed on the observer's right, and is so inclined that it casts a diverging beam of subdued light upon the divided arc of the regulating tap, the face of the meter, upon the aerorthometer, and upon the gas examiner's note-book.

All the apparatus on the table upon which light can fall, and which might by reflection illuminate the photoped or catch the eye of the operator, is to be painted dead black; or, if of finished brass, it is to be bronzed before being lacquered.

The correct position of the photoped and of the two burners is to be verified as follows: Each burner is provided with a measuring-rod securely fastened transversely to a cylindrical and shouldered plug which just fits into the steatite ring and rests upon it. The rod belonging to the ten-candle lamp is to be 1.000 metre from the axis of the plug to the extreme point. The rod belonging to the London Argand is to be 1.265 metre from the axis of the plug to the extreme point. Each rod is to be balanced about the plug. Each must be capable of being placed in its burner without disarranging the burner, except in the removal of the glass chimney of the London Argand or the conical shade of the ten-candle lamp. Each rod should terminate in a rounded ivory point. When these rods are in position upon their burners, and the long ends are moved gradually round towards the photoped, they should just come in contact with the paper under the clamping plate at the middle point.

A third rod is provided with two plugs, one to fit each burner, and with their centres exactly 0.522 metre apart. The two plugs should just drop into the steatite rings of the two burners. If any one of these tests shows the burners to be incorrectly placed, their position is to be altered until all the measurements are correct. After this process the burners are to be lighted, the flames turned low, and the reflection of one is to be observed over the other on the glass of the photoped. If the reflection appears central, the photoped is symmetrically placed with respect to the two burners; if not, the nut on the standard is to be loosened and the plate turned until the reflection is central. The two lights are then to be turned up and the slit is to be moved in or out until the two rectangular spaces illuminated by the two lights just meet but do not overlap.

Fig. 109 shows the complete apparatus as fitted on the table ready for use.

Radial Photometers.

The photometers above described are all arranged for testing the rays of light emitted in a horizontal direction only, and afford no means of estimating those directed either above or below that line.

The introduction of electric light and of high-power gas burners for the improved illumination of open spaces and large areas, however, led to a reconsideration of the methods for estimating the value of the various systems then in use.

Before their introduction it was considered sufficient to estimate the intensity of the luminous rays in a horizontal direction only, irrespective of the value of those rays which are actually utilised in practice. Such a system was doubtless useful in those cases where burners of similar primary construction, such as flat flame and Argand burners, were employed; but with the introduction of the various improved forms of burners and lanterns such as are now in use, a modification of these methods became necessary.

In order to ascertain the true value of a luminous agent, it is necessary to determine the power of those rays falling below the horizontal line, and indeed through the whole of the semicircle from the vertical line above to the vertical line below the point of illumination.

This will be evident when it is remembered that when two lights are opposed to each other in a horizontal direction and a vertical screen is placed between them, the rays that impinge thereon are in each case horizontal rays and therefore comparable, and the intensity of the source of light can be measured under the law of inverse squares. If one of the lights is moved through the circumference of a circle of which the centre is coincident with the centre of the disc, the number of rays impinging on any unit area of the disc will, provided the disc is kept in its original vertical position, decrease as the position of the light becomes more remote from the horizontal, in ratio to the cosine of the angle formed by the horizontal line and the line which joins the light and the centre of the disc. It is quite evident, therefore, that when the light is raised through a quadrant the number of rays impinging on the disc will be nil, whereas the burner may really be emitting a considerable amount of light in this direction.

The loss of light due to reflection and absorption when the two lights are not in the same plane with the disc is no inconsiderable amount, and would of itself prohibit the use of the vertical disc.

A series of experiments made upon lights of various powers and in different positions, with the disc arranged, first, in the usual vertical position, and secondly, so that the light from the two sources should impinge upon it at equal angles of incidence, clearly demonstrated this point.

After correcting the results obtained when working with a vertical disc for the diminished number of rays impinging upon the disc when the light is at different angles, the value obtained was deducted from that found by estimation with the disc arranged for equal angles of incidence, and the difference between the two results calculated into percentages. By this means it was found that, when the burner is at an angle of 22.5° above the horizontal, the average loss due to reflection from the vertical disc is 4.4 per cent.; at 45° it is 12 per cent., and at 67.5° 69 per cent.

It is obvious, therefore, that the method of estimating the illuminating power of angular rays by means of a vertical disc is erroneous.

By arranging the disc so that the angle of incidence is equal on either side, both the proportionate number of rays impinging thereon and the loss due to reflection are equalised.

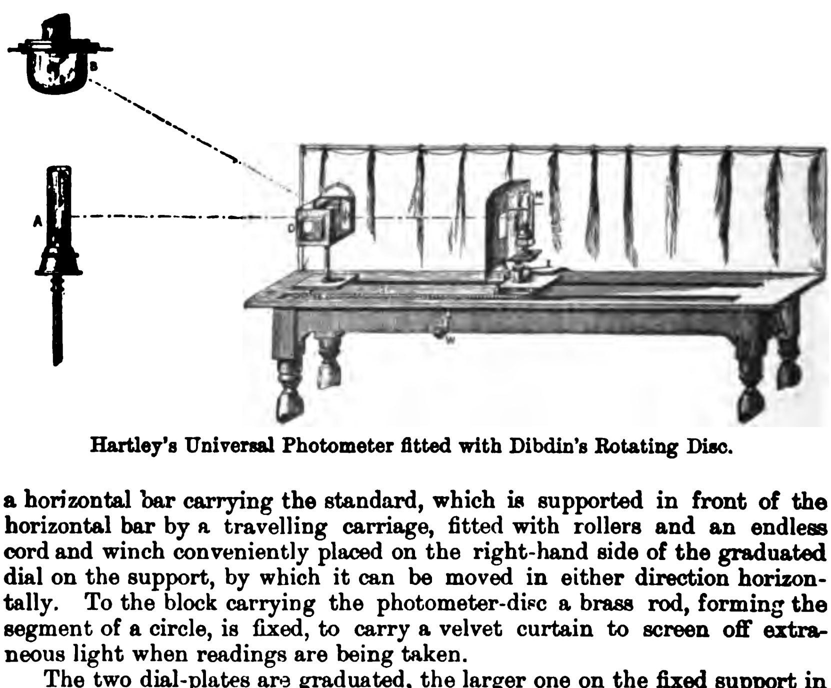
Hartley's Universal Photometer.—This instrument consists of a narrow table 11 inches wide, 2 feet 6 inches high and 5 feet 6 inches in length, in the centre of the top of which a slot runs practically the whole length. The base of the standard burner passes through this slot and is connected by a wire passing over pulleys to a winch-handle fixed in the centre of the table, as in the Evans' photometer. The disc carrier is mounted on a stand which also passes through the slot in the table, and is capable of adjustment. To the base of this stand, in a vertical line with the disc, is fixed a pointer, maintained at the zero of a scale, which can be moved in a groove throughout the length of the table. The burners under examination are supported on a sliding pillar, the base of which, like the photometer, is fitted with levelling screws and plumb-lines. For use with this photometer, Fig. 110, Mr. Hartley calculated a series of tables which greatly facilitated its use. When first constructed the disc was rigidly fixed in the usual vertical position, but later this was so altered as to be capable of adjustment to any angle required, so that the rays from the standard and the burner under examination, whatever its position, would impinge on the disc at equal angles.

Dibdin's Radial Photometer.—This photometer, which was designed in 1883 to estimate the angular rays emitted from a light in any position, consists of two vertical supports, one of which is permanently fixed to a base-board or foot, while the other on the right hand (Fig. 111) travels on rollers on the same base-board in such a position that it will run in front of the fixed support.

These two uprights are connected by a bar, the ends of which work upon trunnions or axles attached to blocks, which travel in grooves in the uprights, and can be clamped in any desired position. One end of the bar is attached to the front of the fixed upright, while the other end is attached to the travelling upright at the back, so that when the two uprights are in juxtaposition the bar is perpendicular between them. The centres of the trunnions correspond in position to the centres of the two graduated dial-plates in front of the uprights, the distance between the centres of these dial-plates being 50 inches. By this means, whatever *position* the bar may be in, the *distance* from the centre of one dial to that of the other is constant. In front of the dial-plate on the travelling upright the screen or disc-holder is fixed, so that its centre is coincident with the centre of the dial.

Attached to the block in the groove of the travelling upright support is

FIG. 110.



Hartley's Universal Photometer fitted with Dibdin's Rotating Disc.

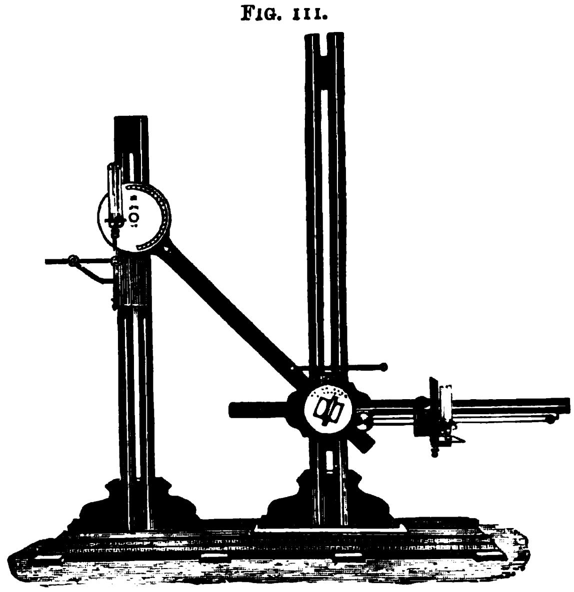
a horizontal bar carrying the standard, which is supported in front of the horizontal bar by a travelling carriage, fitted with rollers and an endless cord and winch conveniently placed on the right-hand side of the graduated dial on the support, by which it can be moved in either direction horizontally. To the block carrying the photometer-disc a brass rod, forming the segment of a circle, is fixed, to carry a velvet curtain to screen off extraneous light when readings are being taken.

The two dial-plates are graduated, the larger one on the fixed support in degrees and the smaller one on the travelling support in half degrees, the latter being numbered as whole degrees for the purpose of facilitating the setting of the disc for equal angles of incidence, so that when the bar is set (say) at 40°, the disc-pointer is to be set at the point marked 40°. It will then be in the proper position—viz. 20°. The disc may be arranged to work automatically with the movement of the bar by means of a simple mechanical appliance, so that, whatever may be the position of the bar, the disc will be at the correct angle.

A brass rod is used for adjusting the position of the burner, &c., under examination, and is pushed through the centre of the block and trunnion on the fixed upright support; it is then at right angles with the plane of the dial, and projects exactly through its centre, by which means it is easy to fix the correct position of the flame in front of the apparatus. The light to be tested may be brought forward to the full extent that can be attained by the disc and standard, which, obviously, can be regulated as desired, so that the size of the burner or lantern to be tested by this apparatus is practically unlimited, due regard being paid to the length of the bar and the power of the light.

In order to estimate the illuminating value of any lamp it is fixed on the support attached to the block of the fixed upright, and accurately centred with the dial-plate, which is then lowered to the bottom of the groove in the support. The block in the travelling support is next raised, thus bringing it immediately over the burner, the travelling upright being in front of the fixed support, and the pointer on the bar indicating 90° on the large dial-plate. The photometer disc is arranged for equal angles of incidence by

FIG. III.



Dibdin's Radial Photometer.

turning it until its pointer is at 90°, and a reading is taken. The clamp holding the top block in position is then loosened, and the travelling support moved away from the fixed support until the bar is at an angle of 80°, when the block is again clamped, the disc adjusted to 80°, and further readings taken, this adjustment and measurement being repeated for each degree or 10 degrees as desired, until the horizontal rays are estimated. The block supporting the light is then raised to the top position, the bar adjusted for the desired angle below the horizontal, and a series of readings taken until the downward vertical rays are estimated.

Comparative tests of various burners should be so conducted as to show the actual work done by them, not only in one but in all directions. With Argand and all other circular burners, this can be done by making one series of tests from the vertical above to the vertical below, at every 10 degrees. But in the case of flat-flame burners it is necessary that this series should be made in duplicate, one with the flame flat, or at right angles, *Flat-flame Burners—Illuminating Power of Horizontal Rays.*

Position of Flame.	Burner No. 1 Candles.	Burner No. 2 Candles.	Burner No. 3 Candles.
Flat to Photometer Bar . . .	30.8	24.2	8.5
Flame turned . . 10°	30.8	24.2	8.5
„ „ . . 20°	30.9	24.3	8.5
„ „ . . 30°	30.9	24.2	8.5
„ „ . . 40°	30.8	24.0	8.4
„ „ . . 50°	30.2	24.0	8.3
„ „ . . 60°	30.1	23.8	8.2
„ „ . . 70°	30.2	23.5	8.2
„ „ . . 80°	29.8	22.4	8.2
Edge to Bar „ „ . . 90°	24.4	20.3	7.9
„ „ . . 100°	28.7	21.6	8.2
„ „ . . 110°	29.6	22.8	8.3
„ . . 120°	30.3	23.5	8.3
„ . . 130°	30.5	23.4	8.3
„ „ . . 140°	30.5	23.2	8.3
„ „ . . 150°	30.5	23.4	8.4
„ „ . . 160°	30.1	23.5	8.4
„ „ . . 170°	30.4	23.2	8.3
Flat to Bar „ „ . . 180°	30.3	23.1	8.4
„ „ . . 190°	30.4	22.8	8.4
, „ . . 200°	30.8	23.0	8.4
„ . . 210°	30.8	22.7	8.4
, . . 220°	30.7	22.9	8.3
„ „ . . 230°	31.0	22.9	8.3
„ „ . . 240°	30.6	22.8	8.3
„ „ . . 250°	30.1	22.0	8.2
„ „ . . 260°	29.5	21.2	8.1
Edge to Bar „ „ . . 270°	25.0	18.6	7.8
„ „ . . 280°	28.5	20.6	7.8
„ „ . . 290°	29.5	21.9	8.1
„ „ . . 300°	29.7	22.2	8.3
„ „ . . 310°	29.8	23.0	8.3
„ „ . . 320°	30.3	23.0	8.4
„ „ . . 330°	30.3	23.5	8.3
„ „ . . 340°	30.5	23.4	8.4
„ „ . . 350°	30.7	23.5	8.4
Flat to Bar „ „ . . 360°	30.9	23.4	8.5

Flat-flame Burners—Illuminating Power of Angular Rays.

Direction of Rays.	Burner No. 1 Candles.	Burner No. 2 Candles.
90° above horizontal	27.8	8.9
80° „ „	29.2	9.0
70° „ „	29.0	9.3
60° „ „	30.5	9.3
50° „ „	30.8	9.2
40° „ „	30.9	8.7
30° „ „	30.3	9.4
20° „ „	30.4	9.3
10° „ „	29.4	9.3
Horizontal	29.8	9.7
10° below horizontal	29.9	9.9
20° „ „	30.2	10.0
30° „ „	30.2	10.1
40° „ „	29.8	10.0
50° „ „	29.8	10.0
60° „ „	30.0	10.7
70° „ „	29.2	10.3
80° „ „	28.7	11.2
90° „ „ . . .	19.6	5.8

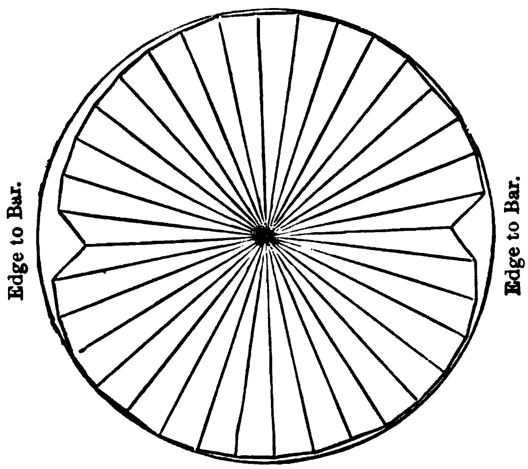
Effect of Reflectors and Shades.

Direction of Rays.	Argand No. 1.			Argand No. 2.			Argand No. 3.		Christiania.		Union.	
	Without Shade, &c.	With Reflector only.	With Reflector and Cup.	Without Shade, &c.	With Reflector only.	With Reflector and Cup.	Without Shade, &c.	With Paper Reflector.	Without Globe.	With Globe.	Without Reflector.	With Compound Reflector.
90° above horizontal	16 8	27.6	33.0	19.0	25.0	29.0	10.6	9.3	—	17.6	—	—
80° " "	20.0	30.8	36.6	21.0	29.0	33.0	14.0	13.7	14.0	18.4	—	—
70° " "	17.4	24.4	31.2	19.4	21.4	28.4	14.2	12.9	14.1	19.3	8.7	9.2
60° " "	18.2	14.8	21.0	18.8	13.8	19.2	15.0	11.0	13.4	10.3	8.7	9.2
50° " "	18.6	11.2	14.8	18.8	10.0	14.0	15.0	4.0	13.6	8.4	8.7	9.8
40° " "	18.8	9.8	12.8	18.4	8.4	11.0	15.1	1.3	12.8	8.0	8.6	10.4
30° " "	18.6	9.0	11.8	17.0	7.8	9.2	15.1	1.3	13.0	7.0	8.7	12.6
20° " "	18.6	7.6	10.1	17.2	6.4	8.4	15.0	2.0	12.4	6.5	8.8	19.6
10° "	18.6	6.2	8.8	16.8	5.4	7.2	15.0	1.0	12.3	6.7	7.2	50.0
Horizontal	18.6	5.2	8.6	16.8	4.8	7.6	15.0	0	12.2	7.0	6.6	28.0
10° below horizontal	18.8	14.4	13.8	17.2	16.0	15.0	15.6	2.0	12.3	7.6	—	—
20° " "	19.2	24.2	15.6	17.8	21.6	14.2	15.8	12.5	13.0	7.6	—	—
30° " "	18.2	25.6	12.2	17.2	23.0	12.0	15.6	25.4	12.7	8.0	—	—
40° " "	16.4	26.0	11.8	16.8	23.4	13.4	14.0	31.0	12.8	9.0	—	—
50° " "	15.2	24.8	13.2	14.4	23.4	16.2	12.3	30.8	12.3	15.0	—	—
60° " "	11.2	22.0	17.4	11.0	20.0	19.4	8.4	30.0	11.6	17.2	—	—
70° " "	6.0	18.8	20.8	6.2	17.0	23.4	4.8	29.4	10.8	15.1	—	—
80° " "	2.6	21.2	21.8	4.0	20.8	25.2	2.5	33.0	6.3	10.3	—	—
90° " "	2.0	25.6	26.6	2.0	20.2	23.6	1.0	30.4	1.6	7.0	—	—
Average	15.46	—	—	15.26	—	—	12.31	—	11.73	—	—	—

to the disc of the photometer, and the other with the edge of the flame towards the disc. An extensive series of experiments on this point has

FIG. 112.

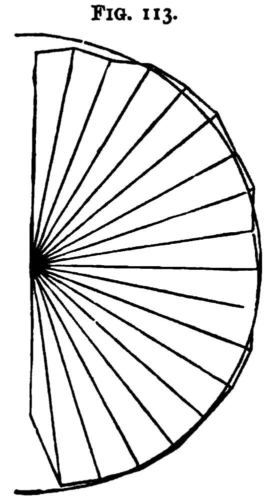
Flat to Bar.



Flat to Bar.

Horizontal Rays.

FIG. 113.



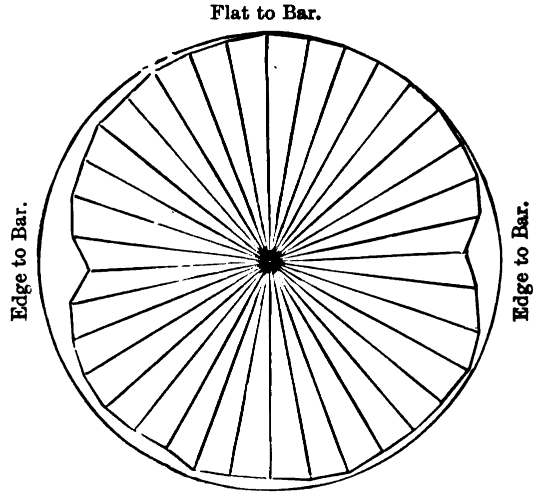
Angular Rays.

Flat-flame Burner, No. 1.

shown that very considerable differences exist between the quantity of light emitted from the flat surface and the edge of the flame in various burners

FIG. 114.

Flat to Bar.

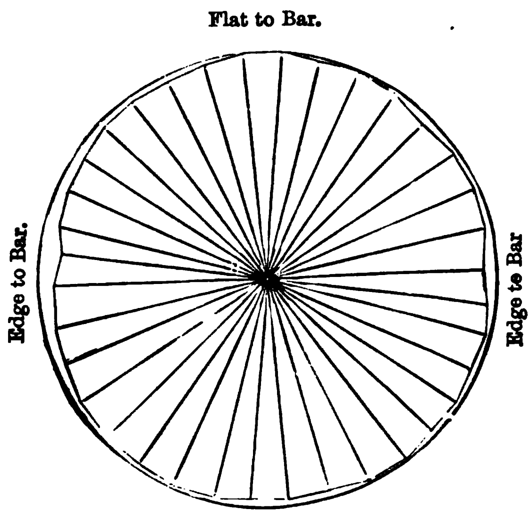


Flat to Bar.

Flat-flame Burner, No. 2.—Horizontal Rays.

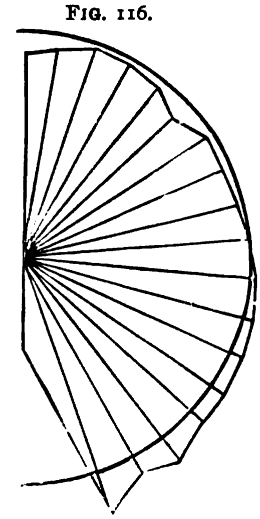
(see page 294), this difference varying from 10 to 35 per cent. of the light emitted from the flat surface. It is very necessary, therefore, that two such series of tests should be made and an average taken to obtain the representative value of the burner.

FIG. 115.



Horizontal Rays.

FIG. 116.

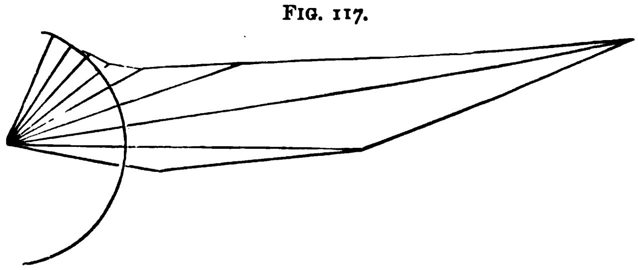


Angular Rays.

Flat-flame Burner, No. 3.

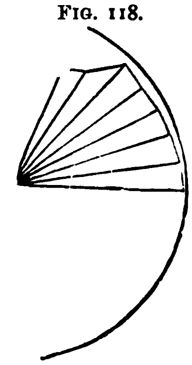
This photometer is of special value in the examination of burners shaded by globes, reflectors, &c., which may be tested at every degree where neces-

FIG. 117.



With Compound Reflector.

FIG. 118.

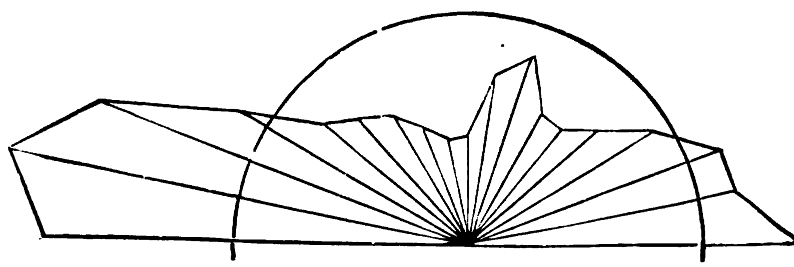


Without Reflector.

Union Burner, No. 4.—Angular Rays.

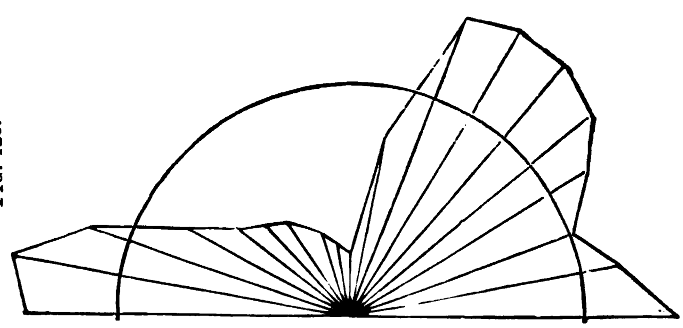
sary, and thus most valuable comparative results obtained. The table on p. 295 contains a typical set of results, also put in diagrammatic form, which were obtained from three Argand burners fitted with different shades.

FIG. 121.



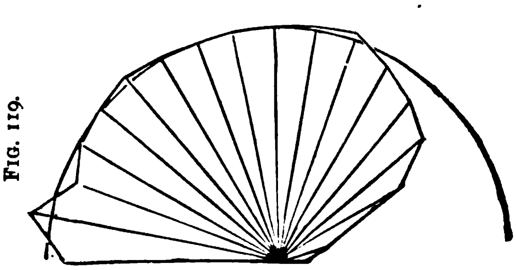
With Reflector and Cup.

FIG. 120.



With Reflector only.
Argand Burner, No. 1.

FIG. 119.



Without Reflector or Cup.

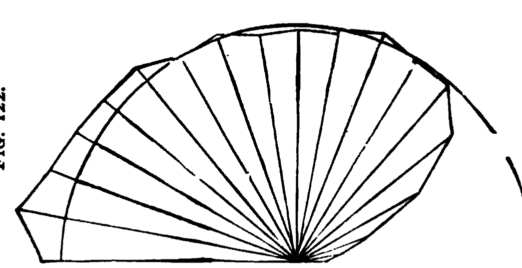


Fig. 122.

Without Reflector or Cup.

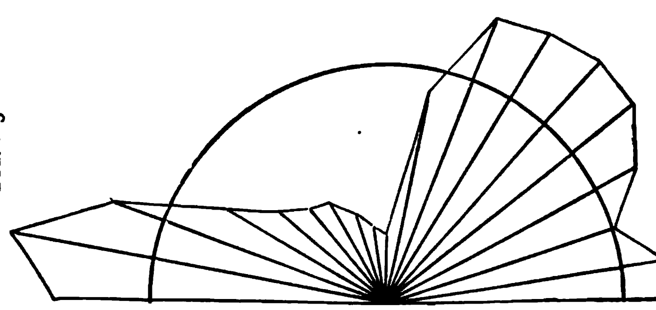


Fig. 123.

With Reflector only.
Argand Burner, No. 2.

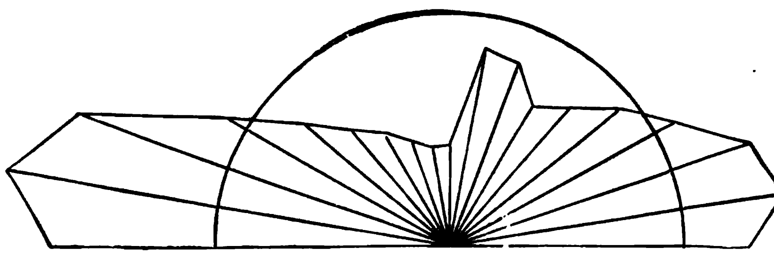
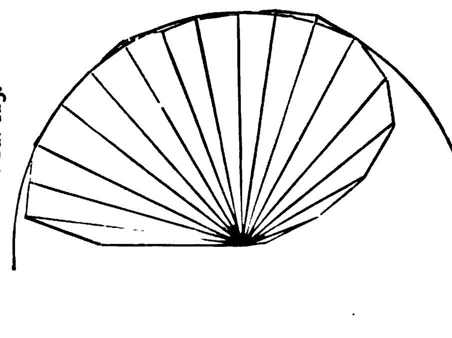


Fig. 124.

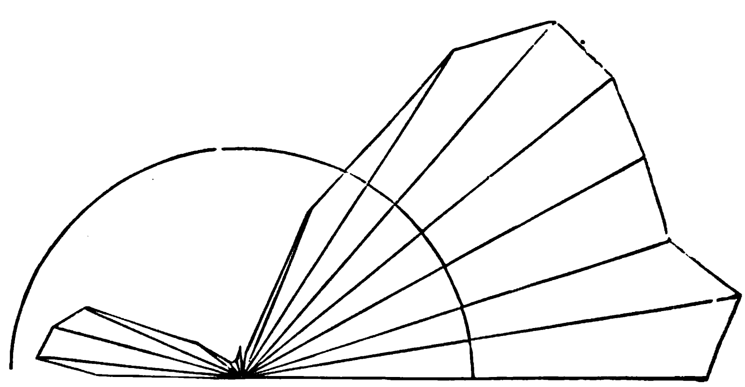
With Reflector and Cup.

FIG. 125.



Without Cardboard Shade.

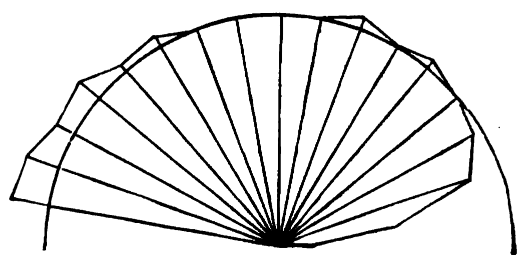
FIG. 126.



With Cardboard Shade.

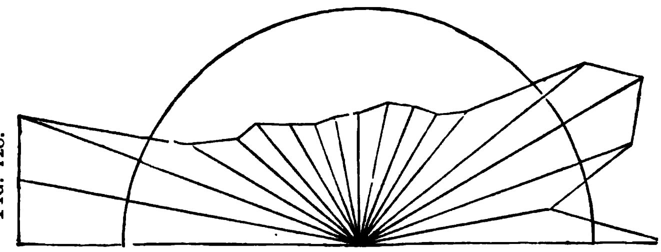
Argand Burner, No. 3.

FIG. 127.



Without Opal Globe.

FIG. 128.

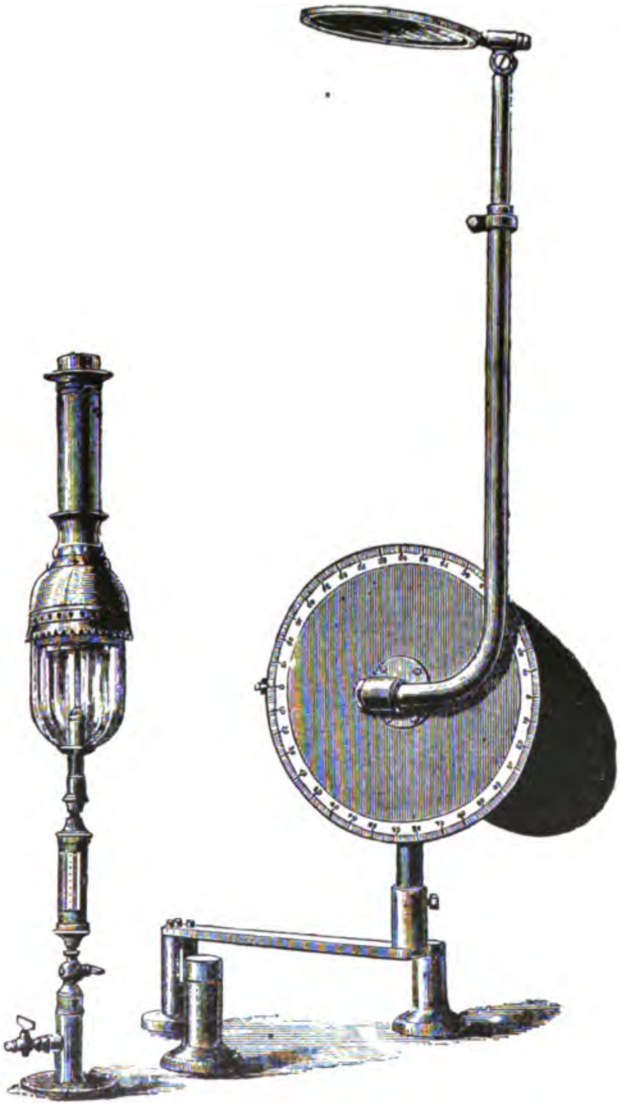


With Opal Globe.

"Christiania" Governed Burner.

*Harcourt's Holophotometer.** — The holophotometer is an instrument designed, like the "Radial" Photometer, to measure the light emitted in every direction by any luminous source. It is mounted upon a table capable

FIG. 129.



Harcourt's Holophotometer.

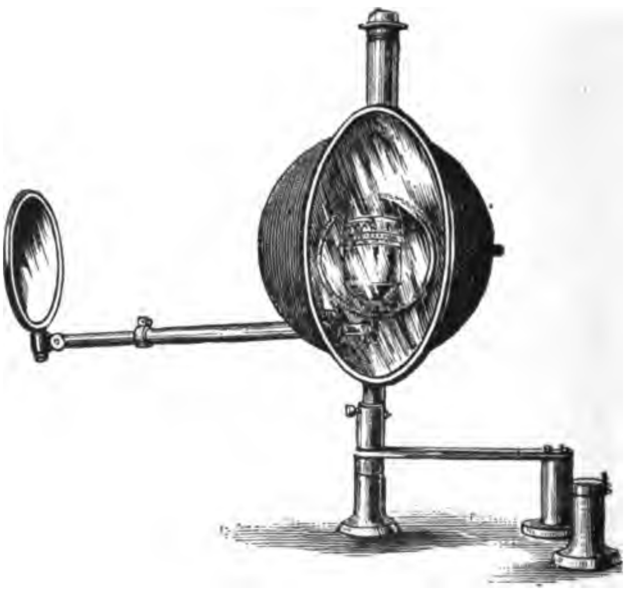
of being moved nearer to, or farther from, a fixed table containing a graduated bar with movable disc, and having a standard lamp fixed at the zero of the bar. The light to be measured is mounted upon, or is in rigid connection with, the movable table, and is therefore not moved during a series of readings.

* "Journal of Gas-Lighting," July 17, 1888.

The instrument consists of an axis working friction-tight in a collar supported by a vertical pillar. The axis is accurately fixed at the same height, and in a line with the centre of the disc. At the end of the arm nearest to the disc is placed a larger mirror, with its centre concentric with the axis but so arranged that the plane of the mirror may be inclined and clamped at any angle to the axis, and at the other end is fixed a telescopic arm, carrying a small mirror, which is capable of being turned in any required position. The arms being rigidly fixed to the rotating axis of the instrument, to which is also attached the larger mirror, it follows that the rotatory motions of the mirrors about the axis are identical. The angles of rotation are measured by indications upon a divided circle attached to the moving axis, and are shown by a pointer fixed to the upright support, Fig. 129.

The mirrors are adjusted in such a way that the light from the lamp to

FIG. 130.



be measured falls upon the smaller mirror, thence is reflected on to the larger one, and finally along the axial line of the photometer disc. As both mirrors rotate together, it follows that if a horizontal beam is reflected correctly, all other beams will find their way along the axis of the photometer. If, therefore, the arm carrying the small mirror be moved through various angles, it will receive the light emitted from the lamp at those angles, and the light will at every angle be transmitted along the axis of the photometer. The divided circle is made large enough to serve as a complete screen for all direct light; and only the light falling on the small mirror can find its way to the disc. For the purpose of making an absolute test an additional measurement must be made. The direct horizontal light is measured without the interposition of the holophotometer (which is mounted so as to be easily moved out of the direct line); then the mirrors are interposed, and a new measurement made. The additional path travelled by the light is allowed for in calculation; and thus the absorption of the mirrors found. The absorption of the two mirrors used is stated usually to be only about 1.8 per cent.

The employment of mirrors in photometry has sometimes led to serious errors, but it will be seen from the foregoing description that inasmuch as the relative angle of the mirrors is never changed, and as their absorption is easily calculated and allowed for, the only objections to their use have been guarded against and avoided.

In order to eliminate the second source of error—viz., that arising from the formation of a principal focus—it is only necessary to take a

FIG. 131.

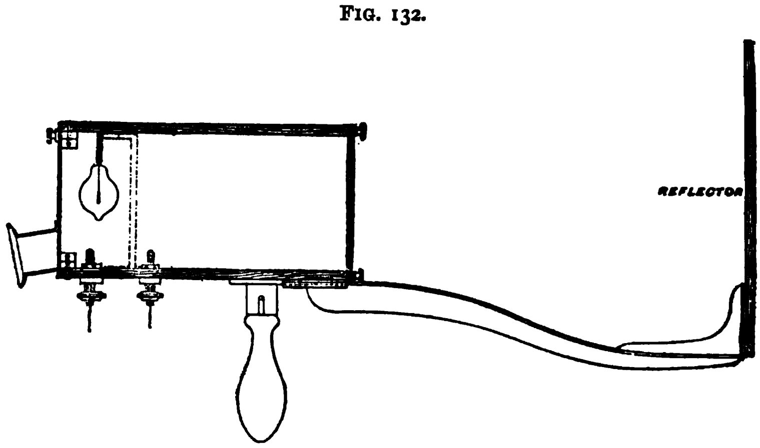
series of readings with the table in one position, and then take another series with the table at a greater distance. If a focus is formed at sufficient distance to produce an appreciable error, it will clearly appear in the difference between the readings at the two distances, when it is only necessary to wheel the table to such a distance that the discrepancy is inappreciable. In other words, this is equivalent to using a bar of sufficient length to make it practically infinite, compared with the distance between the focus and the real source of light.

The instrument was designed specially for use in lighthouse work, where it is of the highest importance to measure accurately the total light given by any lamp, and not only that emitted in any one particular direction, which may or may not be the maximum, but in every direction.

Fig. 129 is a view of this instrument from behind showing the divided scale; Fig. 130 is a view taken from the end of the photometer-bar, showing how the horizontal light from the lamp is transmitted to the disc; and Fig. 131 is a view taken from the disc showing how the vertical light would be transmitted to the disc.

*Preece's Illumination Photometer.**—This photometer, described by Mr. (now Sir William) Preece to the Royal Society in 1883, is in principle similar to the original Bunsen photometer. "A small glow-lamp (Fig. 132) is fixed in a box, carefully blackened in the interior. Over the end is stretched a Bunsen screen of paper, on the middle of which is a grease-spot. At about twelve inches from the latter is another screen in which drawing-paper is fixed. The grease-spot is so screened that no light falls upon it beyond what is reflected from the screen. At the end of the box opposite the Bunsen screen is an eye-piece, consisting of a plain tube. To make an

FIG. 132.



Preece's Photometer.

observation, it is only necessary to place the instrument so that the reflecting screen receives the illumination which it is desired to measure, and to alter the electric current of the glow-lamp by means of an adjustable resistance, or a rheostat, until the grease-spot becomes invisible. Preece found by experiments that the candle-power of the glow-lamp increased as the sixth power of the current. The current in ampères thus gave, for a particular lamp, a constant whose sixth power expressed the illumination measured. Professor Kittler of Darmstadt and Captain Abney independently corroborated this function, and recent observations show that, in modern glow-lamps of eight candle-power, the candle-power varies as the current, raised to powers of from 5.3 to 6.9. By the use of a reflecting screen, Preece avoids the difficulty met by Professor Massart; but, for feeble illuminations, a serious loss of the dim light to be measured is entailed.

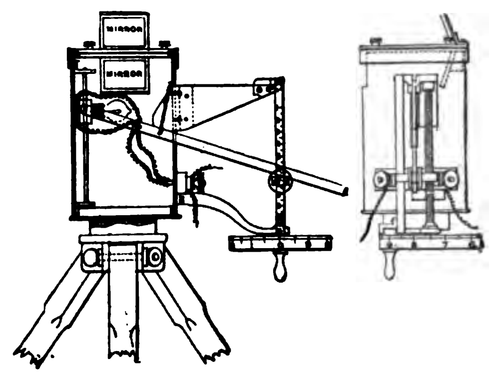
Preece and Trotter Photometer.—A modification was designed by Trotter† in conjunction with Preece in April 1884, with the view of obviating the colour difficulty and the liability of error produced by different kinds of Bunsen screens. The usual arrangement of screen with two mirrors was

* Trotter on the "Distribution and Measurement of Illumination," Proc. Inst. C.E., vol. cx. part iv.

† *Ibid.*

employed, allowing both sides of the spot to be seen simultaneously. Upon a tripod, a cylindrical case, Fig. 133, is covered at the top by a horizontal Bunsen screen, and two observing mirrors are inclined at a suitable angle. A glow-lamp slides on a vertical rod, and connection with external terminals is maintained by coiled wires. The lamp is moved by a lever which pushes it in opposition to a spring. The lever is pressed against the cam, and bears against the roller. This roller is mounted on a nut which traverses a vertical screw. Its position may be read on a scale. At the lower end of

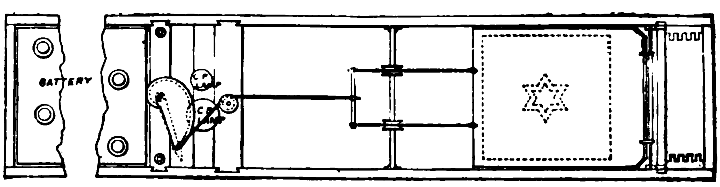
FIG. 133.



Preece and Trotter's Photometer

the screw is a handle and a graduated wheel. The cam is shaped to such a curve that, when the nut moves through any given distance, the displacement of the lamp is as the square of that distance; the light of the lamp being adjusted to any required power, balances a given illumination when the scale reads a unit. A balance being effected for any other illumination, its value in terms of the said unit may be read off on the scale. It is not necessary to measure the distance of the filament of the lamp from the screen. This instrument is easy to use, but the range is only from one to ten, and

FIG. 134.



Trotter's Photometer (Plan).

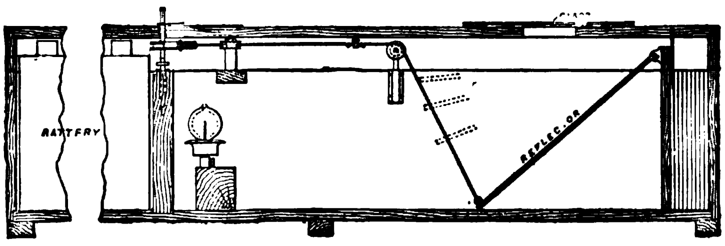
cannot easily be increased. A sliding rheostat and an ampère meter were used for maintaining at a fixed value the current required to balance the unit illumination.

Subsequently Trotter somewhat modified this photometer. He wished to make the measurements as near the ground as possible; therefore, avoiding the tripod, he arranged a Bunsen screen 6 inches from the ground. To see both sides simultaneously would require three mirrors, and would necessitate a very limited view. As it is very much easier to make observations without an eye-piece, using both eyes, he decided to return to the observation of one side of the screen only and to make an empirical correction if necessary. A 6-inch cube, covered by a Bunsen screen at the top and open at the side, was used. Numerous experiments were made with different kinds of Bunsen spots, with the result that a simple cardboard screen, with a star-shaped hole cut in it, was found to be far more sensitive than any other arrangement (Figs. 134 and 135).

Very little difficulty was found in matching the illumination from an arc lamp even when the standard lamp gave a light of about the same colour as that of a candle. Greater accuracy was possible between 0.6 candle-foot and 0.2 candle-foot than with higher or lower illuminations.

The electric lamp was mounted in a box, so that it stood 5 inches above the ground. The object of raising it above the level of the middle of the reflecting screen was to prevent any light from falling directly on the underside of the Bunsen screen, and many erroneous measurements were made before this precaution was taken. Telescopic tubes were used to shut out stray light from the reflecting screen; these tubes, when fully extended, measured 1 foot 4 inches in length. The storage battery consisted of four lithanode cells manufactured by the Mining and General Electric Lamp Co. Two of these are quite capable of running a $\frac{3}{4}$-candle lamp, at a fair

FIG. 135.



Trotter's Photometer (Section).

brightness, for ten hours, but in order to allow a good margin, two more cells were connected in parallel. These proved to be sufficient for the purpose, and no appreciable difference in the candle-power was observed between the preliminary calibration and the one which followed each evening's work. A slightly higher power was given immediately after charging, but a quarter of an hour's continuous discharge seemed to bring the batteries into a very steady condition. The lamp was lighted for as short periods as possible, about ten seconds being sufficient for each reading.

The instrument was calibrated by direct comparison with various lights of known intensity.

As a typical example of an old-fashioned gas-lit street, Great George Street, Westminster, was the scene of the first street-lighting measurements, and the first observation was made 2 feet from the curb, immediately opposite the entrance to the institution of Civil Engineers. The illumination was found to be 0.03 candle-foot. This was read off on a measuring-tape graduated directly in candle-feet, the divisions being the reciprocals of the square of the length in feet. In the case of feeble illuminations, it was found that stray light, especially from distant lamps, fell on the reflecting screen, and caused the readings to be too low in spite of the telescope tubes which were used. It is convenient, especially for feeble illumination, to have the Bunsen screen at least $3\frac{1}{2}$ inches square, and the star-shaped hole should not be less than $1\frac{1}{4}$ inch across. Trotter finally adopted the method of inclining the reflecting screen at different angles mounted on an axis passing through its upper edge and arranged so that it could fold up quite out of the beam. In order that a convenient scale might be provided, motion was given to the reflecting screen by a fine chain wound upon a snail-cam. The cam was designed upon the assumption that the illumination upon the screen would be proportional to the cosine of the angle of incidence of the light upon it. This is not strictly the case; especially as a convex lens was used in many of the tests to increase the available light from the electric lamp. The object of the snail-cam was merely to spread the divisions of the scale more evenly, and did not aim at uniform division. The scale was empirically calibrated with a standard candle.

Trotter's Photometer.—Mr. A. P. Trotter, in a communication to the Physical Society on June 9, 1893, described a new photometer based upon his former suggestion of a horizontal screen of white cardboard having a clear star-shaped hole in the middle, below which and enclosed in a box was an inclined white screen illuminated by a small glow-lamp. In this communication Mr. Trotter described his arrangement of screens to ordinary light photometry (as distinguished from illumination photometry). His first plan consisted of two screens (Fig. 136) each inclined at 45° to the direction of the lights and the eye. One screen was immediately behind the other; the first screen was perforated, and mounted on a sliding-carriage on a photometer bar. The lights were placed, the one a little in front and the other a little behind the plane of intersection of the screens. The back of the perforated screen was blackened and was shaded from the light which illuminated the back screen. The edge of the perforations was bevelled, to assist the complete disappearance of the hole. The hole consisted of two

FIG. 136.

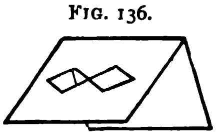
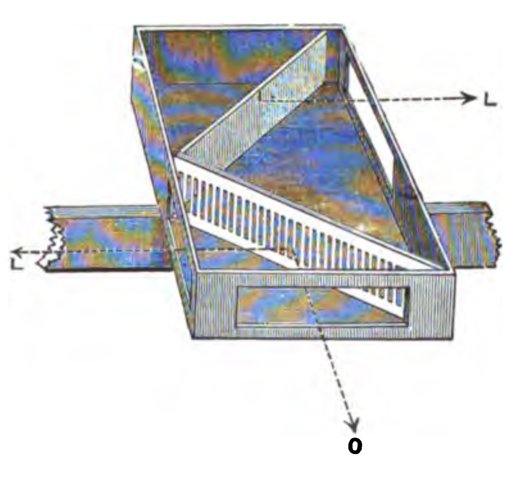


FIG. 137.



lozenge-shaped apertures one over the other, point to point, the object being to concentrate attention on a vertical line. The screens were held in a frame capable of rotation round a vertical axis through a small angle, for the purpose of producing small and rapid variations. But although one screen thus received more light and the other less, the cosine law of illumination caused the former to increase but slightly in brightness, while the latter diminished considerably. It should be observed that this arrangement of screens, although developed from a Bunsen photometer, is a modification of the Thompson-Starling photometer, in which two screens at 45° to the lights and to the eye are used; but side by side, however, instead of one behind the other.

Mr. Trotter subsequently used a slotted screen or grid, as shown in Fig. 137, for measuring rapidly fluctuating lights. At one end of the grid the perforations appeared as dark strips on a light ground, and at the other as light strips on a dark ground. At the point of balance the strips were not distinguishable from each other.

The final form of this photometer, for ordinary work, is a pair of screens arranged so that the light falls on them at an angle of 35°, the angle included between the screens is therefore 125°. This angle is chosen because considerable variations may be made from it without appreciably affecting the result. A star-shaped hole is perhaps best, but the edges must be carefully bevelled, and the easiest form of hole to make is a circular one, cut in a lathe.

The effect of such a photometer is precisely the same as that arrived at by much more complicated means in the Lummer-Brodhun instrument—viz. one screen is seen through a hole in the other. Being constructed of ordinary white Bristol board, the screens may be very cheaply replaced when soiled.

In addition to the foregoing methods of direct comparison of two lights many other systems have been devised, amongst which may be mentioned:

Obscuration methods, which are, however, mostly fitted for the estimation of the *intensity per unit area* or *brightness* of a radiant, rather than for the estimation of the total light volume; as, for instance, the case of a gas-flame produced by a flat-flame burner. The Bunsen disc is suitable for estimating only the total quantity of light emitted from any source, and any increase in the size of the flame will immediately affect the indications of the disc; but if this same flame is examined through an opaque glass ground into a wedge shape so that at its thinnest part it is translucent, it will be found that at a given point on the wedge the light of the flame will be eclipsed. If the flame be then diminished or enlarged, the indication of the obscuring wedge of glass will remain the same. Let the gas be next so burnt that a greater intensity per unit area is obtained, but the volume of gas be reduced so as to afford the same indications by the Bunsen disc as against the same standard of comparison employed in the first experiment, and then let it be re-examined by the wedge of glass. It will now be found that the indications are decidedly higher, and thus, although the light volume is the same, the brightness has increased, *i.e.*, the obscuration method indicates brightness, but not total illuminating value. It is, therefore, always necessary to carefully bear in mind the object of the investigation. If it is desired to ascertain the total volume of light emitted from a given radiant, then one of the methods of direct comparison, such as the Rumford or Foucault shadow systems, or the Bunsen disc system, must be employed. If, on the contrary, the intensity per unit area, or brightness, is required, then an obscuration method must be used. It does not appear that this material difference between sources of luminous energy and illumination has received the careful attention it deserves. Many experimenters and writers use the term "intensity" as indicating the total light volume, or quantity of light, whereas the term "intensity" should clearly be reserved to indicate the energy of the state of ignition—brightness or incandescence.

Various suggestions for measuring the brightness of a source of light have been made by different scientists, commencing with Bouguer, who judged the relative brightness by counting the number of the pieces of glass that it was necessary to interpose, or the number of reflectors required, respectively for extinction. Huyghens used the system of diminution of aperture. These two methods apparently form the foundation upon which nearly all other obscuration methods are based. The most satisfactory of these is the wedge of smoke-coloured glass first employed by Dawes in 1851, and recently developed and placed upon a scientific basis by Professor Pritchard.*

Chemical Photometers.—The American physicist, Draper, in 1843 noticed that light caused a mixture of the two gases hydrogen and chlorine to combine and form hydrochloric acid, and estimated the intensity of the light by noting the diminution in volume of the mixed gases, when exposed to a light, in a glass vessel over hydrochloric acid saturated with chlorine, a solution which dissolves the acid as it is formed, but does not dissolve either of the unchanged gases. Hunt, in 1884, employed the indications afforded by the precipitation of carbonate of iron from a solution of sulphate of iron in common water. Such a precipitation takes place slowly under any circumstances, but if the solution is exposed to sunlight this precipitation takes place rapidly, and the weight of the precipitate is, up to a certain point, a measure of the light to which the solution has been exposed.

Angus Smith utilised the action of light on a solution of iodide of potassium, acidulated with nitric acid, the quantity of iodine liberated being the indicator.

Various photographic methods have been tried, but none appear to have been available for purposes other than the special object to which they were applied.

The fact that, when light is absorbed by a black surface, heat is produced, has been utilised by several experimenters, the first of whom, Leslie, in 1797, estimated the intensity of the light by the depression of the liquid in the limb of a differential thermometer, one of the two bulbs of which he blackened.

Polarisation Methods.—In the various phenomena which take place when a ray of light encounters the surface of a new medium, it has been supposed that the direction and intensity of the several portions into which it is subdivided will continue the same, on whatever side of the ray the surface is presented, provided that the angle and the place of incidence continue unchanged. In other words, it was taken for granted that a ray of light had no relation to space, with the exception of that dependent on its direction; that around that direction its properties were on all sides *alike*; and that, if the ray be made to revolve round that line as an axis, the resulting phenomena would be unaltered.

Huyghens was the first to prove that this was not always the case. In the course of his researches on the law of double refraction, he found that when a ray of solar light is received upon a rhomb of Iceland spar, in any but one direction, it is subdivided into two of equal intensity. But, on transmitting these rays through a second rhomb, he observed that the two portions into which each of them was subdivided were no longer equally intense; that their relative brightness depended on the position of the second rhomb with regard to the first; and that there were two positions in which one of the rays vanished altogether.

On analysing the phenomena, it was found that it depended on the relative positions of the planes or principal sections passing through the axes of the crystals, and perpendicular to the refracting surfaces. When these sections are parallel, the ray which has undergone ordinary refraction by the first crystal will also be refracted ordinarily by the second; and the ray

* "Memoirs of the Royal Astronomical Society," vol. xlvii.

which has been extraordinarily refracted by the first will also be extraordinarily refracted by the second. On the other hand, when the principal sections of the two crystals are perpendicular, the ray which has suffered ordinary refraction by the first crystal will undergo extraordinary refraction by the second; and the extraordinary of the first will be refracted according to the ordinary law in the second. In the intermediate positions of the two principal sections, each of the rays reflected by the first crystal will be divided into two by the second, and these two pencils are generally different in intensity; their intensities being measured by the squares of the cosines of the distances from the position of greatest intensity.*

This physical fact has been utilised by a number of experimenters; it will suffice, however, to shortly describe the following as illustrative of the methods employed.

Becquerel, in 1860, constructed an instrument which consisted of two small telescopes 35 centimetres long by 3 centimetres diameter, with their axes at right angles, and having the same eye-piece. A right-angled prism is fitted so that the observer may see the two images side by side. In order to reduce the stronger light, a Nicols prism is inserted in the tube which is straight with the eye-piece, and another similar prism is inserted near the eye-piece. The relative intensities are calculated from the angle through which this second prism is rotated.†

In 1868 Crookes constructed the following instrument: A brass tube, blacked inside, was fitted with two short side tubes which are near one extremity and opposite to one another. At the same end is slipped in a separate piece with sloping sides, which are covered with white paper, or finely ground porcelain, so that one slope is illuminated by the light which enters through one side tube and the other slope by that entering through the other tube. At the other end of the long tube is the eye-piece made up in the following way: At the end nearer the illuminated surfaces is a lens; then, taking the internal fittings in order as they approach the observer, we have first a series of thin plates of glass capable of moving round the axis of the tube and furnished with a pointer and graduated arc; next a prism of Iceland spar, a film of selenite, and at an appropriate distance, a second prism of Iceland spar. At the end nearer the eye is added a lens adjusted to give a sharp image of the two discs produced by the second prism. In comparing a flame with a standard light the former must be moved until the two discs of light are nearly equal in tint. The final adjustment is then effected by the eye-piece turning the polarimeter one way or the other up to 45° until the images are seen without any trace of colour. The square of the number of inches between the flames and the centre gives their approximate ratios, and the number of degrees the eye-piece is rotated will give the number previously determined by comparing equal lights to be added or subtracted to obtain the necessary accuracy.‡

In 1878 Heisch modified this arrangement in the following manner: Two brass tubes were fastened together in the shape of a T, and where they joined two reflecting prisms were placed which reflected the rays from the two sources of light up the tube. Immediately over the faces of the prisms a plate of tourmaline, or a Nicols prism, and then a plate of selenite were fixed, and at the eye-end a double-image prism. Two images of each of the reflecting faces were thus seen, and by proper arrangement of the eye-piece the ordinary image of one prism could be made to overlap the extraordinary image of the other, and when the lights were of equal intensity this com-

* Lloyd, "Wave Theory of Light."
† "Am. Chem. Phys." (3) lxii. 14, 1861.
‡ "Chemical News," xviii. 28, 1868.

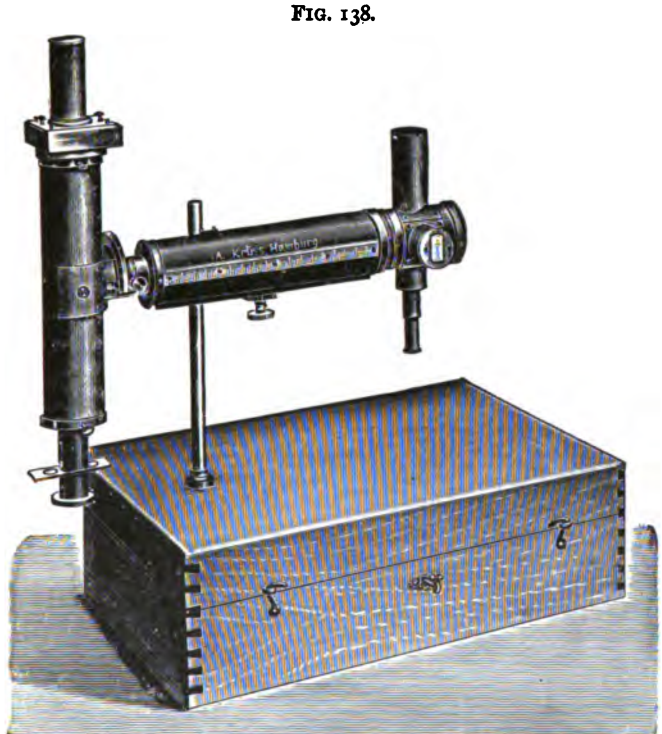
pound image appeared white. The inventor, however, states that the disadvantages of this instrument are:

1. That many people are deficient in the perception of certain colours, so that what to them would appear quite white might to others seem distinctly coloured.

2. That no two artificial lights are of the same colour, so that if red predominates in one it will have the same effect as an increase of intensity if the red image of that light be used. The personal errors of different observers may generally be allowed for, but it is almost impossible to overcome the error caused by the different colours of the lights.*

Guoy (*Govi*) compared two sources of light by allowing the rays to enter at the opposite ends of a tube, in the centre of which were placed two total

FIG. 138.



reflection prisms. The rays which were thus brought side by side and parallel to one another were allowed to fall on the collimator slit of a spectroscope. By this means the eye, instead of having to judge between two illuminated surfaces, had two spectra presented to it, and could thus detect the differences of tint as well as differences of intensity in the two sources of light. In this method the lights are equalised by varying their distances. It will be seen that this is not a polariscopic but a spectroscopic instrument (see page 316).

L. Weber's Photometer (Fig. 138)† consists of a horizontal tube with a revolving tube at right angles to it, supported on a column which, as the carrier of the instrument, is firmly screwed on to a box. The rigid tube

* "Light and Health," Dec. 21, 1878.

† 'Journal of Soc. of Chemical Industry," 1885, p. 446.

carries on its middle part a millimetre scale; on the right, fastened with a bayonet-clasp, is the lamp-case with a benzine lamp; on the left is a graduated arc, on which an index travels and moves with the revolving tube.

The rigid tube contains a ring fitted with an opal glass which, by means of a rack and pinion, can be moved backwards and forwards. A pointer always shows on the millimetre scale the distance of the opal glass from the benzine lamp. In the case is a rigid hook for regulating the flame height, as well as a scale fastened on to a mirror on which the flame height can be read off. The movable tube can be revolved over about 180° and fixed in any position. It has (in the figure turned downwards) an eye-piece, and in the centre a reflecting prism,* one of the cathet surfaces of which is turned towards the central axis, and the other towards the eye-piece. The light coming from the rigid tube is refracted 90° by means of the prism, and so made visible to the observer. The sheet metal box at the other end of the tube, to which can be added a shading-off tube, serves for holding one or more opal glasses. The light coming from here occupies the left-hand portion of the field of vision, whereas on the right-hand half there can only be light from the rigid tube.

On the eye-piece is a slide with red and green glass plates, with a free opening; so that adjustments can be made with natural white light, green, or red light. Besides this, the eye-piece has a reflecting prism as well to hinge over it, which can be used for greater comfort when the light falls slantingly or perpendicularly.

When measuring point-shaped light sources with a colour equal to that of the standard light (Benzine lamp) the apparatus is set up in the manner described; the movable tube directed towards the flame and the benzine lamp flame adjusted to 20 millimetres height. An opal glass is now inserted into the box, its distance (R) from the light source measured and the distance (r) of the movable glass plate from the benzine lamp altered until both halves of the field of vision show with equal brilliancy. If this should not be possible with one plate several must be used. The influence of the plate is determined by first directing it towards a standard lamp and the value of C found according to the formulæ $J = \frac{R^2}{r^2} C$ where $J = 1$; that is, by first finding the constant value for the plates. This constant value is determined once for all, for all the plates. If, for instance, when testing a light source, $R = 100$ c.m. and $r = 25.5$ c.m.; and $C = 9.33$, already determined, the intensity of the flame tested $J = \frac{100 \times 100}{25.5 \times 25.5} \times 0.33 = 5.07$ candles.

With diffused light, of equal colour with the standard light, a white card can be used, which is placed at the desired inclination at the place where the measurement is to take place. The revolving tube is directed towards the centre of the card, the distance of which is generally unimportant. An adjustment is now made, as previously mentioned, and the strength of illumination found, after reading off r, from the formula $E = \frac{10000}{r^2} C_1$, in which C_1 is a constant coefficient to be determined once for all and has different values according to whether the adjustment is made with or without plates.

If in a given case $C = 0.0757$ and $r = 18.5$ cm., then $E = 2.21$ metre candles. If in this, as well as in the preceding instance, it had been found that the colour of the light source to be tested did not coincide

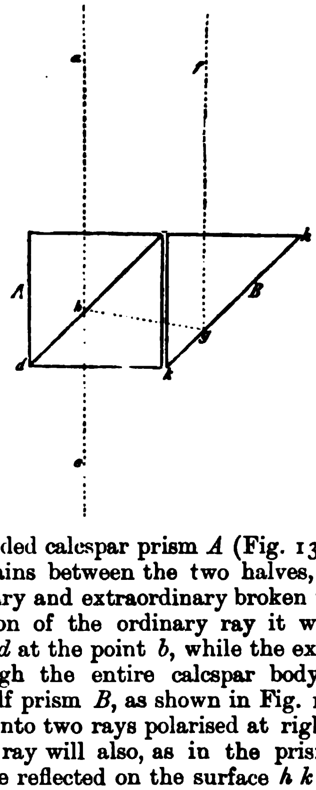
* Instead of this reflecting prism the Lummer-Brodhun prism combination is mostly used at the present time (see p. 317).

with that of the benzine lamp, a case which renders an adjustment for equal brilliancy of both halves of the field of vision difficult, the procedure is somewhat different. Two readings must then be taken, viz., one with green and one with red glass. The result obtained for red is then to be multiplied by a factor *k*; *k* being less than 1 for redder flames than the benzine lamp, and for whiter flames, greater than 1. It is dependent entirely on the colour intensity of the light source. It has been found that *k* alters directly with the number obtained by dividing the intensity or brilliancy found with the green glass (*Gr*) by that of red glass (*R*).

A table can thus be drawn up for each sort of light which gives the value for *k* which the relation $\frac{Gr}{R}$ represents.

Grosse's Photometer.—The following description by Dr. Kruss* of a polariscopic photometer recently devised by Grosse will be interesting as the latest outcome of this branch of the subject of photometry:

FIG. 139.



By cutting a four-sided calcspar prism *A* (Fig. 139) diagonally, so that a thin space of air remains between the two halves, a ray *a b* falling on it will be split into ordinary and extraordinary broken rays, and with a correct position for the division of the ordinary ray it will be reflected on the surface of separation *c d* at the point *b*, while the extraordinary ray *b c* will pass undeflected through the entire calcspar body. By connecting this prism with a second half prism *B*, as shown in Fig. 139, the ray *f g* thrown on it will also be split into two rays polarised at right angles to each other, and the extraordinary ray will also, as in the prism *A*, pass through, but the ordinary one will be reflected on the surface *h k* at the point *g*, and will again be reflected on the surface *c d* in the first prism *A* at the point *b*, so that this extraordinary polarised ray from prism *B* reappears in the same direction with the extraordinarily polarised ray *a b c* from the prism *A*. In order to pass light from two different sources J_1 and J_2 (Fig. 140) through this combination of prisms in the way described by Dr. Grosse, two simple reflecting glass prisms, 1 and 2, are used in the position indicated in Fig. 140.

From the light source J_2 a single bunch of rays passes into the combina-

* Schilling's Journal für Gasbeleuchtung, &c.

tion, but from the source J_1 two bunches so pass, one of which passes through the calcspar A only, while the other with repeated reflection passes through both B and A and at the same time falls in with the one from source J_2. The sight surface is therefore divided into two halves, the right receiving light from J_1 only and the left from both J_2 and J_1. In consequence of the different loss of light on the double course in the combination of prisms, the share of J_1, appearing in the left half of the surface of light, must be multiplied by a factor x, which is easily determined and supplied with each instrument. Both halves being arranged at equal intensity, and the distances of the sources J_1 and J_2 taken as L_1 and L_2, then

$$\frac{J_2}{L_2^2} + x\frac{J_1}{L_1^2} = \frac{J^2}{L_1^2}$$

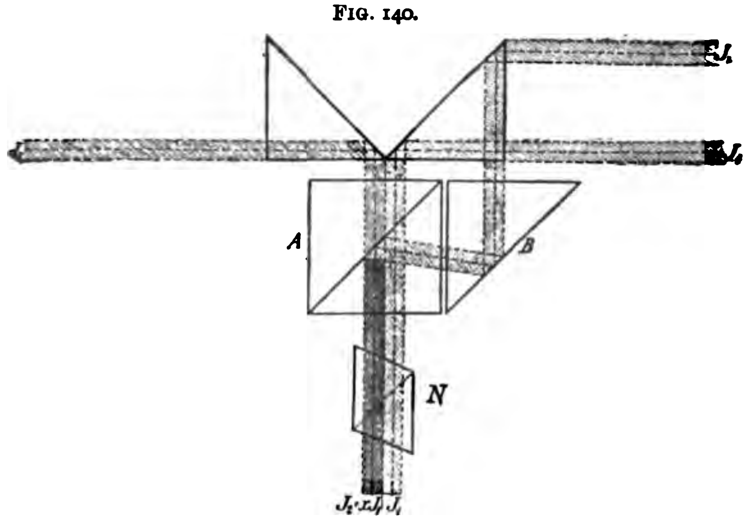
$$\frac{J^2}{L_2^2} = \frac{J_1}{L_2^2}(1 - x)$$

and therefore the proportion of intensity to be determined

$$\frac{J_2}{J_1} = \frac{L_2^2}{L_1^2}(1 \quad x).$$

A certain measurable portion of the stronger source of light can be admixed with the light of the weaker; whereby, first, the difference of

FIG. 140.

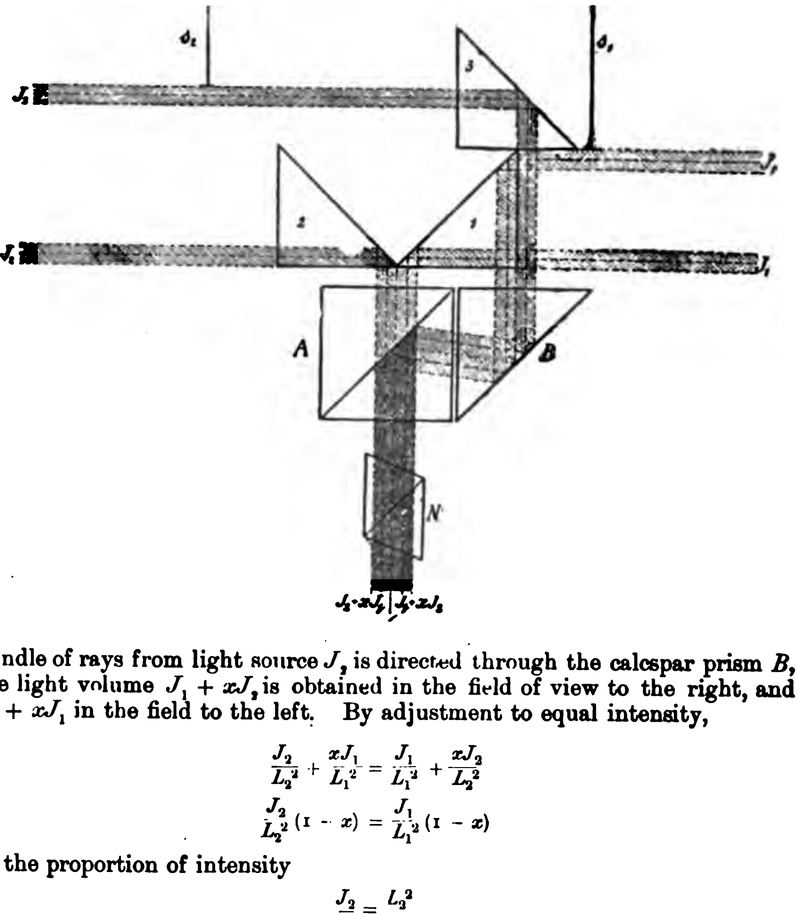


intensity between the two sources of light is diminished, and, secondly, the difference of colour which makes photometrical comparisons so extremely difficult is diminished. But the instrument gives still further results by taking advantage of the peculiarity of the ray which passes straight through prism A and is polarised at right angles to those reflected by B and A. By interposing in the way of the rays a calcspar prism similar to A and a so-called Nicols prism N, all the light from the rays passing straight through prism A will pass through N, as maincut of prism N is parallel to that of prism A, but with a deflection of 90° nothing of this light will pass through prism N. In the case of the rays from the prism B the proportion is reversed, therefore either of the rays can be entirely extinguished; by extinguishing the rays passing through the prism B, this photometer can be used as an ordinary one, and in this way the factor x can be easily determined.

By adjusting the Nicols prism at any other angle of inclination than the one at which one of the bundles of rays was extinguished, a share from each of these bundles is admitted and its intensity calculated. Starting from the position of Nicols prism in Fig. 140, by inclining the same the light coming from prism A alone, it is gradually reduced, while that coming from prism B (being the portion of xJ_1) is increased. A table is provided with the instrument and gives the influence of the angle of inclination on the intensity.

By adding another small reflecting prism 3, Fig. 141, by which a second

FIG 141.



bundle of rays from light source J_2 is directed through the calcspar prism B, the light volume $J_1 + xJ_2$ is obtained in the field of view to the right, and $J_2 + xJ_1$ in the field to the left. By adjustment to equal intensity,

$$\frac{J_2}{L_2^2} + \frac{xJ_1}{L_1^2} = \frac{J_1}{L_1^2} + \frac{xJ_2}{L_2^2}$$

$$\frac{J_2}{L_2^2}(1 - x) = \frac{J_1}{L_1^2}(1 - x)$$

or the proportion of intensity

$$\frac{J_2}{J_1} = \frac{L_2^2}{L_1^2}$$

the factor x is therefore entirely done away with, the calculation of the proportion of intensity is obtained simply from the proportion of the squares of the distance as in the ordinary Bunsen Photometer, and the usual scales from which the intensity is read off direct are also applicable.

With this arrangement a complete mixture of the rays from the two sources of light J_1 and J_2 takes place, and in both halves of the field of view we have the same colour mixture, whereby a photometrical comparison of different-coloured lights is made possible with remarkable ease.

It is claimed that this photometer provides quite a new method for the correct adjustment for equal intensity.

In the course of a series of experiments on Standards of Light the writer employed the spectroscope for comparing the different colours of the various units. The results were obtained by viewing the spectra of two lights side by side, and thus qualitative comparisons were readily made. Professor E. L. Nicols has used this method in the following manner, by which quantitative results are readily and conveniently obtained. In this apparatus the principle of the Bunsen photometer is applied successively to the various regions of the visible spectra of the sources of light under comparison. He employed a spectroscope, the optical axis of the collimator being horizontal, and at right angles to the photometer bar. The slit is horizontal and lies in a straight line joining the sources of light, which are set up in the usual manner at the ends of the bar. The bar itself is preferably of considerable length, and in the original instrument was 500 centimetres long. In front of the spectroscope slit are placed two right-angled prisms of the same size and made of the same glass. Their vertical edges bisect the slit, and the light coming from either end of the photometer-bar is totally reflected by them, entering the right- or left-hand end of the slit in a direction parallel to the optical axis of the collimator tube. The two sets of rays thus gathered into the spectroscope from the lights at the end of the bar are vertically dispersed by the prisms, and appear in the field of view as two vertical spectra standing side by side. Equal wave-lengths are in the same horizontal line, and any desired region may be brought into the centre of the field by an angular movement of the ocular telescope.

When the instrument is placed at the middle of the bar between two lights of identical amount and brightness, the two spectra are of equal brilliancy throughout, from red to violet. If the two lights differ in intensity but not in quality, their spectra will differ in brightness by the same amount from end to end and the instrument may be used as a simple photometer. When the lights to be compared differ both in intensity and quality, ordinary photometric indications do not possess any perfectly definite significance. In this case the brightness of different points of the spectra must be compared. Professor Nicols used the new instrument to compare the lights of a Welsbach incandescent burner with that of an Argand, which, as determined by a Bunsen photometer, had a relative brilliancy of 1.701 : 0.015. The following was the result: *

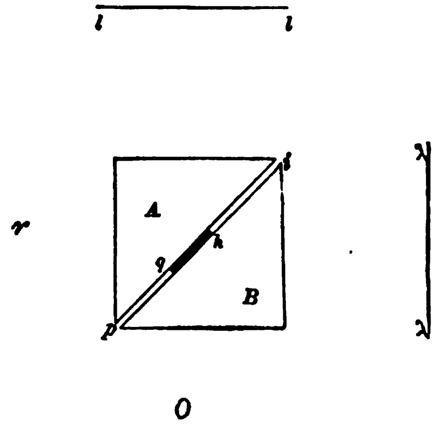
Colour.	Wave Length.	Ratios.	Probable Error of a Simple Observation.
Red . . .	702	0.709 : 0.017	2.45 per cent.
Yellow . .	589	1.476 : 0.017	1.14 "
" . .	558	1.760 : 0.023	1.34 "
Green . .	500	2.395 : 0.047	1.99 "
Blue . . .	466	2.738 : 0.036	1.30 "
Violet . .	439	3.090 : 0.073	2.35 "
			Average 1.76 "

Lummer and Brodhun's Photometer Head.—For the purpose of the experiments which the German *Imperial Technical Physical Institute* carried out at the instigation of the German *Society of Gas and Water Experts* on the various light units the Bunsen photometer was first employed.

* "Journal of Gas-Lighting," vol. lvi. p. 141.

In order to find, if possible, a contrivance which would give more sensitive readings Messrs. Lummer and Brodhun devised the following apparatus:

FIG. 142.



In order to exemplify the principle used it is necessary to refer to Fig. 142.

Let *l* and λ be diffusely illuminating surfaces and *A* and *B* such a combination of two rectangular glass prisms that at certain parts (*pq* and *hi*) of the hypotenuse surface of the prism *B*, the light coming from λ, is reflected to *O*, whereas at the remaining parts (*qh*) it passes through the prism and goes to *r*; the reverse being the case in regard to the hypotenuse surface of the prism *A* with the rays emitted by *l*.

If an eye stationed at *O* looks towards the surface *pqhi* it sees the portion of it, *qh*, illuminated by the light from *l*, and the portion *pq* and *hi* by the light from λ. At a certain relative intensity of the fields *l* and λ, *pqhi* appears as a completely uniform bright surface.

Suitable prism combinations can be made in many ways, the following being that generally used:

FIG. 144.

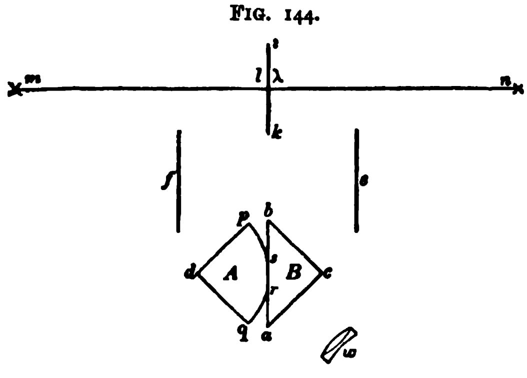
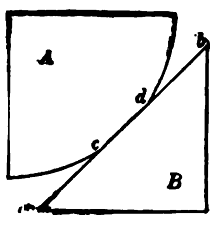


FIG. 143.



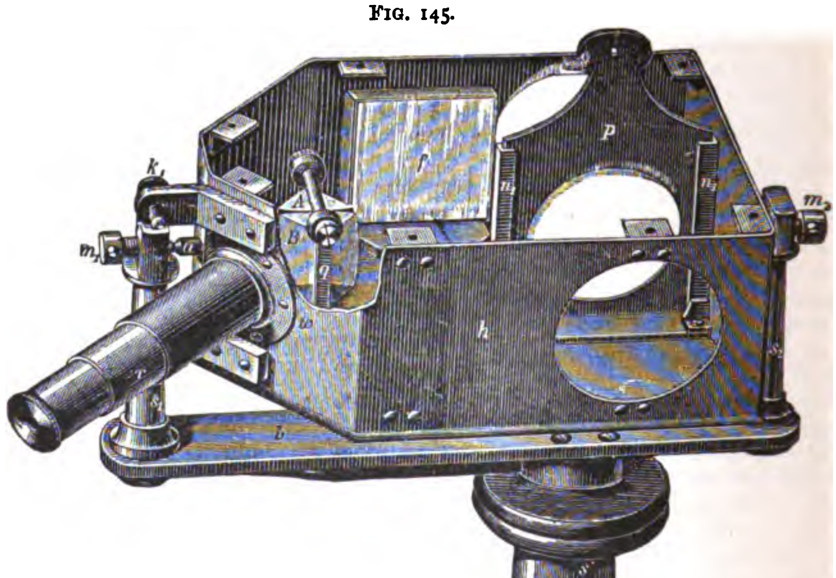
The spherically-shaped surface of the prism *A* is cut flat at *cd* (Fig. 143) and pressed against the similarly flat hypotenuse surface of the prism *B*. The elliptical-looking spot appearing in this case has perfectly sharp edges and completely disappears with equality of the fields.

In order to make the "photometer head" slide on a straight bench like that of the Bunsen photometer, the arrangement sketched in Fig. 144

was made. Perpendicular to the axis of the photometer bench is the opaque screen *ik*, the sides of which are illuminated by the light sources *m* and *n* respectively. The diffused rays of light reflected from the two sides of the screen λ and *l* fall on the mirrors *e* and *f*, which throw them perpendicularly on to the cathet surfaces *cb* and *dp* of the prisms *B* and *A*; the observer at *O* looking through the magnifying-glass *W* perpendicularly to *ac* focuses sharply on the surface *arsb*.

Fig. 145 gives a perspective view of a photometer-head made according to arrangement for the experiments in the workshop of the German *Imperial Institute*. The vertical brass column *S* carries the metal cross-piece *b* into which the small columns S_1 and S_2 are screwed. In the upper part of these are the screws m_1 and m_2 with conical cups turned in their ends. These cups form the bearing for the horizontal axis *a* of the photometer-case *h*. On the case at *w* is placed the tube *r* with a sliding magnifying-glass. In the inside of the case lie the prism combination *A B*; the two mirrors, of

FIG. 145.



which only the one *f* is visible, and the photometer screen *P*. This latter rests in the frame *n*, the foot-plate of which is movable and adjustable on the floor of the case *h*; for the purpose of renewal or turning round over 180° the screen can be removed from the frame *n*. Each of the mirrors *e* and *f* can be revolved in a vertical as well as in a horizontal direction from the outside by means of two screws each passing through the floor of *h*. The fastening *q* presses the prism *A* and *B* closely together and rests on a plate which is movable in a similar manner as the frame *n*. The case *h* is closed by a lid, which in the figure has been removed, with slot for the handle of the screen *P*, the light striking the paper of the screen *P* through the side openings. In the position of the photometer-case represented, a screw head *k* (not visible in Fig. 145) is pressed hard against the column *S*, and acts as a stop-block, and on revolving the axis of the case over 180° a second screw head *k* serves as the other stop-block. The column *S* placed on a slide of the photometer bench can be moved up and down in a circular direction on a vertical axis.

The screen *P* is made up of double layers of paper, separated by a sheet of tinfoil fixed between two metal sheets having circular openings; *e* and *f* are selected, even mirrors, cut from the same piece and coated with silver amalgam. In place of these mirrors, totally-reflecting prisms can be used. In front of the magnifying glass a diaphragm rather larger than the pupil is fixed, and by painting on the outer portion of the hypotenuse surface of *B* with asphalt varnish a sharp definition of any desired form is given to the field of vision.

Discs.

The Bunsen disc, most commonly used in England, is made by rotating a circular piece of stout paper, the centre of which is clamped between two metal blocks, in melted spermaceti, thus coating the outer half with wax whilst the centre remains opaque The excess of spermaceti is eliminated, whilst still in a molten condition, by centrifugal force and the disc allowed to dry in an atmosphere free from dust. In Germany the discs are made of thinner paper and rectangular in shape. Instead of being partially coated with wax, several bar-like marks, usually three, are made on the discs with sperm oil. Both of these forms give delicate readings. When used, however, for testing lights of different colours, such as electric lights and recuperative gas-burners, considerable difficulty is experienced in judging whether the two sides of the disc are equally illuminated owing to the difference in colour of the standard light and that under examination.

The Leeson star disc in a great measure eliminates this difficulty. As originally made it consisted of a stout piece of paper the centre of which was perforated in the form of a star, with a number of short radiations, the two sides having sheets of thin paper attached to them. Owing to the thin paper not being contiguous a serious error at times crept in, and the Metropolitan Gas Referees refused to sanction it as a substitute for the Bunsen disc.

Recognising its value and utility for comparing different-coloured lights, the writer modified it somewhat, so that it was impossible for either of the papers to buckle individually, the three papers being moistened with starch water, pressed together and dried under pressure. In this form it is now considerably used for testing lights which have a different colour to the standard employed, such as electric arcs and Welsbach mantles, and was prescribed by the gas referees in their notification for use with the bar photometers in the London testing-stations.

Various alternative discs have been suggested of which the Lummer & Brodhun photometer head, already described, and Joly's disc, consisting of a pair of rectangular spermaceti blocks used together or with a sheet of tinfoil separating them, are the principal.

Standards of Light.

In England, the spermaceti candle is the only Parliamentary unit, although in London the gas companies have at present agreed to accept, for use in the London gas-testing stations, Harcourt's ten-candle pentane lamp. In France the Carcel lamp is steadily adhered to, but in Germany the paraffin candle has given way to the Heffner lamp, whilst in Holland a lamp burning ether and benzine has been adopted as the standard.

This variation in standards would not be of so much importance if the different methods for producing a working unit were all referable to an agreed constant, such as the platinum unit of M. Violle. Unfortunately, however, no such agreement exists. A solution of the problem would be found in an agreement between the various Governments concerned, including that of America, to appoint a commission consisting of an independent body of international representatives, to examine and compare the various legal standards, and the substitutes proposed for them, which commission should be empowered to agree to a definite international standard unit of light, and suggest any method or methods by which this standard might be conveniently duplicated for use in practical work. Until some such course is pursued we shall have, unfortunately, to continue to rely on the isolated exertions of individuals whose efforts must be always more or less open to hostile criticism. There can be no doubt that the absence of a generally accepted international standard is most unsatisfactory, and the present position of the question is a reproach to the scientific and industrial spirit of the age. It should be clearly and definitely agreed, however, that before any commission such as that above suggested, be appointed, its decision should be immediately registered in all the countries concerned as part of the law of the land. There are many excellent standards which have been proved to be sufficiently reliable for practical use, several of which are now in use in different countries, and no possible harm could arise by the adoption of any one of them.

In the Metropolis Gas Act of 1860 (England) the standard of light is described as "sperm candles of six to the pound, each burning 120 grains per hour." In France the standard is the "Carcel" lamp, burning refined colza oil at the rate of 42 grammes per hour. In Germany the standard is a paraffin candle of which ten weigh 500 grammes, the flames of which should have a height of 50 millimetres. While these are the three recognised legal standards, many proposals have been made for substitutes for them. It will be well, however, to deal with the present legal instruments first, and then to describe the various systems suggested as improvements upon them.

The Sperm Candle.—The only definition of this legal candle is that given above, with the addition of the Gas Referees' instruction that, when the sperm actually consumed falls short of 114 grains per hour, or rises above 126 grains per hour, they shall not be used for testing purposes. In practice these figures are determined by noting the time required by two candles to consume 40 grains weight of sperm, which should fall within the limits of nine and a half minutes and ten and a half minutes, or, calculated on the weight consumed in ten minutes, 38 and 42 grains, the prescribed rate of 120 grains per hour being 40 grains for two candles in ten minutes. The weight of a single candle as supplied by the maker should be 1167 grains nearly. The extreme variations from this weight rarely exceed 20 grains, and more generally fall within a few grains. The length of the candle varies, with different makers, from $8\frac{1}{4}$ inches to 9 inches, measured from the shoulder. The diameter at the shoulder is very nearly 8/10ths of an inch, and $8\frac{1}{2}$/10ths to 9/10ths at the bottom. The writer is indebted to Messrs. Miller and Co. for the following definition of what they understand to be a "sperm candle" according to the Act of 1860:

"We think that there can be no doubt that, at the time the Act was passed, a sperm candle was understood to consist exclusively of spermaceti (the product of the spermaceti whale), pure white and dry, having a melting-point of as nearly as possible 109°, and to which was added just so much air-bleached beeswax, having a melting-point of 140°, as would suffice to break the crystals of the spermaceti; the rate of combustion, fixed at 120 grains an hour, being secured by a properly proportioned cotton plait serving as the wick. With regard to the size of the candle to be used, we have never attempted to make candles which should individually weigh 1/6th lb., as we have understood the intention of the Act to be to indicate that the candles to be used should be those known in the trade as 'short sixes,' and which do approximately weigh six to the pound."

Unfortunately considerable variations have taken place in the number of threads to each strand in the wick. This has arisen from the endeavour of the makers to free the spermaceti as much as possible from the "sperm oil," and thus obtain a more solid product. Naturally a higher melting-point has been thus obtained, which necessitates the employment of larger wicks to effect the same rate of combustion, a remedy which unfortunately reduces the light yielded per unit of sperm consumed. *The Standards of Light Committee of the British Association for the Advancement of Science*, in their report presented in 1888, stated:

"Thus the effect of the improvements in spermaceti has been that standard candles give less light than they gave ten years ago, and probably still less light than they gave at earlier dates, when the average consumption of candles of six to the pound was 140 grains per hour."

On the other hand, there is on record a statement to the contrary effect, made by two gentlemen of no little skill—viz. Messrs. Heisch and Hartley—who in 1883 said:

"We may here mention what we are convinced to be a fact—namely, that sperm candles generally now develop more light per grain of sperm burned than they did several years ago."

Owing to the want of uniformity in the manufacture of candles and the fact that they were gradually being altered from the form intended for use when the Act was passed, the Gas Referees laid down the following regulations for their manufacture:

"1. The wicks shall be made of three strands of cotton plaited together, each strand consisting of eighteen threads. The strands shall be plaited with such closeness, that when the wick is laid upon a rule and extended by a pull of about 1 ounce, just sufficient to straighten it, the number of plaits in 4 inches shall not exceed thirty-four nor fall short of thirty-two.

"As it is found to conduce to the regular burning of candles that the wicks should have been as far as possible cleaned and freed from mineral matters, it is recommended that the candle-maker, before steeping the wicks, shall wash them first in distilled water made alkaline with between 1 and 2 per cent. of strong liquid ammonia, then soak them for several hours in dilute nitric acid containing about 10 per cent. of strong acid, and finally wash them in distilled water made alkaline with a few drops of ammonia.

"Each wick shall be of suitable length, not less than 12 inches, and looped ready for fixing in the mould. After having been bleached in the usual manner and thoroughly washed, the wicks shall be steeped in a liquid made by dissolving 1 ounce of sal ammoniac and half an ounce of crystallised boracic acid in a gallon of distilled water; they are then to be gently wrung or pressed till most of the liquid has been removed, and dried at a moderate heat while lying horizontally.

"Such a wick cut to a length of 12 inches when stretched as above shall weigh not more than 7 nor less than 6 grains. The weight of the ash remaining after the burning of ten wicks which have not been steeped in boracic acid, or from which the boracic acid has been washed out, shall be not more than 0.03 grain.

"Wicks made in accordance with this prescription shall be sent to the office of the Gas Referees, by whom they will be examined and certified.

"The wicks so certified are to be used by the candle-maker in the condition in which they are returned to him.

"When the wicks are set in the mould they should be pulled with only so much force as is necessary to straighten them.

"2. The spermaceti of which the candles are made shall be genuine spermaceti, extracted in the United Kingdom from crude sperm oil, the product of the sperm-whale (*Physeter Macrocephalus*). It shall be so refined as to have a melting-point lying between 112° and 115° Fahr.

"As various methods are used by different refiners of spermaceti for determining the melting-point, which lead to different results, it must be noted that the temperatures here given as the limits within which the melting-point of a sample of refined spermaceti should fall—viz. 112° and 115° Fahr.—have been found by the following method, which is known as the capillary-tube method:

"A small portion of the spermaceti is placed in a short test-tube, and melted by plunging the lower end of the tube in hot water. A glass tube drawn out at one end into a capillary tube about 1 millimetre in diameter is dipped narrow end downwards into the liquid spermaceti, so that when the tube is withdrawn 2 or 3 millimetres of its length are filled with spermaceti, which immediately solidifies. The corresponding part of the exterior of the tube also becomes coated with spermaceti, which must be removed.

"The narrow part of the tube is then immersed in a large vessel of water at a temperature not exceeding 110° Fahr. The lower end of the tube which contains the spermaceti should be 3 or 4 inches below the surface and close to the bulb of a thermometer. The upper end of the tube must be above the surface, and the interior of the tube must contain no water. The water is then slowly heated, being at the same time briskly stirred so that the temperature of the whole mass is as uniform as possible. When the plug of spermaceti in the tube melts it will be forced up the tube by the pressure of the water. The temperature at the moment when this movement is observed is the melting-point.

"Since candles made with spermaceti alone are brittle, and the cup which they form in burning has an uneven edge, it is necessary to add a small proportion of beeswax or paraffin to remedy these defects. The best air-bleached beeswax, melting at or about 144° Fahr., and no other material, shall be used for this purpose, and the proportion of beeswax to spermaceti shall be not less than 3 per cent. nor more than 4½ per cent.

"3. The candles made with the materials above prescribed shall each weigh, as nearly as may be, one-sixth of a pound, and will be found to answer to the following test: Immerse a candle taper-end downwards in water of 60° Fahr. with a brass weight of 40 grains attached to the wick by a small piece of thread; when a further weight of 2 grains is laid on the butt-end of the candle it will still float, but with a weight of 4 grains it will sink."

The following is the procedure for the use of this standard: the candle selected for the test must be a straight one, with the wicks central in the longitudinal axis, and must not be too tapered from end to end. The sloping top is to be cut off at the shoulder, and the candle then equally divided in the centre. The two new ends thus obtained are to be trimmed, so as to form new wicks, which, when lighted and burning, are to be set in such a position that the plane of the curvature of one wick is perpendicular to the plane of the curvature of the other wick.

The candles should be mounted on the candle-balance in the photometer for ten minutes, or longer if necessary, before making a test, so that the "cups" are "fairly dry," the wicks curved and the ends glowing. If the candles are used while the wick is in a vertical position, the results obtained are certain to be too high.

In Schedule A, Part II., of the Gasworks Clauses Act, 1871, it is stated that "candles are to be lighted at least ten minutes before beginning each testing, so as to arrive at their normal rate of burning, which is shown

Table for finding the Consumption of Sperm by two Candles in 10 Minutes from Observations of the Time required to burn 40 Grains.

Time required to burn 40 Grains.	Consumption in 10 Minutes.	Time required to burn 40 Grains.	Consumption in 10 Minutes.
Min. Sec.	Grains.	Min. Sec.	Grains.
9.0	44.44	10.1	39.94
9.1	44.36	10.2	39.87
9.2	44.28	10.3	39.80
9.3	44.20	10.4	39.74
9.4	44.12	10.5	39.67
9.5	44.04	10.6	39.60
9.6	43.96	10.7	39.54
9.7	43.88	10.8	39.47
9.8	43.80	10.9	39.40
9.9	43.72	10.10	39.34
9.10	43.64	10.11	39.28
9.11	43.56	10.12	39.21
9.12	43.48	10.13	39.15
9.13	43.40	10.14	39.09
9.14	43.32	10.15	39.02
9.15	43.24	10.16	38.96
9.16	43.16	10.17	38.90
9.17	43.08	10.18	38.83
9.18	43.01	10.19	38.77
9.19	42.93	10.20	38.71
9.20	42.85	10.21	38.65
9.21	42.78	10.22	38.59
9.22	42.70	10.23	38.52
9.23	42.63	10.24	38.46
9.24	42.55	10.25	38.40
9.25	42.48	10.26	38.34
9.26	42.40	10.27	38.28
9.27	42.33	10.28	38 22
9.28	42.25	10.29	38.16
9.29	42.18	10.30	38.10
9.30	42.11	10.31	38.03
9.31	42.03	10.32	37.97
9.32	41.96	10.33	37.91
9.33	41.88	10.34	37.85
9.34	41.81	10.35	37.80
9.35	41.74	10.36	37.74
9.36	41.67	10.37	37.68
9.37	41.60	10.38	37.62
9.38	41.52	10.39	37.56
9.39	41.45	10.40	37.50
9.40	41.38	10.41	37.44
9.41	41.31	10.42	37.38
9.42	41.24	10.43	37.32
9.43	41.17	10.44	37.26
9.44	41.10	10.45	37.21
9.45	41.03	10.46	37.15
9.46	40.96	10.47	37.09
9.47	40 89	10.48	37.03
9.48	40.82	10.49	36.98
9.49	40.75	10.50	36.92
9.50	40.68	10.51	36.87
9.51	40.61	10.52	36.81
9.52	40.54	10.53	36.75
9.53	40.47	10.54	36.70
9.54	40.40	10.55	36.64
9.55	40.34	10.56	36.59
9.56	40.27	10.57	36.53
9.57	40 20	10.58	36.47
9.58	40.13	10.59	36.42
9.59	40.07	11.00	36.36
10.00	40.00		

when the wick is slightly bent and the tip glowing." Although it does not appear that this Act has been overruled by any subsequent one, the instructions of the Gas Referees omit the latter part, and simply say that the candles shall attain "their normal rate of burning." Probably they presume that this expression relates as much to their condition of burning as to the actual rate at which the sperm is volatilised; otherwise it would be correct to use a candle with the wick in such a position that a large proportion of the sperm escapes as unconsumed carbon.

The candles, having thus been brought into readiness for the test, are counterpoised upon the balance until the weight is slightly in excess of that of the counterpoise. An experimental seconds-clock being in readiness, with the hand pointing at zero, the candle-balance is watched, and as soon as the pointer passes the zero mark the clock is started. A 40-grain weight is then carefully placed in the pan under the candles, which thus brings them again to rest, and the comparison of the two lights proceeded with one reading being taken each minute for ten minutes. When the tenth reading has been taken the candle-balance is again watched, and as soon as the pointer passes the zero mark the clock is stopped and the time noted.

It is now necessary to calculate the amount of sperm burnt in a given time from the time it took to burn 40 grains—*i.e.* suppose it took 10 minutes 30 seconds to burn 40 grains; then in 10 minutes it would have burnt: 10 mins. 30 secs. = 630 seconds : 40 : : 600 : x = 38.1 grain; or divide 24,000 by the time, in seconds, and the result will give the number of grains of sperm per 10 mins.

The table on p. 324 will be found convenient for reference:

A very short experience with candles will suffice to convince a careful operator that the only way to attain concordant results is to burn them in such a manner that they are not overheated by exposure to an excessive temperature in an insufficiently ventilated chamber, such as that of the original "Evans" photometer. They give the best result in a perfectly open room free from draughts. As this cannot always be obtained, good results may, however, be ensured by surrounding them with a large box, 18 or 20 inches square, perfectly open for 3 or 4 inches at the bottom, and closed at the top except for a circular aperture at least 6 inches in diameter (see p. 283). This arrangement provides for a steady current of cool air, free from side and top draughts, in which the combustion of the sperm will be uniform and complete, provided, of course, the candles are properly made.

"*Carcel*" *Lamp.*—This lamp was devised by M. Carcel in 1800. It consists of an annular wick as first arranged by Argand, fed with refined colza oil by means of a small clockwork pump. M. Monnier, in his "Etude sur les Etalons Photométriques," gives the following instructions for the use of this standard: "The conditions to be observed when testing with the Carcel lamp are by no means definite, as each lamp must first be tested before being used as a photometric standard. The rule is to arrange the height of the wick and chimney so that the consumption of oil falls within the limits of 38 and 46 grammes per hour; but for exact experiments it is preferable to restrict these limits and maintain the consumption between 40 and 44 grammes per hour. The light given by the lamp is corrected by simple calculation on the assumption that 42 grammes of oil per hour yield one 'Carcel'" (see page 326).

The results of experiments made by MM. Audouin and Berard show, first, that an increase in the height of the wick up to a certain point—10 millimetres—increases the consumption of the oil as well as the intensity the light, beyond which both the consumption of the oil and the intensity diminish; and, secondly, that the elevation of the constricted portion of the glass chimney tends to augment the consumption of the oil in an increasing ratio; but that there is a point where, although the consumption continues to increase, the intensity diminishes. Consequently there is a certain position for the glass which corresponds to the maximum illuminating power of the lamp.

For each experiment a new wick, which must be cut level with the wick-holder, is necessary. The height of the wick must be from 8 to 10 millimetres, the shoulder of the glass being fixed about 7 millimetres above the wick, and that of the flame about 36 millimetres. The lamp, replenished with oil up to the level of the gallery, is allowed to burn for half an hour before commencing the experiment. The calculations for correction from the observed weight of oil consumed are facilitated by reference to the table on the next page:

FIG. 146.

The Carcel Lamp and Balance.

The value of the "Carcel" in terms of English sperm candles was determined by Mr. Sugg in 1870 as 9.6 candles. A series of experiments conducted by the writer in 1885 gave 9.4 as its mean value. It may, therefore, safely be inferred that it is equal to about 9.5 English candles.

The German Standard.—As a result of experiments carried out by the German Society of Gas and Water Experts in conjunction with the Imperial Technical Institute it was found that:

If (*a*) The amyl-acetate flame 40 mm. in height = 1.000,

Then:
- (*b*) The German Society's Paraffin Candle, flame 59 mm., = 1.224 amyl-acetate flame, or A. A. L.
- (*c*) The English Spermaceti Candle, flame (L), 45 mm. in height, = 1.135 A. A. L.
- (*d*) The Spermaceti Candle, flame (K), 45 mm. in height, = 1.140 A. A. L.;

(L) and (K) being candles obtained from different sources; or conversely:

Table showing the Weight of Oil Burned per Hour, calculated from the Time occupied in burning 10 *Grammes.*

Time required to burn 10 Grms. of Oil.	Rate of Consumption per Hour.	Relation to the Carcel Lamp burning 42 Grms. of Oil per Hour.	Time required to burn 10 Grms. of Oil.	Rate of Consumption per Hour.	Relation to the Carcel Lamp burning 42 Grms. of Oil per Hour.	Time required to burn 10 Grms. of Oil.	Rate of Consumption per Hour.	Relation to the Carcel Lamp burning 42 Grms. of Oil per Hour.
Min. Secs.	Grms.		Min. Secs.	Grms.		Min. Secs.	Grms.	
13.0	46.15	1.0989	14.0	42.86	1.0204	15.0	40.00	0.9524
13.1	46.09	1.0975	14.1	42.81	1.0192	15.1	39.96	0.9513
13.2	46.03	1.0961	14 2	42.76	1.0180	15.2	39.91	0.9503
13.3	45.98	1.0947	14.3	42.70	1.0168	15.3	39.87	0.9492
13.4	45.92	1.0933	14.4	42.65	1.0156	15.4	39.82	0.9482
13.5	45.86	1.0919	14.5	42.60	1.0144	15.5	39.78	0.9471
13.6	45.80	1.0905	14 6	42.55	1.0132	15.6	39.74	0.9461
13.7	45.74	1.0891	14.7	42.50	1.0120	15.7	39.69	0.9450
13.8	45.68	1.0877	14.8	42.45	1.0108	15.8	39.65	0.9440
13.9	45.62	1.0864	14.9	42.40	1.0096	15.9	39.60	0.9430
13.10	45.57	1.0850	14.10	42.35	1.0084	15.10	39.56	0.9419
13.11	45.51	1.0836	14.11	42.30	1.0072	15.11	39.52	0.9409
13.12	45.45	1.0823	14.12	42.25	1.0060	15.12	39.47	0.9308
13.13	45.40	1.0809	14.13	42.20	1.0049	15.13	39 43	0.9388
13.14	45.34	1.0795	14.14	42.15	1.0037	15.14	39.39	0.9378
13.15	45.28	1.0782	14.15	42.10	1.0025	15.15	39.34	0.9368
13.16	45.22	1.0768	14.16	42.06	1.0013	15.16	39.30	0.9357
13.17	45.16	1.0755	14.17	42.01	1.0002	15.17	39.26	0.9347
13.18	45.11	1.0741	14.18	41.96	0.9990	15.18	39.22	0.9337
13.19	45.06	1.0728	14.19	41.91	0.9978	15.19	39.17	0.9327
13.20	45.00	1.0714	14.20	41.86	0.9967	15.20	39.13	0.9317
13.21	44.94	1.0701	14.21	41.81	0.9955	15.21	39.09	0.9307
13.22	44.88	1.0687	14.22	41.76	0.9944	15.22	39.05	0.9297
13.23	44.83	1.0674	14.23	41.71	0.9932	15.23	39.00	0.9286
13.24	44.78	1.0661	14.24	41.66	0.9921	15.24	38.96	0.9276
13.25	44.72	1.0648	14.25	41.61	0.9909	15.25	38.92	0.9266
13.26	44.66	1.0635	14.26	41.57	0.9898	15.26	38.88	0.9256
13.27	44.61	1.0621	14.27	41.52	0.9886	15.27	38.83	0.9246
13.28	44.55	1.0608	14.28	41.47	0.9875	15.28	38.79	0.9236
13.29	44.50	1.0595	14.29	41.42	0.9864	15.29	38.75	0.9226
13.30	44.46	1.0582	14.30	41.37	0.9852	15.30	38.71	0.9217
13.31	44.39	1.0569	11.31	41.33	0.9841	15.31	38.67	0.9207
13.32	44.33	1.0556	14.32	41.28	0.9830	15.32	38.63	0.9197
13.33	44.28	1.0543	14.33	41.23	0.9818	15.33	38.59	0.9187
13.34	44.23	1.0530	14.34	41.19	0.9807	15.34	38.54	0.9177
13.35	44.17	1.0517	14.35	41.14	0.9796	15.35	38.50	0.9167
13.36	44.12	1.0504	14.36	41.09	0.9785	15.36	38.46	0.9158
13.37	41.06	1.0491	14.37	41.04	0.9774	15 37	38.42	0.9148
13.38	44.01	1.0479	14.38	41.00	0.9762	15.38	38.38	0.9138
13.39	43.96	1.0466	14.39	40.96	0.9751	15.39	38.34	0.9128
13.40	43.90	1.0453	14.40	40.91	0.9740	15.40	38.30	0.9119
13.41	43.85	1.0440	14.41	40.86	0.9729	15.41	38.26	0.9109
13.42	43.80	1.0428	14 42	40.81	0.9718	15.42	38.22	0.9099
13.43	43.74	1.0415	14.43	40.77	0.9707	15.43	38.18	0.9090
13.44	43.69	1.0402	14.44	40.72	0.9696	15.44	38.14	0.9080
13.45	43.64	1.0390	14.45	40.68	0.9685	15.45	38.10	0.9070
13.46	43.58	1.0377	14.46	40.63	0.9674	15.46	38.05	0.9061
13.47	43.53	1.0364	14.47	40.59	0.9663	15.47	38.01	0.9051
13.48	43 48	1.0352	14.48	40.54	0.9653	15.48	37.97	0.9042
13.49	43.42	1.0339	14.49	40.49	0.9642	15.49	37.93	0.9032
13.50	43.37	1.0327	14.50	40.45	0.9631	15.50	37.89	0.9023
13.51	43.32	1.0315	14.51	40.40	0.9620	15.51	37.85	0.9013
13.52	43.27	1.0302	14.52	40.36	0.9609	15.52	37.82	0.9004
13.53	43.22	1.0290	14.53	40.31	0.9598	15.53	37.78	0.8994
13.54	43.16	1.0277	14.54	40.27	0.9588	15.54	37.74	0.8985
13.55	43.11	1.0265	14.55	40.22	0.9577	15.55	37.79	0.8975
13.56	43.06	1.0253	14.56	40.18	0.9566	15.56	37.66	0.8966
13.57	43.01	1.0241	14.57	40.13	0.9556	15.57	37.62	0.8957
13.58	42.96	1.0228	14.58	40.09	0.9545	15.58	37.58	0.8947
13.59	42.91	1.0216	14.59	40.04	0.9534	15.59	37.54	0.8938

(*a*) 1 amyl-acetate flame 40 mm. in height has an illuminating power equal to:

(*b*) 0.808 German Society's Paraffin Candle, flame 50 mm. in height.

(*c*) 0.883 English Spermaceti Candle, flame (L), 45 mm. in height; and

(*d*) 0.879 English Spermaceti Candle, flame (K), 45 mm. in height.

At the Munich meeting in 1890 the Commission reported as the result of further tests that:

1 German Society's Paraffin Candle = 1.22 amyl-acetate lamp.

1 English Spermaceti Candle = 1.145 to 1.160 „ „

As a result of the work of the Photometrical Commission in conjunction with the Imperial Technical Physical Institute it was decided that:

(1) The amyl-acetate lamp, which in future is to be called the "Hefner Light," shall be accepted as the Light Measure of the Society in place of the Society's Paraffin Candle.

(2) The relation of the illuminating power of the Hefner lamp, constructed according to the description in Schilling's *Journal of Gas Lighting and Water Supply*, 1884, p. 74 *et seq.*, with a flame 40 mm. in height compared with the illuminating power of the Society's Paraffin Candle is established as 1 to 1.20, with a plus or minus variation up to 0.05.

At the request of the Society, the Imperial Institute undertook to further verify the Hefner lamp.

At a consultation on March 15, 1897, at Berlin, between the Photometrical Commission and the representatives of the Society of Electricians a complete understanding was arrived at, based on the Geneva resolution on the question of a light unit and certain measurements connected with it which have to be considered in photometry. By this agreement the expression "Hefner-candle" and the following table of names, symbols, units and their abbreviations was agreed upon for recommendation to the Society of Electricians and to the German Society of Gas and Water Experts:

Quantity.		Unit.	
Name.	Symbol.	Name.	Symbol.
Light Power	J	Candle (Hefner Candle)	HK
Light Current	$\phi = Jw = \frac{J}{r^2} S$	Lumen	Lm.
Illuminating Power	$E = \frac{\phi}{S} = \frac{J}{r^2}$	Lux (Meter Candle)	Lx.
Surface Illumination	$e = \frac{J}{s}$	Candle to 1 sq. m.	—
Light Supply	$Q = \phi T$	Lumen Hour	—

w, a solid angle.
S, a surface in sq. metres } both perpendicular to the
s, a surface in sq. cm. } direction of the rays.
r, a distance in metres.
T, time in seconds.

In addition to this table the following remarks were appended as a part of the agreement:

"By light current is understood the whole mass of light, within a solid angle, given off from a source of light; or the whole quantity of light which a surface S receives at a distance r from the source of light—*e.g.*, suppose the surface to be the inside surface of a sphere with a radius r, then the light current represents the total quantity of light given off by the source of light.

The unit of light current is represented by that quantity of light given off by a source of light with a light-power of J = 1 HK inside the solid angle w = 1, or on a surface S = 1 square metre at a distance r = 1 metre. This unit of light-current is expressed by $\phi = 1$ lumen.

"The strength of illumination of a surface E is measured in *Lux* (Lx) a quantity which has the same magnitude and meaning as the former metre-candle already in use. It is represented by the magnitude of the light-current in relation to the magnitude of the illuminated surface in square metres, or by the magnitude of the light power in relation to the square of the distance from the surface to the source of light.

"On the other hand, the surface illumination *e* represents the brilliancy of a surface expressed in candles per square centimetre. By one metre-candle is expressed an illumination such as a surface receives from a candle placed at a distance of one metre from it. This unit surface illumination is formed by that brilliancy of a surface which is so constituted that 1 square centimetre of it sends out a brilliancy equal to one candle. The surface illumination is, therefore, in case the surface receives its illumination from outside, dependent not only on the brilliancy of the illuminating source of light, and its distance from the surface of light, but also on the nature of the surface. The surface illumination comes, in the first place, under consideration with self-illuminating bodies, such as the carbon filament of the electric glow-lamp, or the illuminating surface of the incandescent mantle of an incandescent gas burner. For this reason 1 square metre could not be used as surface unit, but 1 square centimetre had to be chosen.

"The last rule on the light supply Q refers to the quantity of light supplied by a source of light in a given time."

Herr von Hefner-Alteneck's Amyl-acetate Lamp.—The following is the official description of the Hefner lamp :

The Hefner lamp with Hefner-Alteneck sight gauge is shown in sectional elevation in Fig. 147 and in plan in Figs. 148 and 149. Fig. 153 shows an elevation and Fig. 154 a plan of the flame measure of Kruss. Figs. 155, 156, and 157 show the check gauge to be supplied. All diagrams are drawn full size.

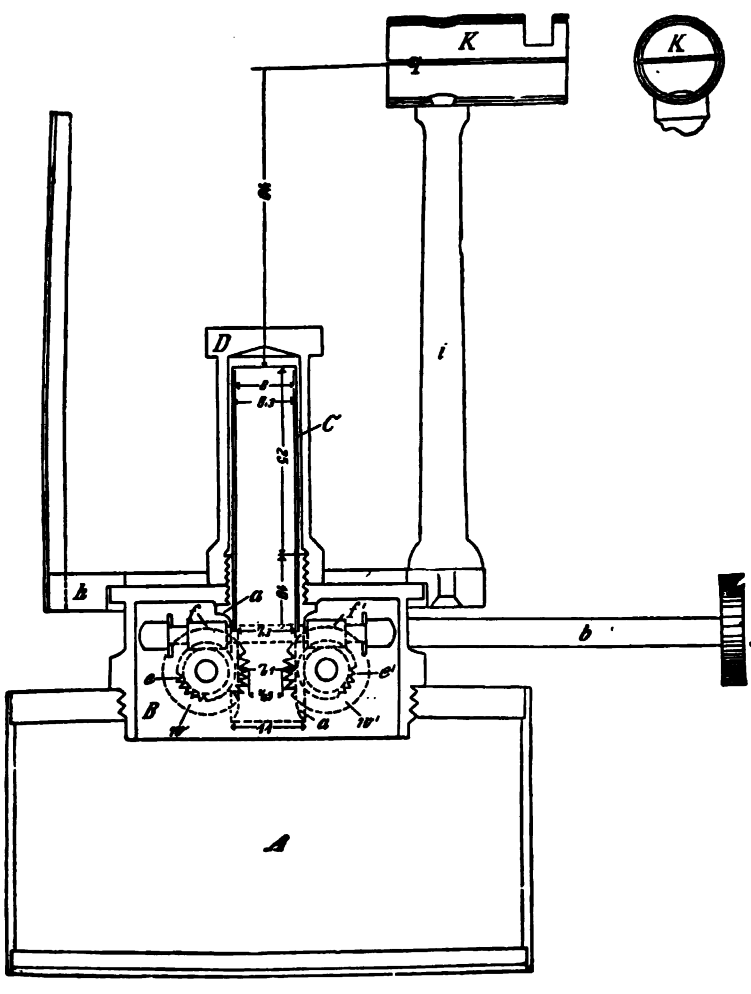
The lamp itself consists of a vessel *A*, a head *B*, containing the wick guide, and a wick tube *C*.

The vessel *A* serves for the reception of the amyl-acetate, and is made either of sheet or cast brass tinned inside.

The head *B* contains the wick-guiding tube *A* (Figs. 147 and 148) at the bottom of which there are two right-angled slots opposite each other, and an arrangement for altering the height of the wick. The latter consists of two axles *d* and *d* (Fig. 148) on which are fixed two toothed rollers *w* and *w'* (Figs. 147 and 148) which intrench within the above-mentioned right-angled slots. On one side of the rollers and rigidly connected with these arcs are the toothed wheels *e* and *e'*, which, by means of the two endless screws *f* and *f'* fastened to the same angle axle *b*, can be turned in opposite directions. The axle terminates in the head *g* by means of which the gearing is set in motion with the hand. The axle *b* is prevented from sliding backwards or forwards, first, by the strong spring *l*, and secondly, by a circular enlargement of the axle *b* between the screws *f* and *f'*, which runs in a metal fork *m*, fixed to the top of the head *B*. The wick-guiding tube *A* projects above the top plate of the head *B*, by about 4 millimetres and has on this projecting end an outside thread with which the shell *D* (Fig. 147) protecting the wick tube can be screwed up. Close against the tube *a* there are in the upper plate of the head *B* two vertical openings of about 1 millimetre diameter which serve to let in air to take the place of the consumed combustible, and are so placed that they are covered by the shell *D* when this is screwed up.

The wick tube is made of german silver and jointless; its length must be 35 millimetres, its inside diameter 8 millimetres, and its thickness of metal 0.15 millimetres. It is pushed into the tube *a* as far as it will go. The projecting end of the wick tube must then be 25 millimetres in length. The wick tube must be movable in its socket with little friction, so that it can

FIG. 147.



The Hefner Lamp.

be easily removed, but it must fit sufficiently tight for it not to be raised with the motion of the wick.

The flame measure, which is used for ascertaining the proper flame height (40 millimetres), is fastened to a movable revolving ring *h* (Figs. 147, 149, 153, and 154), which can be fixed at any position and rests on the upper plate of the head *B*. The arrangement of the fixing appliance will be seen from Figs. 150 and 152. The carrier *i* (Figs. 147 and 153) which connects the ring with the measuring appliance proper, must be so rigid that it is difficult to bend without mechanical appliances.

For measuring purposes either the Hefner-Alteneck sight-gauge or the optical appliance of Dr. Kruss may be used. One lamp can be supplied with both flame measures, but both may not be fastened to the same ring.

FIG. 148.

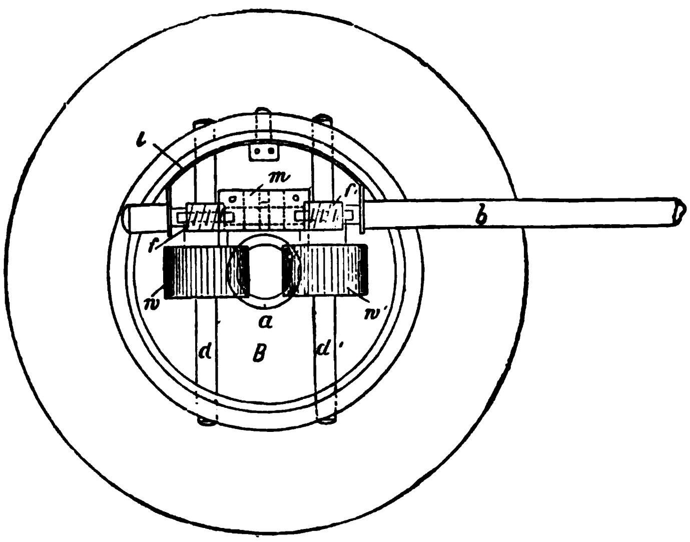
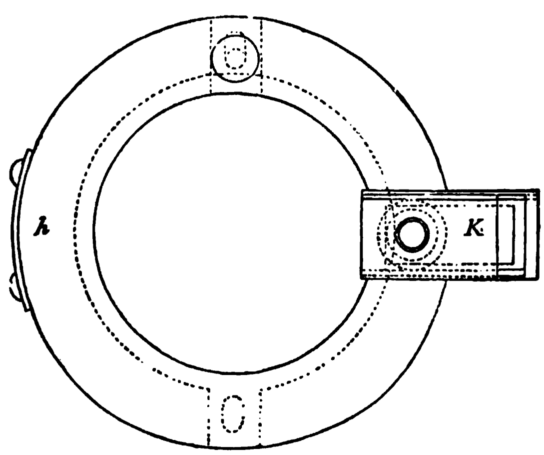


FIG. 149



The sight-gauge *K* consists of two tubes sliding one into the other with horizontal axes passing through the axis of the wick tube. The inner tube is cut along its entire length and carries a horizontal thin bright steel plate *q* (Figs. 147 and 152), 0.2 millimetres in thickness and having a rectangular opening; the underside of this steel plate must lie 40 millimetres above the top edge of the wick-tube.

The optical arrangement *r* (Figs. 153 and 156) consists of a tube about 30 millimetres long the axis of which is also horizontal and passes through the axis of the wick-tube. This tube is closed up on the side turned towards the wick-tube by a small lens of about 15 millimetre focus, and on the opposite side by a piece of ground glass of fine grain with the ground side turned towards the lens; the ground glass having a horizontal black mark across its centre not more than 0.2 millimetres in thickness. The picture of the upper edge of this mark projected by the lens must be exactly 40 millimetres over the centre of the edge of the wick tube.

FIG. 150.

FIG. 151.

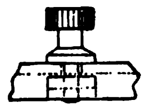
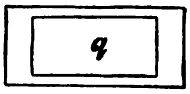


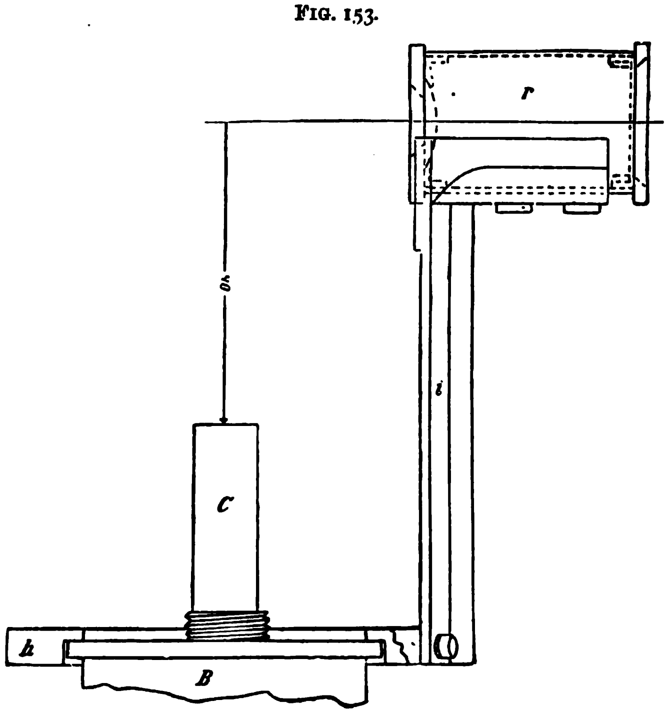
FIG. 152.



No part of the flame measure must be capable of being revolved or unscrewed. Where screws are used in joining parts together their heads must be filed off flush so that the slot disappears.

The gauge serves to check the proper position of the upper edge of the wick tube as well as that of the flame measure. Its arrangement is shown in Figs. 150, 151, and 152. When it is slipped over the wick tube so that it

FIG. 153.



stands rigidly on the top of the head *B*, on looking through the slot *S* (Figs. 151 and 152), about half way up the gauge, a fine line of light must be visible, less than 0.1 millimetre wide between the top edge of the wick tube and the horizontal top of the hollowed out space in the gauge, and when using the sight gauge the edge of the upper part of the gauge must be on the flame of the lower surface of the sheet plate. When using the optical flame measure the edge of the gauge must be sharply reproduced on the upper edge of the mark on tho flame measure, by which means the distance between the upper edge of the wick tube and the edge of the gauge will be exactly 40 millimetres.

The upper part of the gauge has a diameter of rather less than 8 millimetres. It must be capable of being easily slipped over the wick tube and serves to pull out the latter in case it requires cleansing.

FIG. 154.

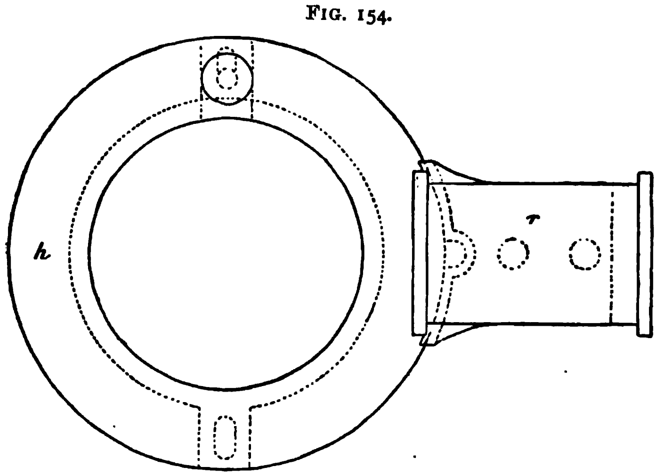


FIG. 155.

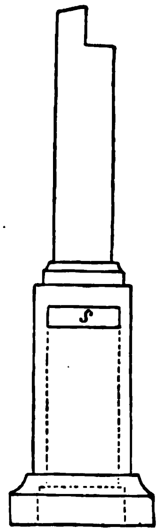


FIG. 156.

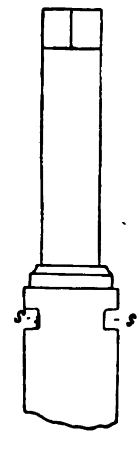
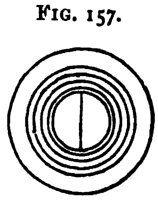


FIG. 157.



The gauge is of brass and is made in one piece.

All metal parts of the lamp, excepting the wick-tube and the steel plate of the sight gauge, must be coloured dull black.

The following are the official instructions for the use of the Hefner lamp :

The Wick.—The nature of the wick has generally no influence on the light power. Care must, however, be taken that it completely fills the wick tube, and also that it is not pressed too hard in it. It is, therefore, preferable to use a sufficient number of thick cotton threads laid together. As this kind of wick is sometimes improperly raised by gearing which is not carefully finished, and as it easily forms loops in the inside of the vessel which jam in the toothed wheels and rollers of the gearing, twisted wicks are often used. There is no objection to the use of these so long as they fulfil the condition previously mentioned—viz., that they completely fill the wick tube without fitting too tightly in it.

The Amyl-acetate.—In order to lessen the difficulty of obtaining serviceable amyl-acetate the "German Society" of Gas and Water Experts has undertaken to procure suitable amyl-acetate in sufficient quantity, to test it as to its serviceability, and to supply it in a sealed bottle (of from 1 litre upwards) through its place of business (Court Councillor Dr. Bunte, of Karlsruhe).

If the amyl-acetate is not obtained from this source, it is advisable to examine it as to its serviceability before use by tests given by Dr. Bannow, who states that amyl-acetate is applicable for photometry when the following conditions are fulfilled:

(1) The specific gravity must be between 0.872 to 0.876 at 15° Cent.

(2) When distilled (in glass vessels), at least $\frac{9}{10}$ of the volume of amyl-acetate must distil over between 137° and 145° Cent.

(3) Amyl-acetate must not turn blue litmus paper red strongly.

(4) If to the amyl-acetate is added an equal volume of benzine or carbon disulphide, the two substances must mix without becoming cloudy.

(5) If in a graduated cylinder 1 c.c. of amyl-acetate with 10 c.c. of a mixture of 90 per cent. alcohol and 10 per cent. water are shaken together, a clear solution should result.

(6) A drop of amyl-acetate on white filter paper should evaporate without leaving behind a permanent grease spot.

Amyl-acetate should be kept well corked, preferably in the dark.

The following details of manipulation should be carefully attended to.

Before Measurement.—When the lamp has been filled and the wick put in, it must be left until the latter is completely saturated. Before use the lamp must be examined to see that the gearing moves the wick up and down properly without carrying the wick tube with it. The wick must then be raised out of the tube, and the end projecting out of the wick tube cut off as smooth as possible with a sharp pair of scissors, and the proper position of the edge of the wick tube examined by means of the gauge supplied with the lamp as well as the flame measure, so that the following conditions are fulfilled:

The gauge having been slipped over the wick tube so that it stands rigidly on the head carrying the gearing, on looking through the slot about half way up the gauge against a light, even background (white paper illuminated by the sky), a fine light streak, not more than 0.1 millimetre wide, must be visible between the upper edge of the wick tube and the inner hollowed out space of the gauge. The edge of the gauge, when using the sight gauge, must be on a level with the under surface of the steel plate; when using the optical flame measure the edge of the gauge must be sharply reproduced on the upper edge of the mark on the flame measure.

The holes situated against the wick tube must not be stopped up.

The measurement must not be made until the lamp has been alight at least ten minutes, and the temperature of the room in which the observations are made must be between 15° and 20° Cent.

During the Measurement.—The lamp must be placed during the measurement on a small horizontal table, free from vibration and in a pure air free from draught. Vitiation of the air, especially by carbonic acid (through the burning of open flames, breathing of several persons, etc.), lessens the illuminating power of the Hefner lamp considerably. The photometer room must consequently be carefully ventilated before each measurement. In very small rooms or in closed photometrical apparatus the Hefner lamp should not be used. Draughts of air prejudice to a very high degree the steady burning of the flame, and render impossible a sufficiently exact adjustment of the proper flame height.

"Light measure" is represented by the illuminating power of the Hefner lamp in a horizontal direction with a flame height of 40 millimetres measured from the upper edge of the wick tube (Hefner light). This height is adjusted by means of the flame measure supplied, and the following regulations given by Herr von Hefner Alteneck hold good when using the Hefner sight gauge:

When looking through the flame to the sight gauge the light core of the lamp must appear to play on the under side of the light gauge, the less intense end of the flame point then coincides with the thickness of the sight gauge; on a close observation a glimmer of light appears up to about 0.5 millimetre above the sight gauge. The edges of the sight gauge illuminated by the flame must always be kept bright.

With the Krüss flame measure the outer border of the flame is absorbed by the ground glass, accordingly when using it the flame height must be so regulated that the outermost visible point of the flame picture touches the mark on the ground glass, and the observer must therefore look at the ground glass in a direction as perpendicular as possible.

An error of 1 millimetre in the height of the flame causes a variation of about three per cent. in the light power.

Care must be taken that, with the exception of the wick tube, the parts of the lamp illuminated by the flame, particularly the flame measure, are well blackened. If the fittings do not appear to be sufficiently blackened it is as well to place a black screen with an opening in it between the flame and the photometer screen near the lamp, thus cutting off all reflection, care must however be taken that portions of the flame are not cut off at the same time.

After Measurement.—Whilst the light is burning a brown thick liquid residue forms on the edge of the wick tube. This must be wiped off as often as possible whilst it is still hot and always after using the lamp. If the lamp has not been used some time the amyl-acetate as well as the wick must be removed and the lamp thoroughly cleaned. If it is necessary to remove the wick tube for this purpose this may be done by means of the upper portion of the gauge.

The writer in the course of his investigations on different standards found this flame to be very steady, but considerably less than 1 candle in value when adjusted to the indicated height—viz., 40 millimetres, but when the height of the flame was raised to 51 millimetres, or 2 inches, it gave results agreeing with the Pentane and Methven standards. The extreme simplicity and portability of the arrangement are strongly in its favour, but on the other hand, the colour of the light, even when pure amyl-acetate is used and the flame fixed at 40 millimetres in height, renders it extremely difficult for various operators to agree. When compared with the Pentane standard the depth of its colour is most marked. This is an important point, as the tendency at the present time is to insist as far as possible upon a white light from all artificial sources, and the adoption of a yellow flame as a standard of comparison would undoubtedly be a mistake.

Krüss Flame Measure.—The measurement of the flame height by means of a pair of compasses or by direct measure is most inexpedient, because on the one hand the candle or lamp flame is disturbed in its normal combustion by the close proximity of the observer, and on the other a disturbance is brought about by the contact of the measure with the soft edge of the candle or wick. In order to obviate these difficulties Rindorff placed a millimetre measure behind the candle and observed it at a distance with a telescope.

Somewhat more convenient, especially when dealing with a long series of tests, is the experimental device of Krüss (Fig. 158) in which an optical flame measure is used. On the front end of the tube *A* an achromatic objective *B* is fixed, and on the back portion of a ground glass screen *C* with a millimetre scale. The distance of the optical centre *H* of the objective from the ground glass screen is equal to twice the focal length of the objective. The complete tube *A* is adjustable in the shell *D* by means of the button *a* and the ground glass screen, with the scale in a vertical direction, by means of the button *b*, the complete apparatus being adjustable in height by means of the button *C*.

FIG. 158.

The use of this apparatus is very simple. It is placed at such a distance from the candle that the distance from the candle to the objective is about equal to the distance of the latter from the ground glass screen. It is then set at the proper height by means of the button *C*, and afterwards by means of the button *A*, the picture of the flame *F* is sharply focussed on the ground glass screen.

When this sharp focus is obtained, the distance of the optical centre *H* of the objective is exactly equal to the distance of the optical centre from the ground glass screen *C*, and the picture of the flame is consequently exactly the same size as the flame itself. A millimetre division on the glass plate represents therefore exactly a millimetre of the flame itself.

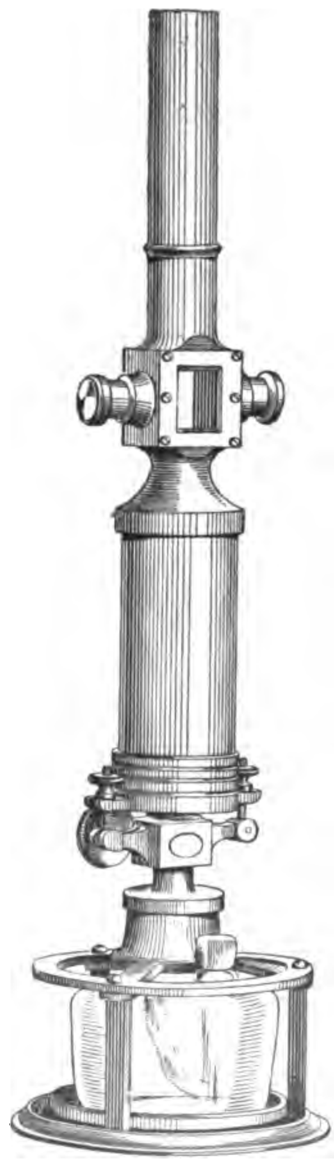
The scale is 100 millimetres long, and when it is in its highest position the 50 division is exactly in the axis of the objective. The height of the complete apparatus being regulated by means of the button *C*, the picture of the flame is symmetrical to the optical axis of the objective. As the scale can be moved by means of the button *b* until the zero stroke just touches the bluish root of the flame, its height can thus be read off direct with the picture at this point.

As the candle burns down the zero stroke no longer coincides with the beginning of the flame, and the height of the complete apparatus must be altered by means of the button *C*, leaving the scale unaltered, so that the picture of the flame remains symmetrical to the optical axis of the apparatus, following the candle as it burns down. It is unnecessary to be very particular about the symmetry of the picture with the axis, but complete equality between flame and picture can no longer be attained when the flame appears in a very oblique position, owing to the properties of the optical picture. This, however, is easily prevented by the construction of the apparatus.

Dutch Standard of Light.—A Committee of the Dutch Gas Association in 1894 issued a report on photometry and standards of light, in which

after reviewing the English, German, and French standards they concluded that no lamp in use meets all the requirements, and they accordingly proceeded to the construction of a new one (Fig. 159). This was a lamp designed upon the basis of Vernon Harcourt's screened one-candle lamp (No. 2) but burning a mixture of ether and benzol in the proportion of nine parts of benzol to 100 of ether by weight, or at 15° Cent., 500 of ether by volume to 36.65 of benzene. Of this mixture the lamp consumes about 30 c.c. (about 1 fluid ounce) per hour, and affords a light equal to 1.48 English standard candles, which is practically constant when the proportion of benzene to ether is between 8.5 and 10.2 parts of the former to 100 of the latter. This mixture of 9 of benzol to 100 of ether, made up with ether of specific gravity 0.7215 and benzene of specific gravity 0.886, had a specific gravity of 0.7335, all the gravities being taken at 15° Cent., and it was found that after 33 per cent. of the mixture had burned away the residue in the reservoir retained exactly the original specific gravity, *i.e.*, 0.7335, so that the margin of variation which had been found possible did not affect the mixture, it having evaporated as a whole. The ether and benzene used were redistilled ethyl-ether and purified benzene (free from thiophene) obtained from Khalbaum, Berlin. The Committee recommended that this lamp should be called the "æther benzol" or "A. B. Lamp," that it should be adopted as the standard, the results being stated in terms of the English Parliamentary Standard Candle as the unit of light.

FIG. 159.



The results of tests of various standards by the Committee were as follows:

Amyl-acetate lamp—0.9213 English candle—0.8333 German candle.

English candle—1.0854 amyl-acetate lamp—0.9045 German candle.

German candle—1.2 amyl-acetate lamp—1.1053 English candle.

Carcel lamp—9.631 English candles.

Proposed Substitutes for Candles.

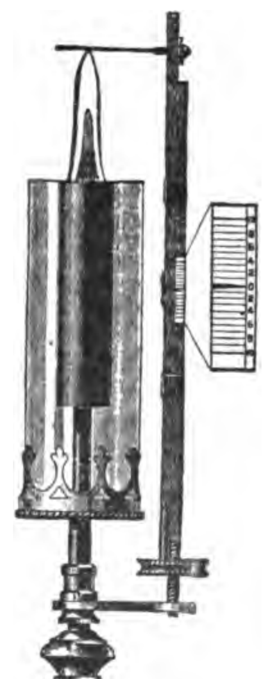
The most important of these are, in the order of their introduction: Keates' lamp, Harcourt's one-candle Pentane unit, Methven's screen, Sugg's ten-candle screened Argand, Violle's molten platinum, Hefner-Alteneck's amyl-acetate lamp, Dibdin's Pentane Argand, Harcourt's Pentane lamp, and Blondel's ether-benzol lamp.

Keates' Lamp, when first introduced in 1869, was arranged to yield a light equal to ten candles. Subsequently it was improved and made to yield a light equal to sixteen candles.

The lamp is a modified form of the "Moderator" lamp which, when burning sperm oil at the rate of 925 grains per hour with a 2-inch flame, gives a light equal to sixteen candles. As with candles and the Carcel lamp, the consumption of oil must be weighed and a correction made. Mr. Sugg has modified this lamp by placing a screen with an aperture in it in front of the flame, so that the light may be regulated from two or ten candles, without the necessity of weighing the oil consumed.

Harcourt's Pentane Air-Gas.—Mr. A. Vernon Harcourt, F.R.S., introduced this form of proposed standard to the notice of the Physical and Chemical Sections of the British Association at their meeting held at Plymouth in August 1877.

FIG. 160.



Harcourt's One-Candle Pentane Air-Gas Unit.

The following detailed description was presented by Mr. Harcourt to the Board of Trade Committee in 1892:

1. *The Burner.*—This consists of a brass tube 4 inches in length and 1 inch in diameter which the gas enters near the bottom. The upper end of the tube is closed by a brass plug, half an inch in thickness, in the middle of which is a round hole a quarter of an inch in diameter. Around the burner is placed a glass cylinder 6 × 2 inches, the top of which is level with the top of the burner, air entering through the gallery on which the chimney stands. A piece of platinum wire, about 0.6 millimetre diameter and from 2 to 3 inches in length, is supported at a height of 63.5 millimetres above the burner.

2. *The Air-Gas.*—This is made by bringing together, in a gasholder, air and liquid pentane, which evaporates and mixes with the air, in the proportion of 1 cubic foot of air to 3 cubic inches of pentane. The pentane used is a mixture of pentane with some of the paraffins of lower and higher boiling-points, which is prepared by distilling the light petroleum at 60° Cent., at 55° Cent., and twice at 50° Cent. The pentane thus prepared must satisfy the following tests: On agitation with $\frac{1}{20}$th of its bulk of fuming sulphuric acid for five minutes, it must impart to the acid only a faint brown colour. The density of the liquid must lie between 0.62 and 0.63 at 62° Fahr. The liquid must evaporate at the ordinary temperature absolutely without residue when the tension of its vapour is not less than 7.5 inches of mercury. The density of the vapour compared with that of air must be not less than 2.47, nor greater than 2.53.

3. *Measurement of the Gas and other Conditions for Obtaining a Light of One Candle.*—For the preparation of pentane air-gas it is convenient to use a gasholder consisting of a cylindrical bell of about 7 cubic feet capacity, suspended and counterpoised in the usual manner over a tank having an annular space filled with water. A graduated scale attached to the bell serves to measure the volume of air drawn in, and also the volume of

vapour formed from the measure of pentane which is discharged from a pipette through a tap into the holder. Three cubic feet of air (corrected for the actual conditions under which the air is measured) and 9 cubic inches of pentane (measured at 62° Fahr.) yield, after standing for some hours, a volume of air-gas which, corrected to standard conditions, should not be less than 4.02, nor more than 4.1 cubic feet.

The air-gas should pass to the burner through a small meter delivering at each revolution $\frac{1}{60}$th of a cubic foot. The flame having been set at the standard height, the meter is read two or three times at intervals of two minutes. A test should be rejected in which the rate of the air-gas has exceeded 0.52 cubic foot, or fallen short of 0.48 cubic foot per hour.

After the meter, the air-gas should pass through a small governor of the usual construction, fitted to regulate a flow of half a cubic foot per hour.

The height of the flame is to be adjusted, by means of a delicate stop-cock, by gradually raising it until the top appears to touch, but not to pass, a horizontal platinum wire, which must be placed exactly over the flame, and extend not less than half an inch beyond it.

Since the apparent position of the tip of the flame varies slightly with the sensitiveness of the eyes of the observer, and the principal variations in sensitiveness are due to the greater or less exposure of the observer's eyes to light, both during an observation and for some time previously, it is necessary to define the conditions under which the height of the flame is to be judged.

For photometry in which the relative illumination of two adjacent surfaces is compared, the observer must be in a darkened room and screened from the two sources of light. In the screen which is between the observer and the one-candle flame there should be an opening, the horizontal length of which is about 1 inch, and its width about $\frac{1}{4}$ inch, at the same level as the top of the flame. Through this slot the observer looks, lowering his head until he sees only the tip of the flame and the wire extending above it. Behind the flame and wire the background should be as uniform and dark as possible.

The variations of temperature and humidity, though affecting the absolute light which the standard yields, and needing to be corrected for where absolute measures are concerned, do not affect comparisons made between this standard and other hydrocarbon flames.

Summary of Observations on the Amount of Light given by the Pentane Flame at Different Heights.—A pentane lamp, adjusted to give the same light as the standard pentane flame, was set at such distances from the photoped (rectangle of paper illuminated as to part of its surface by light from one source, and as to another adjoining part by light from another source, see p. 287), as to give an illumination of 1.2, 1.1, 1, 0.9— — —0.1 times the normal illumination, given by a light of one candle at the distance of one foot.

The light from the pentane standard fixed at a distance of 12.17 inches was made such by so adjusting the height of the flame so as to give an equal illumination. Thus the light of the pentane flame was made successively 1.2—0.1 candle, and for each light the height of the flame was measured two or three times by depressing a horizontal platinum wire by means of a rack and pinion carrier. The mean of these measurements, and of several settings of the flame to produce equal illumination, was taken as the height corresponding to each fraction of a candle.

Four such sets of measurements were made over different parts of the scale.

The actual distance between the fixed pentane standard and the photoped being 12.17 inches (hypotenuse of a triangle whose vertical is 12 and whose base is 2 inches), the pentane lamp was set at the following distances to produce such an illumination as would be produced from a constant distance of 12.17 inches by a light having the values given in the second line under the corresponding distances:

Distance	12.17	12.82	13.6	14.54	15.705
Light	1	.9	.8	.7	.6
Distance	17.205	19.23	22.21	27.2	38.5
Light	.5	.4	.3	.2	.1

Light.	Set 1.	Set 2.	Set 3.	Set 4.	Mean.	Diff.
1.2	—	—	70	71.3	70.6	—
1.1	—	—	—	—	($\frac{1}{2} \times 6.4$)	3.2
1.0	—	65	—	63.5	64.2	3.2
0.9	61	60.5	—	60	60.5	3.7
0.8	56.5	55.5	—	56.5	56.2	4.3
0.7	52	52	51	52.5	51.9	4.3
0.6	47.5	48	—	48	47.8	4.1
0.5	43	44	43.5	44	43.6	4.2
0.4	38.5	39	39	39.5	39	4.6
0.3	35	35	34	35.8	35	4.0
0.2	28.5	29	29	29.3	29	6.0
0.1	24	22.5	—	23.3	23.3	5.7

Even taking the average of several observations, the height of the flame for a given light cannot be estimated within about 0.5 millimetres. If the flame were to be used above the standard height, further observations must be made to fix its value. The mean difference of height between 1 and 1.2 candles is probably too low; both values were only observed in Set 4, and these give 3.9 as the difference. Probably, the differences from 1.2 to 0.3 may be taken as equal, and as approximately of the value 4 . $\frac{70.6 - 35}{9} = 3.96$.

If a difference of 4 millimetres makes a difference in light of 0.1 candle, a variation in the height of the flame of 1 millimetre makes a difference in the light of 0.025 candle.

As will be seen from Mr. Harcourt's description, the method of preparing the air-gas from the liquid pentane is very simple. For every cubic foot of gas 3 cubic inches of the liquid pentane are required—the air being measured at a pressure of 30 inches of mercury, and a temperature of 0° Cent., the pentane at 60° Fahr. In practice, 3 cubic feet of air and 9 cubic inches of pentane are usually taken. Mr. Harcourt's method of introducing the liquid pentane into the gasholder containing the measured volume of air, is to pass the bent end of a pipette to the bottom of a syphon-tube, sealed with water, the long limb of which passes through a cork fitted tightly in the top of the bell of the holder. On opening the stopcock of the pipette, the pentane passes down through the tube, and, taking the direction of the bent end, rises upward through the column of water and over the top bend of the syphon into the bell. Finding this system very liable to accidents, the writer employed another of a more simple and reliable character. The bent end of the pipette is cut off, and the pipette ground accurately into a second shorter and stouter tube, provided with a stopcock, which is fitted into the crown of the bell of the holder by means of a tightly-fitting indiarubber cork. The charging of the holder with pentane, without either letting air into the holder or losing pentane, thus becomes a matter of absolute certainty. The pentane-pipette is first filled in the usual manner, and the ground end gently but firmly fitted into the open end of the tube in the bell of the holder. When the two stopcocks are opened, the pentane runs through the tube into the holder at once without possibility of loss. When the pipette is nearly empty, it is closed at the top with the finger, and the bulb warmed by clasping it with the hand, the pentane

FIG. 161.

"Methven's" Standard Light Unit or Screen, with double slot.

vapour thus becoming expanded, drives the last portions of pentane into the holder. The stopcock in the short fixed tube, which is ground perfectly gas-tight, is closed, and the pipette removed.

The adoption of Harcourt's pentane air-gas unit as a standard of reference was recommended by a committee of the Board of Trade in 1881; by the Metropolitan Board of Works in 1887; and by the Standards of Light Committee of the British Association in 1888, and accepted by the Board of Trade Committee in 1895 as "a true representative of the average light furnished by the sperm candle constituting the present standard."

The Methven Screen was introduced in 1878 by the late Mr. Methven as a means of obtaining a light of constant illuminating power. The apparatus consists of an upright rectangular metallic plate or screen, with a horizontal flange or bracket, upon which a standard "London" Argand burner is fixed, the latter being supplied with gas through a plug or nose piece projecting downwards. The upright plate has a slot or hole above the bracket holding the Argand burner; over which is fixed a thin silver plate, having a vertical slot of such dimensions as "will allow of the passage of as much light as equals that afforded by two average standard sperm candles when the Argand burner is delivering sufficient gas to give a flame 3 inches in height." Finding that this arrangement was only to be depended on when gas of a certain quality was used, Mr. Methven experimented with "carburetted" gas—*i.e.*, gas enriched with certain hydrocarbons, adopting the same agent as Mr. Harcourt—viz., pentane. From his experiments Methven found that all carburetted gases were too rich to be burnt properly in a standard Argand with a 6-inch by 2-inch chimney, unless the flame was reduced to 2 inches in length, but with a flame of this length the amount of light yielded was constant and altogether independent of the actual illuminating power of the coal and cannel gases employed for enrichment. In order to compensate for the greater luminosity of the flame so obtained, he employed an aperture of smaller area than that used with the plain coal gas.

In 1883, Messrs. Heisch and Hartley reported on this proposal to the Gas Institute in the following terms:

"The range in qualities of the gases with which the Methven plain gas standard can be safely used is much wider than has been generally supposed; as in our experiments the extremes are 13.65 and 22.4—a range of 8.75 candles. . . . The Methven standards are simple in construction; not liable to get out of order; and extremely easy to use. They do best, like candles, in an open photometer; but can be readily used in a closed one, if due care is taken to freely ventilate the photometer and avoid violent air currents—conditions which are extremely difficult to fulfil with closed photometers. . . The only conclusion which can be drawn from such a mass of evidence is that the Methven units are not only perfectly reliable instruments for ordinary gas testings, but are suitable for use in photometric investigations of a much more refined character."

Sugg's Ten-Candle Standard.—This standard consists of an Argand burner, burning ordinary gas in a 3-inch flame; the height being accurately fixed by regulating the pressure. The top of the flame is cut off for photometrical purposes by means of a screen, which leaves the whole of its width visible, but reduces the height of the light to about 1¾ inches. The standard is mounted on a meter, which registers the amount of gas consumed, and constitutes an indication of the highest value of the variations of the flame. Thus the standard is not based on the assumed constancy of a portion of a gas-flame, or on the height of flame and pressure of gas; but is essentially a variable standard, the variability of which is known, and can be allowed for.

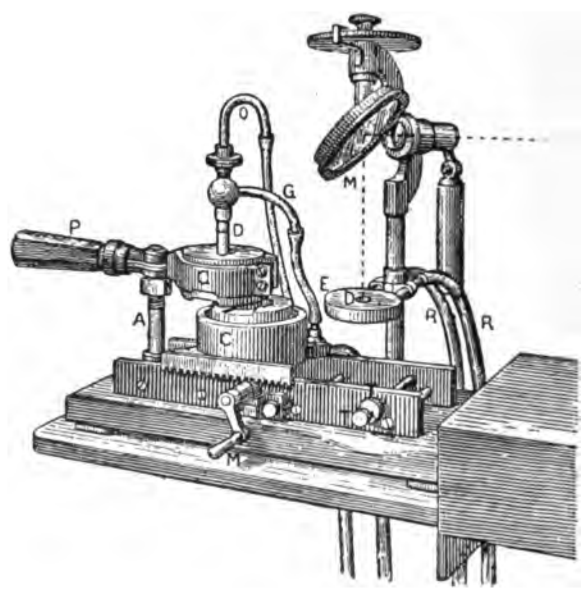
Violle's Molten Platinum Standard.—In this proposal the unit of light suggested is that emitted from a square centimetre of platinum in a solidifying condition. Professor Violle states that "the principle of the standard is the constancy of the point of fusion, and the constancy of the temperature during the whole time of the change of state," when the maximum light is given off, and the reading of the photometer taken. This system was recommended by a Congress of Electricians held in Paris, as an international standard; but in 1881 another Congress rejected it, on account of the difficulty attending its application, and the colour of the light—at the same time recommending the adoption of the Carcel lamp.

Fig. 162 illustrates the arrangement constructed by M. Carpentier at the instance of M. Violle for conveniently effecting the fusion of the platinum.

The crucible *C* containing the platinum which is heated by the blowpipe *GO*, is carried on a slide so that it can be moved rapidly by the rack-work and pinion *M*, under the screen *ED*, which is kept cool by the flow of water through the pipes *RR*.

This screen is pierced with a round hole *D* having an area of 1 sq. cm. The rays passing through this hole are thrown on the photometer by reflection from the mirror *M*, the coefficient of absorption of which is determined.

FIG. 162.

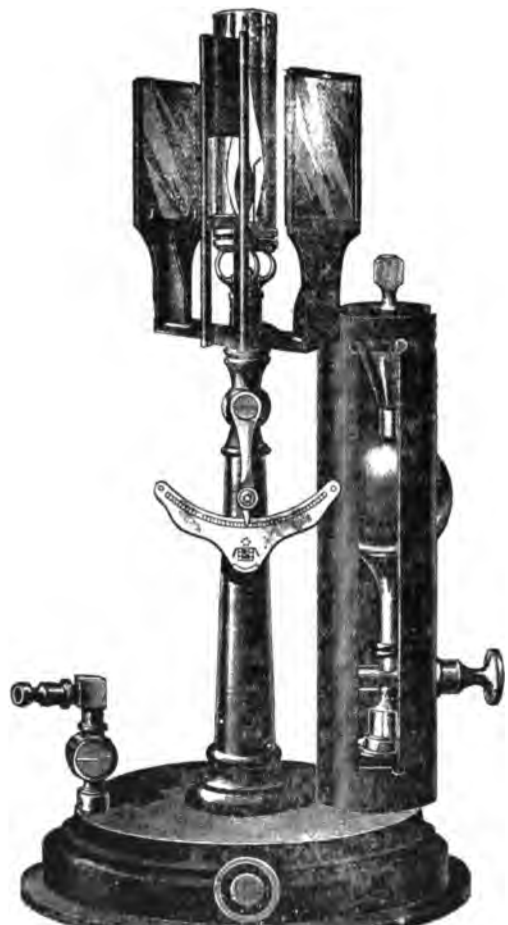


The British Association Committee on Standards of Light, in their report presented in 1888, stated that, in their opinion, Professor Violle's standard of molten platinum was not a practical standard of light, although they were quite prepared to agree to the adoption of the light emitted by a square centimetre of molten platinum as a unit, but not as a standard of light.

Dibdin's Pentane Argand.—This proposed standard, Fig. 163, is a modification of Sugg's 10-candle test, and Harcourt's pentane air-gas unit, used in conjunction with Methven's carburetter. The burner is an Argand of the type used by Sugg, but modified to burn air-gas, the height of the flame being regulated to 3 inches, seven-tenths of which is cut off at the top by a screen. The air-gas is obtained by passing air over liquid pentane contained in an ordinary Methven carburetter. For practical purposes coal gas may be used equally with air, the difference in the luminosity of the flame being negligible.

This standard is made to give a light equal to 10 candles, and owing to the nature of the flame and the fact that, unlike the Methven standard, only the top portion is screened off, a variation of 1.5 inches in the height of the flame makes no difference to the luminosity of the unscreened part. This is due to the whole of the light emitted from the lower and blue part of the flame being included in that of the "standard" portion, which admits of considerable variation in the height of the flame, because when the flame is lowered, although there is less body beneath the screen there is also less

FIG. 163.



W. J. Dibdin's Pentane Argand and Carburetter.

Measurements of Dibdin's Ten-Candle Pentane Argand Burner.

Number of holes	42		
Diameter of holes	0.71	mm.	= 0.028 inche
Inside diameter of steatite	9.90	„	= 0.390 „
Outside diameter of steatite	19.05	„	= 0.750 „
Diameter of inside of metal cone at top	23.62	„	= 0.930 „
Chimney length	152.4	„	= 6.000 „
„ inside diameter	38.1	„	= 1.500 „
Height of cut-off	54.61	„	= 2.150 „

The centre of the flame to be immediately over the terminal of the photometer bar.

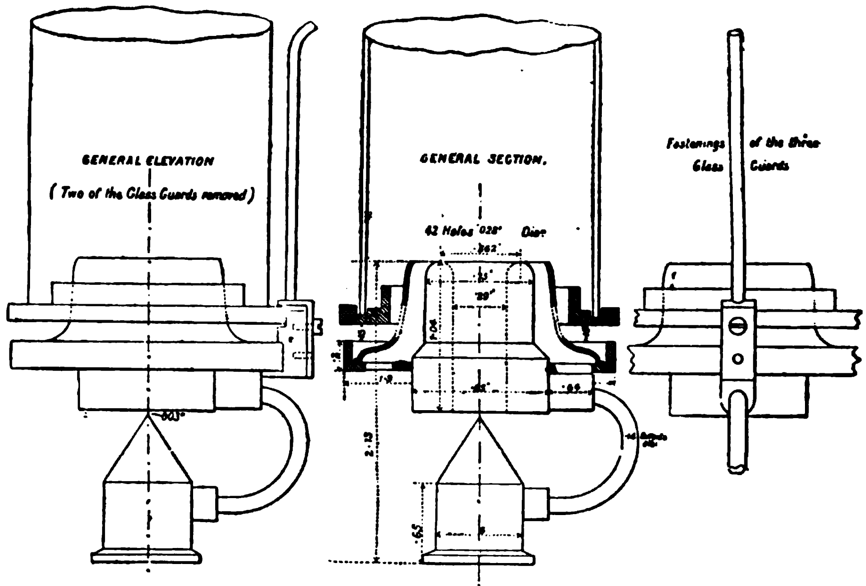
" blue," and inversely, when the flame is lengthened, the " body " of white light is increased, and at the same time the amount of " blue " is also increased, and these two differences compensate for each other. As it might be thought that temperature would influence the quality of the pentane gas formed by merely driving air over liquid, the carburetter was first surrounded with ice and water, and afterwards with water at 90° Fahr. After adjusting the flame to the altered flow of gas thus caused, the luminosity was found to be precisely the same in each case.

It was recommended by the Board of Trade Committee, 1895, as the practical standard of light at the same time as Harcourt's pentane air-gas unit was recommended as the standard of reference. The following description is reproduced from the report of that Committee.

Dibdin's 10-Candle Pentane Argand Air-Gas Standard, as Recommended by the Committee for Use in Gas Testing.

The apparatus used in producing this standard of light consists of two separate portions; viz., the burner and the carburetter.

FIG. 164. FIG. 165. FIG. 166.



Elevation and Section of Pentane Argand Burner.

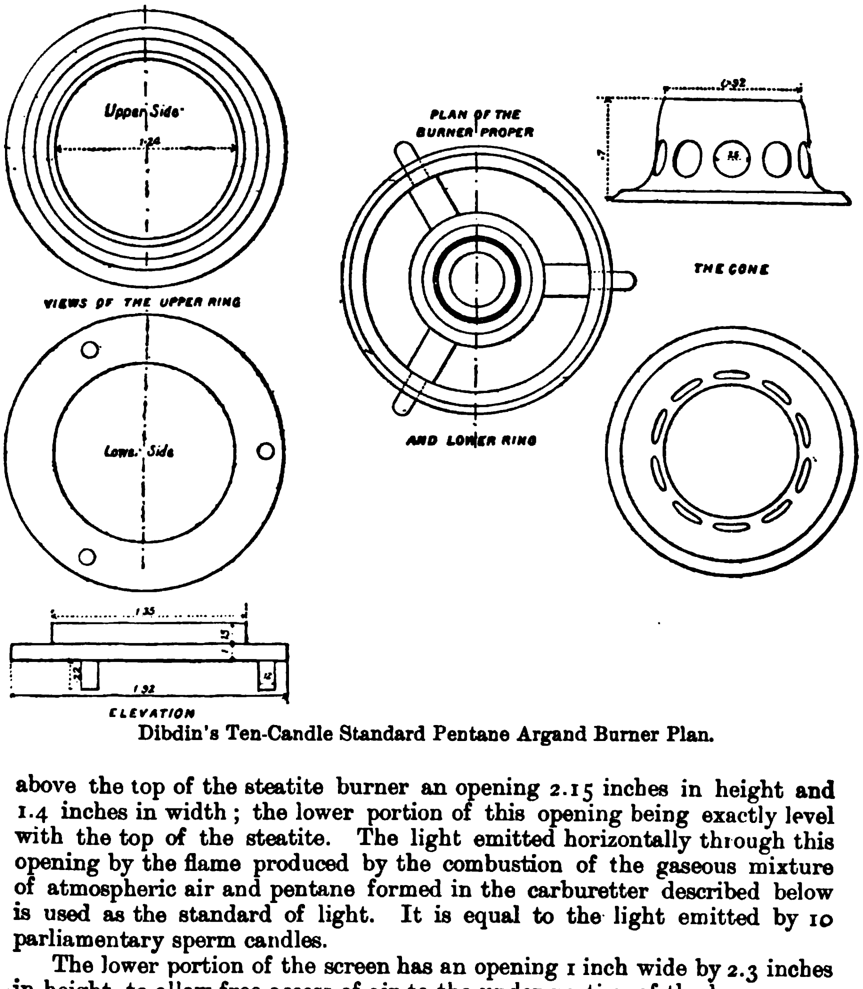
The burner, Figs. 164, 165, 166, is a specially constructed tri-current Argand burner, the annular steatite ring being perforated with forty-two holes, each hole being 0.71 millimetre in diameter. The three air currents are: (1) The central current rising inside the steatite to the inner portion of the flame; (2) a current rising outside the steatite, and caused to impinge upon the flame by an inner metal perforated and incurved cone, the top of which is level with the top of the steatite; (3) an outer current rising on the outside of the above cone, and between that cone and the glass chimney.

The inner perforated cone, Fig. 169, is punctured with ten apertures 0.25 inch in diameter, which are provided for the purpose of equalising the two outer currents of air as may be required to suit the height of the flame.

The glass chimney is carried in the groove provided on the outer cone, which answers the purpose of a gallery; the dimensions of the chimney being 6 inches high and 1½ inches inside diameter. The top of the flame should be maintained as nearly as possible at three inches above the steatite; this point being indicated by the wires crossing the blue glass screens carried on each side of the burner on the metal supports. The flame is steadied by the small air-directing cone situated centrally beneath the steatite; the apex being 0.03 inch below the metal support carrying the steatite.

On the side of the burner to be presented to the photometer disc, a metal screen, Fig. 170, 8½ inches in height, is placed and screwed securely to the base-plate. The middle portion of this screen is cut way so as to leave

FIG. 167. FIG. 168. FIG. 169.



Dibdin's Ten-Candle Standard Pentane Argand Burner Plan.

above the top of the steatite burner an opening 2.15 inches in height and 1.4 inches in width; the lower portion of this opening being exactly level with the top of the steatite. The light emitted horizontally through this opening by the flame produced by the combustion of the gaseous mixture of atmospheric air and pentane formed in the carburetter described below is used as the standard of light. It is equal to the light emitted by 10 parliamentary sperm candles.

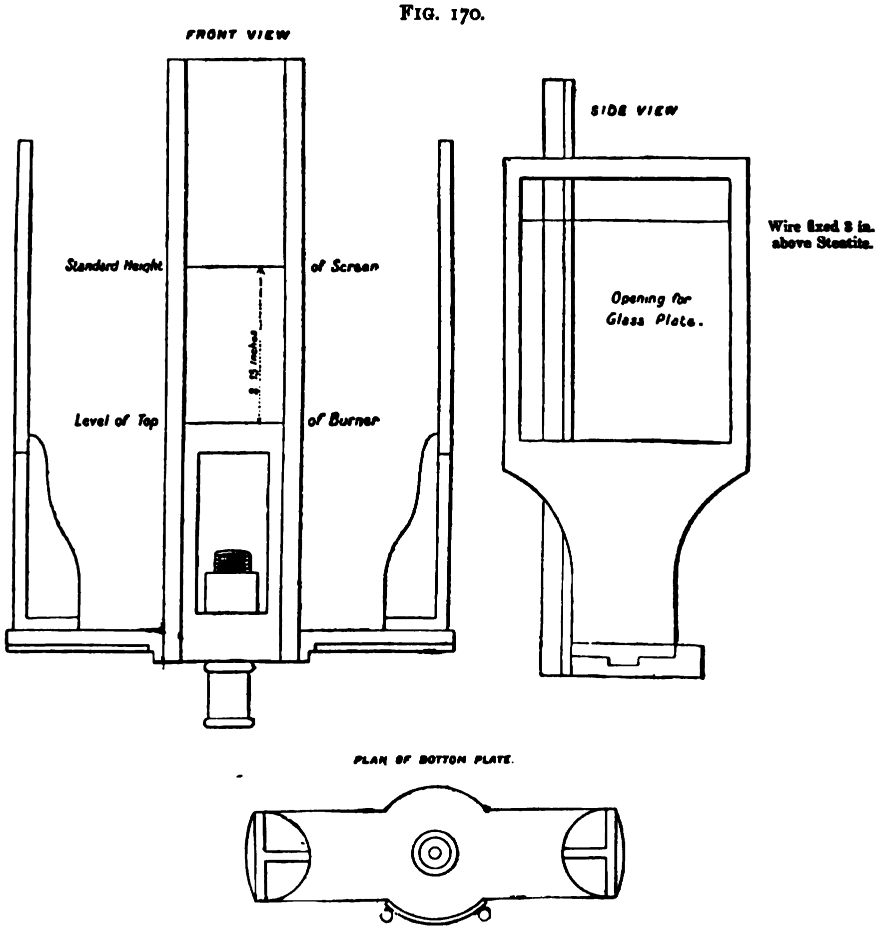
The lower portion of the screen has an opening 1 inch wide by 2.3 inches in height, to allow free access of air to the under portion of the burner.

The various dimensions and arrangements of the parts are more particularly described in the following table of measurements and accompanying detailed plans.

The position of the burner in relation to the photometer disc is to be fixed by the burner fitting gas-tight into a faced joint attached to the photometer at the required point; and the burner is to be set at such a height that the centre of the illuminated disc and the bottom edge of the cut-off shall be in the same horizontal plane. The length of the connection between the burner and the carburetter may be varied, but should not be more than 5 feet.

The centre of the flame is to be immediately over the terminal point of the photometer-bar.

FIG. 170.



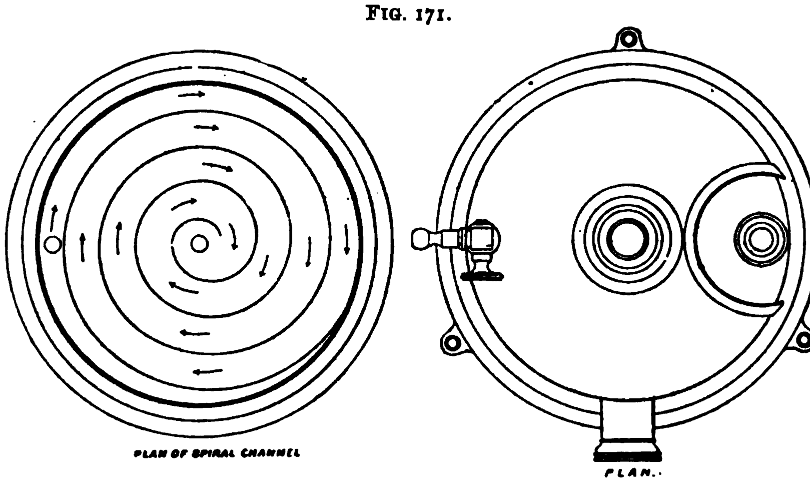
Framing and Screen of Dibdin's Ten-Candle Standard Pentane Argand Burner.

The carburetter, Fig. 171, for the 10-candle pentane Argand consists of a circular vessel constructed of tinned plate—

Diameter	203.2 mm. = 8 inches.
Depth	50.8 „ = 2 „

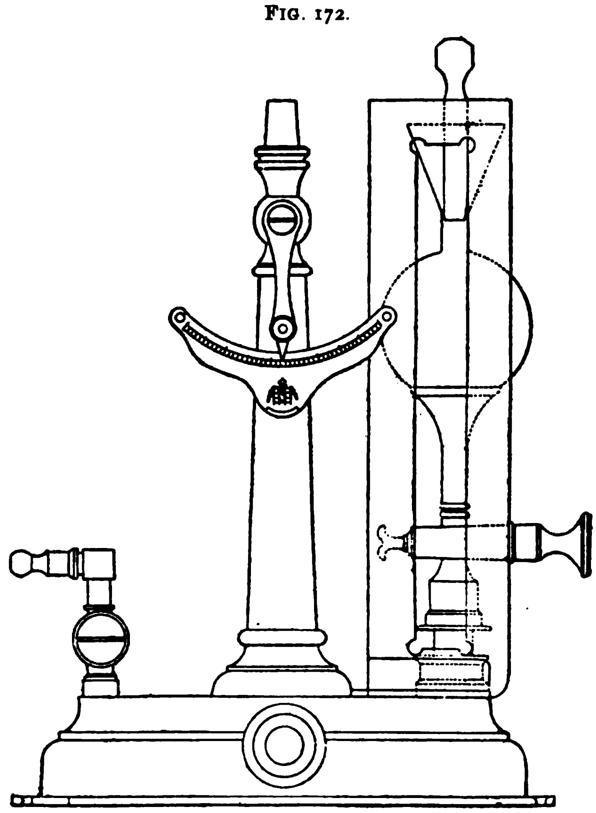
having a spiral division 25.4 mm. = 1 inch in width. This division is made by soldering in a spiral strip of metal 4 feet 6 inches in length and 2 inches wide, gas-tight, to the under side of the top of the carburetter, so that when the top is fixed on, the bottom of the strip comes close to the bottom of the

FIG. 171.



Carburetter for use with Dibdin's Ten-Candle Standard Pentane Argand Burner.

FIG. 172.



Carburetter for use with Dibdin's Ten-Candle Standard Pentane Argand Burner.

vessel and is sealed by the pentane, so that the air has to pass over pentane for a distance of about 4 feet 6 inches, and becomes thoroughly saturated.

At the end of the spiral division, near the side of the carburetter, a bird fountain is fixed for charging the carburetter, Fig. 172, and keeping it charged at a constant level with liquid pentane.

The lower end of the inlet fountain tube is closed, and rests upon the bottom of the tank.

Through the side of the tube, which is $\frac{4}{10}$ths of an inch (10.1 mm.) in diameter, 16 holes 1 mm. in diameter are bored close to the bottom; and through these the pentane enters the carburetter. At one side of the inlet-tube, and one inch from the lower end, a small tube 33 mm. in diameter, and 20 mm. in length, is connected thereto, and turned upwards. The fountain inlet-tube is carried up through the top of the carburetter, and continued in the form of a bulb having a capacity of about 200 c.c. Stop-cocks are provided at the top and bottom of the bulb for convenience in filling with pentane, and the portion above the upper stop-cock is opened out in a funnel shape for the same purpose. When the carburetter is being charged, the gas must be extinguished to avoid the risk of the vapour firing and causing an explosion.

The inlet for gas or air is at the side of the carburetter, and at one terminal of the spiral division, Fig. 171; the outlet being placed in the centre of the vessel, so that the air or gas may travel over the liquid pentane throughout the whole length of the spiral division, and thus become fully charged with the volatile vapour of the pentane.

When using this standard, the pentane must be visible in the fountain bulb.

Harcourt's Screened Pentane Lamp (*No.* 2) is constructed as follows: The vessel *A*, which may conveniently be of glass and of the form and dimensions of an ordinary spirit-lamp, contains the oil or liquid which is used in the lamp, preferably pentane obtained by purification and repeated rectification from American petroleum. This liquid is so volatile that it is converted into gas within the burner; the wick serving only to bring the liquid to a part of the tube where the heat is sufficient to cause it to evaporate at the required rate.

The two illustrations show—Fig. 173 sectional front view, and Fig. 174 side view of the lamp. The glass vessel *A* is mounted upon a stand *B*, provided with levelling-screws *C*. To the vessel is fitted a cap *D* surmounted by a tube *E*, in which a wick is wound up and down by the ordinary arrangement of a double-spiked wheel *F* turned by a handle. Around the upper part of this tube, the diameter of which may be about $\frac{1}{4}$ inch, and its length 6 or 7 inches, is a second tube *G* of about 1 inch in diameter and 4 inches in length, which serves as a jacket to keep more constant the temperature of the inner tube, and to guide the air current, upon which the steadiness and brightness of the flame depend. The two tubes are joined by flat plates *H* above and below, and constitute the burner of the lamp.

Attached to the inner tube by branches is a gallery *J* carry a metal chimney *K*, which surrounds both the burner and the lower part of the flame. Above the burner the part K^1 of this chimney is reduced to a diameter intermediate between that of the aforesaid outer tube *G* and inner tube *E* of the burner, and terminates at a short distance above the burner. The upper part of the flame is again enclosed by a continuation *L* of this metal chimney, which is of the same diameter as the lower part, but is enlarged in diameter towards its upper end.

This upper portion of the chimney is connected with the lower chimney by curved metal bands *M*, usually two in number, and sufficiently removed from the flame on either side as not to affect it. Through the space thus left between the upper and lower metal chimneys, the central part of the long flame which the burner produces is alone visible. The attachment of these bands connecting the upper to the lower chimney is adjustable by set screws *N*, so that the opening through which the central part of the flame is seen may be made longer or smaller as desired. By any simple means, such as an adjusting screw, or preferably by means of cylindrical gauges of the same diameter as the tubes which they separate, this opening can be set quickly and accurately to such sizes as will give exactly the light of 0.5 candle, 1 candle, 1.5 candles, or values intermediate between these as desired.

At opposite sides of the lower part of the upper chimney are two narrow

FIG. 173.

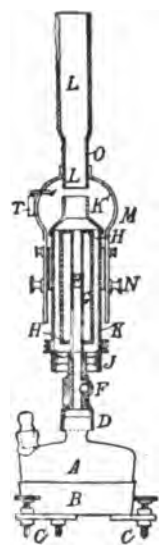
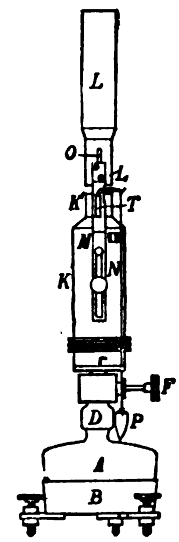


FIG. 174.



Harcourt's Pentane Lamp (No. 2).

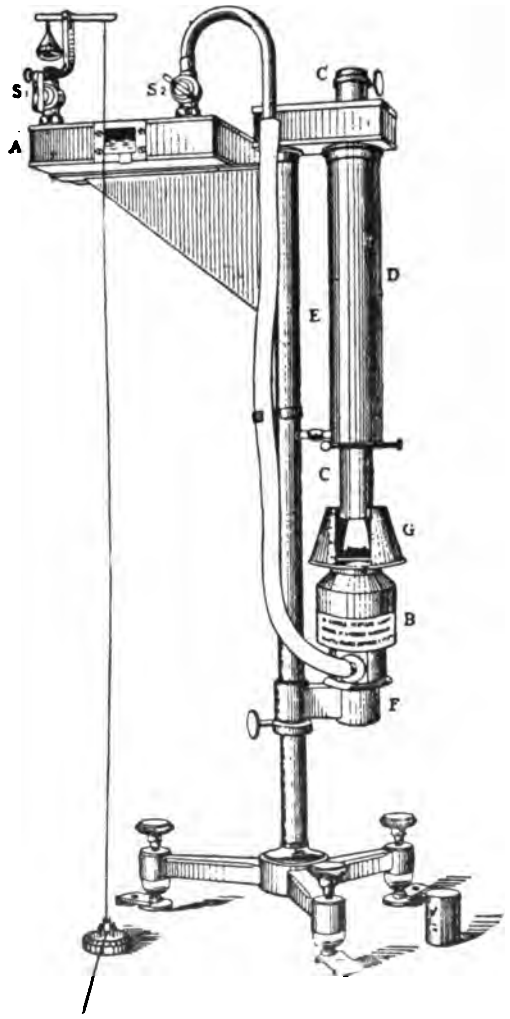
slots *O*, through either of which the tip of the flame may be seen; and the construction of the lamp is such that the light emitted through the opening between the two chimneys is the same whenever the tip of the flame appears opposite the slot, whether towards the lower or the upper end.

The bands *M* connecting the two chimneys are made half the width of the tube that surrounds the flame. When the lamp is vertical so that these bands are in a plane perpendicular to the horizontal bar of the photometer, a point in which the plane containing the edges of the bands nearest to the photometric disc, midway between these edges, and at the height of the centre of the aperture through which the luminous flame is visible, is to be taken as the point from which distances are to be measured. This point represents the zero of the usual photometric scale.

In order to easily obtain the plane in which this point lies, two slots *S* are cut in the bands *M* on the side nearest the disc, and into these slots a flat piece of metal fits of the same thickness as the depth of the slots. The point from which distances are measured lies on the surface of this piece nearest to the disc.

Suitable attachments are provided for carrying a plumb-line *P* to serve in setting the lamp vertical, and for carrying a small piece of coloured glass fitting in the plumb-line socket *T*, so as to stand opposite to the slot *O*. By reflection from, or direct vision through this glass, it may easily be observed whether the tip of the flame is within the slot or not. The height of gauges which produce, when burning pentane, a light equivalent to 0.5, 1,

FIG. 175.



Harcourt's Ten-Candle Pentane Lamp.

or 1.5 standard English parliamentary candles, is respectively 7, 16, and 27.5. millimetres.

This lamp is a great improvement upon the first one devised by the same inventor. In addition to being very constant, it is exceedingly simple to manipulate. It is in reality an improved amyl-acetate lamp, burning pentane. As in the Methven standard, only a portion of the centre of the flame is taken for the standard.

Harcourt's Ten-Candle Pentane Lamp.—The following description of Harcourt's ten-candle pentane lamp is taken from the notification of the Gas Referees.

This lamp is one in which air is saturated with pentane vapour, the air gas so formed descending by its gravity to a steatite ring burner. The flame is drawn into a definite form, and the top of it is hidden from view, by a long brass chimney above the steatite burner. The chimney is surrounded by a larger brass tube, in which the air is warmed by the chimney, and so tends to rise. This makes a current which, descending through another tube, supplies air to the centre of the steatite ring. No glass chimney is required, and no exterior means have to be employed to drive the pentane vapour through the burner.

Fig. 175 shows the general appearance of the lamp. The saturator *A* is at starting about two-thirds filled with pentane.* It should be replenished from time to time so that the height of liquid as seen against the windows may not fall below one-eighth of an inch. The saturator *A* is connected with the burner *B* by means of a piece of wide india-rubber tube. The rate of flow of the gas can be regulated by the stop-cock S_2, or by checking the ingress of air at S_1. For this latter purpose a metal cone, acting as a damper, is suspended by its apex from one end of a lever, to the other end of which is attached a thread for moving the cone up or down. The lever is supported by an upright arm clamped to the upper end of the stop-cock immediately beneath the cone. From the top of the lamp the thread descends to a small pulley on the table, and thence passes horizontally to the end of a screw moving in a small block, by turning which the gas examiner can regulate the lamp without leaving his seat. It is best so to turn the stop-cock S_2 as to allow the flame to be definitely too high, but not to turn it full on, before letting down the regulating cone to its working position. Both stop-cocks should be turned off when the lamp is not alight.

The chimney tube *C C* should be turned or screened so that no light passing through the mica window near its base can fall upon the photoped. The low end of this tube should, when the lamp is cold, be set 47 millimetres above the steatite ring burner. A cylindrical boxwood gauge, 47 millimetres in length and 32 in diameter, is provided with the lamp to facilitate this adjustment. The exterior tube *D* communicates with the interior of the ring-burner by means of the connecting box above the tube *E* and the bracket *F* on which the burner *B* is supported. A conical shade *G* is provided. This should be placed so that the whole surface of the flame beneath the tube *C* may be seen at the photoped through the opening.

The lamp should be adjusted by its levelling screws so that the tube *E*, as tested with a plumb-line, is vertical, and so that the upper surface of the steatite burner is 353 millimetres from the table. A gauge is provided to facilitate this latter measurement. The tube *C* is brought centrally over the burner by means of the three adjusting screws at the base of the tube *D*. This adjustment is facilitated by means of the boxwood gauge.

When the lamp is in use the stop-cocks are to be regulated so that the tip of the flame is about half-way between the bottom of the mica window and the cross-bar. A variation of a quarter of an inch either way has no material influence upon the light of the flame. The saturator *A* should be placed upon the bracket as far from the central column as the stop at the end will allow. If it is found, after the lamp has been lighted for a quarter

* CAUTION.—Pentane is extremely inflammable; it gives off at ordinary temperatures a heavy vapour which is liable to ignite at a flame at a lower level than the liquid. *The saturator must never have pentane poured into it when in position, if the lamp is alight.*

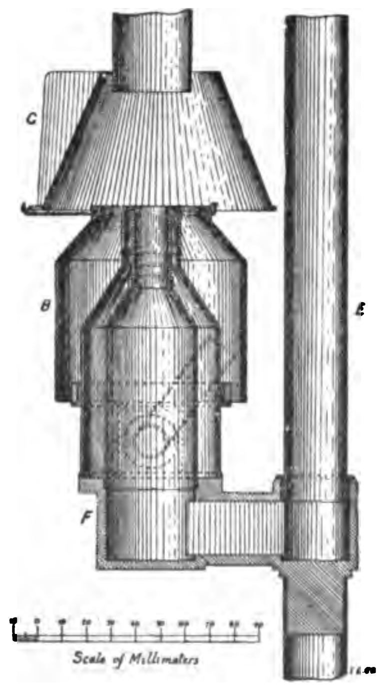
of an hour, that the tendency of the flame is to become lower, the saturator may be placed a little nearer the central column.

To prevent a gradual accumulation of dust in either the burner or the air-passage, a small cover of the size of the top of *B* and shaped like the lid of a pill box should be kept upon the lamp when not in use.

The following are the more important dimensions on which the precision of the lamp depends; but no departure should be made from any of the dimensions as shown by the working drawings. All dimensions are given in millimetres.

Saturator A.—184 × 184 × 38 deep, inside measurement, with seven partitions alternately meeting either side and stopping 25 short of the

FIG. 176.



Note.—The entrance pipe for the pentane, shown dotted in Fig. 176, should be more nearly horizontal, as shown in Fig. 175.

opposite side to cause the air to pass eight times across the box. These partitions must be soldered to the top, not to the bottom of the box.

Siphon Tube from Saturator.—Outer diameter, 14 (half-inch full).

India Rubber Tube.—Inner diameter, 13 (half-inch).

Steatite Burner.—Outer diameter, 24.
Inner diameter, 14.
30 holes, not less than 1.25 or more than 1.5 in diameter.

The holes must be evenly spaced, and in any one burner they must not differ from one another in diameter by more than .05 millimetre.

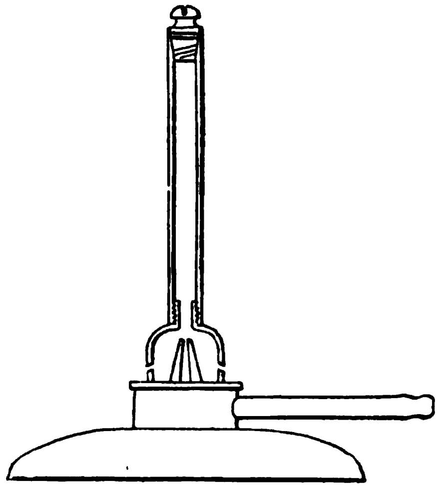
Brass Chimney C.—Outer diameter, 32.
Inner diameter, 30.
Length, 431.

Brass Outer Tube D.—Outer diameter, 52.
Inner diameter, 50.
Length, 290.
Chimney *C* projects 68 below and 73 above the tube *D*.
Brass Tube E.—Outer diameter, 25.
Inner diameter, 23.
Length, 529½.
Distance between axis of tube *E* and axis of tubes *C* and *D*, 67.
Shade G.—Diameter of base, 102.
Diameter at top, 55.
Height, 57.
Opening 38 within, 34 without.

The structure of the actual burner is shown in the sectional drawing, Fig. 176.

This proposed standard has been adopted for use in the London Gas Testing Stations in the place of candles under an agreement between the Gas Companies concerned and the Metropolitan Gas Referees, the standard sperm candle, however, still remaining the parliamentary standard.

FIG. 177.



Violle's Acetylene Standard.

Violle's Acetylene Standard.—In 1895 M. Violle proposed to use as a secondary standard an acetylene flame burning under pressure, in a Manchester burner, Fig. 177. The acetylene passing through a small conical opening like that of a Bunsen burner, draws with it the necessary supply of air. The mixed gases then pass through a small hole into a cylindrical tube where they thoroughly mix. The flame is said to be perfectly steady and remarkably white; either the whole or a portion of it may be used as the standard. The flame is enclosed in a box, not shown in the figure, one of the faces of which carries an iris disc diaphragm by means of which the amount of light emitted may be regulated, whilst the other face is fitted with a rotating diaphragm which carries four openings of various known sizes. The total illuminative value of the flame is 100 candles (French) when burning under a pressure equal to 30 centimetres of water, the flow of the acetylene being equal to 58 litres per hour. The light differs slightly from that of the fused platinum used by M. Violle as the absolute unit, but the apparatus is said to be very convenient for practical use.

Methods of Determining the Illuminating Power of Coal Gas.

The usual method of testing the illuminative value of coal gas has been described under the head of photometers and in the notification of the Gas Referees in Appendix C.

The question of the actual illuminating power is however in some doubt, in consequence of the altered conditions introduced by the changes in the standard quality of the London gas supply, by means of which the Parliamentary standard has in some cases been reduced from 16 to 14 candles. When this alteration was made the question naturally arose as to the method by which this lower quality of gas was to be estimated, as the standard burner was specially constructed to burn 16-candle gas. The Gas Referees prescribed, when the table photometer was employed, that the gas should be burned at such a rate that the light afforded by the burner should equal 16 candles and that the illuminating power of the gas should be ascertained by calculating to a standard rate of consumption of 5 cubic feet per hour. This prescription was made in regard to the slight variation which prevailed with the ordinary so-called 16 candle gas, but when Parliament sanctioned the extension of this method to the testing of 14 candle gas the matter became more involved as the correction for the rate of consumption gave different results to those which were obtained when the gas was burnt at the hitherto standard rate of 5 cubic feet per hour: differences of more than one candle being thus in some cases obtained. The different illuminating values ascribed to a gas by different methods is by no means a new point, as the late Dr. Pole, formerly one of the Metropolitan Gas Referees, in October 1870, published in the Journal of Gas Lighting a most careful investigation on the "Theory of Gas burners."

Although the results of this research has been much neglected, in consequence of the all but general practice of prescribing that the illuminating power of the gas shall be such that it will afford a certain degree of illumination when burnt in a standard burner at the rate of 5 cubic feet per hour, recent legislation and the practice of the Metropolitan Gas Referees has placed the question on a different footing, and it therefore becomes necessary to ascertain how these altered conditions affect the question as to the quantity of light which is meant to be represented by the term "illuminating power."

Dr. Pole found that "the law which governs the relation between the quantities (of gas consumed) is that during the normal state of action of a gas burner the light given varies directly as the consumption, *minus* a constant quantity. In algebraical language, let q equal quantity of gas consumed per hour in a given burner," and L equal light produced thereby, then the true law appears to be, L varies as $(q - c)$ where c is constant for the same burner, . . ."

"The principle involved in this law appears to be somewhat as follows: When the quantity of gas supplied to the burner is very small, compared to its normal capacity, it is burnt at a disadvantage having an excess of air; it is, in fact, in the position of a Bunsen burner. Hence, as has been often explained, the deposition of the light-giving particles is impeded, the flame burns blue, and the light developed is smaller than is fairly due to the gas employed. But as more and more gas is admitted, this defect tends gradually to remedy itself, until a point arrives where a normal and proper condition is reached, and beyond that point every increment of gas gives a corresponding and uniform increment of light. The quantity of gas necessary to develop this condition in the first instance is represented in our equation by the constant c; and, for want of a better name, I may call it the *developant* for that burner. This quantity, though constant for the same burner, varies materially for different kinds of burners and also under other changes of condition. . . ."

Shortly "the law is that in a given burner, taken through its normal range, the light given varies as the quantity of gas consumed, *minus* a *constant quantity*. That is, if L represents the photometric amount of light produced by the consumption of q cubic feet per hour, the $L = A(q - c)$, where A and c are constant for the same gas and the same burner."

In order to apply the law the illuminating value of the gas is observed at different rates of consumption within the obvious range of the burner. Each increase of light is then divided by its corresponding increase of consumption: the mean of these several results equal A, *i.e.*, the amount of candle-power increment per cubic foot throughout the above range. To find the developant c, divide each individual illuminating value by the constant A and subtract each result from the corresponding gas consumption from this particular illuminating value: the mean of these results equals c. As the standard rate of consumption in ordinary gas testing is 5 cubic feet per hour, this quantity is taken as representing the value of q.

The table on p. 356 affords an illustration of this method. Comparative results are given in which the illuminating power is estimated by other methods.

From this it will be seen that Dr. Pole's law gives practically identical results whether the gas is burnt at a rate which affords 10, 12, 14 or 16 candles of light, *i.e.*, the calculated results from observations at 10 and 12 candles equals 14.0; from those at 12 and 14 candles 13.95; and from those at 14 and 16 candles 13.95 candle-power, the average for all results being 13.96 candle-power for 5 cubic feet per hour, which agrees closely with the direct observation of 14.00 when the gas was actually burned at the rate of 5 cubic feet per hour. When the gas was burned at such a rate as was required to yield a 16-candle flame and the result calculated back to 5 cubic feet per hour the illuminating power was 14.76 candles.

ESTIMATION OF ILLUMINATING POWER BY DIFFERENT METHODS.

Method of Estimating Illuminating Power.	Observed Illuminating value in candles.	Corresponding consumption in cubic feet per hour.	Difference in consumption.	Increment of Illuminating value ÷ corresponding increment of consumption.	Illuminating value ÷ A and subtracted from consumption for that Illuminating value.	Illuminating Power deduced from these results
By Pole's Law	10.0	4.22			4.22 − (10 ÷ 5.04) = 2.22	L = A(q − c)
			0.39	2.0 ÷ 0.39 = 5.13		
	12.0	4.61			4.61 − (12 ÷ 5.04) = 2.23	= 5.04(5 − 2.23)
			0.40	2.0 ÷ 0.40 = 5.00		
	14.0	5.01			5.01 − (14 ÷ 5.04) = 2.23	= 5.04 × 2.77 =
			0.40	2.0 ÷ 0.40 = 5.00		
	16.0	5.41			5.41 − (16 ÷ 5.04) = 2.24	
				Mean = 5.04 = A	Mean = 2.23 = C	13.96 Candle power.
By burning the gas at a 16.0 candle flame and calculating to 5 cubic feet per hour by Rule of three.	16.0	5.42	—	—	—	$\frac{16 \times 5}{5.42} =$ 14 76 Candle power.
By burning the gas at 5 cubic feet per hour	14.0	5.0	—	—	—	14.0 Candle power.

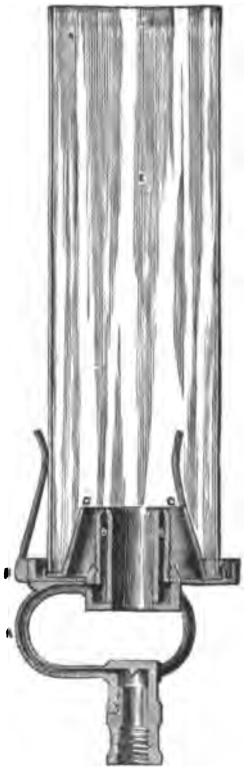
APPENDIX A.

The burner which has been adopted as the standard burner for testing common gas was designed by Mr. Sugg and was called by him "Sugg's London Argand, No. 1."

A section is appended, in which A represents a supply pipe, B the gallery, C the cone, D the steatite chamber, E the chimney.

The following are the dimensions of those parts of the burner upon which its action depends:

FIG. 178.



Diameter of supply pipes	0.08 inch.
External diameter of annular steatite chamber	0.84 "
Internal ditto	0.48 "
Number of holes	24
Diameter of each hole	0.045 "
Internal diameter of cone at the bottom .	1.5 "
" " " " top . .	1.08 "
Height of upper surface of cone and of steatite chamber above floor of gallery	0.75 "
Height of glass chimney	6 "
Internal diameter of chimney . . .	1⅞ "

The standard burner for testing cannel gas is a steatite batswing burner, consisting of a cylindrical stem the top of which is divided by a slit of uniform width.

External diameter of top of stem . .	0.31 inch.
Internal diameter of stem	0.17 "
Width of slit	0.02 "
Depth of slit	0.15 "

APPENDIX B.

Tabular Numbers, being a Table to facilitate the Correction of the under different Atmospheric Pressures

Bar.	Ther. 40°	42°	44°	46°	48°	50°	52°	54°	56°	58°	60°
28.0	.979	.974	.970	.965	.960	.956	.951	.946	.942	.937	.932
28.1	.983	.978	.973	.969	.964	.959	.955	.951	.945	.941	.936
28.2	.986	.981	.977	.972	.967	.963	.958	.953	.949	.944	.939
28.3	.990	.985	.980	.976	.971	.966	.961	.957	.952	.947	.942
28.4	.993	.988	.984	.979	.974	.970	.965	.960	.955	.951	.946
28.5	.997	.992	.987	.983	.978	.973	.968	.964	.959	.954	.949
28.6	1.001	.995	.991	.986	.981	.977	.972	.967	.962	.958	.953
28.7	1.004	.999	.994	.990	.985	.980	.975	.970	.966	.961	.956
28.8	1.007	1.003	.998	.993	.988	.984	.979	.974	.969	.964	.959
28.9	1.011	1.006	1.001	.997	.992	.987	.982	.977	.973	.968	.963
29.0	1.014	1.010	1.005	1.000	.995	.990	.986	.981	.976	.971	.966
29.1	1.018	1.013	1.008	1.004	.999	.994	.989	.984	.979	.975	.969
29.2	1.021	1.017	1.012	1.007	1.002	.997	.992	.988	.982	.978	.973
29.3	1.025	1.020	1.015	1.011	1.006	1.001	.996	.991	.986	.981	.976
29.4	1.028	1.024	1.019	1.014	1.009	1.004	.999	.995	.990	.985	.980
29.5	1.032	1.0-7	1.022	1.018	1.013	1.008	1.003	.998	.993	.988	.983
29.6	1.036	1.031	1.026	1.021	1.016	1.011	1.006	1.001	.996	.992	.986
29.7	1.039	1.034	1.029	1.025	1.019	1.015	1.010	1.005	1.000	.995	.990
29.8	1.043	1.038	1.033	1.028	1.023	1.018	1.013	1.008	1.003	.998	.993
29.9	1.046	1.041	1.036	1.031	1.026	1.022	1.017	1.012	1.007	1.002	.997
30.0	1.050	1.045	1.040	1.035	1.030	1.025	1.020	1.015	1.010	1.005	1.000
30.1	1.053	1.048	1.043	1.038	1.033	1.029	1.024	1.019	1.014	1.009	1.003
30.2	1.057	1.052	1.047	1.042	1.037	1.032	1.027	1.022	1.017	1.012	1.007
30.3	1.060	1.055	1.050	1.045	1.040	1.036	1.030	1.025	1.020	1.015	1.010
30.4	1.064	1.059	1.054	1.049	1.044	1.039	1.034	1.029	1.024	1.019	1.014
30.5	1.067	1.062	1.057	1.052	1.047	1.042	1.037	1.032	1.027	1.022	1.017
30.6	1.071	1.066	1.061	1.056	1.051	1.046	1.041	1.036	1.031	1.026	1.020
30.7	1.074	1.069	1.064	1.059	1.054	1.049	1.044	1.039	1.034	1.029	1.024
30.8	1.078	1.073	1.068	1.063	1.058	1.053	1.048	1.043	1.037	1.032	1.027
30.9	1.081	1.076	1.071	1.066	1.061	1.056	1.051	1.046	1.041	1.036	1.031
31.0	1.085	1.080	1.075	1.070	1.065	1.060	1.055	1.049	1.044	1.039	1.034

⁂ The numbers in the above table have been calculated from the formula on the Fahrenheit scale, and *a* the tension of aqueous vapour at *t*°. If *v* is any pressure,

APPENDIX B.

Volume of Gas Measured over Water at different Temperatures and (from the Notification of the Gas Referees).

Bar.	Ther. 62°	64°	66°	68°	70°	72°	74°	76°	78°	80°	82°	84
28.0	.927	.922	.917	.912	.907	.902	.897	.892	.887	.881	.875	.870
28.1	.930	.926	.921	.916	.911	.905	.900	.895	.890	.884	.879	.873
28.2	.934	.929	.924	.919	.914	.909	.904	.898	.893	.887	.882	.876
28.3	.937	.932	.928	.922	.917	.912	.907	.902	.896	.891	.885	.880
28.4	.941	.936	.931	.926	.921	.915	.910	.905	.900	.894	.888	.883
28.5	.944	.939	.934	.929	.924	.919	.914	.908	.903	.897	.892	.886
28.6	.947	.943	.938	.932	.927	.922	.917	.912	.906	.901	.895	.889
28.7	.951	.946	.941	.936	.931	.925	.920	.915	.909	.904	.898	.893
28.8	.954	.949	.944	.939	.934	.929	.924	.918	.913	.907	.901	.896
28.9	.958	.953	.948	.942	.937	.932	.927	.921	.916	.910	.905	.899
29.0	.961	.956	.951	.946	.941	.935	.930	.925	.919	.914	.908	.903
29.1	.964	.959	.954	.949	.944	.939	.933	.928	.923	.917	.911	.906
29.2	.968	.963	.958	.952	.947	.942	.937	.931	.926	.920	.914	.909
29.3	.971	.966	.961	.956	.950	.945	.940	.935	.929	.923	.918	.912
29.4	.975	.969	.964	.959	.954	.949	.943	.938	.932	.927	.921	.915
29.5	.978	.973	.968	.962	.957	.952	.947	.941	.936	.930	.924	.919
29.6	.981	.976	.971	.966	.960	.955	.950	.944	.939	.933	.927	.922
29.7	.985	.980	.974	.969	.964	.959	.953	.948	.942	.937	.931	.925
29.8	.988	.983	.978	.972	.967	.962	.957	.951	.946	.940	.934	.928
29.9	.991	.986	.981	.976	.970	.965	.960	.954	.949	.943	.937	.932
30.0	.995	.990	.985	.979	.974	.968	.963	.958	.952	.946	.941	.935
30.1	.998	.993	.988	.983	.977	.972	.966	.961	.955	.950	.944	.938
30.2	1.002	.996	.991	.986	.980	.975	.970	.964	.959	.953	.947	.941
30.3	1.005	1.000	.995	.989	.984	.978	.973	.968	.962	.956	.950	.945
30.4	1.008	1.003	.998	.993	.987	.982	.976	.971	.965	.959	.954	.948
30.5	1.012	1.006	1.001	.996	.990	.985	.980	.974	.969	.963	.957	.951
30.6	1.015	1.010	1.005	.999	.994	.988	.983	.977	.972	.966	.960	.954
30.7	1.018	1.013	1.008	1.003	.997	.992	.986	.981	.975	.969	.963	.957
30.8	1.022	1.017	1.011	1.006	1.000	.995	.990	.984	.978	.972	.967	.961
30.9	1.025	1.020	1.015	1.009	1.004	.998	.993	.987	.982	.976	.970	.964
31.0	1.029	1.023	1.018	1.013	1.007	1.002	.996	.991	.985	.979	.973	.967

$n = \frac{17.64\,(h - a)}{460 + t}$, where h is the height of the barometer in inches, t the temperature volume at $t°$ and h inches pressure and V the corresponding volume at 60° and 30 inches $V = v\,n$.

APPENDIX C.

METROPOLITAN GAS REFEREES' NOTIFICATION OF METHOD FOR TESTING THE GAS SUPPLIED TO LONDON.

As to the Standard Lamp to be used for Testing Illuminating Power.

The standard to be used in testing the illuminating power of gas shall be a Harcourt pentane ten-candle lamp which has been examined and certified by the Gas Referees. The residue of pentane in the saturator shall, at least once in each calendar month, be removed, and shall not be used again in any testings.

All pentane provided by the Gas Companies will be examined and certified by the Gas Referees, and will be sent to the testing places in one-pint cans which have been both sealed and labelled by them; and no pentane shall be used in the testing places other than that which has been thus certified.

As to the Times and Mode of Testing for Illuminating Power.

The testings for illuminating power shall be three in number daily. But if the average of three testings of illuminating power falls below the prescribed illuminating power, a fourth testing shall be made. It is required (Gaslight and Coke and other Gas Companies Acts Amendment Act, 1880, section 7) "That the tests for illuminating power shall be taken at intervals of not less than one hour." Also (section 8) "That the average of all the testings at any testing place on each day of the illuminating power of the gas supplied by the Company at such testing place shall be deemed to represent the illuminating power of such gas on that day at such testing place."

The photometer to be used in the testing places shall be the table-photometer as described on pages 284 *et seq.* The air-gas in the lamp is to be kept burning so that the flame is near its proper height for at least ten minutes before any testing is made. At the completion of every testing the air-gas is to be turned off; but, if the interval between two testings does not much exceed one hour and the Gas Examiner is present during the interval, he may, instead of turning it off, turn it down low.

The gas burner attached to each photometer shall be a standard burner corresponding to that which has been deposited with the Warden of the Standards in accordance with, among others, section 37 of the Gaslight and Coke Company Act, 1876. A description of the standard burner to be used for testing gas is given in Appendix A. No burner shall be used for testing the illuminating power of gas that does not bear the lead seal of the Gas Referees.

A clean chimney is to be placed on the burner before each testing.

The gas under examination is to be kept burning, so that the flame is about the usual height, for at least fifteen minutes before any testing is made; and no gas shall pass through the meter attached to the photometer except that which is consumed by the standard burner in testing or during the intervals between the testings made on any day, and that which is used in proving the meter.

The paper used in the photoped of the photometer shall be white in colour, unglazed, of fine grain and free from water-marks. It shall be as translucent as is possible consistently with its being sufficiently opaque to prevent any change in the apparent relative brightness of the two portions of the illuminated surface, when the head is moved to either side. This paper should, when not in use, be covered to protect it from dust; and if it has been in any way marked or soiled a fresh piece is to be substituted.

Each testing shall be made as follows:

The index of the regulating tap shall be so turned that the gas flame gives rather less light on the photoped than the standard, and shall then be gradually turned on until equal illumination has been obtained. The position of the index shall then be noted. Next, the tap shall be so turned that the gas flame appears to give rather more light than the standard, and shall then be turned off until equality is again attained, and the position of the index shall be again noted. The double operation shall be repeated. In making these adjustments, a small alternating movement of the tap may be employed if the Gas Examiner finds that he can by this means make more consistent readings; but, as stated, the tap is to be turned before each setting, alternately, too high or too low. The mean of the four index positions shall be taken as that which gives true equality of illumination. The index shall be set to this mean position, the equality of illumination verified, and the time that the hand of the meter takes to make two complete revolutions shall be observed.

In order to make this observation, a stop-clock shall be used by which the time which has elapsed since the clock was started can be read with an accuracy of at least half a second. The clock shall be started at the moment when the meter-hand points either to zero or to some other convenient mark, and a note shall be immediately made of the mark chosen. Exactly at the completion of the second turn of the meter-hand the Gas Examiner shall stop the clock. The time of two revolutions thus indicated by the clock is to be read to the nearest half-second. From this and the reading of the aerorthometer, or a determination of the tabular number deduced from readings of the thermometer and barometer, the illuminating power of the gas is to be obtained, either directly or by interpolation. Only one figure after the decimal point need be entered when the result is above 16; where a lower result is found, both figures should be noted and entered. A table giving the tabular numbers for different temperatures and pressures is given in Appendix B.

The method of finding the illuminating power from the table by interpolation, may be illustrated by the two following examples:

I. Time, 1 min. 53 secs. Reading of aerorthometer, 1.073. By the table the illuminating power corresponding to this time of consumption and to the reading 1.070 is 16.12, while for the reading 1.080 it is 16.27. Thus, in this part of the scale, when the reading is 10° higher the illuminating power is greater by 0.15 candle. Hence, when the reading is 3° above 1.070, the corresponding illuminating power is $16.12 + \frac{3}{10} \times 0.15 = 16.165$ candles, and the number to be returned is 16.2.

II. Time, 2 mins. 1½ sec. Reading of aerorthometer, .984. The numbers in the table under .980 are 15.81 for 2 mins. 1 sec., and 15.94 for 2 mins. 2 secs.; therefore the number corresponding to 1½ sec. is the half-way number 15.875; the number found similarly under .990 is 16.035. The increase for 10° is here 0.16; the number corresponding to the reading

984 is accordingly $15.875 + \frac{4}{10} \times 0.16 = 15.939$; and the number to be returned is 15.94.

If, in very exceptional circumstances, the aerorthometer scale or the tables do not include the conditions that are met with, the Gas Examiner shall determine the illuminating power by means of one or other of the formulæ printed below the tables.

Each testing place must be provided with a chemical thermometer, divided into degrees on the Fahrenheit scale, and with a standard clock that will go for a week without re-winding.

The Gas Examiner shall, at least once a week, compare the stop-clock in the testing place with the standard clock or with his watch.

The Gas Examiner shall enter in his book the particulars of every testing of illuminating power made by him at the testing places, during or immediately after such testing; and in the case of any testing which he rejects he shall also state the cause of rejection. No testing is to be rejected on the ground that the result seems improbable.

As to the Times and Mode of Testing for Purity.

The testings for purity shall extend over not less than fifteen hours of each day, and shall be made upon 10 cubic feet of gas. The gas shall be tested successively for sulphuretted hydrogen, ammonia, and sulphur compounds other than sulphuretted hydrogen, in the manner hereinafter prescribed. These testings must be started between 9 A.M. and 5.30 P.M., and must be concluded before 9 A.M. on the following morning. They are concluded by the action of an automatic lever-tap attached to the meter, which stops the passage of the gas when 10 cubic feet have passed. A clock connected with the lever-tap is stopped at the same moment, leaving a record of the time; and the tap of an aerorthometer is turned, leaving a record of the final conditions under which the gas was measured by the meter.

The liquids in the sulphur and ammonia tests, and the slips of paper in the tests for sulphuretted hydrogen then contain the sulphur and ammonia which were present in the gas supplied to the testing place during the day which ended at 9 A.M. The chemical examination of these liquids may be made on the following day—that is to say, after 9 A.M.*

All connections between the following pieces of apparatus, in which the purity of the gas is tested, are to be on or above the surface of the table on which the apparatus stands.

I. *Sulphuretted Hydrogen.*—The gas, as it leaves the service pipe, shall be passed through a small dry governor and thence through an apparatus in which are suspended slips of bibulous paper, impregnated with basic acetate of lead.

The test-paper from which these slips are cut is to be prepared, from time to time, by moistening sheets of bibulous paper with a solution of one part of sugar of lead in eight or nine parts of water, and holding each sheet while still damp over the surface of a strong solution of ammonia for a few moments. As the paper dries all free ammonia escapes.

If distinct discolouration of the surface of the test-paper is found to have taken place, this is to be held as conclusive evidence that sulphuretted hydrogen is present in the gas. Fresh test-slips are to be placed in the apparatus every day.

In the event of any impurity being discovered, one of the test-slips shall

* The gas-testing day begins at 9 A.M. of one civil day and terminates at 9 A.M. of the next. The date is that of the civil day on which it begins (The City of London Gas Act, 1868, section 2).

be placed in a stoppered bottle and kept in the dark at the testing place; the remaining slips shall be forwarded with the daily report.

II. *Ammonia.*—The gas which has been tested for sulphuretted hydrogen shall pass next through an apparatus consisting of a glass cylinder filled with glass beads, which have been moistened with a measured quantity of standard sulphuric acid. A set of burettes, properly graduated, is provided.

The maximum amount of ammonia allowed is 4 grains per 100 cubic feet of gas; and the examination of the liquid shall be made so as to show the exact amount of ammonia in the gas.

Two test-solutions are to be used—one consisting of dilute sulphuric acid of such strength that 25 measures (septems) will neutralise 1 grain of ammonia; the other of a weak solution of ammonia, 100 measures of which contain 1 grain of ammonia.

The correctness of the result to be obtained depends upon the fulfilment of two conditions:

1. The preparation of test-solutions having the proper strength.
2. The accurate performance of the operation of testing.

To prepare the test-solutions the following processes may be used by the Gas Examiner:

Measure a gallon of distilled water into a clean earthenware jar, or other suitable vessel. Add to this 94 septems of pure concentrated sulphuric acid, and mix thoroughly. Take exactly 50 septems of the liquid and precipitate it with barium chloride in the manner prescribed for the sulphur test. The weight of barium sulphate which 50 septems of the test-acid should yield is 13.8 grains. The weight obtained with the dilute acid prepared as above will be somewhat greater, unless the sulphuric acid used had a specific gravity below 1.84.

Add now to the diluted acid a measured quantity of water, which is to be found by subtracting 13.8 from the weight of barium sulphate obtained in the experiment, and multiplying the difference by 726. The resulting number is the number of septems of water to be added.

If these operations have been accurately performed, a second precipitation and weighing of the barium sulphate obtainable from 50 septems of the test-acid will give nearly the correct number of 13.8 grains. If the weight exceeds 13.9 grains, or falls below 13.7 grains, more water or sulphuric acid must be added, and fresh trials made until the weight falls within these limits. The test-acid thus prepared should be transferred at once to stoppered bottles which have been well drained and are duly labelled.

To prepare the standard solution of ammonia, measure out as before a gallon of distilled water, and mix with it 50 septems of strong solution of ammonia (specific gravity 0.88). Try whether 100 septems of the test-alkali thus prepared will neutralise 25 of the test-acid, proceeding according to the directions given subsequently as to the mode of testing. If the acid is just neutralised by the last few drops, the test-alkali is of the required strength. But if not, small additional quantities of water, or of strong ammonia solution, must be added, and fresh trials made, until the proper strength has been attained. The bottles in which the solution is stored should be filled nearly full and well stoppered.

The mode of proceeding is as follows:—Take 50 septems of the test-acid (which is more than enough to neutralise any quantity of ammonia likely to be found in the gas), and pour it into the glass cylinder, so as to well wet the whole interior surface, and also the glass beads. Connect one terminal tube of the cylinder with the gas supply, and the other with the meter, and make the gas pass at a rate of not more than two-thirds of a cubic foot per hour. Any ammonia that is in the gas will be arrested by the sulphuric acid, and a portion of the acid (varying with the quantity of ammonia in the gas) will be neutralised thereby. At the end of each period of testing, wash out the glass cylinder and its contents with distilled water, and collect the washings in a glass vessel. Transfer one-half of this liquid to a separate glass vessel, and add a quantity of a neutral solution of litmus, or other indicator in ordinary use, just sufficient to colour the liquid. Then pour into the burette 100 septems of the test-alkali, and gradually drop this solution into the measured quantity of the washings, stirring constantly. As soon as the colour changes (indicating that the whole of the sulphuric acid has been neutralised), read off the quantity of liquid remaining in the burette. To find the number of grains of ammonia in 100 cubic feet of the gas, multiply by 2 the number of septems of test-alkali remaining in the burette, and move the decimal point one place to the left.

The remaining half of the liquid is to be set aside, in case it should be desirable to repeat the volumetric analysis. This portion of the liquid is to be used in either of the two following cases:

(1) If the analysis of the first portion of the liquid show an excess of impurity, the Gas Examiner shall forthwith give the notice provided for in Acts of Parliament (the Gaslight and Coke Company Act, 1876, sect. 40, and others); and if the Company think fit to be represented by some officer, the second portion of the liquid shall be examined in his presence.

(2) If the analysis of the first portion of the liquid should miscarry, or the Gas Examiner have any reason to distrust the result, he shall be at liberty to make an analysis of the second portion, provided that before doing so he give notice to the Company in order that they may, if they think fit, be represented by some officer.

Unless thus used it is to be preserved, in a bottle properly labelled, for a week.

III.—*Measurement of Gas and of the Rate of Flow.*—The gas which has been tested for sulphuretted hydrogen and ammonia shall pass next through a meter by reference to which the rate of flow can be adjusted, and which is provided with a self-acting movement for shutting off the gas when ten cubic feet have passed, for stopping a clock so as to indicate the time at which the testings terminated, and for turning the tap of the recording aerorthometer. The Gas Examiner shall enter in his book the time thus indicated, as also the time at which the testings began.

The clock required is a good pendulum clock with a wire passing transversely through the case behind the pendulum. Outside the case a lever arm is clamped to the wire, so that when liberated the arm will drop and turn the wire. Inside the case an arm is clamped to the wire, and at the end of the arm a flexible wire is fastened; when the lever drops, this flexible wire is brought into gentle frictional contact with the pendulum so as to stop it without shock.

The clock should be wound from the front, and both hands should be mounted so that they can be set independently also from the front. It is desirable that the clock should be able to go for a week with one winding, and the Gas Examiner must satisfy himself from time to time that the rating is nearly correct.

IV.—*Sulphur Compounds other than Sulphuretted Hydrogen.*—This testing shall be made in a room or closet where no gas is burning other than that which is being tested for sulphur and ammonia. A description of the apparatus to be employed is given in Fig. 180, on p. 371.

Pieces of sesqui-carbonate of ammonia, from the surface of which any efflorescence has been removed, are to be placed round the stem of the burner. The index of the meter is to be then turned forward to the point at which the catch falls and will again support the lever-tap in the horizontal position. The lever is then made to rest against the catch so as to turn on the gas. The index is then turned back to a little short of zero, and the burner lighted. When the index is close to zero the trumpet-tube is placed in position on the stand and its narrow end connected with the tubulure of the condenser. At the same time the long chimney-tube is attached to the top of the condenser.

As soon as the testing has been started, a reading of the aerorthometer is to be made and recorded. The mechanism for stopping the clock is then to be connected with the lever-tap of the meter, so that both may be stopped at the same moment when ten cubic feet of gas have passed through the meter. The clock is to be started and set right, and the time is to be recorded.

After each testing the flask or beaker, which has received the liquid products of the combustion of the ten cubic feet of gas, is to be emptied into a measuring cylinder and then replaced to receive the washings of the condenser. Next the trumpet-tube is to be removed and well washed out into the measuring cylinder. The condenser is then to be flushed twice or thrice by pouring quickly into the mouth of it 40 or 50 cubic centimetres of distilled water. These washings are brought into the measuring cylinder, whose contents are to be well mixed and divided into two equal parts.

One-half of the liquid so obtained is to be set aside, in case it should be desirable to repeat the determination of the amount of sulphur which the liquid contains. This portion is to be examined under the same conditions as have been prescribed for the examination of the second portion of the liquid obtained from the apparatus used in testing for ammonia; unless thus previously used, it is to be preserved, in a bottle properly labelled, for one week.

The remaining half of the liquid is to be brought into a flask, or beaker covered with a large watch-glass, treated with hydrochloric acid sufficient in quantity to leave an excess of acid in the solution, and then raised to the boiling point. An excess of a solution of barium chloride is now to be added, and the boiling continued for five minutes. The vessel and its contents are to be allowed to stand till the barium sulphate has settled at the bottom of the vessel, after which the clear liquid is to be as far as possible poured off through a paper filter. The remaining liquid and barium sulphate are then to be poured on to the filter, and the latter is to be well washed with hot distilled water. (In order to ascertain whether every trace of barium chloride and ammonium chloride has been removed, a small quantity of the washings from the filter should be placed in a test-tube, and a drop of a solution of silver nitrate added; should the liquid, instead of remaining perfectly clear, become cloudy, the washing must be continued until on repeating the test no cloudiness is produced.) Dry the filter with its contents, and transfer it into a weighed platinum crucible. Heat the crucible over a lamp, increasing the temperature gradually, from the point at which the paper begins to char, up to bright redness.* When no black particles remain, allow the crucible to cool; place it when nearly cold in a desiccator over strong sulphuric acid, and again weigh it. The difference between the first and second weighings of the crucible will give the number of grains of barium sulphate. Multiply this number by 11 and divide by 4; the result is the number of grains of sulphur in 100 cubic feet of the gas.

This number is to be corrected for the variations of temperature and atmospheric pressure in the manner indicated under the head of Illuminating

* An equally good and more expeditious method is to drop the filter with its contents, drained but not dried, into the red-hot crucible.

Power, with this difference, that the mean of the aerorthometer readings found at the beginning and at the end of any testing shall be taken as the reading for that testing. The reading at the beginning of the testing is to be made by the Gas Examiner, who before leaving the testing place will set the columns of mercury level in the two tubes of the instrument and will connect the lever-tap of the aerorthometer with that of the meter. The fall of the lever of the meter will release a similar lever turning a tap which closes the tube of the aerorthometer. The reading of the aerorthometer as it stood at the end of the testing will require a small correction for the difference in level of the mercury in the two tubes, which is to be made in the following manner:

Let R be the corrected reading, r_1 the actual reading of the aerorthometer, r_2 the reading of the companion tube, h the mean height of the barometer in units of the aerorthometer scale, a number which will be printed on each instrument and is commonly 0.76. Then

$$R = r_1 \times \frac{h + r_1 - r_2}{h}.$$

The correction by means of the aerorthometer reading may be made most simply and with sufficient accuracy in the following manner:

When the aerorthometer reading is between . . .	.955–.965,	.966–.975,	.976–.985,	.986–.995,
diminish the number of grains of sulphur by . .	4,	3,	2,	1 per cent.

When the aerothometer reading is between .996–1.005, no correction need be made.

When the aerorthometer reading is between . . .	1.006–1.015,	1.016–1.025,	1.026–1.035,
increase the number of grains of sulphur by . .	1,	2,	3 per cent.

Example:

Grains of barium sulphate from 5 cubic feet of gas	4.3	Aerorthometer reading 1.018
Multiply by 11, and divide by 4.	11	
	4)47.3	
Grains of sulphur in 100 cub. ft. of gas (uncorrected)	11.82	
Add $11.8 \times \frac{2}{100}$ = ...	.24	Result: 12.1 grs.
Grains of sulphur in 100 cub. ft. of gas (corrected)	12.06	

The aerorthometer reading is the reciprocal of the tabular number. The Gas Examiner shall, not less often than once a month, compare the aerorthometer readings with the reciprocal of the tabular number deduced from observations of the barometer and thermometer, and if there is a difference of more than one-half per cent. the instruments are to be readjusted.

As to the Mode of Testing the Pressure at which Gas is Supplied.

Testings of pressure shall be made at such times and in such places as the controlling authority may from time to time appoint. In order to make this testing the Gas Examiner shall unscrew the governor and burner of one of the ordinary public lamps, and shall attach in their stead a portable pressure-gauge. In places where incandescent burners are used for street lighting, one street lamp in each street or group of streets may be provided under the lantern with a branch closed by a screw stopper. The Gas Examiner shall in such cases connect the pressure gauge by screwing to it an L-shaped pipe fitted with a union, by means of which it may be connected to the service pipe in the place of the screw stopper. The L-shaped pipe is to be of such dimensions as to enable the pressure gauge to be fixed outside the lantern but at about the same level as the incandescent burner. It should be provided with a tap.

The gauge, see Fig. 181, p. 372, to be used for this purpose consists of an ordinary pressure-gauge enclosed in a lantern, which also holds a candle for throwing light upon the tubes and scale. The difference of level of the water in the two limbs of the gauge is read by means of a sliding scale, the zero of which is made to coincide with the top of the lower column of liquid.

The Gas Examiner having fixed the gauge gas-tight, and as nearly as possible vertical on the pipe of the lamp, and having opened the cocks of the lamp and gauge, shall read and at once record the pressure shown. From the observed pressure one-tenth of an inch is to be deducted to correct for the difference between the pressure of gas at the top of the lamp column and that at which it is supplied to the basement of neighbouring houses.

The pressure prescribed in the Acts of the three Metropolitan Gas Companies is to be such as to balance from midnight to sunset a column of water not less than six-tenths of an inch in height, and to balance from sunset to midnight a column of water not less than one inch in height.

METERS.

Each of the meters used for measuring the gas consumed in making the various testings is constructed with a measuring drum which allows one-twelfth of a cubic foot of gas to pass for every revolution. A hand is fastened directly to the axle of this drum and passes over a dial divided into one hundred equal divisions. The dial and hand are protected by a glass. In the meter employed in testing the purity of gas the pattern of dial for showing the number of revolutions and the automatic cut-off hitherto in use shall be retained, but in the meter employed for testing illuminating power, only the dial above described is needed. The stop-clock may be either attached to the meter or separate.

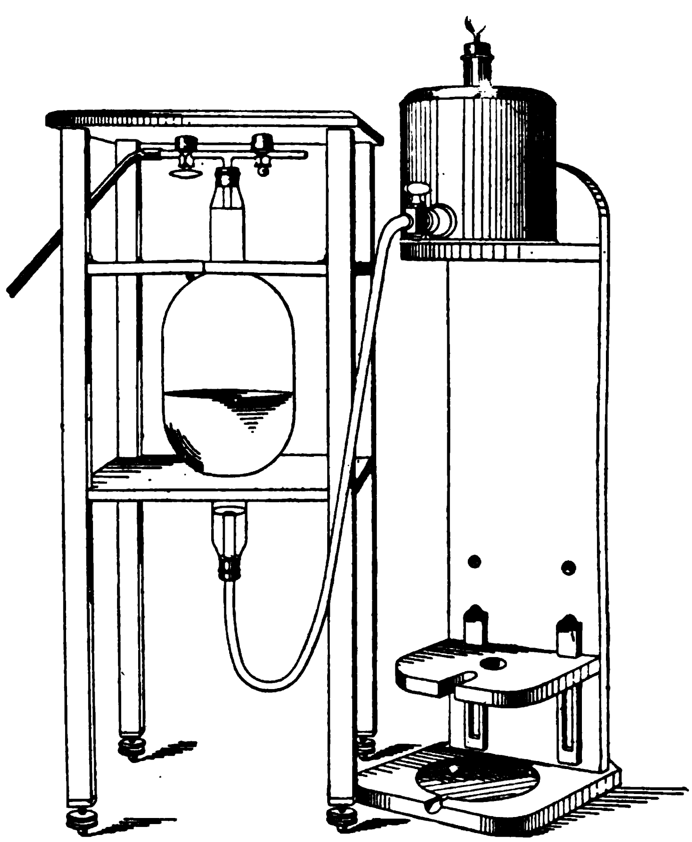
The meters used for measuring the gas consumed in making the various testings having been certified by the Referees, shall, at least once in seven days, be proved by the Gas Examiners by means of the Referees' one-twelfth of a cubic foot measure. The following is the Gas Referees description of this instrument, which is represented in Fig. 179; it consists of a vessel of blown glass of a cylindriacal form with rounded ends terminating in short tubes about 40 millimetres in diameter outside, which are reduced at their outer ends to about 20 millimetres in diameter outside. Lines are etched round each tubular neck in such positions that the capacity of that portion of the vessel included between these marks is exactly one-twelfth of a cubic foot when the glass is at the ordinary temperature. No correction is needed for the cubical expansion of the glass. The two tubular necks of the instrument pass through two boards placed below and parallel to the top of a small four-legged table. For convenience the upper one of these two boards is made in two parts and hinged to the legs.

Into each end of the instrument a glass tube about 8 millimetres in diameter outside is fitted gas- and water-tight by means of india-rubber corks, in such positions that the inner end of the upper tube lies exactly in the plane of the mark as its end of the instrument, while that of the lower is about 1 mm. below the mark.

The upper tube terminates in a T, each branch of which is provided with a stop-cock.

A separate stand carries two shelves, the upper one about 40 millimetres below the level of the upper mark and the lower one below the level of the lower mark. The lower shelf is adjustable, and must be so placed that the action about to be described shall take place.

FIG. 179.



A water vessel is provided having a capacity of about one-tenth of a cubic foot. It should be made of brass or copper, tinned on the inside. It has a tubulure near the bottom, to which is fitted a metal tap. The end of the tap is to be turned slightly downwards, and is to have a diameter outside of about 8 millimetres. The size of the way through the tap and of the connections is such that when a meter is being proved in the manner to be described, the water fills the instrument from one mark to the other in about one minute. The water vessel has a tubulure in the cover, to which a narrow glass tube is fitted by means of a cork, so that air may enter or escape. The end of the tube is bent round upon itself in the form of a crook, so as to exclude dust and dirt. An india-rubber tube connects the tube at the base of the measure with the stop-cock of the water vessel. An ordinary chemical thermometer is provided for taking the temperature of the water.

The pipe supplying gas to each meter is provided near the meter with a three-way stop-cock carrying a short branch pipe, so formed that it either connects the gas supply only with the branch pipe, the meter only with the branch pipe, or the gas supply with the meter, in which latter case the branch pipe is cut off from both. The index of the tap shows which communication is open. In order to avoid sending the gas used in proving the sulphur meter through the sulphuretted hydrogen and ammonia apparatus, a separate gas supply is provided. The branch pipe is so shaped as to be convenient for the attachment of an india-rubber tube.

In order to put the instrument in adjustment the water vessel is placed upon the upper shelf, and water is poured into it until it rises about one-quarter of an inch in the upper narrow tube. One branch of the glass T is then connected by an india-rubber pipe with the branch of the three-way stop-cock. This is now turned so as to connect the branch pipe with the gas supply. The stop-cock in the branch of the glass T to which the rubber-tube is attached is turned on, and the water vessel is placed on the lower shelf. The water will run back into the vessel. The flow should cease when the water has just begun to descend in the lower tube; if not, the height of the lower shelf must be adjusted until this is the case.

The space above the upper mark is always filled with gas, and that below the lower mark with water, so that the capacity of these portions of the instrument has no effect upon the measurements. The narrow tubes are so small that a variation of even an inch of the level at which the water stands in them has no appreciable effect upon the meter reading.

The apparatus shall only be used in proving a meter when the temperature of the meter and of the water in the water vessel have been found not to differ by more than two degrees Fahrenheit.

In order to prove the meters used in the various testings, the position of the index is taken when the instrument has been put in adjustment and filled with gas as described. The tap of the water vessel is turned off; the three-way tap is turned half-way towards the position which will connect the instrument with the gas-meter, and the pressure of the gas in the instrument is reduced to atmospheric pressure by momentarily opening the tap in the free branch of the glass T. The water vessel is placed upon the upper shelf, the regulating tap (Fig. 179) is turned on, the three-way tap is turned into such a position as will connect the instrument with the meter, and the tap of the water vessel is turned on. One-twelfth of a cubic foot of gas will then be discharged through the meter. Fig. 179 represents this operation in progress. The three-way stop-cock is then turned so as to fill the instrument with gas, the water vessel is placed upon the lower shelf, the gas is reduced to atmospheric pressure as before, and a second, and again a third quantity is discharged through the meter. Should the hand attached to the axle of the measuring drum have travelled in the three revolutions as much as one division beyond the point from which it started, some water must be removed from the meter; if the travel of the meter hand is as much as one division short of this point, some water must be poured in. The operation is then to be repeated until the error is found to fall within the specified limits.

The following is an example of the form in which Returns are to be made:

COUNTY OF LONDON GAS-TESTING STATION,

1, CARLYLE SQUARE, CHELSEA, S.W.

REPORT ON GAS SUPPLIED BY THE GAS LIGHT AND COKE COMPANY.

Dates of Supply of Gas.				
Mean Lighting Power, in Candles, corrected.	Sulphur in 100 cubic feet of Gas, in grains.	Sulphuretted Hydrogen.	Ammonia in 100 cubic feet of Gas, in grains.	Testing of Pressure.
				Street. *Time.* *Pressure.*

Gas Examiner.

No meter other than a wet meter shall be used in testing the gas under these instructions.

Results of Tests.

The results of the daily testings for illuminating power and purity shall be recorded, and delivered as provided in the Acts of Parliament.

As to Illuminating Power.

By the Acts of Parliament the illuminating power of the gas supplied by the Gas Light and Coke Company shall be 16 candles, and of the gas supplied by the Commercial Gas Company and by the South Metropolitan Gas Company shall be 14 candles.

As to the Maximum Amounts of Impurity

in each form with which the gas shall be allowed to be charged.

Sulphuretted Hydrogen.—By the Acts of Parliament all gas supplied must be wholly free from this impurity.

Ammonia.—The maximum amount of this impurity shall be 4 grains per 100 cubic feet.

Sulphur Compounds other than Sulphuretted Hydrogen.—The maximum amount of sulphur with which gas shall be allowed to be charged shall be in the six months from April 1 to September 30, 17 grains of sulphur in every 100 cubic feet of gas, and in the other months, 22 grains of sulphur in every 100 cubic feet of gas.

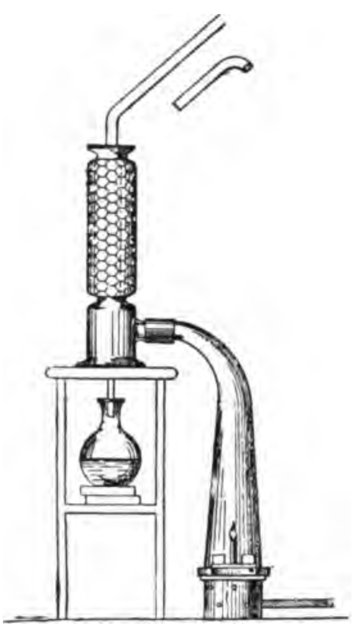
Sulphur Test.

The apparatus to be employed is represented by Fig. 180, and is of the following description:—The gas is burnt in a small Bunsen burner with a steatite top, which is mounted on a short cylindrical stand, perforated with holes for the admission of air, and having on its upper surface, which is also perforated, a deep circular channel to receive the wide end of a glass trumpet-tube. There are both in the side and in the top of this stand fourteen holes of five millimetres in diameter, or an equivalent air-way.

On the top of the stand, between the narrow stem of the burner and the surrounding glass trumpet-tube, are to be placed pieces of commercial sesqui-carbonate of ammonia weighing in all about two ounces.

The products both of the combustion of the gas and of the gradual volatilisation of the ammonia salt go upwards through the trumpet-tube into a vertical glass cylinder with a tubulure near the bottom, and drawn in at a point above this to about half its diameter. From the contracted part to the top the cylinder is packed with balls of glass about fifteen millimetres in diameter, to break up the current and promote condensation. From the top of this condenser there proceeds a long glass pipe or chimney slightly bent over at the upper end, serving to effect some further condensation, as well as to regulate the draught and afford an exit for the uncondensable gases. In the bottom of the condenser is fixed a small glass tube, through which the liquid formed during the testing drops into a flask placed beneath.

FIG. 180.



The following cautions are to be observed in selecting and setting up the apparatus :

See that the inlet-pipe fits gas-tight into the burner, and that the holes in the circular stand are clear. If the burner gives a luminous flame, remove the top piece, and having hammered down gently the nozzle of soft metal, perforate it afresh, making as small a hole as will give passage to two-thirds of a cubic foot of gas per hour at a convenient pressure.

See that the tubulure of the condenser has an internal diameter of not less than 18 millimetres, and that its outside is smooth and of the same size as the small end of the trumpet-tube; also that the internal diameter of the contracted part is not less than 30 millimetres.

See that the short piece of india-rubber pipe fits tightly both to the trumpet-tube and to the tubulure of the condenser.

The small tube at the bottom of the condenser should have its lower end contracted, so that when in use it may be closed by a drop of water.

The india-rubber pipe at the lower end of the chimney-tube should fit into or over, and not simply rest upon, the mouth of the condenser.

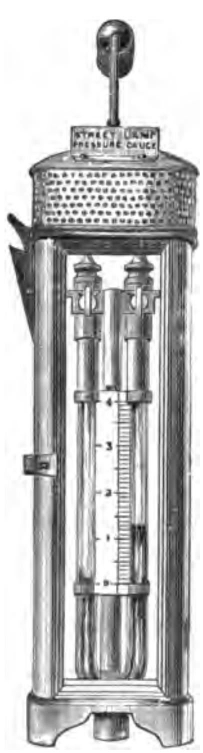
A central hole, about 50 millimetres in diameter, may with advantage be made in the shelf of the stand. If a beaker is kept on the table below, the liquid will still be preserved if by any accident the flask is not in its place.

THE GAS REFEREES' STREET LAMP PRESSURE GAUGE.

This instrument has been designed in compliance with sect. 6 of the Gas Light and Coke and other Gas Companies Acts Amendment Act, 1880, for the purpose of testing in any street at any hour the pressure at which gas is supplied. Its construction and mode of use are as follows :

Within a lantern provided with a handle for carrying and feet for resting on the ground, is placed a candle-lamp, to give light for reading the gauge. In front of the candle-lamp is a sheet of opal glass, and in front of this a glass U-tube, partly filled with coloured water, and communicating at one end with the air, at the other with a metal pipe, which passes through the bottom of the lantern. In order to read easily and accurately the difference of level of the liquid in the two limbs, a scale divided into tenths of an inch is made to slide between them with sufficient friction to retain it in any position. The zero of the scale having been brought level with the surface of the liquid which is pressed upon by the gas, the height above this of the surface which is pressed upon by the air can be read directly. The lantern is closed in front by a glass door, at each side of which is a reflector for throwing light upon the scale of the gauge. Above each limb of the U-tube is a tap which can be closed when the instrument is not in use, to prevent the liquid being accidentally spilt.

FIG. 181.



To make a testing of pressure the governor and burner of a street lamp are to be removed, and the pressure-gauge is to be screwed on to the gas-pipe, by which it is supported. In places where incandescent burners are used, the L-shaped pipe described on p. 367 is to be used for the attachment of the pressure-gauge. The cock is then turned on, and a reading made. If on turning off the cock the level of the liquid is unchanged, or changes slowly, the reading is correct; but if the level changes quickly, the junction between the lamp and the gauge must be made more perfect, and the testing repeated. A small leakage is immaterial, provided the cock is turned fully on.

The pressure at the top of a lamp column is greater by about 0.1 inch than that at the main, which is the pressure required. Accordingly a deduction of 0.1 inch from the observed pressure is to be made.

The Provision of Pentane for Use in the Testing-places.

The following is the procedure which the Gas Referees have arranged with the Gas Companies for the provision and testing of pentane:

Each of the Gas Companies shall keep upon their premises one or more properly closed vessels capable of containing from fifty to one hundred gallons of pentane.

When a supply of pentane is needed for use in the testing-places a number of one-pint metal cans with screw stoppers, of a pattern approved by the Gas Referees (of which a specimen can be seen at their office) shall be provided sufficient to contain the whole quantity required.*

The Gas Referees shall then be informed by letter that this quantity of pentane awaits their examination; and they will arrange to attend at the premises where the pentane is stored. They will see the cans filled, and will affix a numbered lead seal to each can; or where it is convenient to

* The size of can to be used is limited to one pint by the regulations of the Home Office.

send the cans to the testing-places in groups or in boxes they will place one seal on each group or box.

They will then take away one or more of the cans for examination; the remaining cans must be kept until the Gas Referees have reported on the quality of the pentane.

If the results of their testings are satisfactory, they will prepare as many labels as there are cans, or groups or boxes of cans, of pentane. Each label will bear the embossed stamp of the Gas Referees, and will be numbered with the numbers impressed upon the lead seals on the cans or groups or boxes. These labels will then be sent to the Company for attachment.

No cans of pentane which the Gas Referees have certified by the attachment of their lead seals and labels, are to be supplied to or used by any person or persons other than the Gas Examiners at the several testing-places without the written permission of the Gas Referees, and a record must be kept by the Gas Company of all cans to which the lead seal has been attached. If, however, application should be made to the Gas Referees by the London County Council, the Corporation of London, or any of the Metropolitan Gas Companies, to examine and certify pentane in reasonable quantities for non-official testings, they will be willing to do so.

If the Gas Referees, after examination, find that the sample of pentane taken from any vessel does not satisfy the requirements of their notification, they will inform the Gas Company of the fact; and in such case the lead seals are to be cut off from the other cans filled from the same vessel, and returned to the Gas Referees.

The Gas Companies will send the certified cans of pentane to the testing-places in their several districts. The Gas Examiner at any testing-place will take the presence of the Gas Referees' lead seal and label, bearing identical numbers, upon any can, group or box of cans, as evidence that the pentane therein has been certified, and no pentane shall be used in any testing that has not been so certified.

INDEX.

Catalogue of the Medical, Dental, Pharmaceutical, Chemical, and Scientific Books Published by P. Blakiston's Son & Co., 1012 Walnut Street, Philadelphia.

Established 1843.

SPECIAL NOTE.

The prices as given in this catalogue are absolutely net—no discount will be allowed retail purchasers under any consideration. This rule has been established in order that every one will be treated alike, a general reduction in former prices having been made to meet previous retail discounts. Upon receipt of the advertised price any book will be forwarded by mail or express, **all charges prepaid.**

We keep a large stock of Miscellaneous Books relating to Medicine and Allied Sciences, published in this country and abroad. Inquiries in regard to prices, date of edition, etc., will receive prompt attention.

CATALOGUES AND CIRCULARS SENT FREE UPON APPLICATION:

Catalogue No. 1.—A complete list of the titles of all our publications on Medicine, Dentistry, Pharmacy, and Allied Sciences, with Classified Index.

Catalogue No. 3.—Pharmaceutical Books.

Catalogue No. 4.—Books on Chemistry and Chemical Technology.

Catalogue No. 5.—Books for Nurses and Lay Readers.

Catalogue No. 6.—Books on Dentistry and Books used by Dental Students.

Catalogue No. 7.—Books on Hygiene and Sanitary Science; Including Water and Milk Analysis, Microscopy, Physical Education, Hospitals, etc.

Catalogue No. 8.—List of about 300 Standard Books classified by Subjects.

Catalogue No. 9.—Books on Nervous and Mental Diseases.

Catalogue No. 10.—Books on Diseases of the Eye, Refraction, Spectacles, etc.

A General Catalogue.—Containing 2000 titles of Standard Books on Medicine and Surgery. American and English.

Special Circulars.—Morris' Anatomy; Gould and Pyle's Cyclopedia; Deaver's Surgical Anatomy; Tyson's Practice; Gould's Medical Dictionaries; Books on the Eye; Books on Diseases of the Nervous System; The ?Quiz-Compend? Series, Visiting Lists, etc. We can also furnish **sample pages** of most of our publications.

P. Blakiston's Son & Co.'s publications may be had through the booksellers in all the principal cities of the United States and Canada, or any book will be sent, postpaid, upon receipt of the price. Special terms of payment will be allowed to those of approved credit. No discount can be allowed retail purchasers under any circumstances. Money should be remitted by express or post-office money order, registered letter, or bank draft.

THE PRICES OF ALL BOOKS ARE NET.

CLASSIFIED LIST, WITH PRICES,

OF ALL BOOKS PUBLISHED BY

P. BLAKISTON'S SON & CO., PHILADELPHIA.

When the price is not given below, the book is out of print or about to be published. Cloth binding, unless otherwise specified. For full descriptions see following Catalogue.

ANATOMY.

Ballou. Veterinary Anat. $0.80
Broomell. Anatomy and Histol. of Mouth and Teeth. 4.50
Campbell. Dissection Outlines. .50
Deaver. Surgical Anatomy. 24.00
Gordinier. Anatomy of Nervous System. Illustrated. 6.00
Heath. Practical. 9th Ed. 4.25
Holden. Dissector. 2 Vols. 3.00
—— Osteology. 8th Ed. 5.25
—— Landmarks. 4th Ed. .75
Hughes. Dissector. Part I. 3.00
Part II. 3.00
Part III. 3.00
Macalister's Text-Book. 5.00
McMurrich. Embryology. 3.00
Minot. Embryology 4.50
Marshall's Phys. & Anatomical Diagrams. $40.00 and 60.00
Morris. Text-Book Anat. 3d Ed. 846 Ill. Clo., $6.00; Sh., 7.00
Potter. Compend of. 6th Ed. 133 Illustrations. .80
Wilson's Anatomy. 11th Ed. 5.00

ANESTHETICS.

Buxton. Anesthetics. 1.50
Turnbull. 4th Ed. 2.50

BACTERIOLOGY.

Conn. Agricultural Bacteriology. Illustrated. 2.50
—— Bact. in Milk Products. 1.25
Emery. Bacteriolog. Diag. 1.50
Hewlett. Manual of. Illus. 4.00
Williams. Student's Manual of. 2d Edition. 90 Illus. 1.50
Smith. Bacteriology. 1.50

BRAIN AND INSANITY.

Blackburn. Autopsies. 1.25
Chase. General Paresis. 1.75
Horsley. Brain and Sp. Cord. 2.50
Ireland. Mental Affections of Children. 4.00
Lewis. Mental Diseases. 7.00
Mann's Psychological Med. 3.00
Régis. Mental Medicine. 2.00
Stearns. Mental Dis. Illus. 2.75
Tuke. Dictionary of Psychological Medicine. 2 Vols. 10.00
Wood. Brain and Overwork. .40

CHEMISTRY.

Technol'g'l Books, Water, Milk, etc.
Allen. Commercial Organic Analysis. Vol. I. 4.50
—— Vol. II. Part I. 3.50
—— Vol. II. Part II. 3.50
—— Vol. II. Part III. ——
—— Vol. III. Part I. 4.50
—— Vol. III. Part II. 4.50
—— Vol. III. Part III. 4.50
—— Vol. IV. 4.50
Bailey and Cady. Chem. Analysis. 1.25
Bartley. Medical Chemistry. 3.00
—— Clinical Chemistry. 1.00
Bloxam's Text-Book. 9th Ed. ——
Bunge. Physiologic and Pathologic Chemistry. 3.00
Caldwell. Qualitative and Quantitative Analysis. 1.00
Cameron. Oils & Varnishes. 2.25
—— Soap and Candles. 2.00
Clowes and Coleman. Quantitative Analysis. 5th Ed. 3.50
Coblentz. Volumetric Anal. 1.25
Congdon. Laboratory. 1.00
Gardner. Brewing, etc. 1.50
Gray. Physics. Vol. I. 4.50
Groves and Thorp. Chemical Technology. Vol. I. Fuels 5.00
—— Vol. II. Lighting. 4.00
—— Vol. III. Gas Lighting. 3.50
—— Vol. IV. Elec. Lighting. ——
Heusler. The Terpenes. 4.00
Holland. Urine, Gastric Contents, Poisons and Milk Analysis. 6th Ed. $1.00
Leffmann's Medical Chem. .80
—— Food Analysis. 2.50
—— Milk Analysis. 1.25
—— Water Analysis. 1.25
—— Structural Formulæ. 1.00
Muter. Pract. and Anal. 1.25
Oettel. Electro-Chem. .75
—— Electro-Chem. Exper. .75
Richter's Inorganic. 5th Ed. 1.75
—— Organic. 3d Ed. 2 Vols.
Vol. I. Aliphatic Series. 3.00
Vol. II. Carbocyclic " 3.00
Rockwood. Chemical Anal. 1.50
Smith. Electro-Chem. Anal. 1.25
Smith and Keller. Experiments. 4th Ed. Illus. .60
Sutton. Volumetric Anal. 5.00
Symonds. Manual of. 2.00
Traube. Physico-Chem. Meth. 1.50
Thresh. Water Supplies. 2.00
Ulzer and Fraenkel. Technical Chemical Analysis. 1.25
Woody. Essentials of. 4th Ed. 1.50

CHILDREN.

Hatfield. Compend of. 3d Ed. .80
Power. Surgical Diseases of. 2.50
Smith. Wasting Diseases of. 2.00
Starr. Digestive Organs of. 3.00
—— Hygiene of the Nursery. 1.00
Taylor and Wells. Manual. 4.50

CLINICAL CHARTS, ETC.

Griffith's Temp't're Charts. Pads of 50 .50
Keen. Outline Drawings of Human Body. Pads. .25
Schreiner. Diet Lists. Pads. .75

COMPENDS.

Ballou. Veterinary Anat. .80
Brubaker's Physiol. 11th Ed. .80
Cushing. Histology. .80
Gould and Pyle. The Eye. .80
Hatfield. Children. 3d Ed. .80
Horwitz. Surgery. 5th Ed. .80
Hughes. Practice. 2 Pts. Ea. .80
Kyle. Ear, Nose, Throat. ——
Landis. Obstetrics. 7th Ed. .80
Leffmann's Chemistry. 4th Ed. .80
Potter's Anatomy, 6th Ed. .80
—— Materia Medica. 6th Ed. .80
Schamberg. Skin Diseases. .80
Stewart. Pharmacy. 5th Ed. .80
Thayer. General Pathology. .80
—— Special Pathology .80
Warren. Dentistry. 3d Ed .80
Wells. Gynecology. 2d Ed. .80
Any of above, Interleaved, $1.00.
Self-Examination. 3500 Questions on Medical Subjects. Paper, .10

CONSUMPTION.

Knopf. Pulmon. Tuberculosis. 3.00
Steell. Physical Signs of Pulmonary Disease. 1.25

DENTISTRY.

Barrett. Dental Surg. 1.00
Broomell. Anat. and Hist. of Mouth and Teeth. 4.50
Fillebrown. Op. Dent. Illus. 2.25
Gorgas. Dental Medicine. 4.00
—— Questions and Answers. 6.00
Harris. Principles and Prac. 6.00
—— Dictionary of. 6th Ed. 5.00
Richardson. Mech. Dent. 5.00
Smith. Dental Metallurgy. 2.00
Taft. Index of Dental Lit. 2.00
Tomes. Dental Surgery. 4.00
—— Dental Anatomy. 4.00
Warren's Compend of. .80
—— Dental Prosthesis and Metallurgy. Illus. 1.25
White. Mouth and Teeth. .40

DIAGNOSIS.

Brown. Medical. 4th Ed. $2.25
Tyson's Manual. 4th Ed. Illus. 1.50

DICTIONARIES, ETC.

Gould's Illustrated Dictionary of Medicine, Biology, and Allied Sciences, etc. 5th Edition. Leather, $10.00; Half Russia, Thumb Index, 12.00
Gould's Student's Medical Dictionary. 11th Ed., Illus., ½ Mor., $2.50; Thumb Ind., 3.00
Gould's Pocket Dictionary—30,000 medical words. 4th Edition. Enlarged. Leather, 1.00
Gould and Pyle. Cyclopedia of Med. and Surg. One Vol. Illus. Leather, 10.00
Gould and Pyle's Pocket Cyclopedia of Medicine. 1.00
Harris' Dental. Clo. 5.00; Shp. 6.00
Longley's Pronouncing. .75
Maxwell. Terminologia Medica Polyglotta. 3.00
Treves. German-English. 3.25

EAR.

Burnett. Hearing, etc. .40
Hovell. Treatise on. 5.50
Kyle. Ear, Nose, Throat. ——
Pritchard. Diseases of. 3d Ed. 1.50

ELECTRICITY.

Bigelow. Plain Talks on. 1.00
Hedley. Therapeutic Elec. 2.50
Jacobi. Electrotherapy. 2 Vols. 5.00
Jones. Medical Electricity. 3.00

EYE.

Donders. Refraction. 1.25
Fick. Diseases of the Eye. 4.50
Gould and Pyle. Compend. .80
Greeff. Microscopic Examination of. 1.25
Harlan. Eyesight. .40
Hartridge. Refraction. 11th Ed. 1.50
—— Ophthalmoscope. 4th Ed. 1.50
Hansell and Reber. Muscular Anomalies of the Eye. 1.50
Hansell and Bell. Clinical Ophthalmology. 120 Illus. 1.50
Jennings. Ophthalmoscopy. 2.50
Morton. Refraction. 6th Ed. 1.00
Ohlemann. Ocular Therap. 1.75
Parsons. Optics. 2.00
Phillips. Spectacles and Eyeglasses. 49 Illus. 3d Ed. 1.00
Swanzy's Handbook. 7th Ed. 2.50
Thorington. Retinoscopy. 1.00
—— Refraction. 200 Illus. 1.50
Walker. Student's Aid. 1.50
Wright. Ophthalmology. 3.00

GYNECOLOGY.

Bishop. Uterine Fibromyomata. Illustrated. 3.50
Byford (H. T.). Manual. 3d Edition. 363 Illustrations. 3.00
Dührssen. Gynecological Practice. 105 Illustrations. 1.50
Lewers. Dis. of Women. 2.50
—— Cancer of Uterus. 3.00
Montgomery. Text-book of. 527 Illus. 5.00
Roberts. Gynecological Pathology. Illustrated. 6.00
Wells. Compend. Illus. .80

HEALTH AND DOMESTIC MEDICINE.

Bulkley. The Skin. .40
Burnett. Hearing. .40
Cohen. Throat and Voice. .40
Dulles. Emergencies. 5th Ed. 1.00
Harlan. Eyesight. .40
Hartshorne. Our Homes. .40
Osgood. Dangers of Winter. .40
Packard. Sea Air, etc. .40
Richardson's Long Life. .40
White. Mouth and Teeth. .40
Wilson. Summer and its Dis. .40

CLASSIFIED LIST OF P. BLAKISTON'S SON & CO.'S PUBLICATIONS.

HISTOLOGY.

Cushing. Compend. - - $0.80
Stirling. Histology. 2d Ed. 2.00
Stöhr's Histology. Illus. - 3.00

HYGIENE.

Canfield. Hygiene of the Sick-Room. - - - - 1.25
Coplin. Practical Hygiene. —
Kenwood. Public Health Laboratory Guide. - 2.00
Lincoln. School Hygiene. .40
McFarland. Prophylaxis. 2.50
Notter. Practical Hygiene. 7.00
Parkes' (L. C.), Manual. 3 00
Rosenau. Disinfection and Disinfectants. Illus. - 2.00
Starr. Hygiene of the Nursery. 1.00
Stevenson and Murphy. A Treatise on Hygiene. In 3 Vols. *Circular* Vol. I, 6.00
upon application. Vol. II, 6.00
Vol. III, 5.00
Thresh. Water Supplies. 2.00
Wilson's Handbook. 8th Ed. 3.00
Weyl. Coal-Tar Colors. 1.25

MASSAGE, ETC.

Mitchell and Gulick. Mechanotherapy. Illustrated. 2.50
Ostrom. Massage. 115 Illus. 1.00

MATERIA MEDICA.

Bracken. Materia Med. 2.75
Coblentz. Newer Remedies. 1.00
Davis. Essentials of. - 1.50
Gorgas. Dental. 5th Ed. 4.00
Groff. Mat. Med. for Nurses. 1.25
Heller. Essentials of. - 1.50
Potter's Compend of. 6th Ed. .80
Potter's Handbook of. 9th Ed. Cloth, $5.00; Sheep, 6.00
Sayre. Organic Materia Med. and Pharmacognosy. - 4.50
Tavera. Medicinal Plants of the Philippines. - - 2.00
White and Wilcox. Mat. Med., Pharmacy, Pharmacology, and Therapeutics. 5th Ed. Enlarged. Cl., $3.00; Sh. 3.50

MEDICAL JURISPRUDENCE.

Mann. Forensic Med. - 6.50
Reese. Med. Jurisprudence and Toxicology. 6th Ed. $3.00; Sh. 3.50

MICROSCOPE.

Carpenter. The Microscope. 8th Ed. 850 Illus. - 8.00
Lee. Vade Mecum of. 5th Ed. 4.00
Oertel. Med. Microscopy. 2.00
Reeves. Med. Microscopy. 2.50
Wethered. Medical Microscopy. Illus. - - - 2.00

MISCELLANEOUS.

Black. Micro-organisms. .75
Burnet. Food and Dietaries. 1.50
Cohen. Organotherapy. 2.50
Da Costa. Hematology. - 5.00
Davis. Alimentotherapy. 2.50
Fenwick. Cancer of Stom. 3 00
Goodall and Washbourn. Infectious Diseases. Illus. 3.00
Gould. Borderland Studies. 2.00
—— Biographic Clinics. 1.00
Greene. Medical Examination in Life Insurance. Illus. - 4.00
Haig. Uric Acid. 5th Ed. 3.00
—— Diet and Food. 4th Ed. 1.00
Hare. Mediastinal Disease. 2.00
Hemmeter. Diseases of Stomach. 2d Edition. Illus. - 6.00
—— Diseases of Intestines. Illustrated. 2 Vols. - 10.00
Henry. Anæmia. - - .50
McCook. Amer. Spiders. 40.00
New Sydenham Society's Publications, each year. - 8.00
Schofield. The Force of Mind. 2.00
Thorne. Schott Methods in Heart Disease. - - 2.00
Tissier. Pneumatotherapy. 2.50
Treves. Physical Education. .75
Weber and Hinsdale. Climate. 2 Vols. Illustrated. 5.00
Winternitz. Hydrotherapy. 2.50

NERVOUS DISEASES, ETC.

Dercum. Rest, Mental Therapeutics, Suggestion. - $2.50
Frenkel. Tabetic Ataxia. 3.00
Gordinier. Anatomy of Central Nervous System. - 6.00
Gowers. Manual of. 530 Illus. Vol. I, $4.00; Vol. II, - 4.00
—— Syphilis and the Nervous System. - - - 1.00
—— Epilepsy. New Ed. 3.00
Ormerod. Manual of. - 1.00
Pershing. Diagnosis of Nerv. and Mental Diseases. - 1.25
Preston. Hysteria. Illus. 2.00

NURSING.

Canfield. Hygiene of the Sick-Room. - - - - 1.25
Cuff. Lectures on. 3d Ed. 1.25
Davis. Bandaging. Illus. 1.50
Domville's Manual. 8th Ed. .75
Fullerton. Obst. Nursing. 1.00
—— Surgical Nursing. 1.00
Gould. Pocket Medical Dictionary. Limp Morocco. 1.00
Groff. Mat. Med. for Nurses. 1.25
Hadley. Manual of. - 1.25
Humphrey. Manual. 23d Ed. 1.00
Starr. Hygiene of the Nursery. 1.00
Temperature Charts. Pads. .50
Voswinkel. Surg. Nursing. 1.00

OBSTETRICS.

Cazeaux and Tarnier. Text-Book of. Colored Plates. 4.50
Edgar. Text-book of. - —
Landis. Compend. 6th Ed. .80
Winckel's Text-book. 5.00

PATHOLOGY.

Barlow. Pathological Anat. 6.50
Blackburn. Autopsies. 1.25
Coplin. Manual of. 3d Ed. 3.50
Da Costa. The Blood. - 5.00
Roberts. Gynecological Pathology. Illustrated. - 6.00
Thayer. General Pathology .80
—— Special Pathology. .80
Virchow. Post-mortems. .75
Whitacre. Lab. Text-book. 1.50

PHARMACY.

Beasley's Receipt-Book. - 2.00
—— Formulary. - - 2.00
Coblentz. Manual of Pharm. 3.50
Proctor. Practical Pharm. 3.00
Robinson. Latin Grammar of. 1.75
Sayre. Organic Materia Med. and Pharmacognosy. 2d Ed. 4.50
Scoville. Compounding. 2.50
Stewart's Compend. 5th Ed. .80
U. S. Pharmacopœia. 7th Revision. 1890 Cl. $2.50; Sh., 3.00
Postage extra, .27
Select Tables from U. S. P. .25

PHYSIOLOGY.

Birch. Practical Physiology. 1.75
Brubaker's Compend. 11th Ed. .80
Jones. Outlines of. - - 1.50
Kirkes' New 17th Ed. (Halliburton.) Cloth, $3.00; Sh., 3.75
Landois' Text-book. 845 Illus. —
Starling. Elements of. - 1.00
Stirling. Practical Phys. 2.00
Tyson's Cell Doctrine. - 1.50

POISONS.

Reese. Toxicology. 4th Ed. 3.00
Tanner. Memoranda of. .75

PRACTICE.

Beale. Slight Ailments. 1.25
Fagge. Practice. Vol. I, 6.00
Vol. II, 6 00
Fowler's Dictionary of. - 3.00
Gould and Pyle. Cyclopedia of Medicine. Illustrated. 10.00
Hughes. Compend. 2 Pts. ea. .80
—— Physician's Edition. 1 Vol. Morocco, Gilt edge. 2.25
Taylor's Manual of. 6th Ed. 4.00
Tyson. The Practice of Medicine. Illus. Cl. $5.50; Sheep 6.50

SKIN.

Bulkley. The Skin. - $0.40
Crocker. Dis. of Skin. Illus. 5.00
Schamberg. Compend. .80
Van Harlingen. Diagnosis and Treatment of Skin Dis. 3d Ed. 60 Illus. - - 2.75

SURGERY AND SURGICAL DISEASES.

Berry. Thyroid Gland. - 4.00
Butlin. Surgery of Malignant Disease. - - - 4.50
Davis. Bandaging. Illus. 1.50
Deaver. Appendicitis. - —
—— Surgical Anatomy. - 24.00
Douglas. Surgical Diseases of Abdomen - - - —
Dulles. Emergencies. - 1.00
Hamilton. Tumors. 3d Ed. 1.25
Heath's Minor. 12th Ed. 1.50
—— Clinical Lectures. - 2 00
Horwitz. Compend. 5th Ed. .80
Jacobson. Operations of. - 10.00
Keay. Gall-Stone Disease. 1 25
Kehr. Gall-Stone Disease - 2 50
Macready on Ruptures - 6.00
Makins. Surgical Experiences in South Africa. - 4.00
Maylard. Surgery of the Alimentary Canal. - - 3.00
Morris. Renal Surgery. 2.00
Moullin. Complete Text-book. 3d Ed. by Hamilton. 600 Illustrations. - - 6.00
Smith. Abdominal Surg. 10.00
Voswinkel. Surg. Nursing. 1.00
Walsham. Surgery. 7th Ed. 3.50

THERAPEUTICS.

Beasley's 3000 Prescriptions. 2.00
Coblentz. New Remedies. 1.00
Cohen. Physiologic Therapeutics. 11 Volumes. 27.50
Mays. Theine. - - .50
Murray. Notes on Remedies. 1.25
Potter's Compend. 6th Ed. .80
—— Handbook of Mat. Med. Phar. and Thera. 9th Ed. 5.00
White and Wilcox. Mat. Med., Pharmacy, Pharmacology, and Therap. 5th Ed. 3.00

THROAT AND NOSE.

Cohen. Throat and Voice. .40
Hall. Nose and Throat. - 2.75
Hollopeter. Hay Fever. 1.00
Knight. Throat. Illus. - —
Kyle. Ear, Nose, Throat. —
McBride. Clinical Manual, Colored Plates. 3d Ed. - 7.00
Potter. Stammering, etc. 1.00

URINE & URINARY ORGANS.

Acton. Repro. Organs. 1.75
Holland. The Urine, Milk and Common Poisons. 6th Ed. 1.00
Kleen. Diabetes. - - 2.50
Memminger. Diagnosis by the Urine. 2d Ed. Illus. 1.00
Morris. Renal Surgery. 2.00
Moullin. The Prostate. - 1.75
—— The Bladder. - 1.50
Scott. Clinical and Micros. Examination of Urine. - 5.00
Tyson. Exam. of Urine. 1.50
Van Nüys. Urine Analysis. 1.00

VENEREAL DISEASES.

Gowers. Syphilis and the Nervous System. - - 1.00
Sturgis. Manual of. 7th Ed. 1.25

VISITING LISTS.

Lindsay and Blakiston's Regular Edition. $1.00 to 2.25
—— Perpetual Ed. $1.25 to 1.50
—— Monthly Ed. .75 to 1.00

P. BLAKISTON'S SON & CO.'S

Medical and Scientific Publications.

Acton. The Functions and Disorders of the Reproductive Organs in Childhood, Youth, Adult Age, and Advanced Life, considered in their Physiological, Social, and Moral Relations. By WM. ACTON, M.D., M.R.C.S. 8th Edition. Cloth, $1.75

Allen. Commercial Organic Analysis.

New Revised Editions. A Treatise on the Properties, Proximate Analytical Examination and Modes of Assaying the Various Organic Chemicals and Products employed in the Arts, Manufactures, Medicine, etc., with Concise Methods for the Detection and Determination of Impurities, Adulterations, and Products of Decomposition, etc. Revised and Enlarged. By ALFRED H. ALLEN, F.C.S., Public Analyst for the West Riding of Yorkshire; Past President Society of Public Analysts of Great Britain.

VOL. I. Preliminary Examination of Organic Bodies. Alcohols, Neutral Alcoholic Derivatives, Ethers, Starch and its Isomers, Sugars, Acid Derivatives of Alcohols and Vegetable Acids, etc. Third Edition, with numerous additions yb the author, and revisions and additions by DR. HENRY LEFFMANN, Professor of Chemistry and Metallurgy in the Pennsylvania College of Dental Surgery, and in the Wagner Free Institute of Science, Philadelphia, etc. With many useful tables. Cloth, $4.50

VOL. II—PART I. Fixed Oils, Fats, Waxes, Glycerin, Soaps, Nitroglycerin, Dynamite and Smokeless Powders, Wool-Fats, Dégras, etc. Third Edition, with many useful tables. Revised by DR. HENRY LEFFMANN, with numerous additions by the author. Cloth, $3.50

VOL. II—PART II. Hydrocarbons, Mineral Oils, Lubricants, Asphalt, Benzene and Naphthalene, Phenols, Creosote, etc. Third Edition, Revised by DR. HENRY LEFFMANN, with additions by the author. Cloth, $3.50

VOL. II—PART III. Terpenes, Essential Oils, Resins, Camphors, Aromatic Acids, etc. Third Edition. *In Preparation.*

VOL. III—PART I. Tannins, Dyes, Coloring Matters, and Writing Inks. Third Edition, Revised, Rewritten, and Enlarged by I. MERRITT MATTHEWS, Professor of Chemistry and Dyeing at the Philadelphia Textile School; Member American Chemical Society. Cloth, $4.50

VOL. III—PART II. The Amines and Ammonium Bases, Hydrazines and Derivatives. Bases from Tar. The Antipyretics, etc. Vegetable Alkaloids, Tea, Coffee, Cocoa, Kola, Cocaïne, Opium, etc. Second Edition. 8vo. Cloth, $4.50

VOL. III—PART III. Vegetable Alkaloids concluded, Non-Basic Vegetable Bitter Principles. Animal Bases, Animal Acids, Cyanogen and its Derivatives, etc. Second Edition. Cloth, $4.50

VOL. IV. Proteids and Albuminous Principles. Proteoïds or Albuminoïds. Second Edition, with elaborate appendices and a large number of useful tables. Cloth, $4.50

Bailey and Cady. Chemical Analysis.

Laboratory Guide to the Study of Qualitative Analysis. By E. H. S. BAILEY, PH.D., Professor of Chemistry, and HAMILTON CADY, A.B., Assistant Professor of Chemistry in the University of Kansas. Fourth Edition. Cloth, $1.25

Bigelow. Plain Talks on Medical Electricity and Batteries.

With a Therapeutic Index and a Glossary. By HORATIO R. BIGELOW, M.D. With 43 Illustrations and a Glossary. Second Edition. Cloth, $1.00

Birch. Practical Physiology.

An Elementary Class-Book. Including Histology, Chemical and Experimental Physiology. By DE BURGH BIRCH, M.D., C.M., F.R.S.E., Professor of Physiology in the Yorkshire College of the Victoria University, etc. 62 Illus. 12mo. Cloth, $1.75

Bishop. Uterine Fibromyomata.

Their Pathology, Diagnosis, and Treatment. By E. STANMORE BISHOP, F.R.C.S. (Eng.), President Manchester Clinical Society; Fellow British Gynecological Society. Full-page Plates and other Illustrations. Octavo. Cloth, $3.50

Black. Micro-Organisms.

The Formation of Poisons. A Biological Study of the Germ Theory of Disease. By G. V. Black, M.D., D.D.S. Cloth, .75

Blackburn. Autopsies. Illustrated.

A Manual of Autopsies, Designed for the Use of Hospitals for the Insane and other Public Institutions. By I. W. BLACKBURN, M.D., Pathologist to the Government Hospital for the Insane. Illustrated. Cloth, $1.25

Bloxam. Chemistry (Inorganic and Organic).

With Experiments. By CHARLES L. BLOXAM. Late Professor of Chemistry, King's College, London, and in the Department of Artillery Studies, Woolwich, England. Edited by J. M. THOMPSON, Professor of Chemistry in King's College, London, and A. G. BLOXAM, Head of the Chemistry Department, Goldsmith's Institute, London. Ninth Edition, Revised and Enlarged. 281 Engravings. 8vo. *Preparing.*

Bracken. Outlines of Materia Medica and Pharmacology.

By H. M. BRACKEN, Professor of Materia Medica and Therapeutics and of Clinical Medicine, University of Minnesota. 8vo. Cloth, $2.75

Broomell. Anatomy and Histology of the Mouth and Teeth.

By DR. I. N. BROOMELL, Professor of Dental Anatomy, Dental Histology, and Prosthetic Technics in the Pennsylvania College of Dental Surgery. Second Edition, Revised and Enlarged by 72 pages. 337 handsome Illustrations, the majority of which are original. Large Octavo. *Just Ready.* Cloth, $4.50; Leather, $5.50

Brown. Medical Diagnosis. Fourth Edition.

A Manual of Clinical Methods. By J. J. GRAHAM BROWN, M.D., F.R.C.P., Lecturer on Principles and Practice of Medicine in the School of Medicine of the Royal Colleges, Edinburgh. Fourth Edition. 112 Illustrations. 12mo. Cloth, $2.25

Brubaker. Compend of Physiology. Eleventh Edition.

A Compend of Physiology, specially adapted for the use of Students and Physicians. By A. P. BRUBAKER, M.D., Adjunct Professor of Physiology at Jefferson Medical College; Professor of Physiology, Pennsylvania College of Dental Surgery, Philadelphia. Eleventh Edition, Revised, Enlarged, and Illustrated. *No. 4 ? Quiz-Compend ? Series.* 12mo. Cloth, .80; Interleaved, $1.00

Bulkley. The Skin in Health and Disease.

By L. DUNCAN BULKLEY, M.D. Illustrated. Cloth, .40

Bunge. Physiologic and Pathologic Chemistry.

By DR. C. BUNGE, Professor at Basel. Authorized Translation from the Fourth German Edition. Edited by E. A. STARLING, M.D., F.R.S., Professor of Physiology in University College, London. Octavo. Cloth, $3.00

Cazeaux and Tarnier's Midwifery. With Appendix, by Mundé.

The Theory and Practice of Obstetrics, including the Diseases of Pregnancy and Parturition, Obstetrical Operations, etc. By P. CAZEAUX. Remodeled, rearranged, and revised by S. TARNIER, M.D. Eighth American from the Eighth French and First Italian Edition. Edited by ROBERT J. HESS, M.D. With an Appendix by PAUL F. MUNDÉ, M.D. Illustrated by Lithographs, Full-page Plates, and numerous Engravings. 8vo. Cloth, $4.50; Full Leather, $5.50

Clowes and Coleman. Quantitative Analysis.

Adapted for the Use of the Laboratories of Schools and Colleges. By FRANK CLOWES, SC.D., Emeritus Professor of Chemistry, University College, Nottingham, and I. BERNARD COLEMAN, Assoc. R. C. Sci., Dublin, Professor of Chemistry, Southwest London Polytechnic. Fifth Edition. 122 Illustrations. Cloth, $3.50

Coblentz. Manual of Pharmacy.

A Text-Book for Students. By VIRGIL COBLENTZ, A.M., PH.D., F.C.S., Professor of Chemistry and Physics; Director of Pharmaceutical Laboratory, College of Pharmacy of the City of New York. Second Edition, Revised and Enlarged. 437 Illustrations. Octavo. 572 pages. Cloth, $3.50; Sheep, $4.50

The Newer Remedies.

Including their Synonyms, Sources, Methods of Preparation, Tests, Solubilities, and Doses as far as known. Together with Sections on Organo-Therapeutic Agents and Indifferent Compounds of Iron. Third Edition, very much enlarged. Octavo. Cloth, $1.00

Volumetric Analysis.

A Practical Handbook for Students of Chemistry. Including Indicators, Test-Papers, Alkalimetry, Acidimetry, Analysis by Oxidation and Reduction, Iodometry, Assay Processes for Drugs with the Titrimetric Estimation of Alkaloids, Estimation of Phenol, Sugar, Tables of Atomic and Molecular Weights. Illustrated. 8vo. Cloth, $1.25

Cohen. System of Physiologic Therapeutics. Illustrated.

A Practical Exposition of the Methods Other than Drug-giving, Useful in the Treatment of the Sick and in the Prevention of Disease. Edited by SOLOMON SOLIS COHEN, A.M., M.D., Senior Assistant Professor of Clinical Medicine at Jefferson Medical College; formerly Professor of Medicine and Therapeutics in the Philadelphia Polyclinic; Physician to the Philadelphia and Jewish Hospitals and to the Rush Hospital for Consumption; formerly Lecturer on Therapeutics, Dartmouth Medical College. To be issued in Eleven Compact Octavo Volumes.

By Subscription only. Complete Set, Cloth, $27.50; Half Morocco, $38.50

Electrotherapy. 220 Illustrations. Two Volumes. *Ready.*

By GEORGE W. JACOBY, M.D., New York, Consulting Neurologist to the German Hospital, to the Infirmary for Women and Children, to the Craig Colony for Epileptics, etc. Special articles by EDWARD JACKSON, A.M., M.D., Denver, Col.; Emeritus Professor of Diseases of the Eye in the Philadelphia Polyclinic; Member American Ophthalmological Society; Fellow and ex-President American Academy of Medicine, etc.—By WILLIAM SCHEPPEGRELL, M.D., New Orleans, ex-Vice-President American Laryngological, Rhinological, and Otological Society.—By J. CHALMERS DA COSTA, M.D., Clinical Professor of Surgery in Jefferson Medical College; Surgeon to the Philadelphia and to St. Joseph's Hospitals, etc.—By FRANKLIN H. MARTIN, M.D., Professor of Gynecology, Post-Graduate Medical School of Chicago; Gynecologist Chicago Charity Hospital; Chairman Section of Obstetrics and Diseases of Women of the American Medical Association (1895), etc.—By A. H. OHMANN-DUMESNIL, M.D., Editor *St. Louis Medical and Surgical Journal;* Member International Dermatological Congress; formerly Professor of Dermatology, St. Louis Medical College, etc.

Cohen. Physiologic Therapeutics.—Continued.

Climatology and Health Resorts, Including Mineral Springs. Two Volumes, with Colored Maps. *Ready.*

By F. PARKES WEBER, M.A., M.D., F.R.C.P. (Lond.), Physician to the German Hospital, Dalston; Assistant Physician North London Hospital for Consumption; Author of "The Mineral Waters and Health Resorts of Europe;" and GUY HINSDALE, A.M., M.D., Secretary of the American Climatological Association; President of the Pennsylvania Society for the Prevention of Tuberculosis, etc. Including an article on Hawaii by TITUS MUNSON COAN, M.D., of New York. With Colored Maps, prepared by DR. W. F. R. PHILLIPS, of the U.S. Weather Bureau, Washington, D. C.

Prophylaxis—Personal Hygiene—Civic Hygiene—Care of the Sick. Illustrated. *Ready.*

By DR. JOSEPH MCFARLAND, Professor of Pathology, Medico-Chirurgical College, Philadelphia; DR. HENRY LEFFMANN, Professor of Chemistry in the Woman's Medical College, Philadelphia; ALBERT ABRAMS, A.M., M.D. (University of Heidelberg), formerly Professor of Pathology, Cooper Medical College, San Francisco; and DR. W. WAYNE BABCOCK, Lecturer on Pathology and Bacteriology, Medico-Chirurgical College, Philadelphia.

Dietotherapy: Food in Health and Disease. *Ready.*

By NATHAN S. DAVIS, JR., A.M., M.D., Professor of Principles and Practice of Medicine in Northwestern University Medical School; Physician to Mercy Hospital, Chicago; Member American Academy of Medicine, American Climatological Society, etc. With Tables of Dietaries, Relative Value of Foods, etc.

Mechanotherapy and Physical Education. Illustrated.

By JOHN KEARSLEY MITCHELL, M.D., Assistant Physician to the Orthopedic Hospital and Infirmary for Nervous Diseases; Assistant Neurologist Presbyterian Hospital, Philadelphia, etc.; formerly Lecturer on Symptomology at the University of Pennsylvania; and LUTHER GULICK, M.D., of Brooklyn, N. Y., formerly of Springfield, Mass., Mem. American Association for Advancement of Physical Education, Amer. Medical Association, etc. With a Chapter on Orthopedic Appliances by JAMES K. YOUNG, M.D., Professor of Orthopedic Surgery, Philadelphia Polyclinic; Instructor in Orthopedic Surgery, University of Pennsylvania; and an Article on Ocular Orthopedics by WALTER L. PYLE, M.D.

Rest—Mental Therapeutics—Suggestion.

By FRANCIS X. DERCUM, M. D., Clinical Professor of Nervous Diseases in Jefferson Medical College; Neurologist to the Philadelphia Hospital; Consulting Neurologist to St. Agnes' Hospital; Neurologist to the Jewish Hospital of Philadelphia.

Hydrotherapy—Thermotherapy—Heliotherapy—Crounotherapy—Phototherapy—Balneology. *Ready.*

By DR. WILHELM WINTERNITZ, Professor of Clinical Medicine in the University of Vienna; Director of the General Polyclinic in Vienna, etc.; assisted by DR. ALOIS STRASSER, Instructor in Clinical Medicine, University of Vienna; and DR. B. BUXBAUM, Chief Physician of the Hydrotherapeutic Institute of Vienna; and DR. E. HEINRICH KISCH, Professor in the University of Prague; Physician at Marienbad Spa. With Special Chapters by DR. A. C. PEALE, of the National Museum, Washington, D. C., DR. J. H. KELLOGG, Battle Creek, Mich., and HARVEY CUSHING, M.D., Johns Hopkins Hospital, Baltimore, and an Appendix by DR. COHEN.

Pneumatotherapy and Inhalation Methods. Illustrated.

By DR. PAUL TISSIER, Chief of Clinic of the Faculty of Medicine of Paris.

Cohen. Physiologic Therapeutics.—Continued.

Serotherapy—Organotherapy—Blood-Letting, etc.—Principles of Therapeutics—Digest—Index.

By JOSEPH MCFARLAND, M.D., Professor of Pathology in the Medico-Chirurgical College, Philadelphia; Pathologist to the Medico Chirurgical Hospital, etc.—O. T. OSBORNE, M.D., Professor of Materia Medica and Therapeutics, Medical Department, Yale University, New Haven.—FREDERICK A. PACKARD, M.D., Visiting Physician to the Pennsylvania and to the Children's Hospitals.—The Editor, and AUGUSTUS A. ESHNER, M.D., Professor of Clinical Medicine in the Philadelphia Polyclinic; Physician to the Philadelphia Hospital, etc.

*** *Complete descriptive circular upon application.*

"There is surely room for just such a set of books. We have been too prone to think that we were teaching therapeutics sufficiently when we taught our students the old materia medica and the use of mere drugs, forgetful and careless of the importance of the therapeutic value of the methods of which this series of books will speak."—*Johns Hopkins Hospital Bulletin.*

Cohen. The Throat and Voice.

By J. SOLIS COHEN, M.D. Illustrated. 12mo. Cloth, .40

Congdon. Laboratory Instructions in General Chemistry.

By ERNEST A. CONGDON, Professor of Chemistry in the Drexel Institute, Philadelphia; Member American Chemical Society; Fellow of the London Chemical Society, etc. With an Appendix, useful Tables, and 56 Illustrations. Interleaved, Cloth, $1.00

Conn. Agricultural Bacteriology.

Including a Study of Bacteria as Relating to Agriculture, with Special Reference to the Bacteria in Soil, in the Dairy, in Food Products, in Domestic Animals, and in Sewage. By H. W. CONN, PH.D., Professor of Biology, Wesleyan University, Middletown, Conn.; Author of "Evolution of To-day," "The Story of Germ Life," etc. With Illustrations. Cloth, $2.50

Bacteria in Milk and Its Products.

Designed for Students of Dairying, Boards of Health, Bacteriologists, and all concerned in the Handling of Milk, Butter, and Cheese. Illustrated. 12mo. Cloth, $1.25

Coplin. Manual of Pathology. Third Edition. 330 Illustrations.

Including Bacteriology, the Technic of Post-mortems, and Methods of Pathologic Research. By W. M. LATE COPLIN, M.D., Professor of Pathology and Bacteriology, Jefferson Medical College; Pathologist to Jefferson Medical College Hospital and to the Philadelphia Hospital; Bacteriologist to the Pennsylvania State Board of Health. Third Edition, Rewritten and Enlarged. 330 Illustrations, many of which are original, and 7 Colored Plates. 8vo. Cloth, $3.50

Practical Hygiene.

With Special Articles on Plumbing, Ventilation, etc. 138 Illustrations. 8vo. Second Edition. *In Preparation.*

Crocker. Diseases of the Skin. Third Edition.

Their Description, Pathology, Diagnosis, and Treatment, with Special Reference to the Skin Eruptions of Children. By H. RADCLIFFE CROCKER, M.D., Physician to the Department of Skin Diseases, University College Hospital, London. Third Edition, Thoroughly Revised, with new Illustrations. *Nearly Ready.* Cloth, $5.00

Cuff. Lectures on Medicine to Nurses.

By HERBERT EDMUND CUFF, M.D., late Assistant Medical Officer, Stockwell Fever Hospital, England. Third Edition, Revised. With 25 Illustrations. Cloth, $1.25

Cushing. Compend of Histology.

Specially adapted for the use of Medical Students and Physicians. By H. H. CUSHING, M.D., Director of Histological and Embryological Laboratories, Woman's Medical College of Pennsylvania; Demonstrator of Histology and Embryology, Jefferson Medical College, Philadelphia. Illustrated. *No. 17 ? Quiz-Compend ? Series.* 12mo. *In Press.* Cloth, .80; Interleaved for Notes, $1.00

Davis. Dietotherapy. Food in Health and Disease.

See COHEN, Physiologic Therapeutics, page 10.

Davis. Essentials of Materia Medica and Prescription Writing.

By J. AUBREY DAVIS, M.D. 12mo. Cloth, $1.50

Davis. The Principles and Practice of Bandaging.

By GWILYM G. DAVIS, M.D., M.R.C.S., Universities of Pennsylvania and Göttingen Assistant Demonstrator of Surgery, University of Pennsylvania; Surgeon to the Out-Patient Departments of the Episcopal and Children's Hospitals; Assistant Surgeon to the Orthopædic Hospital. Second Edition, Revised and Rewritten. 163 Illustrations, Redrawn specially for this edition. *Just Ready.* Cloth, $1.50

Domville. Manual for Nurses

and Others Engaged in Attending to the Sick. By ED. J. DOMVILLE, M.D. Ninth Edition, Revised. With Recipes for Sick-room Cookery, etc. 12mo. *In Press.*

Donders. Refraction. Portrait of Author.

An Essay on the Nature and the Consequences of Anomalies of Refraction. By F. C. DONDERS, M.D. Authorized Translation. Revised and Edited by CHARLES A. OLIVER, A.M., M.D. (Univ. Pa.), one of the Attending Surgeons to the Wills Eye Hospital. With a Portrait of the Author. Octavo. Half Morocco, Gilt, $1.25

Da Costa. Clinical Hematology. Colored Plates.

A Practical Guide to the Examination of the Blood by Clinical Methods, with Reference to the Diagnosis of Disease. By JOHN C. DA COSTA, JR., M.D., Assistant Demonstrator of Clinical Medicine in the Jefferson Medical College, Philadelphia; Assistant in the Medical Clinic, Jefferson Medical College Hospital; Hæmatologist to the German Hospital. With six Colored Plates and 48 other Illustrations. Octavo. *Just Ready.* Cloth, $5.00; Sheep, $6.00

Deaver. Surgical Anatomy. 499 Full-page Plates.

A Treatise on Human Anatomy in its Application to the Practice of Medicine and Surgery. By JOHN B. DEAVER, M.D., Surgeon-in-Chief to the German Hospital; Surgeon to the Children's Hospital and to the Philadelphia Hospital; Consulting Surgeon to St. Agnes', St. Timothy's, and Germantown Hospitals; formerly Assistant Professor of Applied Anatomy, University of Pennsylvania, etc. With 499 very handsome Full-page Illustrations engraved from original drawings made by special artists from dissections prepared for the purpose in the dissecting-rooms of the University of Pennsylvania. Three large volumes. Royal square octavo. Sold by Subscription. Orders taken for complete sets only. Description upon Application.
Half Morocco or Sheep, $24.00; Half Russia, $27.00

SYNOPSIS OF CONTENTS.

VOLUME I.—Upper Extremity—Back of Neck, Shoulder, and Trunk—Cranium—Scalp—Face.

VOLUME II.—Neck—Mouth, Pharynx, Larynx, Nose—Orbit—Eyeball—Organ of Hearing—Brain—Female Perineum—Male Perineum.

VOLUME III.—Abdominal Wall—Abdominal Cavity—Pelvic Cavity—Chest—Lower Extremity.

☞ *See next page for Reviews.*

DEAVER'S SURGICAL ANATOMY

The illustrations, which at the first glance appear as the prominent feature of the book--but which in reality do not overshadow the text—consist of a series of pictures absolutely unique and fresh. They will bear comparison from an artistic point of view with any other work, while from a practical point of view there is no other volume or series of volumes to which they can be compared. When originally announced, the book was to contain two hundred illustrations. As the work of preparation progressed, this number gradually increased to nearly five hundred full-page plates, many of which contain more than one figure. With the exception of a few minor pictures made from preparations in the possession of the author, they have all been drawn by special artists from dissections made for the purpose in the dissecting-rooms of the University of Pennsylvania. Their accuracy cannot be questioned, as each drawing has been submitted to the most careful scrutiny.

From The Medical Record, New York.

"**The reader is not only taken by easy and natural stages from the more superficial to the deeper regions, but the various important regional landmarks are also indicated by schematic tracing upon the limbs.** Thus the courses of arteries, veins, and nerves are indicated in a way that makes the lesson strikingly impressive and easily learned. No expense, evidently, has been spared in the preparation of the work, judging from the number of full-page plates it contains, not counting the smaller drawings. Most of these have been 'drawn by special artists from dissections made for the purpose in the dissecting-rooms of the University of Pennsylvania.' In summing up the general excellences of this remarkable work, we can accord our unqualified praise for the accurate, exhaustive, and systematic manner in which the author has carried out his plan, **and we can commend it as a model of its kind, which must be possessed to be appreciated.**"

From The Philadelphia Medical Journal.

"Many members of the profession to whom Dr. Deaver is well known either personally or by reputation as a surgeon, writer, teacher, and practical anatomist, have awaited the appearance of his Surgical Anatomy with the expectation of finding in it a guide in this difficult branch of medicine of much more than ordinary practical value, and their **expectations will not be disappointed.**"

From The Journal of the American Medical Association.

"In order to show its thoroughness, it is only necessary to mention that no less than twelve full-page plates are reproduced in order to accurately portray the surgical anatomy of the hand, **and it is doubtful whether any better description exists in any work in the English language.**"

From The Southern California Practitioner.

"Aside from the merit of this great work, it will be a delight to the lover of books. Its general make-up shows the highest development of the book-making art. The bibliophile, when holding one of these volumes in his hands, would be as careful with it as though he were handling an infant, and to drop it would cause him the keenest pain. The illustrations, the print, and the paper and binding are each and all delightful in themselves, and yet the text is concise and clear, and taken with the illustrations make a remarkably good substitute for the dissecting-room. **To have these three volumes on his library shelves will be a source of pride and joy and profit to every practitioner.** Dr. Deaver has in these volumes conferred a boon upon the medical profession which has, at least, never been surpassed by any one."

From The New Orleans Medical and Surgical Journal.

"While the needs of the undergraduate have been fully kept in view, it has been the aim of the author to provide a work which would be sufficient for reference for use in actual practice. We believe the book fulfils both requirements. **The arrangement is systematic and the discussion of surgical relations thorough.**"

☞ Large Descriptive Circular will be sent upon application

Deaver. Appendicitis. Third Edition.

Its History, Anatomy, Etiology, Pathology, Symptoms, Diagnosis, Prognosis, Treatment, Complications, and Sequelæ. With 22 Plates, 10 of which are Colored. Third Edition, Revised and Rewritten. *Preparing.*

Dercum. Rest—Mental Therapeutics—Suggestion.

See COHEN, Physiologic Therapeutics, page 10.

Douglas. The Diagnosis of Surgical Diseases of the Abdomen.

By RICHARD DOUGLAS, M.D., late Professor of Gynecology and Abdominal Surgery, Medical Department Vanderbilt University; Ex-President of the Southern Surgical and Gynecological Association, etc. Illustrated by Full-page Plates. Large Octavo. *In Press.*

Dührssen. A Manual of Gynecological Practice.

By DR. A. DÜHRSSEN, Privat-Docent in Gynecology in the University of Berlin. Translated from the Fourth German Edition and Edited by JOHN W. TAYLOR, F.R.C.S., Surgeon to the Birmingham and Midlands Hospital for Women; and FREDERICK EDGE, M.D., F.R.C.S. With 105 Illustrations. 12mo. Cloth, $1.50

Dulles. What to Do First In Accidents and Poisoning.

By C. W. DULLES, M.D., Surgeon to the Rush Hospital; formerly Assistant Surgeon 2d Regiment N. G. Pa., etc. Fifth Edition, Enlarged. With new Illustrations. 12mo. Cloth, $1.00

Edgar. The Practice of Obstetrics.

By J. CLIFTON EDGAR, M.D., Professor of Obstetrics Medical Department of Cornell University, New York City; Physician to Mothers' and Babies' Hospital, and to the Emergency Hospital, etc. With many Illustrations, a large number of which are Original. Octavo. *In Press.*

Emery. A Handbook of Bacteriological Diagnosis.

By W. D'ESTE EMERY, M.D., B.Sc. Lond., Lecturer in Pathology and Bacteriology in the University of Birmingham. With two colored plates and 32 other illustrations. *Just Ready.* Cloth, $1.50

Fagge. Practice of Medicine.

A Text-Book of Medicine by the late C. HILTON FAGGE, M.D. Fourth Edition, Revised and Edited by P. H. PYE-SMITH, M.D., Consulting Physician to Guy's Hospital, London, etc. Two Vols. *Just Ready.* 8vo.
Vol. I, Cloth, $6.00; Vol. II, Cloth, $6.00

Fenwick. Cancer of Stomach.

By SAMUEL FENWICK, M.D., M.R.C.P., Physician to the London Hospital, etc., and W. SOLTAN FENWICK, M.D., B.S. Cloth, $3.00

Fick. Diseases of the Eye and Ophthalmoscopy.

By DR. EUGEN FICK, University of Zurich. Authorized Translation by A. B. HALE, M.D., Consulting Ophthalmic Surgeon Charity Hospital, Chicago; late Vol. Assistant Imperial Eye Clinic, University of Kiel. Glossary and 158 Illustrations, many of which are in Colors. 8vo. Cloth, $4.50; Sheep, $5.50

Fillebrown. A Text-Book of Operative Dentistry.

Written by invitation of the National Association of Dental Faculties. By THOMAS FILLEBROWN, M.D., D.M.D., Professor of Operative Dentistry in the Dental School of Harvard University. Illustrated. 8vo. Cloth, $2.25

Fowler's Dictionary of Practical Medicine.

By Various Writers. An Encyclopedia of Medicine. Edited by JAMES KINGSTON FOWLER, M.D., F.R.C.P., Senior Assistant Physician to the Middlesex Hospital, London. 8vo. Cloth, $3.00; Half Morocco, $4.00

Frenkel. Tabetic Ataxia.

Its Treatment by Systematic Exercise. By DR. H. S. FRENKEL. Authorized Translation by L. FREYBERGER, M.D., M.R.C.P. 132 Illustrations. Octavo. Cloth, $3.00

Fullerton. Obstetric Nursing.

By ANNA M. FULLERTON, M.D., Demonstrator of Obstetrics in the Woman's Medical College; Obstetrician and Gynecologist to the Woman's Hospital, Philadelphia, etc. 41 Illustrations. Fifth Edition, Revised and Enlarged. 12mo. Cloth, $1.00

Surgical Nursing.

Comprising the Regular Course of Lectures upon Abdominal Surgery, Gynecology, and General Surgical Conditions delivered at the Training School of the Woman's Hospital, Philadelphia. Third Edition, Revised. 69 Illustrations. 12mo. Cloth, $1.00

Gardner. The Brewer, Distiller, and Wine Manufacturer.

A Handbook for all interested in the Manufacture and Trade of Alcohol and its Compounds. Edited by JOHN GARDNER, F.C.S. Illustrated. Cloth, $1.50

Goodall and Washbourn. A Manual of Infectious Diseases.

By EDWARD W. GOODALL, M.D. (London), Medical Superintendent Eastern (Fever) Hospital, Homerton, London, etc.; and J. W. WASHBOURN, F.R.C.P., Assistant Physician to Guy's Hospital and Physician to the London Fever Hospital. Illustrated with Charts, Diagrams, and Full-page Plates. Cloth, $3.00

Gould. The Illustrated Dictionary of Medicine, Biology, and Allied Sciences. Fifth Edition.

Being an Exhaustive Lexicon of Medicine and those Sciences Collateral to it: Biology (Zoology and Botany), Chemistry, Dentistry, Pharmacology, Microscopy, etc. By GEORGE M. GOULD, A.M., M.D., Editor of *American Medicine;* President, 1893–94, American Academy of Medicine, etc. With many Useful Tables and numerous Fine Illustrations. Large Square Octavo. 1633 pages. Fifth Edition.
Full Sheep or Half Dark-Green Leather, $10.00
With Thumb Index, $11.00; Half Russia, Thumb Index, $12.00

"Few persons read dictionaries as Théophile Gautier did—for pleasure; if, however, all dictionaries were as readable as the one under consideration, his taste for this kind of literature would be less singular. . . . The book is excellently printed, and the illustrations are admirably executed. The binding is substantial and even handsome, but the business-like 'get-up' of the book makes it well fitted for use as well as for the adornment of a book-shelf."—*The British Medical Journal, London.*

The Student's Medical Dictionary. Eleventh Ed. Illustrated.

Enlarged. Including all the Words and Phrases generally used in Medicine, with their proper Pronunciations and Definitions, based on Recent Medical Literature. With Tables of the Bacilli, Micrococci, Leukomains, Ptomains, etc., of the Arteries, Muscles, Nerves, Ganglia, and Plexuses; Mineral Springs of the U. S., etc., and a new Table of Eponymic Terms and Tests. Rewritten, Enlarged, and Improved. **With many Illustrations.** Small octavo. 840 pages.
Half Morocco, $2.50; Thumb Index, $3.00

"One pleasing feature of the book is that the reader can almost invariably find the definition under the word he looks for, without being referred from one place to another, as is too commonly the case in medical dictionaries. The tables of the bacilli, micrococci, leukomains, and ptomains are excellent, and contain a large amount of information in a limited space. The anatomical tables are also concise and clear. . . . We should unhesitatingly recommend this dictionary to our readers, feeling sure that it will prove of much value to them."—*The American Journal of Medical Science.*

☞ *See next page for List of Contributors.*

Gould and Pyle. Compend of Diseases of the Eye.

Including Refraction Treatment and Operations, with a Section on Local Therapeutics. With Formulæ, Glossary, and several Tables. By DRS. GEORGE M. GOULD and W. L. PYLE. Second Edition. 109 Illustrations, several of which are Colored. *No. 8 ? Quiz-Compend ? Series.* Cloth, 80.; Interleaved for Notes, $1.00

Gordinier. The Gross and Minute Anatomy of the Central Nervous System. 261 Illustrations.

By H. C. GORDINIER, A.M., M.D., Professor of Physiology and of the Anatomy of the Nervous System in the Albany Medical College; Member American Neurological Association. With 48 Full-page Plates, and 213 other Illustrations, a number of which are printed in Colors and many of which are original. Large 8vo.

Handsome Cloth, $6.00; Sheep, $7.00; Half Russia, $8.00

"This is an excellent book on a fascinating subject, and the author deserves the thanks of the English-speaking medical world for his labor in getting it up. There are works enough on general anatomy, and dry enough they are, as we all remember only too well; but the anatomy of the nervous system alone is another matter entirely, for it is one of the most interesting of all subjects of medical study at the same time that it is one of the most difficult."—*The Medical Record, N. Y.*

Gorgas' Dental Medicine.

A Manual of Dental Materia Medica and Therapeutics. By FERDINAND J. S. GORGAS, M.D., D.D.S., Professor of the Principles of Dental Science, Oral Surgery, and Dental Mechanism in the Dental Department of the University of Maryland. Seventh Edition, Revised and Enlarged, with many Formulæ. 8vo. *Just Ready.*

Cloth, $4.00; Sheep, $5.00; Half Russia, $6.00

Questions and Answers.

Embracing the Curriculum of the Dental Student. Divided into three parts. By FERDINAND J. S. GORGAS, A.M., M.D., D.D.S., Author of "Dental Medicine," Editor of "Harris' Principles and Practice of Dentistry" and "Harris' Dictionary of Medical Terminology and Dental Surgery," Professor of the Principles of Dental Science, Oral Surgery, etc., in the University of Maryland, Dental Department, Baltimore, Octavo. *Just Ready.* Cloth, $6.00

Gray. A Treatise of Physics.

By ANDREW GRAY, LL.D., F.R.S., Professor of Natural Philosophy in the University of Glasgow. In Three Volumes.

Vol. I. DYNAMICS AND PROPERTIES OF MATTER. 350 Illustrations. Octavo. 688 pages. Cloth, $4.50

Greeff. The Microscopic Examination of the Eye.

By Professor R. GREEFF. Surgeon to the Ophthalmic Department of the Royal Charité Hospital, Berlin. Translated from the Second German Edition by HUGH WALKER, M.A., M.D., Assistant Surgeon and Pathologist to the Ophthalmic Department of the Glasgow Royal Infirmary. 12mo. *Just Ready.* Cloth, $1.25

Greene. The Medical Examination for Life Insurance

and its Associated Clinical Methods. With Chapters on the Insurance of Substandard Risks and Accident Insurance. By CHARLES LYMAN GREENE, M.D., of St. Paul, Clinical Professor of Medicine and Physical Diagnosis in the University of Minnesota. With 99 Illustrations, many of which are original, several being printed in Colors. Second Edition, Revised. Octavo. *In Press.*

Griffith's Graphic Clinical Chart.

Designed by J. P. CROZER GRIFFITH, M.D., Instructor in Clinical Medicine in the University of Pennsylvania. Sample copies free. Put up in loose packages of 50, .50
Price to Hospitals: 500 copies, $4.00; 1000 copies, $7.50.

Groff. Materia Medica for Nurses.

With Questions for Self-examination. By JOHN E. GROFF, Apothecary in the Rhode Island Hospital, Providence; Professor of Materia Medica, Botany, and Pharmacognosy in the Rhode Island College of Pharmacy. Second Edition, Revised and Improved. 12mo. *Just Ready.* Cloth, $1.25

Groves and Thorp. Chemical Technology.

A New and Complete Work. The Application of Chemistry to the Arts and Manufactures. Edited by CHARLES E. GROVES, F.R.S., and WM. THORP, B.SC., F.I.C., assisted by many experts. With numerous Illustrations. *Each volume sold separately.*

Vol. I. FUEL AND ITS APPLICATIONS. 607 Illustrations and 4 Plates. Octavo. Cloth, $5.00; ½ Mor., $6.50

Vol. II. LIGHTING. Candles, Oils, Lamps, etc. By W. Y. DENT, L. FIELD, BOVERTON REDWOOD, and D. A. LOUIS. Illustrated. Octavo. Cloth, $4.00; ½ Mor., $5.50

Vol. III. GAS LIGHTING. By CHARLES HUNT, Manager of the Birmingham Gasworks. Illustrated. Octavo. Cloth, $3.50; ½ Mor., $4.50

Vol. IV. ELECTRIC LIGHTING AND PHOTOMETRY. By ARTHUR G. COOKE, M.A. (Cantab.), Lecturer on Physics and Electric Engineering at the Battersea (London) Polytechnic; and W. J. DIBDIN, F.I.C., F.C.S., late Chemist and Superintending Gas Examiner, London County Council. *Nearly Ready.*

Gowers. Manual of Diseases of the Nervous System.

A Complete Text-Book. By SIR WILLIAM R. GOWERS, M.D., F.R.S., Physician to National Hospital for the Paralyzed and Epileptic, etc. Revised and Enlarged. With many new Illustrations. Two volumes. Octavo.

Vol. I. Diseases of the Nerves and Spinal Cord.

Third Edition. Cloth, $4.00; Sheep, $5.00; Half Russia, $6.00

Vol. II. Brain and Cranial Nerves; General and Functional Diseases.

Second Edition. Cloth, $4.00; Sheep, $5.00; Half Russia, $6.00

*** This book has been translated into German, Italian, and Spanish. It is published in London, Milan, Bonn, Barcelona, and Philadelphia.

Syphilis and the Nervous System.

Being a Revised Reprint of the Lettsomian Lectures for 1890, delivered before the Medical Society of London. 12mo. Cloth, $1.00

Epilepsy and Other Chronic Convulsive Diseases.

Their Causes, Symptoms, and Treatment Second Edition. Cloth, $3.00

Hadley. General Medical and Surgical Nursing.

A Manual for Nurses. By DR. W. G. HADLEY, Physician to, and Lecturer on Medicine to the Nurses at, the London Hospital. With an Appendix on Sick-Room Cookery. 12mo. 326 pages. Cloth, $1.25

Haig. Causation of Disease by Uric Acid. Fifth Edition.

A Contribution to the Pathology of High Arterial Tension, Headache, Epilepsy, Mental Depression, Gout, Rheumatism, Diabetes, Bright's Disease, Anæmia, etc. By ALEXANDER HAIG, M.A., M.D. (Oxon.), F.R.C.P., Physician to Metropolitan Hospital, London. 75 Illustrations. Fifth Edition. 8vo. 846 pages. Cloth, $3.00

Diet and Food.

Considered in Relation to Strength and Power of Endurance, Training and Athletics. Fourth Edition, Revised. 7 Illustrations. Cloth, $1.00

Hall. Diseases of the Nose and Throat.

By F. DE HAVILLAND HALL, M.D., F.R.C.P. (Lond.), Physician to the Westminster Hospital; President of the Laryngological Society of London; Joint Lecturer on the Principles and Practice of Medicine at the Westminster Hospital; and HERBERT TILLEY, M.D., B.S. (Lond.), F.R.C.S. (Eng.), Surgeon to the Throat Hospital, Golden Square; Lecturer on Diseases of the Nose and Throat, London Post-Graduate College and Polyclinic. Second Edition, Thoroughly Revised, with 2 Plates and 80 Illustrations. *Just Ready.* Cloth, $2.75

Hamilton. Lectures on Tumors

from a Clinical Standpoint. By JOHN B. HAMILTON, M.D., LL.D., late Professor of Surgery in Rush Medical College, Chicago; Professor of Surgery, Chicago Polyclinic; Surgeon Presbyterian Hospital, etc. Third Edition, Revised. With New Illustrations. 12mo. Cloth, $1.25

Hansell and Reber. Muscular Anomalies of the Eye.

By HOWARD F. HANSELL, A.M., M.D., Clinical Professor of Ophthalmology, Jefferson Medical College; Professor of Diseases of the Eye, Philadelphia Polyclinic, etc.; and WENDELL REBER, M.D., Instructor in Ophthalmology, Philadelphia Polyclinic, etc. With 1 Plate and 28 other Illustrations. 12mo. Cloth, $1.50

Hansell and Bell. Clinical Ophthalmology.

By HOWARD F. HANSELL, A.M., M.D., and JAMES H. BELL, M.D. With Colored Plate of Normal Fundus and 120 Illustrations. 12mo. Cloth, $1.50

Hare. Mediastinal Disease.

The Pathology, Clinical History, and Diagnosis of Affections of the Mediastinum other than those of the Heart and Aorta. By H. A. HARE, M.D., Professor of Materia Medica and Therapeutics in Jefferson Medical College. 8vo. Illustrated. Cloth, $2.00

Harlan. Eyesight

and How to Care for It. By GEORGE C. HARLAN, M.D., Professor of Diseases of the Eye, Philadelphia Polyclinic. Illustrated. Cloth, .40

Harris' Principles and Practice of Dentistry.

Including Anatomy, Physiology, Pathology, Therapeutics, Dental Surgery, and Mechanism. By CHAPIN A. HARRIS, M.D., D.D.S., late President of the Baltimore Dental College; Author of "Dictionary of Medical Terminology and Dental Surgery." Thirteenth Edition, Revised and Edited by FERDINAND J. S. GORGAS, A.M., M.D., D.D.S., Author of "Dental Medicine;" Professor of the Principles of Dental Science, Oral Surgery, and Dental Mechanism in the University of Maryland. 1250 Illustrations. 1180 pages. 8vo.
Cloth, $6.00; Leather, $7.00; Half Russia, $8.00

Dictionary of Dentistry.

Including Definitions of such Words and Phrases of the Collateral Sciences as Pertain to the Art and Practice of Dentistry. Sixth Edition, Rewritten, Revised, and Enlarged. By FERDINAND J. S. GORGAS, M.D., D.D.S., Author of "Dental Medicine;" Editor of Harris' "Principles and Practice of Dentistry;" Professor of Principles of Dental Science, Oral Surgery, and Prosthetic Dentistry in the University of Maryland. Octavo. Cloth, $5.00; Leather, $6.00

Hartridge. Refraction.

The Refraction of the Eye. A Manual for Students. By GUSTAVUS HARTRIDGE, F.R.C.S., Senior Surgeon Royal Westminster Ophthalmic Hospital; Ophthalmic Surgeon to St. Bartholomew's Hospital, etc. 105 Illustrations and Sheet of Test Types. Eleventh Edition, Revised and Enlarged. *Just Ready.* Cloth, $1.50

On the Ophthalmoscope.

A Manual for Physicians and Students. Fourth Edition, Revised. With Colored Plates and 68 Wood-cuts. 12mo. *Just Ready.* Cloth, $1.50

Hartshorne. Our Homes.

Their Situation, Construction, Drainage, etc. By HENRY HARTSHORNE, M.D. Illustrated. Cloth, .40

Hatfield. Diseases of Children.

By MARCUS P. HATFIELD, Professor of Diseases of Children, Chicago Medical College. With a Colored Plate. Third Edition. *Being No. 14 ? Quiz-Compend ? Series.* 12mo. *Just Ready.* Cloth, .80; Interleaved for the Addition of Notes, $1.00

"Dr. Hatfield seems to have most thoroughly appreciated the needs of students, and most excellently has he condensed his matter into available form. It is in accord with the most recent teachings, and while brief and concise, is surprisingly complete. . . . It is free from irritating repetition of questions and answers which mars so many of the compends now in use. Written in systematic form, the consideration of each disease begins with its definition, and proceeds through the usual subheadings to prognosis and treatment, thus furnishing a complete, readable text-book." —*Annals of Gynecology and Pediatry.*

Heath. Minor Surgery and Bandaging.

By CHRISTOPHER HEATH, F.R.C.S., Holme Professor of Clinical Surgery in University College, London. Twelfth Edition, Revised and Enlarged by BILTON POLLARD, F.R.C.S., Surgeon University College Hospital, London. With 195 Illustrations, Formulæ, Diet List, etc. 12mo. Cloth, $1.50

Practical Anatomy.

A Manual of Dissections. Ninth edition, Edited by H. ERNEST LANE, F.R.C.S. With 321 Illustrations, of which 32 are Colored. Cloth, $4.25

Clinical Lectures on Surgical Subjects.

Second series. Delivered at University College Hospital. Cloth, $2.00

Hedley. Therapeutic Electricity and Practical Muscle Testing.

By W. S. HEDLEY, M.D., M.R.C.S., in charge of the Electrotherapeutic Department of the London Hospital. 99 Illustrations. Octavo. Cloth, $2.50

Heller. Essentials of Materia Medica, Pharmacy, and Prescription Writing.

By EDWIN A. HELLER, M.D., Quiz-Master in Materia Medica and Pharmacy at the Medical Institute, University of Pennsylvania. 12mo. Cloth, $1.50

Henry. Anæmia.

A Practical Treatise. By FRED'K P. HENRY, M.D., Physician to Episcopal Hospital, Philadelphia. Half Cloth, .50

Heusler. The Terpenes.

By FR. HEUSLER, PH.D., Privatdocent of Chemistry in the University at Bonn. Authorized Translation and Revision by F. J. Pond, PH.D., Assistant Professor of Chemistry, Pennsylvania State College. Cloth, $4.00

Hemmeter. Diseases of the Stomach. Third Edition.

Their Special Pathology, Diagnosis, and Treatment. With Sections on Anatomy, Analysis of Stomach Contents, Dietetics, Surgery of the Stomach, etc. By JOHN C. HEMMETER, M.D., PHILOS.D., Professor in the Medical Department of the University of Maryland; Consultant to the University Hospital; Director of the Clinical Laboratory, etc.; formerly Clinical Professor of Medicine at the Baltimore Medical College, etc. Third Edition, Revised. With 15 Plates and 41 other Illustrations, some of which are in Colors. Cloth, $6.00; Leather, $7.00; Half Russia, $8.00

Diseases of the Intestines.

A Complete Systematic Treatise on Diseases of the Intestines, including their Special Pathology, Diagnosis, and Treatment, with Sections on Anatomy and Physiology, Microscopic and Chemic Examination of the Intestinal Contents, Secretions, Feces, and Urine. Intestinal Bacteria and Parasites; Surgery of the Intestines; Dietetics, Diseases of the Rectum, etc. With many Full-page Plates, Colored and other Illustrations, most of which are Original. 2 vols. Octavo. *Just Ready.* Vol. I. Cloth, $5.00; Sheep, $6.00
Vol. II. Cloth, $5.00; Sheep, $6.00

THE SECTION ON ANATOMY has been prepared by DR. J. HOLMES SMITH, Associate Professor and Demonstrator of Anatomy, and Lecturer on Clinical Surgery, University of Maryland, Baltimore. THE SECTION ON BACTERIA OF THE INTESTINES has been prepared by DR. WM. ROYAL STOKES, Associate Professor of Pathology and Bacteriology, and Visiting Pathologist to the University Hospital, University of Maryland, Baltimore. THE SECTION ON DISEASES OF THE RECTUM has been prepared by DR. THOMAS C. MARTIN, Professor of Proctology, Cleveland College of Physicians and Surgeons. THE SECTION ON EXAMINATION OF URINE AND FECES has been prepared by DR. HARRY ADLER, Demonstrator of Clinical Pathology, Associate Professor of Diseases of the Stomach and Intestines, University of Maryland, Baltimore. THE ILLUSTRATIONS form a most useful and practical series of pictures,—nearly all have been reproduced from pathological preparations and original drawings, a few being printed in several colors.

Hewlett. Manual of Bacteriology. 75 Illustrations.

By R. T. HEWLETT, M.D., M.R.C.P., Assistant Bacteriologist British Institute of Preventive Medicine, etc. Second Edition, Revised. *Just Ready.* Cloth, $4.00

Hollopeter. Hay Fever and Its Successful Treatment.

By W. C. HOLLOPETER, A.M., M.D., Clinical Professor of Pediatrics in the Medico-Chirurgical College of Philadelphia; Physician to the Methodist Episcopal, Medico-Chirurgical, and St. Joseph's Hospitals, etc. Second Edition. 12mo. Cloth, $1.00

Holden's Anatomy. Seventh Edition.

A Manual of the Dissections of the Human Body. By JOHN LANGTON, F.R.C.S., Surgeon to, and Lecturer on Anatomy at, St. Bartholomew's Hospital. Carefully Revised by A. HEWSON, M.D., Demonstrator of Anatomy, Jefferson Medical College, Philadelphia, etc. 320 Illustrations. Two small compact volumes. 12mo.

Vol. I. Scalp, Face, Orbit, Neck, Throat, Thorax, Upper Extremity. 435 pages. 153 Illustrations. Oil Cloth, $1.50

Vol. II. Abdomen, Perineum, Lower Extremity, Brain, Eye, Ear, Mammary Gland, Scrotum, Testes. 445 pages. 167 Illustrations. Oil Cloth, $1.50

Human Osteology.

Comprising a Description of the Bones, with Colored Delineations of the Attachments of the Muscles. The General and Microscopical Structure of Bone and its Development. Eighth Edition, Carefully Revised. Edited by CHARLES STEWART, F.R.S., and R. W. REID, M.D., F.R.C.S. With Colored Lithographic Plates and Numerous Illustrations. Cloth, $5.25

Landmarks.

Medical and Surgical. Fourth Edition. 8vo. Cloth, .75

Holland. The Urine, the Gastric Contents, the Common Poisons, and the Milk. Illustrated.

Memoranda (Chemical and Microscopical) for Laboratory Use. By J. W. HOLLAND, M.D., Professor of Medical Chemistry and Toxicology in Jefferson Medical College of Philadelphia. Sixth Edition, Enlarged. Illustrated and Interleaved. 12mo. Cloth, $1.00

Horwitz's Compend of Surgery.

Including Minor Surgery, Amputations, Bandaging, Fractures, Dislocations, Surgical Diseases, etc., with Differential Diagnosis and Treatment. By ORVILLE HORWITZ, B.S., M.D., Professor of Genito-Urinary Diseases, late Demonstrator of Surgery, Jefferson Medical College. Fifth Edition. 167 Illustrations and 98 Formulæ. 12mo. *No. 9 ? Quiz-Compend ? Series.* Cloth, .80; Interleaved for Notes, $1.00

*** *A Spanish translation of this book has recently been published in Barcelona.*

Horsley. The Brain and Spinal Cord,

the Structure and Functions of. By VICTOR A. HORSLEY, M.B., F.R.S., etc., Assistant Surgeon University College Hospital, London, etc. Illustrated. Cloth, $2.50

Hovell. Diseases of the Ear and Naso-Pharynx.

A Treatise including Anatomy and Physiology of the Organ, together with the treatment of the affections of the Nose and Pharynx which conduce to aural disease. By T. MARK HOVELL, F.R.C.S. (Edin.), M.R.C.S. (Eng.), Aural Surgeon to the London Hospital for Diseases of the Throat, etc. 128 Illus. Second Edition. Cloth, $5.50

Humphrey. A Manual for Nurses. Twenty-third Edition.

Including General Anatomy and Physiology, Management of the Sick-room, etc. By LAURENCE HUMPHREY, M.A., M.B., M.R.C.S., Assistant Physician to Addenbrook's Hospital, Cambridge, England. 23d Edition. 12mo. 79 Illustrations. Cloth, $1.00

Hughes and Keith. Dissections. Illustrated.

A Manual of Dissections by ALFRED W. HUGHES, M.B., M.R.C.S. (Edin.), late Professor of Anatomy and Dean of Medical Faculty, King's College, London, etc., and ARTHUR KEITH, M.D., Lecturer on Anatomy, London Hospital Medical College, etc. In three parts, with many Colored and other Illustrations.

I. Upper and Lower Extremity. 38 Plates, 116 other Illustrations. *Just Ready.* Cloth, $3.00

II. Abdomen. Thorax. 4 Plates, 149 other Illus. *Just Ready.* Cloth, $3.00

III. Head, Neck, and Central Nervous System. 16 Plates and 204 other Illustrations. *Just Ready.* Cloth, $3.00

Hughes. Compend of the Practice of Medicine. Sixth Edition.

Giving the Synonyms, Definition, Causes, Symptoms, Pathology, Prognosis, Diagnosis, Treatment, etc., of each Disease. The Treatment is especially full and a number of valuable Prescriptions have been incorporated. Sixth Edition, Revised and Enlarged. By DANIEL E. HUGHES, M.D., Chief Resident Physician Philadelphia Hospital; formerly Demonstrator of Clinical Medicine at Jefferson Medical College, Philadelphia. *Being Nos. 2 and 3 ? Quiz-Compend ? Series.*

Quiz-Compend Edition, in two Parts.

PART I.—Continued, Eruptive, and Periodical Fevers, Diseases of the Mouth, Stomach, Intestines, Peritoneum, Biliary Passages, Liver, Kidneys, Blood, etc., Parasites, etc., and General Diseases, etc.

PART II.—Physical Diagnosis, Diseases of the Respiratory System, Circulatory System, Diseases of the Brain and Nervous System, Mental Diseases, etc.

Price of each Part, in Cloth, .80; Interleaved for the Addition of Notes, $1.00

Physicians' Edition.

In one volume, including the above two parts, a Section on Skin Diseases, and an Index. *Sixth Revised and Enlarged Edition. 625 pages.*

Full Morocco, Gilt Edges, Round Corners, $2.25

Kirkes' Physiology. Seventeenth Edition.

(*The only Authorized Edition. 12mo. Dark Red Cloth.*) A Handbook of Physiology. Seventeenth London Edition, Revised and Enlarged. By W. D. HALLIBURTON, M.D., F.R.S., Professor of Physiology, King's College, London. Thoroughly Revised and in many parts Rewritten. 681 Illustrations, a number of which are printed in Colors. 888 pages. 12mo. Cloth, $3.00; Leather, $3.75

IMPORTANT NOTICE. This is the identical Edition of "Kirkes' Physiology," as published in London by John Murray, the sole owner of the book, and containing the revisions and additions of Dr. Halliburton, and the new and original illustrations included at his suggestion. This edition has been carefully and thoroughly revised.

Kleen. Diabetes Mellitus and Glycosuria.

Their Diagnosis and Treatment. By DR. EMIL KLEEN. Octavo. Cloth, $2.50

Knight. Diseases of the Throat.

A Manual for Students. By CHARLES H. KNIGHT, M.D., Professor of Laryngology, Cornell University Medical College; Surgeon to Throat Department, Manhattan Eye and Ear Hospital, etc. Illustrated. *Nearly Ready.*

Knopf. Pulmonary Tuberculosis. Its Modern Prophylaxis and the Treatment in Special Institutions and at Home.

By S. A. KNOPF, M.D., Physician to the Lung Department of the New York Throat and Nose Hospital; former Assistant Physician to Professor Dettweiler, Falkenstein Sanatorium, Germany, etc. Illustrated. Octavo. Cloth, $3.00

Kyle. Diseases of the Ear, Nose, and Throat.

A Compend for Students and Physicians. By JOHN J. KYLE, M.D. Illus. *In Press.*

Landis' Compend of Obstetrics.

By HENRY G. LANDIS, M.D. Seventh Edition, Revised by WM. H. WELLS, M.D., Demonstrator of Clinical Obstetrics, Jefferson Medical College; Member Obstetrical Society of Philadelphia, etc. With 52 Illustrations. *No. 5 ?Quiz-Compend? Series.* Cloth, .80; Interleaved for the Addition of Notes, $1.00

Landois. A Text-Book of Human Physiology.

Including Histology and Microscopical Anatomy, with Special Reference to the Requirements of Practical Medicine. By DR. L. LANDOIS, Professor of Physiology and Director of the Physiological Institute in the University of Greifswald. Fifth American translated from the last German Edition, with Additions, by WM. STIRLING, M.D., D.Sc., Brackenbury Professor of Physiology and Histology in Owens College, and Professor in Victoria University, Manchester. With 845 Illustrations, many of which are printed in Colors. 8vo. *In Press.*

Lazarus-Barlow. Pathological Anatomy.

By W. S. LAZARUS-BARLOW, M.D., Demonstrator of Pathology at the University of Cambridge, England. 705 pages. Octavo. Cloth, $6.50

Lee. The Microtomist's Vade Mecum. Fifth Edition.

A Handbook of the Methods of Microscopic Anatomy. By ARTHUR BOLLES LEE, formerly Assistant in the Russian Laboratory of Zoology at Villefranche-sur-Mer (Nice). 894 Articles. Enlarged, Revised, and Rearranged. 532 pages. 8vo. Cloth, $4.00

Leffmann and Beam. Food Analysis. Illustrated.

Select Methods in Food Analysis. By HENRY LEFFMANN, M.D., Professor of Chemistry in the Woman's Medical College of Pennsylvania and in the Wagner Free Institute of Science; Pathological Chemist, Jefferson Medical College Hospital, Philadelphia; Vice-President (1901) Society Public Analysts, etc.; and WILLIAM BEAM, A.M. With many useful Tables, 4 Plates and 53 other Illustrations. 12mo. Cloth, $2.50

Leffmann. Compend of Medical Chemistry.

Inorganic and Organic. Including Urine Analysis. By HENRY LEFFMANN, M.D., Professor of Chemistry in the Woman's Medical College of Pennsylvania and in the Wagner Free Institute of Science, Philadelphia; Pathological Chemist Jefferson Medical College Hospital, etc. *No. 10 ? Quiz-Compend ? Series.* Fourth Edition, Rewritten.
Cloth, .80; Interleaved for the Addition of Notes, $1.00

The Coal-Tar Colors.

With Special Reference to their Injurious Qualities and the Restrictions of their Use. A Translation of Theodore Weyl's Monograph. 12mo. Cloth, $1.25

Examination of Water

for Sanitary and Technical Purposes. Fourth Edition, Enlarged. Illustrated. 12mo. Cloth, $1.25

Analysis of Milk and Milk Products.

Arranged to suit the needs of Analytical Chemists, Dairymen, and Milk Inspectors. Second Edition, Revised and Enlarged. Illustrated. 12mo. Cloth, $1.25

Handbook of Structural Formulæ

for the Use of Students, containing 180 Structural and Stereo-chemic Formulæ. 12mo. Interleaved. Cloth, $1.00

Lewers. On the Diseases of Women.

A Practical Treatise. By DR. A. H. N. LEWERS, Obstetric Physician to the London Hospital. 146 Engravings. Fifth Edition, Revised. Cloth, $2.50

Cancer of the Uterus.

A Clinical Monograph on its Diagnosis and Treatment, with the After-Results in Seventy-three Cases Treated by Radical Operation. With 51 Original Illustrations and 3 Colored Plates. 8vo. 328 pages. Cloth, $3.00

Lewis (Bevan). Mental Diseases.

A Text-Book having Special Reference to the Pathological Aspects of Insanity. By BEVAN LEWIS, L.R.C.P., M.R.C.S., Medical Director West Riding Asylum, Wakefield, England. 26 Lithograph Plates and other Illustrations. Second Edition, Revised and Enlarged. 8vo. Cloth, $7.00

Lincoln. School and Industrial Hygiene.

By D. F. LINCOLN, M.D. Cloth, .40

Longley's Pocket Medical Dictionary.

Giving the Definition and Pronunciation of Words and Terms in General Use in Medicine. With an Appendix, containing Poisons and their Antidotes, Abbreviations Used in Prescriptions, etc. By ELIAS LONGLEY. Cloth, .75; Tucks and Pocket, $1.00

Macalister's Human Anatomy. 816 Illustrations.

Systematic and Topographical, including the Embryology, Histology, and Morphology of Man. With Special Reference to the Requirements of Practical Surgery and Medicine. By ALEX. MACALISTER, M.D., F.R.S., Professor of Anatomy in the University of Cambridge. 816 Illustrations. Octavo. Cloth, $5.00; Leather, $6.00

McBride. Diseases of the Throat, Nose, and Ear.

A Clinical Manual for Students and Practitioners. By P. MCBRIDE, M.D., F.R.C.P. (Edin.); Lecturer on Diseases of Throat and Ear, Edinburgh School of Medicine, etc. With Colored Illustrations from Original Drawings. Third Edition, Revised and Enlarged. Octavo. Cloth, Gilt Top, $7.00

McCook. American Spiders and Their Spinning Work.

A Natural History of the Orbweaving Spiders of the United States. By HENRY C. MCCOOK, D.D., Vice-President of the Academy of Natural Sciences of Philadelphia, etc. Three volumes. Handsomely Illustrated in Colors. Cloth, $40.00

Macready. A Treatise on Ruptures.

By JONATHAN F. C. H. MACREADY, F.R.C.S., Surgeon to the Great Northern Central Hospital; to the City of London Hospital for Diseases of the Chest, etc. 24 Full-page Plates and Wood Engravings. Octavo. Cloth, $6.00

McFarland. Prophylaxis—Personal Hygiene—Nursing and Care of the Sick.

See COHEN, Physiologic Therapeutics, page 10.

McMurrich. The Development of the Human Body.

A Manual of Human Embryology. By J. PLAYFAIR MCMURRICH, A.M., PH.D., Professor of Anatomy, Medical Department of the University of Michigan, Ann Arbor. 276 Illustrations. Cloth, $3.00

Makins. Surgical Experiences in South Africa, 1899–1900.

Being mainly a Clinical Study of the Effects of Injuries Produced by Bullets of Small Calibre. By GEORGE HENRY MAKINS, F.R.C.S., Surgeon to St. Thomas's Hospital, London; and late one of the Consulting Surgeons to the South African Field Force. With 25 Plates and 96 other Illustrations. Octavo. Cloth, $4.00

Mann. Forensic Medicine and Toxicology.

By J. DIXON MANN, M.D., F.R.C.P., Professor of Medical Jurisprudence and Toxicology in Owens College, Manchester, etc. Illustrated. Octavo. Cloth, $6.50

Mann's Manual of Psychological Medicine

and Allied Nervous Diseases. Their Diagnosis, Pathology, Prognosis, and Treatment, including their Medico-Legal Aspects. With Chapter on Expert Testimony and an Abstract of the Laws Relating to the Insane in all the States of the Union. By EDWARD C. MANN, M.D. With Illustrations. Octavo. Cloth, $3.00

Marshall's Physiological Diagrams, Life Size, Colored.

Eleven Life-size Diagrams (each 7 feet by 3 feet 7 inches). Designed for Demonstration before the Class. By JOHN MARSHALL, F.R.S., F.R.C.S., Professor of Anatomy to the Royal Academy; Professor of Surgery, University College, London, etc. In Sheets, $40.00; Backed with Muslin and Mounted on Rollers, $60.00
Ditto, Spring Rollers, in Handsome Walnut Map Case, $100.00
Single Plates, Sheets, $5.00; Mounted, $7.50; Explanatory Key, 50 cents.
Purchaser must pay freight charges.

No. 1—The Skeleton and Ligaments. No. 2—The Muscles and Joints, with Animal Mechanics. No. 3—The Viscera in Position. No. 4—The Heart and Principal Blood-vessels. No. 5—The Lymphatics. No. 6—The Digestive Organs. No. 7—The Brain and Nerves. Nos. 8 and 9—The Organs of the Senses. Nos. 10 and 11—The Microscopic Structure of the Textures and Organs. (*Send for Special Circular.*)

Maxwell. Terminologia Medica Polyglotta.

By DR. THEODORE MAXWELL. Octavo. Cloth, $3.00

The object of this work is to assist the medical men of any nationality in reading medical literature written in a language not their own. Each term is usually given in seven languages, viz.: English, French, German, Italian, Spanish, Russian, and Latin.

Maylard. The Surgery of the Alimentary Canal.

By ALFRED ERNEST MAYLARD, M.B., B.S., Senior Surgeon to the Victoria Infirmary, Glasgow. Second Edition. 97 Illustrations. Octavo. Cloth, $3.00

Mays' Theine in the Treatment of Neuralgia.

By THOMAS J. MAYS, M.D. 16mo. ½ bound, .50

Memminger. Diagnosis by the Urine.

The Practical Examination of Urine, with Special Reference to Diagnosis. By ALLARD MEMMINGER, M.D., Professor of Chemistry and Hygiene; Clinical Professor of Urinary Diagnosis in the Medical College of the State of South Carolina; Visiting Physician in the City Hospital of Charleston, etc. Second Edition, Enlarged and Revised. 24 Illustrations. 12mo. Cloth, $1.00

Minot. Embryology.

A Laboratory Text-Book of Embryology. By CHARLES S. MINOT, S.D., LL.D., Professor of Histology and Human Embryology, Harvard University Medical School. Illustrated. Cloth, $4.50

Montgomery. A Text-Book of Practical Gynecology.

By EDWARD E. MONTGOMERY, M.D., Professor of Gynecology in Jefferson Medical College, Philadelphia; Gynecologist to the Jefferson and St. Joseph's Hospitals, etc. 527 Illustrations, many of which are from original sources. 800 pages. Octavo. Cloth, $5.00; Leather, $6.00

*** This is a systematic modern treatise on Diseases of Women. The author's aim has been to produce a book that will be thorough and practical in every particular. The illustrations, nearly all of which are from original sources, have for the most part been drawn by special artists.

"The author has a clear conception of his subject; this, with his manner of treatment, introduces the reader to questions otherwise intricate in such a manner as to make them easily comprehended. His introduction, together with his comments on diagnosis and examination of the patient are delightfully clear and instructive. Therapeutics, local and systematic, are clearly and intelligently discussed."—*Brooklyn Medical Journal.*

Morris. Text-Book of Anatomy. Third Edition. 846 Illustrations, 267 in Colors.

A Complete Text-Book. Edited by HENRY MORRIS, F.R.C.S., Surgeon to, and Lecturer on Anatomy at, Middlesex Hospital, assisted by PETER THOMPSON, M.D., J. BLAND SUTTON, F.R.C.S., J. H. DAVIES-COLLEY, F.R.C.S., WM. J. WALSHAM, F.R.C.S., H. ST. JOHN BROOKS, M.D., R. MARCUS GUNN, F.R.C.S., ARTHUR HENSMAN, F.R.C.S., FREDERICK TREVES, F.R.C.S., WILLIAM ANDERSON, F.R.C.S., ARTHUR ROBINSON, M.D., M.R.C.S., and PROF. W. H. A. JACOBSON. One Handsome Octavo Volume, with 846 Illustrations, of which 267 are printed in Colors. *Thumb Index and Colored Illustrations in all Copies.* Cloth, $6.00; Leather, $7.00; Half Russia, $8.00

"Of all the text-books of moderate size on human anatomy in the English language, Morris is undoubtedly the most up-to-date and accurate. . . . For the student, the surgeon, or for the general practitioner who desires to review his anatomy, Morris is decidedly the book to buy."—*The Philadelphia Medical Journal.*

*** MORRIS' ANATOMY is now the recognized standard text-book in a large number of medical schools throughout the United States, England, and Canada. It is in many respects the best book for students' use, and in its present edition is the latest and best illustrated of all books on anatomy. The revisions have been carefully made and edited, several sections having been almost entirely rewritten, old illustrations replaced and new ones added, a larger number being printed in colors.

Renal Surgery.

With Special Reference to Stone in the Kidney and Ureter, and to the Surgical Treatment of Calculous Anuria, together with a Critical Examination of Subparietal Injuries of the Ureter. Illustrated. 8vo. Cloth, $2.00

Mitchell and Gulick. Mechanotherapy.

See COHEN, Physiologic Therapeutics, page 10.

Morton on Refraction of the Eye.

Its Diagnosis and the Correction of its Errors. With Chapter on Keratoscopy and Test Types. By A. MORTON, M.B. Sixth Edition, Revised. Cloth, $1.00

Moullin. Surgery. Third Edition, by Hamilton.

A Complete Text-Book. By C. W. MANSELL MOULLIN, M.A., M.D. (Oxon.), F.R.C.S., Surgeon and Lecturer on Physiology to the London Hospital; formerly Radcliffe Traveling Fellow and Fellow of Pembroke College, Oxford. Third American Edition, Revised and Edited by the late JOHN B. HAMILTON, M.D., LL.D., Professor of the Principles of Surgery and Clinical Surgery, Rush Medical College, Chicago; Professor of Surgery, Chicago Polyclinic; Surgeon, formerly Supervising Surgeon-General, U. S. Marine Hospital Service; Surgeon to Presbyterian Hospital. 600 Illustrations, over 200 of which are original, and many of which are printed in Colors. Octavo. 1250 pages. Cloth, $6.00; Leather, $7.00; Half Russia, $8.00

Enlargement of the Prostate.

Its Treatment and Radical Cure. Illustrated. Second Edition, Enlarged. Octavo. Cloth, $1.75

Inflammation of the Bladder and Urinary Fever.

Octavo. Cloth, $1.50

Murray. Rough Notes on Remedies.

By WM. MURRAY, M.D., F.R.C.P. (Lond.), Consulting Physician Newcastle-on-Tyne Hospital for Sick Children. Fourth Edition, Enlarged. Crown 8vo. Cloth, $1.25

Muter. Practical and Analytical Chemistry.

By JOHN MUTER, F.R.S., F.C.S., etc. Second American from the Eighth English Edition. Revised to meet the Requirements of American Medical and Pharmaceutical Colleges. 56 Illustrations. Cloth, $1.25

New Sydenham Society Publications.

From three to six volumes published each year. *List of Volumes upon application.* Per annum, $8.00

Notter. The Theory and Practice of Hygiene. Second Edition.

A Complete Treatise by J. LANE NOTTER, M.A., M.D., F.C.S., Fellow and Member of Council of the Sanitary Institute of Great Britain; Professor of Hygiene, Army Medical School; Examiner in Hygiene, University of Cambridge, etc.; and W. H. HORROCKS, M.D., B. Sc. (Lond.), Assistant Professor of Hygiene, Army Medical School, Netley. Illustrated by 15 Lithographic Plates and 138 other Illustrations, and including many Useful Tables. Second Edition, Carefully Revised. Octavo. 1085 pages. Cloth, $7.00

Oertel. Medical Microscopy.

A Guide to Diagnosis, Elementary Laboratory Methods, and Microscopic Technic. By T. E. OERTEL, M.D., Professor of Histology, Pathology, Bacteriology, and Clinical Microscopy, Medical Department, University of Georgia. 12mo. 131 Illustrations. Cloth, $2.00

Oettel. Practical Exercises in Electro-Chemistry.

By DR. FELIX OETTEL. Authorized Translation by EDGAR F. SMITH, M.A., Professor of Chemistry, University of Pennsylvania. Illustrated. Cloth, .75

Introduction to Electro-Chemical Experiments.

Illustrated. By same Author and Translator. Cloth, .75

Potter. Speech and Its Defects.

Considered Physiologically, Pathologically, and Remedially; being the Lea Prize Thesis of Jefferson Medical College, 1882. Revised and Corrected. Cloth, $1.00

Power. Surgical Diseases of Children

and their Treatment by Modern Methods. By D'ARCY POWER, M.A., F.R.C.S. (Eng.), Demonstrator of Operative Surgery, St. Bartholomew's Hospital; Surgeon to the Victoria Hospital for Children. Illustrated. 12mo. Cloth, $2.50

Preston. Hysteria and Certain Allied Conditions.

Their Nature and Treatment. With Special Reference to the Application of the Rest Cure, Massage, Electrotherapy, Hypnotism, etc. By GEORGE J. PRESTON, M.D., Professor of Diseases of the Nervous System, College of Physicians and Surgeons, Baltimore; Visiting Physician to the City Hospital; Consulting Neurologist to Bay View Asylum and the Hebrew Hospital; Member American Neurological Association, etc. Illustrated. 12mo. Cloth, $2.00

Pritchard. Handbook of Diseases of the Ear.

By URBAN PRITCHARD, M.D., F.R.C.S., Professor of Aural Surgery, King's College, London; Aural Surgeon to King's College Hospital; Senior Surgeon to the Royal Ear Hospital, etc. Fourth Edition. Many Illustrations and Formulæ. *In Press.*

Proctor's Practical Pharmacy.

Lectures on Practical Pharmacy. By BARNARD S. PROCTOR. Third Edition, Revised. With Elaborate Tables of Chemical Solubilities, etc. Illustrated. Cloth, $3.00

Reese's Medical Jurisprudence and Toxicology.

A Text-Book for Medical and Legal Practitioners and Students. By JOHN J. REESE, M.D., Editor of "Taylor's Jurisprudence," formerly Professor of the Principles and Practice of Medical Jurisprudence, including Toxicology, in the University of Pennsylvania Medical Department. Sixth Edition, Revised and Edited by HENRY LEFFMANN, M.D., Pathological Chemist, Jefferson Medical College Hospital; Chemist, State Board of Health; Professor of Chemistry, Woman's Medical College of Pennsylvania, etc. 12mo. 660 pages. Cloth, $3.00; Leather, $3.50

"To the student of medical jurisprudence and toxicology it is invaluable, as it is concise, clear, and thorough in every respect."—*The American Journal of the Medical Sciences.*

Reeves. Medical Microscopy.

Including Chapters on Bacteriology, Neoplasms, Urinary Examination, etc. By JAMES E. REEVES, M.D., ex-President American Public Health Association, etc. Numerous Illustrations, some of which are printed in Colors. 12mo. Cloth, $2.50

Régis. Mental Medicine.

A Practical Manual. By DR. E. RÉGIS, formerly Chief of Clinique of Mental Diseases, Faculty of Medicine of Paris. Authorized Translation by H. M. BANNISTER, M.D., late Senior Assistant Physician, Illinois Eastern Hospital for the Insane, etc. With an Introduction by the Author. 12mo. Cloth, $2.00

Richardson. Long Life

and How to Reach It. By J. G. RICHARDSON, formerly Professor of Hygiene, University of Pennsylvania. Cloth, .40

Rockwood. Chemical Analysis.

Introduction to Chemical Analysis for Students of Medicine, Pharmacy, and Dentistry. By ELBERT W. ROCKWOOD, B.S., M.D., Professor of Chemistry, Toxicology, and Metallurgy in the Colleges of Medicine, Dentistry, and Pharmacy, University of Iowa, Iowa City. Illustrated. Cloth, $1.50

Richardson's Mechanical Dentistry.

A Practical Treatise on Mechanical Dentistry. By JOSEPH RICHARDSON, D.D.S. Seventh Edition, Thoroughly Revised and in many parts Rewritten by GEO. W. WARREN, A.M., D.D.S., Professor of Clinical Dentistry and Oral Surgery; Chief of the Clinical Staff, Pennsylvania College of Dental Surgery, Philadelphia. With 691 Illustrations. Octavo. 675 pages. Cloth, $5.00; Leather, $6.00

Richter's Inorganic Chemistry.

A Text-Book for Students. By PROF. VICTOR VON RICHTER, University of Breslau. Fifth American from Tenth German Edition by PROF. H. KLINGER, University of Königsberg. Authorized Translation by EDGAR F. SMITH, M.A., PH.D., SC.D., Professor of Chemistry, University of Pennsylvania; Member of the Chemical Society of Berlin, etc. With many Illustrations and a Colored Plate. 12mo. Cloth, $1.75

Organic Chemistry.

The Chemistry of the Carbon Compounds. Third American Edition, Translated from PROF. ANSCHÜTZ'S Eighth German Edition by EDGAR F. SMITH, M.A., PH.D., SC.D., Professor of Chemistry, University of Pennsylvania. Revised and Enlarged. Illustrated. 12mo. Two volumes.

Vol. I. Aliphatic Series. 625 pages. Cloth, $3.00
Vol. II. Carbocyclic and Heterocyclic Series. 671 pages. Cloth, $3.00

Roberts. Gynecological Pathology.

Gynecological Pathology. By CHARLES HURBERT ROBERTS, M.D., F.R.C.S., M.R.C.P., Physician Queen Charlotte's Lying-in Hospital and to the Samaritan Hospital for Women; Demonstrator of Practical Midwifery and Diseases of Women, and House Surgeon St. Bartholomew's Hospital, London. Elaborately Illustrated with 127 Full-Page Plates containing 151 Figures, several being printed in Colors. Octavo. Extra Cloth, Gilt Top, $6.00

"This very attractive volume will be appreciated by all who teach gynecology or who deal practically with diseases of the female reproductive organs."—*Edinburgh Medical Journal.*

"This is a splendid volume, worthy the careful study of every physician who seeks to understand the diseased conditions he so often meets with in his female patients."—*Annals of Gynecology and Pediatry.*

Robinson. Latin Grammar of Pharmacy and Medicine.

By D. H. ROBINSON, PH.D., Professor of Latin Language and Literature, University of Kansas. Introduction by L. E. SAYRE, PH.G., Professor of Pharmacy and Dean of the Department of Pharmacy in University of Kansas. Third Edition, Revised with the help of PROF. L. E. SAYRE, of University of Kansas, and DR. CHARLES RICE, of the College of Pharmacy of the City of New York. Cloth, $1.75

"This method of preparing medical students and pharmacists for a practical use of the language is in every way to be commended. . . . Pharmacists should know enough to read prescriptions readily and understandingly."—*Johns Hopkins Hospital Bulletin.*

Rosenau. Disinfection and Disinfectants.

A Practical Guide for Sanitarians, Health and Quarantine Officers. By M. J. ROSENAU, M.D., Director of the Hygienic Laboratory and Passed Assistant Surgeon, U. S. Marine Hospital Service, Washington, D. C. Illustrated. *Just Ready.* Cloth, $2.00

Sayre. Organic Materia Medica and Pharmacognosy.

An Introduction to the Study of the Vegetable Kingdom and the Vegetable and Animal Drugs. Comprising the Botanical and Physical Characteristics, Source, Constituents, Pharmacopœial Preparations; Insects Injurious to Drugs, and Pharmacal Botany. By L. E. SAYRE, B.S., PH.M., Dean of the School of Pharmacy and Professor of Materia Medica and Pharmacy in the University of Kansas; Member Committee of Revision of the United States Pharmacopœia, etc. With Sections on Histology and Microtechnique by WILLIAM C. STEVENS, Professor of Botany in the University of Kansas. Second Edition, Revised and Enlarged. With 374 Illustrations, the majority of which are from Original Drawings. 8vo. Cloth, $4.50

Starling. Elements of Human Physiology.

By ERNEST H. STARLING, M.D. (Lond.), M.R.C.P., Joint Lecturer on Physiology at Guy's Hospital, London, etc. With 100 Illus. 12mo. 437 pages. Cloth, $1.00

Starr. The Digestive Organs in Childhood.

The Diseases of the Digestive Organs in Infancy and Childhood, with Chapters on the Investigation of Disease, The Management of Children, Massage, etc. By LOUIS STARR, M.D., late Clinical Professor of Diseases of Children in the Hospital of the University of Pennsylvania; Physician to the Children's Hospital, Philadelphia. Third Edition, Revised and Enlarged. Illustrated. Octavo. Cloth, $3.00

The Hygiene of the Nursery.

Including the General Regimen and Feeding of Infants and Children, and the Domestic Management of the Ordinary Emergencies of Early Life, Massage, etc. Sixth Edition, Enlarged. 25 Illustrations. 12mo. Cloth, $1.00

*** General and specific rules for feeding are given, and Diet Lists from the first week up to the eighteenth month, with various recipes for artificial foods, peptonized milk, etc. Directions for the sterilization of milk, substitutes for milk, preparation of food for both well and sick children, nutritious enemata, etc., and the general management of the Nursery.

Stearns. Lectures on Mental Diseases.

By HENRY PUTNAM STEARNS, M.D., Physician-Superintendent at the Hartford Retreat; Lecturer on Mental Diseases in Yale University. With a Digest of Laws of the Various States Relating to Care of Insane. Illustrated. Cloth, $2.75; Sheep, $3.25

Steell. The Physical Signs of Pulmonary Disease.

By GRAHAM STEEL, M.D., F.R.C.P., Lecturer on Clinical Medicine and on Diseases of the Heart at Owens College, Manchester. Illustrated. Cloth, $1.25

Stevenson and Murphy. A Treatise on Hygiene.

By Various Authors. Edited by THOMAS STEVENSON, M.D., F.R.C.P., Lecturer on Chemistry and Medical Jurisprudence at Guy's Hospital, London, and SHIRLEY F. MURPHY, Medical Officer of Health to the County of London. In three octavo volumes.

Vol. I. With Plates and Wood Engravings. Octavo. Cloth, $6.00
Vol. II. With Plates and Wood Engravings. Octavo. Cloth, $6.00
Vol. III. Sanitary Law. Octavo. Cloth, $5.00

*** *Special Circular upon application.*

Stewart's Compend of Pharmacy.

Based upon "Remington's Text-Book of Pharmacy." By F. E. STEWART, M.D., PH.G., late Quiz-Master in Chemistry and Theoretical Pharmacy, Philadelphia College of Pharmacy; Lecturer on Pharmacology, Jefferson Medical College. Fifth Edition. Complete Tables of Metric and English Weights and Measures. *? Quiz-Compend ? Series.* Cloth, .80; Interleaved for the Addition of Notes, $1.00

Stirling. Outlines of Practical Physiology.

Including Chemical and Experimental Physiology, with Special Reference to Practical Medicine. By W. STIRLING, M.D., SC.D., Professor of Physiology and Histology, Owens College, Victoria University, Manchester; Examiner in Physiology, Universities of Edinburgh and London. Third Edition. 289 Illustrations. Cloth, $2.00

Outlines of Practical Histology.

368 Illustrations. Second Edition, Revised and Enlarged. With new Illustrations. 12mo. Cloth, $2.00

Tavera. Medicinal Plants of the Philippines.

By T. H. PARDO DE TAVERA, Doctor of Medicine in Faculty of Paris; Scientific Commissioner S.M. in Philippine Islands, etc. Translated and Revised by JEROME B. THOMAS, JR., A.B., M.D., Captain and Assistant Surgeon United States Volunteers. Cloth, $2.00

Taylor. Practice of Medicine.

By FREDERICK TAYLOR, M.D., Physician to, and Lecturer on Medicine at, Guy's Hospital, London; Physician to Evelina Hospital for Sick Children. Sixth Edition, Revised. Cloth, $4.00

Taylor and Wells. Diseases of Children. Illustrated.

A Manual for Students and Physicians. By JOHN MADISON TAYLOR, A.M., M.D., Professor of Diseases of Children, Philadelphia Polyclinic; Pediatrist to the Philadelphia Hospital; Assistant Physician to the Children's Hospital; Consulting Physician to the Elwyn and the Vineland Training Schools for Feeble-minded Children; Neurologist to the Howard Hospital, etc.; and WILLIAM H. WELLS, M.D., Adjunct Professor of Obstetrics and Diseases of Infancy in the Philadelphia Polyclinic; Demonstrator of Clinical Obstetrics, Jefferson Medical College; Chief Gynecologist, Mt. Sinai Hospital. With Numerous Illustrations. Second Edition, Revised and Enlarged. Octavo. Cloth, $4.50

Temperature Charts

for Recording Temperature, Respiration, Pulse, Day of Disease, Date, Age, Sex, Occupation, Name, etc. Put up in pads; each .50

Thayer. Compend of General Pathology.

Specially adapted for Medical Students and Physicians. By A. E. THAYER, M.D., Assistant Instructor in Pathology, Cornell Medical School; Pathologist to the City Hospital, New York City, etc. 78 Illustrations. *No. 15 ?Quiz-Compend? Series.* 12mo. *Just Ready.* Cloth, .80; Interleaved for Notes, $1.00

Compend of Special Pathology. 34 Illustrations.

No. 18 ?Quiz-Compend? Series. Just Ready. Cloth, .80; Interleaved, $1.00

Thorington. Retinoscopy. Fourth Edition.

(The Shadow Test) in the Determination of Refraction at One Meter Distance with the Plane Mirror. By JAMES THORINGTON, A.M., M.D., Professor of Diseases of the Eye in the Philadelphia Polyclinic; Ophthalmologist to the Elwyn, Vineland, and New Jersey State Training Schools for Feeble-minded Children; Lecturer on the Anatomy, Physiology, and Care of the Eyes in the Philadelphia Manual Training Schools, etc. 51 Illustrations, several of which are Colored. Fourth Edition, Enlarged. 12mo. Cloth, $1.00

Refraction and How to Refract. Second Edition.

With 200 Illustrations, most of which are made from Original Drawings, and 13 of which are in Colors. Second Edition, Revised. 12mo. Cloth, $1.50

SYNOPSIS OF CONTENTS.—I. Optics. II. The Eye; The Standard Eye; Cardinal Points; Visual Angle; Minimum Visual Angle; Standard Acuteness of Vision; Size of Retinal Image, Accommodation; Mechanism of Accommodation; Far and Near Point; Determination of Distant Vision and Near Point; Amplitude of Accommodation; Convergence; Angle Gamma; Angle Alpha. III. Ophthalmoscope; Direct and Indirect Method. IV. Emmetropia; Hyperopia; Myopia. V. Astigmatism or Curvature Ametropia; Tests for Astigmatism. VI. Retinoscopy. VII. Muscles. VIII. Cycloplegics; Cycloplegia; Asthenopia; Examination of the Eyes. IX. How to Refract. X. Applied Refraction. XI. Presbyopia; Aphakia; Anisometropia; Spectacles. XII. Lenses; Spectacle and Eye Glass Frames; How to Take Measurements for Them and How They Should be Fitted. Index.

Thorne. The Schott Methods of the Treatment of Chronic Diseases of the Heart.

With an Account of the Nauheim Baths and of the Therapeutic Exercises. By W. BEZLY THORNE, M.D., M.R.C.P. With Plates and Numerous other Illustrations. Fourth Edition, Revised and Enlarged. Octavo. *Just Ready.* Cloth, $2.00

Thresh. Water and Water Supplies.

By JOHN C. THRESH, D.SC. (Lond.), M.D., D.P.H. (Cambridge), Medical Officer of Health to the Essex County Council; Lecturer on Public Health, King's College, London; Fellow of the Institute of Chemistry; Member Society Public Analysts, etc. Third Edition, Revised and very much Enlarged. Illustrated. 527 pages. 12mo. Cloth, $2.00

Tissier. Pneumatotherapy and Inhalation Methods.

See COHEN, Physiologic Therapeutics, page 10.

Tomes' Dental Anatomy.

A Manual of Dental Anatomy, Human and Comparative. By C. S. TOMES, D.D.S. 263 Illustrations. Fifth Edition. 12mo. Cloth, $4.00

Dental Surgery.

A System of Dental Surgery. By JOHN TOMES, F.R.S. Fourth Edition, Thoroughly Revised by C. S. TOMES, D.D.S. With 289 Illustrations. 12mo. 717 pages. Cloth, $4.00

Traube. Physico-Chemical Methods.

By DR. J. TRAUBE, Privatdocent in the Technical High School of Berlin. Authorized Translation by W. D. HARDIN, Harrison Senior Fellow in Chemistry, University of Pennsylvania. With 97 Illustrations. 8vo. Cloth, $1.50

Treves. German-English Medical Dictionary.

By FREDERICK TREVES, F.R.C.S., assisted by DR. HUGO LANG, B.A. (Munich). 12mo. Half Calf, $3.25

Physical Education: Its Effects, Value, Methods, etc. 8vo.

Cloth, .75

Tuke. Dictionary of Psychological Medicine.

Giving the Definition, Etymology, and Synonyms of the Terms used in Medical Psychology, with the Symptoms, Pathology, and Treatment of the Recognized Forms of Mental Disorders, together with the Law of Lunacy in Great Britain and Ireland. Edited by D. HACK TUKE, M.D., LL.D., Examiner in Mental Physiology in the University of London. Two volumes. Octavo. Cloth, $10.00

"A comprehensive, standard book."—*The British Medical Journal.*

"It is vastly more than a Dictionary. It is an elaborate and complete Encyclopædia of Psychological Medicine; in fact, a small library in itself on that subject. The high expectations which Dr. Tuke's work in this field had raised are more than fulfilled. . . . It will be found to be a most useful reference handbook for the alienist and student. The general physician also cannot fail to find the book exceedingly useful in special cases."—*Boston Medical and Surgical Journal.*

"We believe that the student might obtain a better knowledge of insanity from this work than from most of the text-books, besides a great deal of interesting and valuable information nowhere else accessible."—*American Journal of Insanity.*

Turnbull's Artificial Anesthesia.

A Manual of Anesthetic Agents in the Treatment of Diseases, also their Employment in Dental Surgery; Modes of Administration; Considering their Relative Risks; Tests of Purity; Treatment of Asphyxia; Spasms of the Glottis; Syncope, etc. By LAURENCE TURNBULL, M.D., PH.G., Aural Surgeon to Jefferson College Hospital, etc. Fourth Edition, Revised. 54 Illustrations. 12mo. Cloth, $2.50

Tyson. The Practice of Medicine. Second Edition.

A Text-Book for Physicians and Students, with Special Reference to Diagnosis and Treatment. By JAMES TYSON, M.D., Professor of Medicine in the University of Pennsylvania; Physician to the University and to the Philadelphia Hospitals, etc. With Colored Plates and many other Illustrations. Second Edition, Revised and Enlarged. 127 Illustrations. 8vo. 1222 pages.
Cloth, $5.50; Leather, $6.50; Half Russia, $7.50

*** This edition has been entirely reset from new type. The author has revised it carefully and thoroughly, and added much new material and 37 new illustrations.

"This work not only represents the work of a practitioner of great experience, but of a careful culling of the facts set forth in contemporary literature by one who well understands the art of separating the true from the false."—*The Journal of the American Medical Association, Chicago.*

"Represents the outcome of much well-directed labor, and constitutes a reliable and useful text-book."—*The London Lancet.*

"Few teachers in the country can claim a longer apprenticeship in the laboratory and at the bedside, none a more intimate acquaintance with students, since in one capacity or another he has been associated with the University of Pennsylvania and the Philadelphia Hospital for nearly thirty years. Moreover, he entered medicine through the portal of pathology, a decided advantage in the writer of a text-book. . . . The typography is decidedly above works of this class issued from our publishing houses. There is no American Practice of the same attractive appearance. The print is unusually sharp and clear, and the quality of the paper particularly good. . . . It is a piece of good, honest work, carefully conceived and conscientiously carried out."—*University Medical Magazine.*

***** Sample Pages and Illustrations sent free upon application.**

Guide to the Examination of Urine.

For the Use of Physicians and Students. With Colored Plate and Numerous Illustrations Engraved on Wood. Tenth Edition, Revised, Enlarged and partly Rewritten. 12mo. *Just Ready.* Cloth, $1.50

"The book is a reliable one and has no superior among the numerous manuals devoted to the subject."—*Boston Medical and Surgical Journal.*

"No similar treatise has been so long before the professional public, and none comes so near to being a classic on the subject of which it treats as does this one."—*Buffalo Medical Journal.*

Handbook of Physical Diagnosis.

Fourth Edition, Revised and Enlarged. With two Colored Plates and 55 other Illustrations. 298 pages. 12mo. Cloth, $1.50

Cell Doctrine.

Its History and Present State. Second Edition. Cloth, $1.50

United States Pharmacopœia, 1890.

Seventh Decennial Revision. Cloth, $2.50 (Postpaid, $2.77); Sheep, $3.00 (Postpaid, $3.27); Interleaved, $4.00 (Postpaid, $4.50). Printed on one side of page only, unbound, $3.50 (Postpaid, $3.90).

Select Tables from the U. S. P.

Being Nine of the Most Important and Useful Tables, printed on Separate Sheets. Carefully put up in Patent Envelope. .25

Ulzer and Fraenkel. Introduction to Chemical-Technical Analysis.

By PROF. F. ULZER and DR. A. FRAENKEL, Directors of the Testing Laboratory of the Royal Technological Museum, Vienna. Authorized Translation by HERMANN FLECK, NAT.SC.D., Instructor in Chemistry and Chemical Technical Analysis in the John Harrison Laboratory of Chemistry, University of Pennsylvania, with an Appendix by the Translator relating to Food Stuffs, Asphaltum, and Paint. 12 Illustrations. 8vo. Cloth, $1.25

Van Nüys on the Urine.

Chemical Analysis of Healthy and Diseased Urine, Qualitative and Quantitative. By T. C. VAN NÜYS. 39 Illustrations. Octavo. Cloth, $1.00

Van Harlingen on Skin Diseases.

A Practical Manual of Diagnosis and Treatment, with Special Reference to Differential Diagnosis. By ARTHUR VAN HARLINGEN, M.D., Emeritus Professor of Diseases of the Skin in the Philadelphia Polyclinic; Dermatologist to the Children's Hospital. Third Edition, Revised and Enlarged. With Formulæ and Illustrations, several being in Colors. 580 pages. Cloth, $2.75

"As would naturally be expected from the author, his views are sound, his information extensive, and in matters of practical detail the hand of the experienced physician is everywhere visible."—*The Medical News.*

Virchow's Post-mortem Examinations.

A Description and Explanation of the Method of Performing them in the Dead-House of the Berlin Charité Hospital, with Especial Reference to Medico-Legal Practice. By PROFESSOR VIRCHOW. Translated by DR. T. P. SMITH. Illustrated. Third Edition. Cloth, .75

Voswinkel. Surgical Nursing.

A Manual for Nurses. By BERTHA M. VOSWINKEL, Graduate Episcopal Hospital, Philadelphia; late Nurse-in-Charge Children's Hospital, Columbus, O. Second Edition, Revised and Enlarged. 111 Illustrations. 12mo. Cloth, $1.00

Walker. Students' Aid in Ophthalmology.

By GERTRUDE A. WALKER, A.B., M.D., Clinical Instructor in Diseases of the Eye at Woman's Medical College of Pennsylvania. 40 Illustrations and Colored Plate. 12mo. Cloth, $1.50

Walsham. Surgery: Its Theory and Practice. Seventh Edition.

For Students and Physicians. By WM. J. WALSHAM, M.D., F.R.C.S., Senior Assistant Surgeon to, and Demonstrator of Practical Surgery in, St. Bartholomew's Hospital; Surgeon to Metropolitan Free Hospital, London. Seventh Edition, Revised and Enlarged by 100 pages. With 483 Illustrations and 28 Skiagrams. Cloth, $3.50

Warren. Compend of Dental Pathology and Dental Medicine.

Containing all the most Noteworthy Points of Interest to the Dental Student and a Chapter on Emergencies. By GEORGE W. WARREN, D.D.S., Professor of Clinical Dentistry and Oral Surgery; Clinical Chief, Pennsylvania College of Dental Surgery, Philadelphia. Third Edition, Enlarged. Illustrated. *Being No. 13 ?Quiz-Compend? Series.* 12mo. Cloth, .80; Interleaved for the Addition of Notes, $1.00

Dental Prosthesis and Metallurgy.

129 Illustrations. Cloth, $1.25

Weber and Hinsdale. Climatology—Health Resorts—Mineral Springs.

See COHEN, Physiologic Therapeutics, page 10.

Wells. Compend of Gynecology.

By WM. H. WELLS, M.D., Demonstrator of Clinical Obstetrics, Jefferson Medical College, Philadelphia; Chief Gynecologist Mt. Sinai Hospital; Fellow of the College of Physicians of Philadelphia. Second Edition, Revised. 140 Illustrations. *Being No. 7 ?Quiz-Compend? Series.* 12mo. Cloth, .80; Interleaved for Notes, $1.00

Wethered. Medical Microscopy.

A Guide to the Use of the Microscope in Practical Medicine. By FRANK J. WETHERED, M.D., M.R.C.P., Demonstrator of Practical Medicine, Middlesex Hospital Medical School; Assistant Physician, late Pathologist, City of London Hospital for Diseases of the Chest, etc. With a Colored Plate and 101 Illustrations. 406 pages. 12mo. Cloth, $2.00

Weyl. Sanitary Relations of the Coal-Tar Colors.

By THEODORE WEYL. Authorized Translation by HENRY LEFFMANN, M.D., PH.D. 12mo. Cloth, $1.25

Whitacre. Laboratory Text-Book of Pathology.

By HORACE J. WHITACRE, M.D., Demonstrator of Pathology, Medical College of Ohio, Cincinnati. Illustrated with 121 Original Drawings and Microphotographs. 8vo. Cloth, $1.50

White. The Mouth and Teeth. Illustrated.

By J. W. WHITE, M.D., D.D.S. Cloth, .40

White and Wilcox. Materia Medica, Pharmacy, Pharmacology, and Therapeutics. Fifth Edition.

A Handbook for Students. By W. HALE WHITE, M.D., F.R.C.P., etc., Physician to, and Lecturer on Materia Medica and Therapeutics, Guy's Hospital; Examiner in Materia Medica to the Conjoint Board, etc. Fifth American Edition, Revised by REYNOLD W. WILCOX, M.A., M.D., LL.D., Professor of Clinical Medicine and Therapeutics at the New York Post-Graduate Medical School and Hospital; Visiting Physician, St. Mark's Hospital; Assistant Visiting Physician, Bellevue Hospital. Enlarged and Improved. 12mo. Cloth, $3.00; Leather, $3.50

Williams. Manual of Bacteriology. Second Edition.

By HERBERT U. WILLIAMS, M.D., Professor of Pathology and Bacteriology, Medical Department, University of Buffalo. Second Edition, Revised and Enlarged. 90 Illustrations. 12mo. 290 pages. Cloth, $1.50

Wilson. Handbook of Hygiene and Sanitary Science.

By GEORGE WILSON, M.A., M.D., F.R.S.E., Medical Officer of Health for Mid-Warwickshire, England. With Illustrations. Eighth Edition. 12mo. Cloth, $3.00

Wilson. The Summer and its Diseases.

By JAMES C. WILSON, M.D., Professor of the Practice of Medicine and Clinical Medicine, Jefferson Medical College, Philadelphia. Cloth, .40

Wilson. System of Human Anatomy.

Eleventh Revised Edition, Edited by HENRY EDWARD CLARK, M.D., M.R.C.S. 492 Illustrations, 26 Colored Plates, and a Glossary of Terms. 12mo. Cloth, $5.00

Winckel. Text-Book of Obstetrics.

Including the Pathology and Therapeutics of the Puerperal State. By DR. F. WINCKEL, Professor of Gynecology, Royal University Clinic for Women in Munich. Authorized Translation by J. CLIFTON EDGAR, A.M., M.D., Professor of Obstetrics and Clinical Midwifery, Cornell University Medical Department, New York. 190 Illustrations. Octavo. Cloth, $5.00; Leather, $6.00

Winternitz. Hydrotherapy—Thermotherapy—Balneology.

See COHEN, Physiologic Therapeutics, page 10.

Wood. Brain Work and Overwork.

By H. C. WOOD, Clinical Professor of Nervous Diseases, University of Pennsylvania. 12mo. Cloth, .40

Woody. Essentials of Medical and Clinical Chemistry.

With Laboratory Exercises. By SAMUEL E. WOODY, A.M., M.D., Professor of Chemistry and Diseases of Children in the Medical Department, Kentucky University, Louisville. Fourth Edition, Revised and Enlarged. Illustrated. 12mo. Cloth, $1.50

"The fact that Prof. Woody's little book has reached a third edition in such a short time is sufficient proof of its usefulness for, and demand by, the medical student. The selection of the material and its plan of presentation, resulting from the author's large experience as a practitioner and teacher of medical chemistry, is well intended to offer to the student that which is really essential for his limited college course, and, it is to be hoped, a basis for further instruction in the important branch of medical science."—*The American Journal of Medical Sciences, Philadelphia.*

Wright. Ophthalmology. New Edition. 117 Illustrations.

A Text-Book by JOHN W. WRIGHT, A.M., M.D., Professor of Ophthalmology and Clinical Ophthalmology in Ohio Medical University; Ophthalmologist to the Protestant and University Hospitals, etc. Second Edition, Revised, Rewritten, and Enlarged. With many new Illustrations. Cloth, $3.00

THE STANDARD TEXT-BOOK

MORRIS' ANATOMY New Edition

Third Revised Edition, Enlarged and Improved
846 Illustrations, of which 267 are Colored
Octavo. 1328 Pages. Cloth, $6.00; Leather, $7.00

THUMB INDEX IN EACH COPY

"Morris' Anatomy" was published at a time when *methods of teaching, the art of engraving, and distinct advance in anatomical illustration* made desirable a *new* and *modern text-book.* The rapid sale of the first edition, its immediate adoption as a text-book by a large number of medical schools, and its purchase by physicians and surgeons proved its value and made it from the day of publication a standard authority.

In making this new edition the editors and publishers have used every endeavor to enhance its value. The text has been thoroughly revised and in many parts rewritten; the editor has devoted himself to the task of making it a harmonious whole; many new illustrations have replaced those used in the first edition, and a large number have been printed in colors, while the typographical appearance has been improved in several particulars.

The illustrations, in correctness and excellence of execution, are equaled by no similar treatise; about $1000 having been expended on new and improved blocks for this edition alone.

"The evergrowing popularity of the book with teachers and students is an index of its value, and it may safely be recommended to all interested."—*Medical Record, New York.*

"Of all the text-books of moderate size on human anatomy in the English language, Morris is undoubtedly the most up-to-date and accurate."—*Philadelphia Medical Journal.*

*** CIRCULAR WITH SAMPLE PAGES AND ILLUSTRATIONS FREE.