PRACTICAL ELECTRICAL ENGINEERING.

A COMPLETE COURSE ON THE CONSTRUCTION AND MANAGEMENT OF ELECTRICAL APPARATUS,
AS USED IN LIGHTING, HEATING & THE ELECTRIC TRANSMISSION OF POWER.

By

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PRACTICAL
ELECTRICAL ENGINEERING.

A complete treatise on the Construction and Management of Electrical Apparatus as used in Electric Lighting and the Electric Transmission of Power.

Illustrated with many Hundreds of Illustrations.

BY

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INTRODUCTION.

In these modern days, when the dissemination of information is so easy, the time required for the development of an industry is short compared with what it was before the era of the technical newspaper. No sooner does a new idea seem practical than hundreds of minds are directed towards it, each attempting some modification to render it cheaper and more practical. Till the time of Davy, Morse, Cooke, and Wheatstone, between the years 1830 and 1840, there was no practical application of electricity. These men have the credit between them of introducing electric telegraphy. Towards the latter part of the same period Spencer, Jacobi, Smee, and the Elkingtons introduced the art of electro-deposition. Also during or about the same time Faraday, Sturgeon, and Henry obtained the germs and constructed the first rough apparatus of what has developed into the dynamo machine. Far and away before the other names mentioned must that of Faraday be placed. He was the Homer and the Shakespeare of investigators. More recently still Hughes applied with wonderful success his knowledge of mechanism to the wants of telegraphy. Sir W. Thomson, too, invented the apparatus that made ocean telegraphy practicable. Nearer still as to time Holmes, Ladd, Siemens, Pacinotti, and Gramme have given us the machines; Brush, Crompton, Brockie, and others the arc lamps; Swan and Edison the incandescent lamps, that furnish the apparatus for electric lighting purposes and for the transmission of power.

The purpose of this treatise is to consolidate the knowledge that applies more directly to the production and the use of apparatus connected with electric lighting, and the transmission of power. The use of electricity in the transmission of power is destined to become far more important than its use as a lighting agent.

The plan adopted is, in the first place, to consider the requirements of a central station. Supposing the building finished, the prime motors must be considered. Usually these will be steam-engines—hence it is necessary for the electrical engineer to consider generally the relation between this part of his apparatus and the other parts. There will be no attempt to deal exhaustively with engines and boilers; but the general practical details necessary to be followed in constructing these in order that they may comply with the special requirements in ordinary working for regulation and maintenance in electrical installations, will be amply described. Gearing and lubrication must also be considered. The main object of the book, however, is the electrical part. Owing to the subject having never till recently been considered from an engineer's point of view, there is absolutely no literature upon the subject. There is no book to inform the practical man how to construct a dynamo. Books with a mass of mathematical formulæ there are, though only one of them, that of Dr. Silvanus Thompson, is worth reading—hence plain information given by practical men to practical men should supply a vacant place as regards this class of literature. To Gisbert Kapp and Dr. Hopkinson we owe the investigations which rendered possible the specification of a machine which, when completed, should have the output for which it is designed. Till the publication of their papers, machines were made very much by rule of thumb. The notation and nomenclature of electrical literature was altogether against the engineer. Up to the introduction of the dynamo electricians had had to deal with minute quantities, when all at once the consideration of the subject involved quantities thousands and millions of times greater than had been considered before. Engineers have done something to
assist them in this part of the subject, but they cannot as yet prevail against the pure theoretist. Dr. Hopkinson introduced, in his papers to the Institution of Mechanical Engineers, a graphic notation which has proved of inestimable value. Mr. Kapp in his papers has suggested for one practical unit a value six thousand times greater than that used in laboratory practice, and this suggestion falls in with the requirements of engineers, as it takes “revolutions per minute” instead of “revolutions per second.” It is comparatively easy to count “revolutions per minute,” but far from easy to count them “per second.”

The materials of which the apparatus is constructed will be discussed, the best methods of using them, and the right proportions described. Dynamos are required for various purposes, and the design of each machine should be prepared with a due consideration of the work it will have to do. Thus, large constant-current and alternate-current machines are required for large central stations, smaller ones for smaller installations for isolated plants, and for ship lighting. Then the machines differ in construction if required to produce high pressure, from those required to produce a lower pressure, and the slow-speed machines from the high speed.

These requirements will all be discussed, and as far as possible plain, workable instructions given for the design of any class of machine.

Before leaving the interior of the central station the various methods of control must be described, also the instruments and methods of measurement. Outside the station the various systems of distribution will claim attention, as will the transformers, lamps, whether arc or incandescent, methods of wiring, safety devices and fittings.

Another important part of the work is the utilisation of electricity for obtaining mechanical power. In hundreds, if not thousands of cases the use of electricity is not only less costly, but far more convenient, and as the possibility of obtaining the necessary current becomes more and more common, there will be an immense demand for small and for large motors. These may be termed reversed dynamos, for the latter absorb mechanical energy, and produce pressure which gives rise to current, while the former absorb electrical energy and give out mechanical energy. Motors, again, will be largely used in tramway work, in haulage work in mines, for lifts, for lifting, for travelling cranes, and probably for the training of big guns.

The principles of electrical science involved in these applications will be given as briefly as possible, and those desirous of knowing more of these principles will have to study special books written to elucidate particular points. The general principles of the science as applied in engineering work are neither difficult to understand, nor do they involve a knowledge of higher mathematics. Formule, it is true, must be extensively used, but the greater number of these formulae when used in practice involves a knowledge only of the rules of simple arithmetic, and by using these aids the matter can be presented in a far simpler and more concrete form than by restricting description to words only. There is every indication, too, that as our knowledge of the subject advances, the mathematics of the subject will be considerably simplified. Hitherto, mathematicians have made their mathematics fit the knowledge, and this they can always do by using more or less complex formulæ, many of which tax the highest mathematical skill to expound, and are altogether untranslatable to the non-mathematician. Considerable use is made of the graphic notation and its developments since its first introduction.

No doubt in many things this book will be found to wander considerably from the popular notions now prevailing. But this is a necessary sign of progress, and especially may this be thought to be the case in taking the stand that all electrical apparatus as used generates electrical pressure, or creates a difference of electrical pressure only. The term electrical pressure, or difference of pressure, will be used instead of the commoner terms electromotive force or difference of potential, terms which do not appeal to the engineer, and which the foremost thinkers have, since the general introduction of dynamos desired to see replaced by “pressure.” The view that the apparatus employed generates pressure only is unorthodox to this extent, that the writers of school books have not yet seen that it is involved in the view which now generally prevails in the front ranks that “electricity,” whatever it is, is a constant quantity in the universe. It can neither be destroyed nor created, and if this be so, then it is far simpler and more in accordance with such views to consider the apparatus as altering the condition of what already exists,” than as creating equal quantities of something in two different conditions, a creation which complicates the whole consideration of the subject. The views thus put forward in this book are merely the advanced views held by the men who devote their working lives almost exclusively to the investigation of the subject, whose opinions unorthodox to-day become orthodox to-morrow.

Readers should make themselves thoroughly acquainted with the elementary principles which form the introduction to the practical part of the work. No attempt has been made therein to apply the principles, except perhaps in the solution of a few questions, done more to show how to use the formulæ than to directly apply them, or in a casual remark as to the particular branch where the principle involved is prominent.

The use of such a knowledge of principles to handycraftsmen is obvious; it gives every man a chance, according to his natural talents, of becoming an improver of the art he works at, and even a discoverer in the science connected with it. He is daily handling the tools and materials with which new experiments are to be made and daily watching the operations, so that a knowledge of the principles will frequently suggest a more or less slight modification of the apparatus, tending to improvement. All opportunities of
making experiments must be improved, all strange appearances observed, and in this way the apparatus in use perfected. It must never be forgotten, however, that perfection does not mean development in one direction only. A good machine is always a compromise, and the problem to be solved in designing a first-class machine is the best relations that all the principles involved shall bear to each other. For example, a dynamo is a mechanical as well as an electrical machine, hence the electrical requirements cannot be pushed to extremes without considering the requirements of the mechanism. Then, again, the dynamo is only one part of a system—a system involving boilers, engines, and distributing arrangements. The dynamo therefore should always be designed with a view to its position in this system—that is, with a view to make it fit its work as perfectly as possible. After all, in one way the introduction of a dynamo or any other piece of mechanism into a circuit must be looked upon as a loss. The prime consideration is the energy involved in the combustion of fuel, and the amount of that energy we can apply to humanity's requirements. Every piece of apparatus inserted between the burning fuel and the point where the energy developed is utilised causes a loss of some of the energy, so that if the energy of combustion could be directly utilised as electrical energy, an immense step would be gained. According to the present state of our knowledge the intervention of apparatus is necessary, and all improvement in such apparatus tends towards less loss between the point where the energy is developed and where it is utilised. A further consideration of this subject will show that if a piece of apparatus, however good and perfect in itself, involves the use of other apparatus, it may prove that this latter necessity completely vitiates the value of the perfect apparatus.

Very few discoveries have been made by chance or by ignorant persons—much fewer than is generally supposed. It is commonly told of the steam-engine that an idle boy, being employed to stop and open a valve, saw that he could save himself trouble by fixing it to a moving part of the engine. This is possible, no doubt, yet the tale is a little doubtful; but improvements of value are seldom so easily found out, and hardly another instance can be named of important discoveries being so accidental.

So far as electrical apparatus is concerned it owes little to accident. Faraday, was a born investigator into nature's secrets, and to his labours we owe the germ of the modern dynamo. Sturgeon and Henry devoted almost the whole of their lives to the study of electrical phenomena—hence, the electromagnet is by no means an accidental discovery. Pacinotti made a great step in advance, but he did not realise the value of his work. Thirty years or so after Faraday's discovery, Gramme really fashioned a machine that was to create an industry. The work of Siemens or of Wilde must not be overlooked, but sufficient names have been mentioned to show that electrical progress is due to persevering study, and not to accidental discovery. But, in so far as chance has anything to do with discovery, surely it is worth the while of those who are constantly working in a particular employment to obtain the knowledge required, because their chances are greater than other people's of being able to apply that knowledge to new and useful ideas; they are always in the way of perceiving what is wanting, and this in itself is half-way towards obtaining what is wanting.

One of the most important features in modern engineering of all kinds is the accuracy of the methods of measurement employed. It is essentially important in all that concerns electrical engineering to make careful and accurate measurements. The instruments employed are simple and extremely elegant in construction, nor does their use involve difficulties. Perhaps the least successful instrument at the time of writing is the "meter." It is desirable that purchasers of electrical energy should be able to measure as easily the energy they consume as they measure the gas that passes through the gas-meter.

These then are the subjects to be treated, and when it is remembered that the electrical industry will become, nay must become, one in which an exceedingly large sum of money is invested, it will be allowed that it is high time the existing principles and practice were rigidly defined.
CHAPTER 1.

GENERAL PRINCIPLES.

What electricity is we do not know. Certain strange phenomena have been noticed through many centuries, and to these has been given the name electrical. It is these phenomena that have been studied and investigated, and laws relating to their action have been deduced. From time to time the deductions made have had to be remodelled, as new experiments throw new light upon the subject, and not even now can we say for certain that this or that deduction is absolutely correct. All we can say is that it fits best the results of all known experiments and phenomena. In electrical matters, then, the student must keep his mind open, and suffer no dogmatism to rule supreme. An effort will be made in this introductory sketch to present as clearly and succinctly as possible the principles of electrical science which in the state of our present knowledge must guide the engineer in his work. Just as the subject of chemistry has grown so large that no one man can hope to become thoroughly proficient in all its branches, and restricts his studies to one branch, thus becoming a specialist, so must the student of electricity restrict his energies to one branch if he desires to become proficient therein.

The work of the electrical engineer is a special branch of mechanical engineering, and the better the mechanical engineer the better the electrical engineer. The builder of steam-engines should have some knowledge of the theory of steam, the strength and the properties of iron and steel; so also the dynamo builder and the dynamo user should have some knowledge of the theory of electricity. The operations which come within the scope of this work are those connected with electric lighting, with isolated or central station lighting, the machinery and apparatus used therein and in connection therewith; also with the electrical transmission of power, whether by means of isolated or self-contained plants or from central stations.

Without entering to any great length upon the various theories which have, from time to time, been put forward as explanatory of electrical phenomena, we shall, for the purposes of this book, speak of electricity as an entity, as a something which under electrical pressure is moved from point to point along well defined paths. The phenomena due to electricity can be controlled by controlling the pressure under whose influence the movements are made.

Constant in Quantity.—The idea that electricity, so far as this mundane sphere is concerned, is constant in quantity is by no means new, although it is only during recent years that it has been formulated. It is a convenient euphonism sometimes to speak about the generation of electricity, but it is inaccurate. Unfortunately, the majority of text-books, following each other like sheep do the bell-wether, insert paragraphs of antediluvian origin about the generation of electricity—hence the popular notion is that the apparatus employed generates electricity, whereas it produces only electrical pressure. Just as we get no flow of water without a difference of water level, so we get no electrical manifestations without a difference of electrical levels or pressure.

All the apparatus constructed and employed is for the purpose of producing this difference of pressure, for measurements connected therewith, or for placing the electricity at the point where it is intended it shall be utilised. Again, just as in the distribution of water we have to provide duly suitable channels, so in the distribution of electricity it is necessary to provide suitable channels, paths, or, as they are technically termed, circuits.

Circuits.—Electricity manifests itself in two different ways, and for these different manifestations two different kinds of channels, paths, or circuits have to be provided. These two kinds of circuits will be discussed under the respective heads of the Conductive Circuit and the Magnetic Circuit.

All the phenomena due to electricity can be best studied by a careful examination of these circuits, and we are fain to believe in a much better and much simpler manner than by any other method. It may be thought necessary to introduce a subsidiary circuit, to be called an inductive circuit, as an aid to the reader, but the idea of "action at a distance," which seems involved in the ordinary notions of induction, will find no place here. It is assumed that no action originates at one point and its effects perceived at another point without some physical connection between the two points. The phenomena of the circuits are many,
and the interactions of the circuits important, inasmuch as it is these interactions that can be modified and moulded to suit the requirements of the engineer. The latter troubles himself little about the immense mass of investigations which delight the worker in the domain of pure science, and has but one simple question about everything, "What is the use of it?" If there is any direct application the engineer is glad to know all about it, and sooner or later he will probably harness it in another direction, forming a newer and more perfect combination. Still it is requisite to respect the work of pure science, as at any moment a new experiment may give results that can be usefully applied in practical work. Thus there may prove to be phenomena connected with the circuits not discussed, and if so, it may be taken for granted that our knowledge of them is so meagre that their place in applied science cannot at present be determined.

### CHAPTER II.

#### THE CONDUCTIVE CIRCUIT.

**Assume** that we have a source of electrical pressure, which source, as will be seen further on, can be obtained in many different forms, it is only necessary in addition to provide the channel or circuit through which the electricity is to pass. This circuit must be a closed path or a series of closed paths, and if a suitable circuit is obtained, it is only necessary to insert the source at some point in the circuit and put it in action, when it appears as if the electricity naturally existing in the circuit is set into greater or lesser motion according to the pressure. The path or circuit may be long or short, symmetrical or unsymmetrical, of the same or of different but suitable materials; the essential point about it is that from whatever point it starts, to that point it must again return. We have been careful to mention suitable materials, for all materials are not suitable, and some are more so than others; in fact, it seems as if a circuit of one material presented more difficulties to the action of the electricity than a circuit of another material. The difficulty placed by the material of the circuit in the way of electricity is termed resistance. Thus metals usually offer very little resistance, while dry air, glass, indiarubber, etc., offer very great resistance—hence it is customary to divide materials into two classes, conductors and non-conductors or insulators, the former being those of least resistance, the latter those of the greatest resistance. We may indicate a simple circuit diagrammatically as in Fig. 1, where S indicates the source of the electrical pressure, shortly called the source, and R the circuit outside of the source, the interior of the source completing the entire circuit.

**Conductors and Insulators.**—Conductors are used to convey the electricity to the point where it is to be used, insulators are used to stop it from going where it is not wanted. The best conductors present some obstacles to the motion of the electricity, generally called the current, and the best insulators are only those which present an enormously greater resistance to the current. So far as investigation has yet gone, we have neither perfect conductors nor perfect insulators, nor can a line of demarcation be drawn to say where conduction ceases and insulation begins. Thus the difference between conductors and insulators is merely one of degree. The following list may be of some use, as showing the best conductors and the best insulators. The best conductors are put at the top of the list of conductors, and the best insulators—that is, the worst conductors—at the top of the list of insulators.

- **Conductors.**
  - All metals.
  - Well-burned charcoal.
  - Plumbago.
  - Acid solutions.
  - Saline solutions.
  - Metallic ores.
  - Animal fluids.
  - Living vegetable substances.
  - Moist earth.
  - Water.

- **Insulators (Non-conductors).**
  - Dry air.
  - Shellac.
  - Paraffin.
  - Amber.
  - Resins.
  - Sulphur.
  - Wax.
  - Jet.
  - Glass.
  - Mica.
  - Ebonite.
  - Guttapercha.
  - Indiarubber.
  - Silk.
  - Dry paper.
  - Parchment.
  - Dry leather.
  - Porcelain.
  - Oils.

**Phenomena of the Circuit.**—The phenomena to be considered in connection with the circuit are three:

1. **Resistance,** for which the symbol R will be used.
2. **Electrical Pressure,** or as it is often called electromotive force, for which the symbol E will be used.
3. **Electricity in Motion,** usually called current, for which the symbol C will be used.
Resistance.—The phenomena appearing in one circuit are comparable with the phenomena appearing in other circuits, and in order to be able to make these comparisons with facility, certain units have been adopted for each case. For the conductive circuit, a series of units suitable for laboratory work and pure science have been adopted, as well as the practical units required in our workshops. Unfortunately, as yet only the former kind of units have been adopted for the magnetic circuit, hence calculations for the latter are more cumbersome than is the case for the conductive circuit. It will be unnecessary to enter further than possible into the domain of pure science, so we shall simply give the names and definitions of the practical units as they are required. It may, however, be stated that these practical units are derived from the absolute units, based on the centimetre-gramme-second (C.G.S.) system, so called because the "centimetre" is the unit of length, the "gramme" the unit of mass, and the "second" the unit of time. This absolute system is very well adapted to the wants of pure science, but not to practical work. The unit of resistance for practical work is called the ohm, after Prof. Ohm, to whose labours the present position of our knowledge of the conductive circuit is greatly due. The ohm, according to the latest definition, is the resistance of a column of pure mercury 106 centimetres (41.73 inches) long, 1 square millimetre (0.00155 square inch) in sectional area, at a temperature of 0 deg. C. It may safely be said that the ideal ohm, according to this definition, never has and never will be made. Instrument makers construct their resistances of german silver or platinum silver in terms of standard resistances first obtained by a committee of the British Association, and known as the B.A. unit. The above definition is that known as the legal ohm.

1 B.A. unit = 0.9889 legal ohm.
1 legal ohm = 1.0112 B.A. units.

Instrument makers construct boxes containing various multiples and sub-multiples of the ohm, arranging them as far as possible in the manner best suited for the measurements for which they are to be used.

Equivalent Conductors.—The resistance of any conductor varies directly as its length and inversely as its sectional area. The increasing the length increases the path or circuit, and it seems almost axiomatic that if a conductor of a given length has a certain resistance, and is increased to double that length, it will have double resistance. Increasing the area of a conductor is similar to adding another conductor to the circuit, increasing the size of the path over which the electricity has to travel, rendering it less difficult. If \( R \) is the resistance of a conductor, \( l \) its length, and \( s \) its sectional area,

\[
R = \frac{l}{s}
\]

If we call the power of a body for conducting electricity its conductivity, and represent this by \( c \), recollecting that conductivity is the inverse of resistance, we may write

\[
R = \frac{l}{sc}
\]

It is easy to compare the conductivities of various, say two, substances. Taking them of the same length and section, and let \( c_1 \) and \( c_2 \) represent the conductivities, \( R_1 \) and \( R_2 \) the respective resistances, then

\[
c_1 : c_2 = \frac{l}{R_1} : \frac{l}{R_2}
\]

or the dimensions being the same, the conductivities are inversely as the resistances.

It is sometimes convenient to be able to replace one conductor by another conductor of different materials, at the same time not convenient to increase or decrease the total resistance of the circuit. A conductor so used to replace another without altering the total resistance is termed an equivalent conductor. All that is necessary to obtain equivalent conductors is to measure or calculate that the resistance or conductivity of the conductor required is equal to the resistance or conductivity of that to be replaced. In a section further on the method of measuring resistances will be described. Meanwhile, the sectional area, \( s \), is known, if we know the length, weight, and specific gravity of the substance. Let \( w \) be the weight, and \( \sigma \) the specific gravity, then the volume \( v = l s \); and the volume, \( l s \), multiplied by the specific gravity, \( \sigma \), is the weight, \( w \); or

\[
w = l s \sigma \]

\[
s = \frac{w}{l \sigma}
\]

Putting this value of \( s \) in the formula

\[
c = \frac{l}{sR}
\]

we get

\[
c = \frac{w \sigma}{lR}
\]

Then, with two conductors, \( C, C_1 \), of length \( l, l_1 \), of conductivities \( c, c_1 \), and sectional areas \( s, s_1 \), we should get the same resistance, and one might be substituted for the other, when

\[
\frac{l}{c s} = \frac{l_1}{c_1 s_1}
\]

Another way of attaining the same result is by starting as before with

\[
R \propto \frac{l}{s}
\]

Knowing that different conductors have, for equal lengths and sections, different resistances, and taking unit lengths and unit sections of some conductor, such as pure silver, as our standard, the resistances of similar pieces of every other conductor can be expressed in terms of the standard. Such expression may be called the specific resistance of the material. Thus, if the conductivity of silver is 1, and of copper \( \frac{1}{99} = 0.0100 \), the specific resistance of silver will be 1, and of copper \( \frac{1}{99} = 99 \), the specific resistance being the reciprocal of conductivity. The reciprocal of a number is unity divided by that number. A table of conductivities then gives also
a table of specific resistances. Using specific resistance, \( a \), the above formula becomes

\[ R = \frac{l}{a}. \]

If we have two wires whose lengths are \( l, l_1 \), their sectional areas \( s, s_1 \), their specific resistances \( a, a_1 \), then their actual resistances, \( R \) and \( R_1 \), may be found.

\[ R = \frac{l}{a} \text{ and } R_1 = \frac{l_1}{a_1}. \]

Dividing the second by the first we get

\[ \frac{R_1}{R} = \frac{a}{a_1} \frac{l}{l_1} \frac{s_1}{s}. \]

**Example.**

Assume that the specific resistance of iron is seven times that of copper. How thick must an iron wire be which for the same length shall offer the same resistance as a copper wire ? sq. in. section? In the formula let the symbols \( R_n, a_1, l_1, s_1 \), refer to iron, and \( R, a, l, s \), to copper.

\[ \frac{R_1}{R} = \frac{a}{a_1} \frac{l}{l_1} \frac{s_1}{s}, \]

but \( R_1 = R \) and \( l_1 = l \), \( a_1 = 7 \), \( a = 1 \), \( s_1 = \frac{5}{7} \), therefore the formula becomes

\[ 1 = \frac{7}{1} \frac{1}{1} \frac{s_1}{s}, \]

\[ s_1 = 7 \cdot \frac{5}{7} = \frac{5}{1}, \]

which is simply saying that iron to have the same length and resistance must have a sectional area of 8.5 sq. in., as against the sectional area of copper 6.5 sq. in., which of course, in so simple a case, would be got in practice by saying that as iron had seven times greater resistance than copper, the same lengths would require seven times greater sectional area in the iron than in the copper to have wires of same resistance.

For the purposes of the British Association Committee on the unit of resistance, Prof. Matthiessen determined the conductivities of various metals at different temperatures. These experiments are classic, and the results are given in the following table. Prof. Matthiessen put the conductivity of pure silver at 0 deg. C. = 100.

<table>
<thead>
<tr>
<th>Metals</th>
<th>Conductivities.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At 0 deg. C.</td>
</tr>
<tr>
<td></td>
<td>&quot; 32 deg. F.</td>
</tr>
<tr>
<td>Silver, hard</td>
<td>100</td>
</tr>
<tr>
<td>Copper, hard</td>
<td>99.95</td>
</tr>
<tr>
<td>Gold, hard</td>
<td>77.96</td>
</tr>
<tr>
<td>Zinc, pressed</td>
<td>29.02</td>
</tr>
<tr>
<td>Cadmium</td>
<td>23.72</td>
</tr>
<tr>
<td>Platinum, soft</td>
<td>18.00</td>
</tr>
<tr>
<td>Iron, soft</td>
<td>16.90</td>
</tr>
<tr>
<td>Tin</td>
<td>12.36</td>
</tr>
<tr>
<td>Lead</td>
<td>8.32</td>
</tr>
<tr>
<td>Arsenic</td>
<td>4.76</td>
</tr>
<tr>
<td>Antimony</td>
<td>4.62</td>
</tr>
<tr>
<td>Mercury, pure</td>
<td>1.60</td>
</tr>
<tr>
<td>Bismuth</td>
<td>1.245</td>
</tr>
</tbody>
</table>

The conductivities of the metals are very high, and consequently the resistances very low compared with other substances. Thus, if we take a piece of copper to have a resistance equal 1, a similar length and sectional area of distilled water will have, according to Culley, a resistance of 0.754 million times as great.

**Influence of Temperature.**—The resistance of most conductors increases with rise of temperature, and this peculiarity has to be allowed for in the construction of dynamos and motors, as these machines, and especially dynamos, have frequently to work at temperatures, not only considerably higher than that of the air outside the dynamo-room, but much higher than the surrounding air.

Armstien, Matthiessen, and Siemens made very elaborate experiments to determine the relations between resistance and temperature, and the result of their work comes practically to this, that for every degree Fahrenheit copper increases in resistance about two-tenths of one per cent. \( \frac{2}{10} \) of \( \frac{1}{100} \) or \( \frac{2}{1000} \) or \( \frac{0.002}{0.002} \).

A length of copper having a resistance of 1 ohm at 32deg. F. would therefore have a resistance of 1 + (0.002 x 50), or 1.1 at 82deg. F. In another way, a length of wire that had a resistance of 10 ohms at 32deg. F. would have a resistance of 11 ohms at 82deg. F. We have adopted the Fahrenheit scale because that scale is the most frequently used in England. If the centigrade scale be used the increase of resistance will be about 0.086 for every 1deg. C., for

\[ 100 \text{ deg. C.} = 180 \text{ deg. F.}, \text{ or } 1 \text{ deg. C.} = \frac{9}{5} \text{ F}, \]

and \( \frac{9}{5} \) of \( \frac{0.002}{0.002} = 0.0086. \)

According to the experiments above referred to, the conductivities of all pure metals in the solid state decrease, or the resistances increase, in the same ratio, except in the metals iron and thallium. The conductivity of iron between 1deg. C. and 100deg. C., as 32deg. F. and 212deg. F., varies to the extent of 39.2 per cent., while that of thallium between the same temperatures varies 31.4 per cent., other metals varying only 29.3 per cent. This result we attribute rather to the possibility, although the greatest care might be taken, that the iron and the thallium experimented with were not pure.

The following table shows the amount of resistance of a few substances used for various electrical purposes by which 1 ohm is increased by a rise of temperature 1deg. F., or 1deg. C.

<table>
<thead>
<tr>
<th>Rise of R. of 1 Ohm when heated 1deg. F.</th>
<th>Rise of R. of 1 Ohm when heated 1deg. C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Material</td>
</tr>
<tr>
<td>Platinoid</td>
<td>0.0018</td>
</tr>
<tr>
<td>Platinum-Silver</td>
<td>0.0018</td>
</tr>
<tr>
<td>German Silver</td>
<td>0.0024</td>
</tr>
<tr>
<td>Gold, Silver</td>
<td>0.0036</td>
</tr>
<tr>
<td>Cast Iron</td>
<td>0.0044</td>
</tr>
<tr>
<td>Copper</td>
<td>0.00215</td>
</tr>
</tbody>
</table>

0.00215 to 0.00388
The resistance of true alloys—that is, alloys in which there is no chemical action—depends upon the proportional volumes of the metals entering into their composition. Alloys of lead, tin, cadmium, and zinc are of this class, while the alloys of bismuth, antimony, platinum, palladium, iron, aluminium, sodium, gold, silver, and copper have greater resistance than would be calculated from the properties of metals forming the alloy.

Annealing.—The degree of hardness or softness of a metal or alloy affects its resistance. That of a hard drawn wire is not the same as when the wire has been made hot and let cool again. Resistance is lessened by annealing. Matthiessen gives the following results for copper and silver:

Copper ... 11° ...... 95-31 ...... 97-83
Silver ...... 14-6° ...... 95-36 ...... 103-33

The comparison being made with pure silver at 100 deg. C.

Dr. Siemens, who compared the conductivities of copper, silver, and brass with pure mercury at 0 deg. C., gives the following results:

<table>
<thead>
<tr>
<th>Metal</th>
<th>Hard.</th>
<th>Annealed.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>62-207</td>
<td>55-253</td>
</tr>
<tr>
<td>Silver</td>
<td>56-292</td>
<td>64-380</td>
</tr>
<tr>
<td>Brass</td>
<td>11-499</td>
<td>13-502</td>
</tr>
</tbody>
</table>

These results will show the necessity for all practical purposes of employing soft annealed metals as conductors. Further, as a rule, hard drawn wires do not have a permanent resistance. The question of alteration in resistance is unsettled, but it is believed that there is a molecular change going on in conductors long, for years, after manufacture, which slightly affects their resistance. This change is ordinarily so inappreciable that for constructional purposes it is never considered.

Ohm's Law.—This is by far the most important law that holds in the domain of electrical science. It was first promulgated by Prof. S. J. Ohm in his work, "Die Galvanische Kette, Mathematisch Bearbeitet" (The Galvanic Circuit Mathematically Considered) in 1827, in which was given the general differential equation for the propagation of electricity through prismatic bodies, and from this equation he deduced the simple law which justly bears his name. This law gives us the relationship existing between the three fundamental phenomena of the conductive circuit—viz., electrical pressure, resistance, and current—and it may be written

\[ \text{Current} = \frac{\text{Electrical Pressure}}{\text{Resistance}} \]

or \( E = \frac{C}{R} \)

when \( E \) stands for electrical pressure (electromotive force), \( C \) for current and \( R \) for resistance. The formula can be written

\[ E = CR \text{ or } R = \frac{E}{C} \]

and gives the means of ascertaining the third quantity when the other two quantities are known. We have already referred to the practical unit of resistance adopted, we now give the others.

The unit of resistance is called the ohm.

\[ \text{volts} \text{ amperes} = \frac{\text{volts}}{\text{ohms}}; \text{volts} \times \text{amperes} = \text{ohms} \]

Thus practical calculations become exceedingly simple.

Examples of Calculations.

In Fig. 1 let \( s \) be the source of pressure, and give an effective pressure, \( = 100 \text{ volts} \), through the resistance, \( R = 2 \text{ ohms} \), to find the current, \( C \).

\[ E = \text{volts per ohm} \text{ amperes} = \frac{100}{2} = 50. \]

The number of amperes through \( R \) therefore is 50.

What pressure is required to give 50 amperes through a resistance of 2 ohms?

\[ \text{Pressure} = \text{amperes} \times \text{ohms} = 50 \times 2 = 100 \text{ Answer, 100 volts.} \]

What resistance is required to obtain a current of 50 amperes when the pressure is 100 volts?

\[ \text{Resistance} = \frac{\text{pressure}}{\text{current}} = \frac{100}{50} = 2. \]

Answer, 2 ohms.

But all circuits are not so simple as this, and we may now consider

Divided Circuits.—If the simple circuit is represented in Fig. 2, where \( S \) is the source and \( R \) the resistance, this circuit can be modified by introducing a second

![Fig. 2](image1)

![Fig. 3](image2)

![Fig. 4](image3)

path, as in Figs. 3 and 4. The current due to the pressure of the source, \( S \), has now the choice of two parts, or to divide itself between both. It does the latter and divides itself inversely as the resistances, or rather the original current is added to because the total resistance is lessened, the total current now acting dividing itself as stated. There is no alteration of current in the original circuit. Under the new conditions it is the division of the total current that has to be considered. Let \( R \) and \( R_1 \) represent the resistances, and \( C \) and \( C_1 \) the currents.

\[ C \times R = C_1 \times R_1 \]

or the product of current \( \times \) resistance is constant for
both branches. This can be written
\[ C = \frac{R_1}{R_1 + R_2} \]
which shows the currents are inversely as the resistances. From this equation, if any three of the quantities are known, the fourth can be found—thus:
\[ C = \frac{R_1}{R_1 + R_2}, \quad C = \frac{R_2}{R_1 + R_2}, \quad R = \frac{R_1 R_2}{R_1 + R_2}, \quad R = \frac{R_1 R_2}{R_1 + R_2}. \]

In the case of the double circuit just described, one circuit is said to be a shunt to the other, or the circuits are in multiple arc in parallel. The latter terms, however, are more used when there are several circuits. The use of parallel circuits is very extensive. It will be seen further on that electromagnets are made by coiling a conductive circuit around a core of soft iron. Now if we have two circuits in parallel, there are two ways of winding around two cores. Let \( A \) and \( B \) represent sections of iron cores, they can be encircled by only one branch, as in Fig. 5, or they may be encircled by both branches, as in Fig. 6. In the former case they are said to be shunt-wound, in the latter case compound-wound, so that shunt-winding means that one branch of the circuit only encircles the cores, compound-winding means that both branches of the circuit are wound round the cores.

We have already stated that the adding a shunt to the circuit or any number of branches within certain limits does not interfere with the current going through the original branch or branches. The analogy of water will help to make this clear. If we have a cistern filled with water, and so arranged as to be kept full, or the head of water in it kept constant, and fix an ordinary pipe to the cistern, we can draw off a certain quantity of water per minute through this pipe, and the quantity we can so draw off is not affected by fixing another pipe to the cistern and drawing water through that. As long as the head of water in the cistern is constant, the pipes will each give its full complement of water proportional to that head. If the second pipe is in all respects similar to the first, we get from the two pipes just double the quantity of water in a given time that we should get from either pipe alone—that is, the quantity of water discharged is proportionally increased by the addition of the second pipe. The same holds with electricity. Keeping the electrical pressure constant, the addition of a branch circuit means the motion through it of a current proportional to the pressure and its own resistance. There is practically no interference with the original branch. This, indeed, might be seen from a study of Ohm’s law. The addition of a branch decreases the total resistance of the circuit, and as the current is inversely as the resistance of the latter is decreased, the former is increased. In order to know the increase of current, or to know the total current, it is necessary to know the total resistance of the circuit.

**Total or Joint Resistance.**—If conductors are arranged one after the other as in Fig. 7 or Fig. 8, they are said to be in series, and the total resistance is the sum of their separate resistances. Thus if \( A, B, \) and \( C \) be three conductors arranged in series, having respectively the resistances \( R_1, R_2, R_3 \), while \( R \) represents the total resistance, then
\[ R = R_1 + R_2 + R_3. \]

In the simple circuit referred to in Fig. 9, the total resistance of the circuit is the sum of two resistances, for there is the resistance of the internal parts of the source, and also the resistance of the conductor external to the source, and generally in all circuits these two sets of resistances have to be considered. Both internal and external resistances may be in parallel. It is customary in Ohm’s formula to distinguish the external from the internal resistance by writing \( R \) for the total external, and \( r \) for the total internal resistance, or \[ C = \frac{E}{R + r}. \]

We will now find the total or joint resistance of two branches.

Unless the contrary is stated, the electrical pressure referred to is that available in the external circuit. In Figs. 10 and 11 let \( R_1, R_2 \) represent the resistances of the two branch circuits, and \( R \) the total resistance of the external circuit. The total current in the external circuit will be the sum of the separate currents in each branch. Let \( C \) be the total current, and \( C_1, C_2 \) the currents in branches \( R_1, R_2 \) respectively. Then \[ C = C_1 + C_2; \] but
\[ C = \frac{E}{R_1}; \quad C_1 = \frac{E}{R_1}; \quad \text{and} \quad C_2 = \frac{E}{R_2}. \]
Let $R_1 = 1$, then $C = \frac{1}{R}$; $C_1 = \frac{1}{R_1}$; and $C_2 = \frac{1}{R_2}$;  

or $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$ 

$$R = \frac{R_1 R_2}{R_1 + R_2}$$  

whence $R = \frac{R_1 R_2}{R_1 + R_2}$,  

that is, a current $C$ would flow through the circuit having a resistance $\frac{R_1 R_2}{R_1 + R_2}$, therefore $\frac{R_1 R_2}{R_1 + R_2}$ is the joint resistance of $R_1$ and $R_2$.

Similarly it can be shown that the joint resistance of three branches, Fig. 12, having respectively the resistances $R_1$, $R_2$, $R_3$ is

$$R = \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}.$$  

![Fig. 12.](image)

When the branch resistances are equal this formula is very simple, and becomes

$$\frac{R_1}{R_1} \times n = \frac{R_1}{n},$$

where $R_1$ = the resistance of one branch.  

$n$ = the number of branches.

*Kirchhoff's Laws.*—These laws or propositions are two, one of which may almost be said to be axiomatic or self-evident; the other is merely an amplification of Ohm's law. It is sometimes convenient to use these propositions instead of the above methods in calculations. The first of these propositions is that

*The sum of the currents in all the wires which meet in a point is equal to nothing.*

Which is another way of saying all currents in a conductive circuit going to a point must also go from it, because the point does not act as a reservoir. Let

![Fig. 13.](image)

$C_1, C_2, C_3$ convey currents to the point 0, Fig. 13, and $c_1, c_2, c_3, c_4$ convey currents away, then $C_1 + C_2 + C_3 = c_1 + c_2 + c_3 + c_4$, or $C_1 + C_2 + C_3 - (c_1 + c_2 + c_3 + c_4) = 0$.

The second proposition is that

*The sum of the products of the currents and resistances in all the branches forming a closed circuit is equal to the sum of all the electrical pressures in the same circuit.*

Which is another way of saying that when $E = E_1 + E_2 + E_3$, etc., and $C = C_1 + C_2 + C_3$, etc., and $R$ is the total resistance of $R_1, R_2, R_3$, etc., then

$$E_1 + E_2 + E_3 + \ldots = C_1 R_1 + C_2 R_2 + C_3 R_3 + \ldots$$

that is $E = C R$.

The following table of resistance will perhaps give a better idea of the relative values of the metals as conductors than the table of conductivity previously given:

<table>
<thead>
<tr>
<th>Metal</th>
<th>R in ohms of 1 yard of wire 30 mils diam.</th>
<th>Metal</th>
<th>R in ohms of 1 yard of wire 30 mils diam.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>0.0559</td>
<td>Nickel</td>
<td>0.2526</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0324</td>
<td>Tin</td>
<td>0.2678</td>
</tr>
<tr>
<td>Gold</td>
<td>0.0417</td>
<td>Lead</td>
<td>0.3980</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.0590</td>
<td>Antimony</td>
<td>0.72</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.1274</td>
<td>Bismuth</td>
<td>2.78</td>
</tr>
<tr>
<td>Platinum</td>
<td>0.1386</td>
<td>Mercury</td>
<td>2°</td>
</tr>
<tr>
<td>Iron</td>
<td>0.1970</td>
<td>German silver</td>
<td>4.244</td>
</tr>
</tbody>
</table>

A mil is one-thousandth of an inch, or 1,000 mils make one inch.

*Current.*—If we take a source of electrical pressure, such as the combination, Fig. 14, consisting of a glass jar three parts filled with dilute sulphuric acid (ten parts water to one of acid), with strips of copper (Cu) and zinc (Zn), placed as shown, and joined externally, that is, outside the liquid, by the conductor, W, we get certain electrical phenomena, said to be due to a current of electricity passing along the conductor. It may be well to state here that opinions differ somewhat as to the exact part played by the conductor in the electric circuit. It is usually surrounded by air, or some other non-conductor, and it is very probable that the non-conductor plays as important, if not a more important, part in the phenomena as does the conductor. After due consideration we shall assume that both the conductor and the surrounding dielectric, or non-conductor, have to play their respective parts in the observed phenomena. It is not for us, in a practical work of this kind, to enter into long discussions upon the tendencies of modern scientific thought and investigations, and this reference has been made solely with a view to say that in every case the most advanced, as well as the older, theories have been reviewed, and the views put forward are those deemed most fitted to appeal to workers.

As soon as the external wire in the above combination is connected, if its resistance be not too great, small bubbles will be seen to form upon the copper plate in the fluid, gradually enlarging, and finally bubbling to the surface; also if a small magnet be brought near the wire it is visibly affected. Then, again, if the temperature of the wire was noted in its state before connecting, and again noted in its state
after connecting, it would be found that the latter temperature was higher than the former. These phenomena are said to be due to the current. We have assumed that electrical pressure has been set up at a point in the combination, or that a difference of pressure has been made between two points, and under the influence of this pressure electricity is forced around the circuit. In years gone by, when our knowledge of the subject was less, and when all scientific men spoke of the apparatus as generating electricity, the simplest way to explain certain phenomena was to imagine the generation of two kinds of electricity. There is, as a matter of fact, no reason to imagine two kinds of electricity, or even to imagine one kind. Electrical phenomena may be due, as light phenomena are due, to certain actions upon the ether. However, we have preferred to consider the phenomena as due to action upon electricity. A pressure is exerted upon it, and a path is arranged for its progress; hence the motion of electricity through this path, giving us the phenomena of the current. The pressure generated must be looked upon as directive—that is, acting in a certain direction, or causing action in a certain direction.

Analogy with Flow of Water.—Prof. Perry and Dr. Wormell have both tabulated the analogies between flow of electricity, or current, and flow of water. We quote the following sentences from Dr. Wormell: It will be known as a simple principle of dynamics that to lift a weight a certain height, work must be done, the measure of which is the product of the weight and height to which it is raised, and when a body falls from a given height it acquires an active energy, measured by the product of the weight of the body and the height through which it falls. If, for instance, 1,000 lb. fall through a height of 10 ft., the energy accumulated at the end of the fall is 10,000 foot-pounds. If the 1,000 lb. are then arrested, and no other result follows, this 10,000 foot-pounds of energy is turned into heat. Now Joule has taught us that 772 foot-pounds of dynamical energy are equivalent to the heat that will raise the temperature of 1 lb. of water 1 deg. F. Hence the heat produced in the instance we have taken for illustration is 10,000 + 772 units of heat. These principles enable us to point out certain analogies that exist between the work done by a flow of water and that done by a current of electricity.

**Water.**

1. Suppose a quantity of water to flow from a higher level to a lower, the energy liberated will be measured by the product of the quantity of water, \( Q \), and the difference of the two levels, \( D \). If the water flows away without doing work, and leaves the lower level with the same speed as it entered the upper, then the energy due to the fall has all been converted into heat by the frictional resistance of the pipes through which it flows. If \( H \) be the quantity of heat produced in the pipes, \( H = QD + 772 \).

2. If we let the water do work on the way, turn a mill, for instance, then the backward pressure of the machine tends to stop the flow of water, and if it is to issue at the lower level with the same velocity as before, the resistance of the pipes must be diminished, and less heat will be produced. If \( W \) is the measure of the work done, then \( H = (QD - W) \) divided by 772.

3. Water may be brought from any distance, and be made to give out nearly all its energy to work a machine. To secure this result there must be a great head of water, and only a small quantity allowed to flow per second.

From the first of these analogies we conclude that if \( C \) is the quantity of electricity flowing per second, and \( E \) the difference of pressure between two points of the circuit, then the amount of energy expended between these points is \( CE \). But if \( R \) be the resistance, then, by Ohm's law, \( E = CR \), and the amount of energy liberated is \( C^2R \).

**Electricity.**

1. Suppose a quantity of electricity to flow between points that have a difference of potential, the energy set free will be measured by the product of the quantity, \( Q \), and the difference of the two points, \( D \). If the electricity flows without doing work, all the electrical energy is converted into heat, because of the electrical resistance of the wire. If \( H \) be the measure of the heat produced in the wire, \( H = QD \) divided by 772.

2. If we let the electricity work a machine in passing between the two points, the motion of the machine produces a backward pressure which diminishes the flow of electricity, and in order that the current may remain the same, the resistance must be diminished, and then less heat will be produced. If \( W \) is the measure of the work done, then \( H = (QD - W) \) divided by 772.

3. Electricity may be brought from any distance, and be made to expend itself in working a machine. To secure this result there must be a great difference of pressure, and a small current.

[Diagram of a circuit with a wire carrying a current.]

**Fig. 15.**

MESSRS. B. VERITY AND SONS' ELECTRIC LIGHT FITTINGS.
BRUSH ARC LAMP.
sprinkled upon the cardboard the filings will arrange themselves in circular form, as in Fig. 16. From this

![Fig. 16.](image)

and other experiments it is found that a current through a conductor has an influence external to the conductor, and the whole of the space through which such influence extends is called the field of the conductor. The result upon the iron filings is similar to that of a directive force or forces starting from the conductor and acting in a direction tangential to the axis of the filings when arranged.

Again, if the terminal wires of a source, instead of being connected together, are placed in a liquid solution which is a conductor, the circuit is completed just as if it were wholly composed of wire. In many solutions, as soon as a current is started in the circuit a chemical action takes place, and the solution is decomposed. Such decomposition is called electrolysis. This action seems to take place in the direct line of the conductor, hence we may say the phenomena connected with the current are twofold:

1. Those within the conductor.
2. Those external to the conductor.

Heating Effect of Current.—Of the phenomena connected with the effects of the current within the conductor the two most important are the heating effect and the chemical effect. It is to the heating effect that the value of electricity as a lighting agent is due. Looking, then, at the production of the electric light as one of the most important branches of electrical engineering, this part of the subject to be discussed may be briefly stated. Accepting the modern theory that light is due to vibrations of the ether caused by highly heated bodies, in order to obtain artificial light the highly heated bodies must be placed at the points where the light is desired, and assuming that every reader is fully alive to the impossibility of each individual member of the community arranging for independent sources of generation of light at every point required, we come to the problem of how best to distribute from central points the means of providing artificial lights over large areas, and at the various points in those areas where the light is required. The two great systems in vogue are the production of gas at certain points, and distributing that gas over large areas; and the generation of electrical pressure at certain central points, and distributing an electric current over the required area. Gas is an inflammable material and its burning, or its combustion, with the oxygen in the air gives an artificial illuminant. The value of electricity for this purpose, on the other hand, depends upon its heating effect on the conductor provided to carry the current. Usually, as will be seen further on, the prime motors in electric light installations are steam engines, or, rather, the prime motor of all is the burning fuel in the firebox of the boiler. Then the economical question for all engineers becomes, given a certain amount of heat generated in the firebox of the boiler, how best to get the largest percentage of heat so generated to the points requiring illumination.

It is found that the heat generated in a conductor by a current is proportional to the product of the square of the current into the resistance of the conductor.

\[ \text{Heat generated} = C^2 R. \]

Now as the current flowing across each section of the circuit is the same, and as at some parts of the circuit the heat is not wanted, whilst at other parts it is wanted, the natural course is pursued of inserting a conductor of high resistance at the point where the heat is required. The heat thus obtained raises the temperature of the conductor till we obtain brilliantly incandescent conductors giving light where wanted. Trace the various changes from the burning fuel to the light, and it will be seen how many opportunities there are for loss on the way.

The burning fuel is used to generate steam.

Expansion of steam used to move the piston of the engine.

Belt from engine drives dynamo.

Current due to electrical pressure from dynamo circulates around circuit.

Or,

Heat energy is transformed into mechanical energy.

Mechanical energy is transformed into electrical energy.

Electrical energy is transformed back again into heat energy.

In every transformation there is a loss, and the loss can be measured and calculated. By energy we mean the capacity for doing work. A force does work when its point of application moves in the direction of the force, and the work done is measured by the product of the magnitude of the force and the distance through which the point of application moves in the direction of the force. The unit of work used by English engineers is the foot-pound. It is the work done in raising one pound through the space of one foot against gravity. This old-fashioned unit did not commend itself to the electricians who set to work in the interests of telegraphy to introduce units. They preferred the metric system, hence the attempt to introduce either the gramme or the kilogramme, which gives as units either a gramme raised a metre, or a kilogram raised a metre. The kilogramme = 2.2 lb., and the metre = 3.28 ft., so a kilogramme is 2.2 \times 3.28 or 7.2 foot-pounds.
1 kilogrammetre = 7.2 foot-pounds.

1 foot-pound = \( \frac{1}{7.2} \) kilogrammetre.

But not only have engineers to consider the quantity of work, they must know the rate of working; hence time has to be considered. The unit here adopted is the horse-power, equivalent to the raising of 33,000 lb. one foot in one minute.

Unit of work = foot-pound.

Unit of rate of work = horse-power = 33,000 foot-pounds per minute.

It has long been understood that heat and work are convertible, but it was not till the classic experiments of Joule that the exact equivalents were determined. He proved that 1 lb. falling 77243 ft. would raise the temperature of 1 lb. of water one degree Fahrenheit. This is called the mechanical equivalent of heat, or, shortly, Joule’s equivalent, and is taken as 772 foot-pounds.

The British thermal unit then is 772 foot-pounds, and is designated by J.

1 horse-power = \( \frac{33,000}{772} \) = 42.75 thermal units (British).

If the centigrade scale is used, then the heat equivalent is \( \frac{1}{1,390} \) — that is, the work done in raising 1 lb. of water through 1 deg. C. is equivalent to the falling of 1 lb. through a height of 1,390 ft., for 1 deg. C. = \( \frac{9}{5} \) deg. F., and 772 \( \times \) \( \frac{9}{5} \) = 1,389.6.

According to the French system, the thermal unit is called a calorie.

As a foot-pound = 0.1383 kilogrammetre, the calorie = 1330 \( \times \) 0.1383 = 192 kilogrammetres.

The calorie = 1,390 foot-pounds.

It has been stated that electrical energy is convertible into heat energy, and as heat energy is convertible into mechanical energy, we see that electrical energy is convertible into mechanical energy, and mechanical energy is convertible into electrical energy.

If the whole of the electrical energy passing through a circuit in \( t \) minutes is converted into heat, then

Heat = \( C^2 R t \).

It is customary to speak of electrical energy as equivalent to so many horse-power hours, and using the units ampere, ohm, volt, we have to use the formula \( \frac{C E}{746} \) = horse-power; or, as \( E = C R \), this may be written \( \frac{C^2 R}{746} \) = horse-power.

If, then, a current of 100 amperes flows through a circuit having a resistance of 10 ohms continuously for an hour, we get \( \frac{100^2 \times 10}{746} \) = 134 horse-power (about) for an hour.

As \( \text{volts} \times \text{amperes} \) = horse-power, the unit of work is \( \text{volt} \times \text{ampere} \), and has been called the watt.

1 watt = 1 volt \( \times \) 1 ampere.

746 watts = 1 horse-power.

It will be seen that we have here a simple way of ascertaining the loss by conversion between engine and dynamo. By taking engine diagrams we get the horse-power developed by the engine, and by measuring the current and resistance in the external circuit, or current and pressure, we get the horse-power available for use, the difference between the two is so much loss.

Further, we can ascertain exactly the horse-power put into the dynamo, and the horse-power given out as available electrical energy, and so ascertain the efficiency of the dynamo as a machine. We have said that the heating properties of the current are required at certain parts of the circuit, while the heat developed in other parts of the circuit is so much waste. The resistance of the ordinary conductors increases with temperature, and as our available energy depends upon current as well as upon pressure, the resistance should be kept as low as possible. If the temperature is allowed to rise, it may lead to the fusing of wires, to the destruction of insulation, to the causing of fires to the buildings in which the conductors are placed. So long as a current is passing through a conductor there will be heat generated according to the formula \( C^2 R \), and this heat continually increases the temperature of a conductor unless it is radiated from the surface of the conductor or got rid of in some other way. If the temperature of the conductor rises to a certain point and then remains constant, it means that the heat generated is equal to the heat radiated or conducted away. It will at once be seen that there is less difficulty in getting rid of the heat generated in a straight, or rather in a single, conductor than when the conductor is coiled.

Professor George Forbes has paid particular attention to this problem, and in his paper before the Institution of Electrical Engineers, and from the results of his experiments, the following practical conclusions are derived: “An insulated wire carries a greater current without overheating than a bare wire, if the diameter be not very great.” This would naturally have been expected, as the heat is dissipated from the conductor by conduction through the insulator, and radiation from the surface of the insulator.

“Assuming,” says Prof. Forbes, “the diameter of the cable to be twice that of the conductor, a greater current can be carried in insulated cables than in bare wires up to 1.9 (nearly two) inches diameter of conductor. But if the insulated cable have a diameter four times that of the conductor, this is the case up to 1.4 in. diameter of conductor.”

Where the thickness of insulation is made very great the limiting size of conductor which favours the insulated wire is given in the table.
Dia. of insulation  | Limiting dia. of conductor which favours insulation
--- | ---
2  | 1-9 inches.
4  | 1-1
6  | 0-966
8  | 0-859
10 | 0-786
100 | 0-393

Prof. Forbes calculates a table for wires under the conditions given at the head of the table, viz.:

**TABLE.**—Subaqueous and Aerial Cables (insulated).

<table>
<thead>
<tr>
<th>Diameter of cable</th>
<th>Diameter of conductor</th>
<th>Temperature of air = 20 deg. C.</th>
</tr>
</thead>
</table>
| 4                 |                       | t = excess of temperature of conductor over air.

<table>
<thead>
<tr>
<th>Diameter in centimetres and mils.</th>
<th>CURRENT IN AMPERES.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t=1&quot;.</td>
</tr>
<tr>
<td>cm.</td>
<td>mms.</td>
</tr>
<tr>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
</tr>
<tr>
<td>4</td>
<td>160</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>240</td>
</tr>
<tr>
<td>7</td>
<td>280</td>
</tr>
<tr>
<td>8</td>
<td>310</td>
</tr>
<tr>
<td>9</td>
<td>350</td>
</tr>
<tr>
<td>10</td>
<td>390</td>
</tr>
<tr>
<td>11</td>
<td>430</td>
</tr>
<tr>
<td>12</td>
<td>470</td>
</tr>
<tr>
<td>13</td>
<td>510</td>
</tr>
<tr>
<td>14</td>
<td>550</td>
</tr>
<tr>
<td>15</td>
<td>600</td>
</tr>
<tr>
<td>16</td>
<td>650</td>
</tr>
</tbody>
</table>

Computed from the formula,

\[ C = \sqrt{\frac{\pi^2 D^4 K}{48 E} \cdot \frac{3 D_2}{10 + 3 D_2 \log_{10} \frac{D_2}{D_1}}} \]

where \( K \) = thermal conductivity of insulator, = 0.9048 for gutta-percha;

\( E \) = coefficient of cooling, = 0.0008.

The difficulties surrounding the case of buried conductors are too great to give any practical guidance, but the prevailing practice will be fully discussed in the section dealing with distribution.

A most important practical question, however, is that relating to coils, because as a rule we require to lose as little energy in heating the coils as we possibly can, and especially so in the armature coils of dynamos.

Prof. Forbes says: "It becomes an easy thing in any case to calculate the heating of a coil when we know its cooling surface and its resistance.

Let \( \rho \) = the resistance of a coil in ohms at the permissible temperature.

\( S \) = the surface exposed to the air measured in centimetres (1 square cm. = .155 square inch. 1 square inch = 6.45 square cm).

Let \( t \) = the rise in temperature, centigrade scale.

\( C \) = the current in amperes.

\[ \cdot24 C^2 \rho \text{ = generated } = -E t S \]

where \( E \) is McFarlane's constant varying from .0002 to .0003. The latter value may be taken. If 50 deg. C. be the permissible rise in temperature

\[ C = \sqrt{\frac{0.0003 \times 50 \times S}{24 \times \rho}} = -25 \sqrt{\frac{S}{\rho}} \]

N.B.—It must be remembered in practice that the resistance (cold) must be increased by \( \frac{1}{3} \) of its value to give \( \rho \).

Example.—The resistance of the field-magnets of a dynamo is 1.5 ohms cold, and the surface exposed to the air is 1 metre; find the current to heat it not more than 50 deg. C. Here \( S = 10,000, \rho = 1.8 \) ohms, and

\[ C = -25 \sqrt{\frac{10,000}{1.8}} = 33.5 \text{ amperes.} \]

Those who are accustomed to handling dynamos will know that this is very much what we actually find, and it gives us confidence in the applications of theory."

According to the most recent practice, Mr. Eson gives the ultimate rise in temperature of coils wound with double cotton-covered wires, varnished on the exterior, to be approximately in degrees centigrade for square centimetres of surface. When \( W \) = energy in watts dissipated, and \( S \) = cooling surface in square centimetres,

\[ C = \frac{W}{355} \frac{355}{S} \]

If square inches be taken as the unit, then the formula becomes

\[ C = \frac{W}{55} \frac{55}{S} \]

when \( W \) = energy in watts dissipated, and \( S \) = cooling surface in square inches.

As \( 1^\circ F = \frac{9}{5} C^\circ \), these formulae become on the Fahrenheit scale:

\[ F^\circ = \frac{W}{197} \frac{197}{S} \text{ for square centimetres of surface;} \]

And \( F = \frac{W}{30.5} \frac{30.5}{S} \text{ for square inches.} \)

These formulae being admittedly approximate, we may use the constant 200 instead of 197 without practically affecting the result, and write

\[ F^\circ = \frac{W}{200} \frac{200}{S} \text{ for square centimetres.} \]

The coefficients, says Mr. Eson, have been obtained from practice, but they are liable to some uncertainty. In the cases from which they have been derived the coils were wound on formers of sheet iron, which fitted close to the magnets. These formers were fitted with brass end flanges, and in the spaces between the flanges and the wire, also between the body and the wire, was a thick layer of insulating material. The surface of the end flanges is not included as making up surface \( S \), nor is the inside surface of the former next the magnet.
Though insulated so well thermally, there is certainly a flow of heat towards the interior of the magnets and towards the end flanges, so that, as a matter of fact, the virtual cooling surface is greater than given above. Its value it is, however, difficult to determine, while the above equation is approximately true for machines of medium size, and may be used for all cases in which the coils do not exceed 2\text{in.} or 6\text{in.} in thickness.

For armatures—which in rotating induce a current of air—the equation is different, and the coefficient given above may have a much lower value, according to the velocity and ventilation. For armatures the surface velocity of which is 50\text{ft.} per second (3,000\text{ft. per minute}), and the exterior diameter of the core 1\text{ft.} times the interior, the length being about equal to the diameter, the rise is, approximately,

\[ C^* = \frac{W}{S} \frac{225}{S} \quad \text{(for sq. centimetres)}, \]

or

\[ C^* = \frac{W}{S} \frac{35}{S} \quad \text{(for sq. inches)}, \]

accordingly as the surface is taken in square centimetres or square inches. Here the whole of the cooling surface inside, outside, and at the ends is counted, \text{W} being the total watts dissipated in both electrical waste and hysteresis. The latter must, under no circumstances, be neglected, as it may reach 20 per cent. or more of the total. In giving the above equation, it should be stated that the armatures of the machines which furnished the results are closed at the commutator end, except at the periphery, where a draught of air from the centre through the pulley end is expelled. For slow-speed machines the coefficient is necessarily higher, and a larger surface must be allowed, or special means adopted, in the shape of vanes or blades, to force a draught through the armature. Experience can be the only guide here.

In any case, the ultimate temperature of the machine ought not to rise above a certain value, whatever the temperature of the room in which it works. In Mr. Esson's opinion, an ultimate temperature of from 70\text{deg.} to 75\text{deg.} C. may be permitted with perfect safety, but this should not be exceeded.

Mr. C. Hering, when discussing coils on field-magnets, gives formulæ for them. These formulæ are very different to those of Mr. Esson, whose formulæ accord with English practice, while Mr. Hering has derived his formulæ from American practice. Mr. Hering gives under his conditions a watt of energy as dissipated for every 223 square inches of surface, when the difference between the temperature of the coil and the surrounding air is 1 deg. F.

Putting this into a formula, we get

\[ W = C E = \frac{T S}{223} = 0.004476 T S, \]

where \text{W} = \text{watts lost in coil}, \text{T} = \text{degrees Fahrenheit}, and \text{S} = \text{square inches}.

From the formula \[ W = C E = C R \frac{E^2}{R} = \frac{1}{223} T S, \]

when \text{CER} have their ordinary significations, \text{R},

however, being the resistance at the temperature to which the coil may be raised, we get some very practical information. Suppose we take

\[ C E = \frac{T S}{223}, \quad C = \frac{T S}{223} E \]

this gives the greatest current which can be used in the magnet coils of a shunt machine having a certain pressure, in order that they do not heat above a certain temperature. This current can be calculated before the winding is determined, as it is independent of the number of turns or the resistance, if only the size of the external surface is approximately known. This maximum current should never be exceeded.

Again, the greatest current for any allowable temperature above that of the surrounding air can easily be divided—say, for 50 deg. F.,

\[ C = \frac{50 S}{223} E \approx \frac{224}{E} S. \]

If here we substitute for \text{E} its equivalent \text{C} \text{R}, we get \[ C = \sqrt{\frac{224}{E} S} \]

If 80 deg. F. is the maximum difference of temperature,

\[ C = \frac{80 S}{223} E = \frac{36 S}{E} = \frac{60}{E} \sqrt{\frac{S}{R}} \]

The formulæ can be used for series machines when \text{C} is known, for writing

\[ C^* R = \frac{1}{223} T S \]

we get

\[ R = \frac{T S}{223 C^*} \]

With a permissible rise of 50 deg. F., or of 80 deg. F., we have respectively

\[ R = \frac{224 S}{C^*}; \quad \text{and} \quad R = \frac{36 S}{C^*} \]

The surface area of the coil in square inches may be found from

\[ S = \frac{223 W}{T} = \frac{223 C E}{T} = \frac{223 C^* R}{T}. \]

For a rise of temperature of 50 deg. F. or 80 deg. F., respectively, the surface will be

\[ S = \frac{223 W}{50} = 4.46 W; \quad \text{and} \quad S = \frac{223 W}{80} = 2.6 W. \]

As the number of watts to be allotted to the magnets is approximately known at the outset, this formulæ enables one to determine about what the least surface of the coils should be, and, in fact, knowing the cross section of the core, to arrive at an approximate idea of the least length of core.

When we desire to employ the heating properties of the current for the production of light, it is necessary to employ some conductor having high resistance that does not fuse at the temperature to which it has to be raised. None of the metals are suitable, and hitherto all attempts to find another conductor for this purpose
ELEVATION
CROMPTON'S ELECTRIC TRAVELLING CRANE.

PLAN
CROMPTON'S ELECTRIC TRAVELLING CRANE.
American Fittings.
than carbon have failed. Used as ordinary conductors, however, the metals are seldom raised to a temperature near their melting point. We shall see, however, that metals and alloys are used for protective purposes—that is, they are put in the circuit that should there be by any accident an excess of current, they will melt and break the circuit. The following table of fusibility gives an idea of the utility of the metals for this purpose:

**Table of Fusibility.**

<table>
<thead>
<tr>
<th>Metal</th>
<th>Temperature (deg. F.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tin</td>
<td>442</td>
</tr>
<tr>
<td>Lead</td>
<td>617</td>
</tr>
<tr>
<td>Zinc</td>
<td>773</td>
</tr>
<tr>
<td>Silver</td>
<td>1,800</td>
</tr>
<tr>
<td>Copper</td>
<td>1,990</td>
</tr>
<tr>
<td>Gold</td>
<td>2,000</td>
</tr>
<tr>
<td>Cast Iron</td>
<td>2,800</td>
</tr>
<tr>
<td>Steel</td>
<td>4,000</td>
</tr>
</tbody>
</table>

(about)

In papers to the Royal Society, Mr. W. H. Preece, F.R.S., described a long series of experiments made to determine the heating effects of currents upon wires, from which he deduced the formula for the fusion current:

\[ C = a d^2 \]

and in his third paper he calculated two tables from the final value of the constant \( a \), as determined by the experiments. The metals experimented with were copper, aluminium, platinum, German silver, platinoid, iron, tin, alloy (2 of lead to 1 of tin), lead. The value of \( a \) for these different metals is given as follows:

<table>
<thead>
<tr>
<th>Material</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>10,244</td>
</tr>
<tr>
<td>Aluminium</td>
<td>7,685</td>
</tr>
<tr>
<td>Platinum</td>
<td>5,172</td>
</tr>
<tr>
<td>German silver</td>
<td>5,320</td>
</tr>
<tr>
<td>Platinoid</td>
<td>4,750</td>
</tr>
<tr>
<td>Iron</td>
<td>3,148</td>
</tr>
<tr>
<td>Tin</td>
<td>1,642</td>
</tr>
<tr>
<td>Alloy</td>
<td>3,318</td>
</tr>
<tr>
<td>Lead</td>
<td>1,379</td>
</tr>
</tbody>
</table>

We give a part of the further tables, the part relating more directly to the metals used extensively in electrical engineering. (See Tables I. and II. on next page.)

The Chemical Action of the Current.—The chemical action of a current is best seen in the art of electro-deposition, which to be thoroughly understood requires a considerable knowledge of chemistry. In fact, the art depending upon this chemical action is rapidly being divided into three distinct branches—which may be termed electro-chemical, electro-metallurgical, and electro-depositing.

The chemist tells us that all substances in nature can be broadly divided into two classes:

1. **Elementary substances**, which are the art of the chemist is not yet able to divide into anything dissimilar to themselves.

2. **Compound substances**, which can be divided up into their component elements.

Chemical action is either the combination of elementary substances, or elements with compounds, or compounds with compounds, or the reverse action of the separation of compounds or elements from compounds. Chemical action may be altogether independent of electricity or it may be assisted thereby. Thus, if the clean blade of a knife be dipped into a solution of sulphate of copper, it will become coated with the copper. This we should term simply a chemical action, although copper is deposited upon the steel. If we take an ordinary Daniell's battery, we find that the copper from the sulphate of copper is deposited upon the copper plate, and this only when a current is circulating through the circuit. This deposition, then, is due to electrical action. The full consideration of this subject does not come within the scope of this treatise, but we may state the more important principles connected with electrolysis. It was Faraday who gave us the nomenclature relating to electrolysis. He called the compound to be decomposed the Electrolyte, and the process Electrolysis. The plates or poles of the battery he called Electrodes. The plate where the greatest pressure exists he called the Anode, and the other pole the Cathode. The products of decomposition he called Ions.

Elementary substances, inasmuch as they cannot be decomposed, are not electrolytes. As a rule electrolytes are electrolysed only in the fluid state, because only in that state are they conductors. The components of an electrolyte are resolved during electrolysis into two groups which, so to speak, travel through the electrolyte in opposite directions, one going towards one electrode and one going towards the other. Those bodies only are electrolytes that are composed of a conductor and a non-conductor. It is to be carefully noticed that:

1. The amount of chemical action is the same at whatever part of the circuit it occurs.

2. The amount of an element liberated at an electrode during a given time is proportional to the current.

This latter law permits another way to obtain "unit current." Very careful experiments have been made by Lord Rayleigh, and he finds that a current of one ampere will deposit 0.017253 grain, or 0.0011815 gramme, of silver per second on one of the plates of a silver voltameter, the liquid employed being a solution of silver nitrate containing from 15 to 20 per cent. of the salt.

The weight of hydrogen similarly set free is 0.0001035 grammes—that is, one ampere per second sets free 0.0001035 grammes of hydrogen from water in that time.

Knowing the amount of hydrogen thus set free, and certain other chemical facts, we can calculate exactly what weight of other substances will be set free or deposited in a given time by a given current.

Thus the current that liberates 1 gramme of hydrogen will liberate 8 grammes of oxygen, or 108 grammes of silver, the numbers 8 and 108 being the chemical equivalents for oxygen and silver respectively.
### I.

Giving the Diameters of various Wires which will be Fused by a given Current, from the formula

\[ d = \left( \frac{C}{a} \right)^{\frac{3}{2}} \]

for Tin = 1379 for Lead = 10244 for Copper = 3148 for Iron.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter Inches</td>
<td>Approx. S.W.G.</td>
<td>Diameter Inches</td>
<td>Approx. S.W.G.</td>
</tr>
<tr>
<td>1</td>
<td>0.0072</td>
<td>36</td>
<td>0.0081</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>0.0113</td>
<td>31</td>
<td>0.0128</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0.0149</td>
<td>28</td>
<td>0.0163</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>0.0181</td>
<td>26</td>
<td>0.0203</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>0.0210</td>
<td>25</td>
<td>0.0236</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>0.0334</td>
<td>21</td>
<td>0.0375</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>0.0437</td>
<td>19</td>
<td>0.0491</td>
<td>18</td>
</tr>
<tr>
<td>20</td>
<td>0.0529</td>
<td>17</td>
<td>0.0590</td>
<td>17</td>
</tr>
<tr>
<td>25</td>
<td>0.0614</td>
<td>16</td>
<td>0.0690</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>0.0694</td>
<td>15</td>
<td>0.0779</td>
<td>14</td>
</tr>
<tr>
<td>35</td>
<td>0.0769</td>
<td>14.5</td>
<td>0.0864</td>
<td>13.5</td>
</tr>
<tr>
<td>40</td>
<td>0.0840</td>
<td>13.5</td>
<td>0.0944</td>
<td>13</td>
</tr>
<tr>
<td>45</td>
<td>0.0909</td>
<td>13</td>
<td>0.1021</td>
<td>12</td>
</tr>
<tr>
<td>50</td>
<td>0.0975</td>
<td>12.5</td>
<td>0.1095</td>
<td>11.5</td>
</tr>
<tr>
<td>60</td>
<td>0.1101</td>
<td>11</td>
<td>0.1237</td>
<td>10</td>
</tr>
<tr>
<td>70</td>
<td>0.1220</td>
<td>10</td>
<td>0.1371</td>
<td>9.5</td>
</tr>
<tr>
<td>80</td>
<td>0.1384</td>
<td>9.5</td>
<td>0.1499</td>
<td>8.5</td>
</tr>
<tr>
<td>90</td>
<td>0.1443</td>
<td>9</td>
<td>0.1621</td>
<td>8</td>
</tr>
<tr>
<td>100</td>
<td>0.1548</td>
<td>8.5</td>
<td>0.1739</td>
<td>7</td>
</tr>
<tr>
<td>120</td>
<td>0.1748</td>
<td>7</td>
<td>0.1964</td>
<td>6</td>
</tr>
<tr>
<td>140</td>
<td>0.1937</td>
<td>6</td>
<td>0.2176</td>
<td>5</td>
</tr>
<tr>
<td>160</td>
<td>0.2118</td>
<td>5</td>
<td>0.2379</td>
<td>4</td>
</tr>
<tr>
<td>180</td>
<td>0.2291</td>
<td>4</td>
<td>0.2573</td>
<td>3</td>
</tr>
<tr>
<td>200</td>
<td>0.2437</td>
<td>3.5</td>
<td>0.2760</td>
<td>2</td>
</tr>
<tr>
<td>250</td>
<td>0.2851</td>
<td>1.5</td>
<td>0.3303</td>
<td>0</td>
</tr>
<tr>
<td>300</td>
<td>0.3220</td>
<td>0</td>
<td>0.3617</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### II.

Giving Current in Amperes required to Fuse Wires according to the formula 
\[ C = a d^2 \]

<table>
<thead>
<tr>
<th>No. S.W.G.</th>
<th>Diameter Inches</th>
<th>( d^2 )</th>
<th>Tin ( a = 1642 )</th>
<th>Lead ( a = 1379 )</th>
<th>Copper ( a = 10244 )</th>
<th>Iron ( a = 3148 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.060</td>
<td>0.023627</td>
<td>37.15</td>
<td>31.20</td>
<td>231.8</td>
<td>71.22</td>
</tr>
<tr>
<td>16</td>
<td>0.064</td>
<td>0.016191</td>
<td>26.88</td>
<td>22.32</td>
<td>165.8</td>
<td>50.96</td>
</tr>
<tr>
<td>18</td>
<td>0.048</td>
<td>0.010516</td>
<td>17.27</td>
<td>14.50</td>
<td>107.7</td>
<td>32.10</td>
</tr>
<tr>
<td>20</td>
<td>0.066</td>
<td>0.006831</td>
<td>11.22</td>
<td>9.419</td>
<td>64.97</td>
<td>21.50</td>
</tr>
<tr>
<td>22</td>
<td>0.068</td>
<td>0.004668</td>
<td>7.692</td>
<td>6.466</td>
<td>48.00</td>
<td>14.75</td>
</tr>
<tr>
<td>24</td>
<td>0.022</td>
<td>0.003623</td>
<td>5.557</td>
<td>4.499</td>
<td>32.43</td>
<td>10.27</td>
</tr>
<tr>
<td>26</td>
<td>0.018</td>
<td>0.002415</td>
<td>3.565</td>
<td>3.330</td>
<td>24.74</td>
<td>7.602</td>
</tr>
<tr>
<td>28</td>
<td>0.0148</td>
<td>0.001801</td>
<td>2.958</td>
<td>2.458</td>
<td>18.44</td>
<td>5.667</td>
</tr>
<tr>
<td>30</td>
<td>0.0124</td>
<td>0.001381</td>
<td>2.267</td>
<td>1.904</td>
<td>14.15</td>
<td>4.347</td>
</tr>
<tr>
<td>32</td>
<td>0.0168</td>
<td>0.001122</td>
<td>1.849</td>
<td>1.548</td>
<td>11.50</td>
<td>3.533</td>
</tr>
</tbody>
</table>

**Examples.**

Find weight of silver deposited in 10 seconds by a current of 10 amperes:

Weight of silver = weight of hydrogen liberated per
TABLE III.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H²</td>
<td>1</td>
<td>1</td>
<td>0.01035</td>
<td>9629.9-00</td>
<td>0.03735</td>
<td>4.9083653</td>
<td>5.572090</td>
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<tr>
<td>Potassium</td>
<td>K¹</td>
<td>39.04</td>
<td>39.04</td>
<td>405.39</td>
<td>2467.50</td>
<td>1.45950</td>
<td>3.3202572</td>
<td>3.1642041</td>
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<tr>
<td>Sodium</td>
<td>Na¹</td>
<td>22.99</td>
<td>22.99</td>
<td>233.73</td>
<td>1818.90</td>
<td>0.85942</td>
<td>3.6231000</td>
<td>3.0342053</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Al¹</td>
<td>27.3</td>
<td>9.1</td>
<td>0.9149</td>
<td>1058.30</td>
<td>3.40180</td>
<td>3.0245939</td>
<td>0.5317068</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg¹</td>
<td>23.94</td>
<td>11.97</td>
<td>1213.00</td>
<td>804.03</td>
<td>4.14740</td>
<td>2.9055411</td>
<td>0.6507614</td>
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<tr>
<td>Gold</td>
<td>Au¹</td>
<td>196.2</td>
<td>65.47</td>
<td>679.11</td>
<td>1473.50</td>
<td>2.44480</td>
<td>3.1863561</td>
<td>0.3882433</td>
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<td>Silver</td>
<td>Ag¹</td>
<td>107.66</td>
<td>107.66</td>
<td>1180.00</td>
<td>894.41</td>
<td>4.02800</td>
<td>2.9518566</td>
<td>0.6017659</td>
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<tr>
<td>Copper (Cupric)</td>
<td>Cu²</td>
<td>63</td>
<td>131.56</td>
<td>327.09</td>
<td>3058.60</td>
<td>1.17700</td>
<td>3.4885527</td>
<td>0.0707655</td>
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<tr>
<td>Mercury (Mericuric)</td>
<td>Hg²</td>
<td>200.8</td>
<td>200.8</td>
<td>200.8</td>
<td>1920.30</td>
<td>2.35500</td>
<td>3.1833553</td>
<td>0.371909</td>
</tr>
<tr>
<td>Tin (Stannic)</td>
<td>Sn²</td>
<td>117.8</td>
<td>117.8</td>
<td>303.81</td>
<td>3270.00</td>
<td>1.00900</td>
<td>3.5145748</td>
<td>0.0417479</td>
</tr>
<tr>
<td>Iron (Ferric)</td>
<td>Fe³</td>
<td>55.8</td>
<td>55.8</td>
<td>611.62</td>
<td>1635.00</td>
<td>2.20180</td>
<td>3.2135178</td>
<td>0.3477779</td>
</tr>
<tr>
<td>Nickel</td>
<td>Ni²</td>
<td>58.6</td>
<td>29.3</td>
<td>304.23</td>
<td>3286.80</td>
<td>1.09530</td>
<td>3.5167733</td>
<td>0.0395533</td>
</tr>
<tr>
<td>Zine</td>
<td>Zn²</td>
<td>64</td>
<td>32.43</td>
<td>336.96</td>
<td>2967.10</td>
<td>1.21330</td>
<td>3.4723922</td>
<td>0.0839682</td>
</tr>
<tr>
<td>Lead</td>
<td>Pb²</td>
<td>206.4</td>
<td>103.2</td>
<td>1071.60</td>
<td>933.26</td>
<td>3.85780</td>
<td>2.9700027</td>
<td>0.5863397</td>
</tr>
</tbody>
</table>

* Valency is the atom fixing or atom replacing power of an element compared with hydrogen, whose valency is unity.

† Becquerel's extension of Faraday's law showed that the electro-chemical equivalent of an element is proportional to its chemical equivalent. The latter is equal to its combining weight, and not to atomic weight divided by valency, as defined by Thompson, Henshaw, and others who have copied their tables. For example, the ferric salt is an exception to Thompson's rule, as are sesqui salts in general.

second × no seconds × current strength × 108 = 0.0001035 × 10 × 10 × 108 = .11178 grammes.

Find weight of copper deposited in 1 hour by a current of 10 amperes:

0.0001035 × 60 × 60 × 10 = 11.923 grammes.

We have seen that 1 ampere per second liberates 0.0001035 grammes of hydrogen, therefore strength of current in amperes = weight in grammes of H. liberated per sec. × 0.0001035

Or strength of C in amperes = weight of silver liberated per sec. × 0.0001035 × 108

Or C = weight of element liberated per sec. × 0.0001035 × chemical equivalent of element

The accompanying Table III. is calculated upon Lord Rayleigh's determination of the electro-chemical equivalent and Roscoe's atomic weight.

Voltameter.—The voltameter represented in Fig. 17 consists of a vessel, A, containing acidulated water, two platinum plates with terminals to which the battery can be connected, together with tubes and a measuring apparatus to contain the gas when liberated. The measuring tube is filled with water, then inverted over water in the vessel B. When the battery is joined up to the terminals the water is decomposed. The gases thus obtained pass through the tube and into the tube C, forcing down the water. The volume of mixed gases, hydrogen and oxygen, produced per second by a current of one ampere, is in cubic inches = 0.03 × 76 (273 + C) where C = degrees centigrade and h = pressure in inches of mercury.
If the Fahrenheit scale is used the formula becomes
\[ 0.1058 \times 30 \left( 491 + (I^2 - 32) \right) \]
\[ k \times 491 \]

The phenomena connected with the interior of the conductor, thus briefly described, are exceedingly important, though not more so than the phenomena connected with the exterior of the conductor.

**Phenomena connected with the Exterior of a Conductor carrying a Current.**—We have seen that the current in a wire exercises a directive influence upon iron filings placed around the wire. This directive influence is found at whatever point in the circuit the experiment is tried, and we may assume that a force emanating from the conductor and due to the current in the conductor acts upon these small particles of iron in a certain and in a definite direction. If the lines in Fig. 18 represent the concentric circles into which the filings arrange themselves under the action of the current, a number of circles one above the other, Fig. 19, would indicate how filings would arrange themselves all along the wire. The influence of the current can also be examined by bringing a small magnet near the wire, or a part of the conductor belonging to another conductive circuit.

It is found that the influence of the current gets less and less the further we get away from the conductor. The whole space through which the influence is felt is termed the field of the conductor. Many term it the magnetic field of the conductor. For most practical purposes we may assume that the force or forces acting in the interior of the conductor act in directions parallel to the axis of the conductor, while those in the field act at right angles to the axis of the conductor.

It probably will be found that this assumption is not quite accurate, there being something analogous to a spiral in the direction of the action of the forces.

Faraday, to whose discoveries we owe the present position of electrical science, suggested an excellent and convenient method for discussing questions relating to the field, in supposing the effects on filings and magnets due to “lines of force” coming from the conductor and acting upon the filings. It must not be understood that such lines of force actually exist, but it is very convenient to imagine lines in the direction of which a force or forces act, and “number of lines” or “length of lines” to indicate the magnitude of the force or forces. In this case we use “number of lines” to indicate magnitude of forces acting. It is seen that the iron filings arrange themselves in concentric circles—that is, we can assume that the forces under which they so arrange themselves may be represented by “closed curves,” or instead of “lines” we may use the term “loops” of force. The forces all seem to cause polarity, or the arrangement of the ends of the particles acted upon in definite directions.

It will be well to recapitulate the conventional assumptions made with regard to the loops of force connected with the conductive circuit for the purposes of this book.

1. That the lines or loops of force in the conductor are parallel to the axis of the conductor.
2. That the loops of force external to the conductor are proportional in number to the current in the conductor—that is, a definite current generates a definite number of loops of force. These may be stated as the strength of field is proportional to the current.
3. That the radii of the loops of force are at right angles to the axis of the conductor, as shown in Fig. 20.

The interaction between fields and the influence of fields upon conductors is a most important branch of study. The phenomena connected with dynamos, motors, transformers, etc., are connected with this branch of the subject, which, however, cannot be thoroughly explained till after a study of the magnetic circuit. For the present, then, the interactions of the field will be confined to two cases:

1. The interaction between a conductor carrying a current—that is, having a field—and one with no current.
2. The interaction between two conductors carrying currents.

It is found that if a conductor is brought into the field of another conductor a current is set up in the conductor so brought into the field, the direction of the current in the conductor brought into the field being opposite to that of the conductor causing the field.
Thus, if A B, Fig. 21, represent a conductor surrounded by its field, the arrows showing the direction of the current, and another conductor, C D, is brought into the field of A B, a current is set up in C D in the direction of the arrows and opposite to that in A B.

![Diagram Fig. 21](image)

This current so set up is but momentary. If, while C D is in the position indicated, the current in A B is doubled, there will be another momentary current set up in C D, equal and in the same direction as in the former case. This double current in A B may be represented by double the number of loops, as in Fig. 22. Or if the conductor C D is brought nearer to A B, so that a greater number of the concentric loops go round it, as in the dotted line, C D, a further momentary current is set up, still in the same direction as the former ones. The action may now be reversed, and as the conductor C D is taken to the second position C D, there will be a momentary current in the reverse direction to the original current—that is, in the same direction as that in A B. On making the current in A B what it was originally, there is again another momentary current in C D in the same direction as in A B; and finally, on taking C D out of the field, there is again a momentary current in the same direction as that in A B.

To summarise these actions. On bringing a conductor into the field a momentary current is set up opposite in direction to that causing the field, and this momentary current is continued again and again by "looping" more lines of force round the conductor brought into the field. Thus we find that the current set up is proportional to the number of "loops" passed round the conductor. This is a reverse action. The current causes the "field," the field causes a "current." The field is proportional to the current, and the current is proportional to the field. A current caused by the action of a field of force is said to be an induced current, and the current in C D is said to be induced by the current in A B. The latter might be called the inductor current, then we should have the induced current on entering or advancing in the field is opposite in direction to the inductor current, but in the same direction on retiring or leaving the field.

When we come to consider the interaction between two fields due to two conductors carrying currents, we have two cases: first, when the currents are in the same direction, and, secondly, when the currents are in opposite directions. Let A B and C D, Fig. 23, be two parallel conductors with currents in the same direction. Suppose the currents in each case to be equal, then the forces causing the fields will be equal. Take any pair of loops, which intersect at a point where these loops first come into contact and under the influence of equal and opposite directive forces, and the result is the forces neutralise each other at this point, the effect being as if the inner parts of the loops of force were neutralised, the remaining parts forming one loop around both wires, tending to shorten its diameter, and bringing the conductors A B, C D nearer together. Hence two parallel conductors seem to attract each other. This attraction is due to the interaction of the fields.

The interaction of two fields has a reverse effect, and the conductors seem to be repelled. Let A B, C D, Fig. 24, represent two conductors with currents in opposite directions.

![Diagram Fig. 23](image)

![Diagram Fig. 24](image)

The forces acting in the fields will be in opposite directions, but a little examination of the figure will show that if the fields are brought together the forces at the point of contact are in the same direction, and there is therefore no neutralisation of the field. By extending the ideas involved by lines or loops of forces somewhat, we think the whole of these and other interactive phenomena can be made clear. The result of the force is to form a closed curve of polarised particles. If the field is filled with iron filings we should get a series of concentric rings of iron filings around each conductor. No two rings of filings can occupy the same space. All are agreed upon this. Instead of filings, suppose the matter acted upon to be particles of ether or particles of electricity. Surely the same result will be admitted that no two rings can occupy the same space; carrying
the idea a little further, we may assume that no two lines or loops of force can occupy the same space. With this assumption many difficulties are cleared away.

In the preceding case the loops of force partly neutralised and partly merged into each other. In the present case there can be no neutralisation and no merging. The effect, therefore, of bringing the two fields of A B and the field of C D into contact is very similar to the bringing of two faggots into contact. A weak field brought into contact with a weak field will experience a weak resistance; a strong field brought into contact with a strong field will experience a strong resistance. This resistance, or, if it is preferred, this repulsive force, is simply proportional to the number of concentric circles of polarised particles brought into contact, and to nothing else. The number of loops of force is proportional in each case to the currents, hence this resistance or repulsive effect is also proportional to the currents.

It is to Ampere we owe the discovery of the interactions between these fields, and the laws discovered by him may be thus stated:

1. Two parallel conductors attract one another if the currents in them are flowing in the same direction, and repel one another if the currents flow in opposite directions.

The conductors may be portions of the same or of different circuits.

2. The parts of conductors crossing one another obliquely attract one another if both the currents are either towards or from the point of crossing, and repel one another if one current is towards and one from that point. Thus currents in conductors as in Fig. 25 attract or repel according as shown.

3. The force exerted between two parallel portions of circuits is proportional to the product of the strength of the two currents, to the length of the portions, and inversely proportional to the distance between them.

Ampere also demonstrated certain other propositions, the most important of which is that a conductor doubled back upon itself, so that the return path of the current is close to the outward path of the current, exerts no force upon external points. Examine this proposition in the light of what has been said. Let A B, Fig. 26, represent a straight portion of a conductor. The number of loops of force are equal along equal lengths of the conductor, and the direction of the force or forces carrying the loops is the same. Now double the wire upon itself as in Fig. 27, and we get on first contact of the fields a repulsive action like we get in the case of unlike currents. On bringing them closer and closer together, as in Fig. 28, the respective forces causing "loops" become opposite in direction, and as they are equal they exactly balance or neutralise each other. In Fig. 27 two loops are shown, the arrows pointing in the direction of the forces. It will thus be seen that to produce no effect, the return must, as the proposition states, be close to the outward-going conductor. It does not matter whether the wires be straight or curved—the effect is the same. Thus the field is neutralised by doubling and twisting around, as in Fig. 29. One further remark is necessary here; it is that the doubling back of the wire upon itself, and hereby the destruction of the field, increases the resistance of the circuit; indeed, the partial destruction of the field before referred to also increases the resistance of the circuit, and, in fact, any interference of field with field increases the resistance of one or of both circuits.
CHAPTER III.

THE MAGNETIC CIRCUIT.

The popular notion of a magnet is that it is a piece of steel having certain peculiar properties, the most prominent of which are: (1) If free to move horizontally it takes up a certain definite position, one end pointing nearly to the geographical north, the other end pointing nearly to the geographical south. The end pointing northwards is generally called the north pole of the magnet, the other end being called the south pole. (2) Another property of the magnet is its attraction for iron or steel. (3) It has certain actions upon other magnets. There are other properties which need not detain us now.

A conductive circuit has all the properties of a magnet. It is a magnet. On this part of the subject Dr. Lodge says: "Coil up a wire conveying a current. . . . The result is it behaves like a magnet; compass needles near it are affected, steel put near it gets magnetised, and iron nails or filings get attracted to it—sucked up into it if the current be strong enough; in short, it is a magnet, not, of course, a permanent one, but a temporary one, lasting as long as the current flows. It is thus suggested that magnetism may perhaps be simply electricity in motion. Let us work out this idea more fully.

"First of all, one may notice that everything that can be done with a permanent magnet can be imitated by a coiled wire conveying a current (it would not do altogether to make the converse statement). Float a coil attached to a battery vertically on water, and you have a compass needle; it sets itself with its axis north and south. Suspend two coils and they will attract or repel or turn each other round just like two magnets."

Consider a single turn of a conductive circuit. The loops of force are all around. If now we coil another turn (the conductor must be insulated, otherwise the turns will not be separate) the loops are, as we have previously explained, partly neutralised and partly merged, the result being loops around both turns. If we continue adding turns of conductor to the coil, the loops of the field still pass around the turns, as in Fig. 30. In the consideration of the conductive circuit it was stated that the number of loops around the conductor is proportional to the current through the conductor; also that the coiling of a conductor upon itself increased the resistance of the circuit. Hence, with the same pressure, the current would be less when the circuit was made into a coil than if it consisted of only one large turn. The total number of loops, then, threading the core of the coil is less than the number of loops would be if the coil was straightened out, with the same pressure acting in the circuit. In the coil as shown the loops form closed curves through the air spaces, one part of the curve being inside the coil, the other part outside the coil. The total space in which "loops of force" are found is called the "field," and we now see why the term "magnetic field" is suitable, for we have seen this coil—or, as it is usually termed, solenoid—is a magnet, and the space through which its influence extends is its "magnetic field."

In the form of coils shown all the loops thread the core and distribute themselves equally around the outside of the coil, provided the path through which they pass is of one homogeneous material, such as air. It may at once be stated that the great utility of the magnetic field depends almost entirely upon the portion of the loops outside the core, and their density. A perfect magnet may be defined as one where there is no external field—that is, the total field is within the surfaces bounding the material of which the magnet is made. We may assume that in the case described the closed curves leave the coil at one end or pole, and winding round through the air go into the coil at the other pole. The pole by which the loops are supposed to leave the core is conventionally termed the north pole, N, that by which they enter is called the south pole, S.

If we bend the coil round, as in Fig. 31, so as to make almost a perfect ring of conductor-turns, the
"loops of force" go through the air space between the end turns almost entirely, as shown in the figure. There are a few leakage loops, but these may for the moment be left out of consideration. If the ring of conductor-turns is completed, as in Fig. 32, then the "loops of force" are entirely within the core, and none are found in the external air space. The magnet as shown in Fig. 32 is the perfect magnet, but of no practical value. All the magnets thus composed of conductor-turns are termed "electromagnets," in contradistinction to permanent magnets. The former are temporary magnets, lasting as long as there is a current through the coils, the latter being, as their name implies, permanent and not dependent upon a current through coils. Permanent magnets were known long before electromagnets, as the particular iron ore which possesses magnetic properties is found in various parts of the world. Natural magnets, however, are of no use in practical work. They are at once cumbersome and of little power. In very ancient times it was known that if steel was rubbed with a magnet it became itself magnetic and retained the properties imparted by the rubbing. It was known also that soft iron similarly obtains the magnetic properties, but does not retain them—hence steel bars were magnetised by rubbing with natural or other artificial magnets. Sturgeon, in 1825, made the first electromagnet. Profs. Henry and Moll and Mr. Watkins, between 1825 and 1830, made many experiments with electromagnets, and these names are worthy of record.

If now we take a permanent bar magnet and investigate its field by means of iron filings, we find the filings arrange themselves as in Fig. 33. A simple method of doing this is to place a piece of cardboard just above the magnet, and sprinkle the filings upon the cardboard. A gentle tapping of the cardboard will assist the experiment. But this and dozens of similar experiments are fully described in every little book on the subject. The filings will be seen to be arranged in curves from one pole of the magnet to the other. This shows the influence of the magnet upon the filings in the plane of the cardboard, and if the cardboard were made to describe a complete revolution around the axis of the magnet, the influence would be found to exist at every position. This shows that the "loops of force" from the permanent magnet are similar to those from the coil, leaving one pole and entering the other. A portion of the path of these closed curves is through the steel forming the magnet, the other portion of the path being through air. It is customary in practice to make the length of the path through the air as short as possible by having the magnet bent into the shape of a horse-shoe, bringing the poles near together, as in Fig. 34. Both straight and bent permanent magnets are used, though mostly for purposes where no great magnetic strength is required. As engineers generally require greater magnetic strength, electromagnets are now almost universally used for dynamos and motors, and it is to these magnets we shall more closely direct attention. The number of magnetic loops around a conductor is proportional to the current. If a second turn of conductor is added, keeping the current constant, the number of magnetic loops is doubled, and similarly each turn of conductor adds its quota to the total. So far, then, the number of magnetic loops around a coil depends upon—

1. The strength of the current.
2. The number of conductor-turns.

The number, however, depends also upon another factor, the resistance of the path traversed by the loops of force. Just as in the conductive circuit the
MATHER AND PLATT'S ALTERNATE CURRENT DYNAMO.
LONGITUDINAL TRAVERSE
HOISTING GEAR
CROSS TRAVERSE
MOTOR

ELEVATION.

ANDERSON'S ELECTRIC TRAVELLING CRANE.

PLAN.

ANDERSON'S ELECTRIC TRAVELLING CRANE.
various metals have different conductivities or resistances, so in the magnetic circuit various substances have different magnetic conductivities or magnetic resistances.

Of all known materials, iron has the greatest magnetic conductivity, or the least magnetic resistance. Commercial iron is far from pure, and almost every sample differs somewhat in its chemical constitution, hence the magnetic conductivity of various irons differs considerably. Experiments have shown that the conductivity of iron varies from a little to many thousands of times better than that of air—that is, the magnetic resistance of the iron experimented with has varied to many thousands of times less than that of air.

Besides iron, nickel and cobalt are almost the only substances which possess magnetic conductivity, though a few others, such as chromium, cerium, and manganese, possess magnetic power to an exceedingly feeble extent.

If, then, we take a given current passing through a given number of conductor-turns, the number of magnetic loops will depend upon the resistance of the magnetic circuit, just as the current with a given pressure in the conductive circuit depends upon the resistance of the circuit.

In the conductive circuit we have

\[ C = \frac{E}{E} \]

In the magnetic circuit we have—

No. of loops of force or magnetism = \( \text{Current} \times \text{conductor-turns} \)
\[ \frac{\text{Resistance of magnetic circuit}}{\text{Resistance of magnetic circuit}} \]

As the current is measured in amperes—in practice we use the expression ampere-turns—which allows us to write—

No. of loops = \( \frac{\text{Ampere-turns}}{\text{Resistance of magnetic circuit}} \)

This shows that in the magnetic circuit there is a law similar to that of Ohm in the conductive circuit.

In the conductive circuit we have the electromotive force causing pressure or difference of pressure. The pressure determines the current through a given resistance, while in the magnetic circuit the ampere-turns determine the magnetism or number of magnetic loops through a given magnetic resistance.

If \( N \) represents the number of loops of force, \( R_m \) the total magnetic resistance, and \( A \), the ampere-turns, we get

\[ N = \frac{A}{R_m}. \]

The magnetic pressure due to the ampere-turns

\[ = 4\pi TC \]

where \( T \) = turns, and \( C \) = amperes. This brings the formula to

\[ N = \frac{4\pi TC}{R_m}. \]

The total magnetic resistance, like the total conductive resistance, may be and usually is made up of several separate resistances. When the magnetic resistances are in series the total resistance is the sum of the separate resistances. Thus, if we consider the magnetic resistance of the field-magnets of a dynamo, we get, first, the magnetic resistance of the core and yoke of the field-magnets; secondly, the magnetic resistance of the air spaces within the armature and between the armature and the field-magnet poles; and, thirdly, the magnetic resistance of the armature. Thus, if \( R_m = \text{total magnetic resistance and } R_t = R_a + R_y \), the magnetic resistances of the air spaces, the armature and the field-magnets respectively

\[ R_m = R_a + R_y + R_t \]

or the formula can be written

\[ N = \frac{4\pi TC}{R_a + R_y + R_t}. \]

Leakage.—The magnetic field of a conductor may be deemed to arise from leakage from every part of the conductor surface. A perfect insulator would stop this leakage. Every unit area of surface may then be looked upon as the formation of a branch or shunt circuit, and the total resistance of any conductor is the joint resistance of the conductor itself and these shunt circuits. In the magnetic circuit there is similar need of a magnetic insulator or screen. It may be heterodox, but it is nevertheless true that the best conductor is in one sense the best insulator, and the best magnetic conductor is also the best magnetic insulator—that is, if we wish to screen a particular object from the influence of a magnetic field we do so by surrounding the object with a mass of iron. The loss by leakage is simply a question of resistance. If there is a shunt circuit at all, both the conductive (current) effect and the magnetic (loops of force) effect divide inversely as the resistance. In most magnetic circuits there will be leakage, and it should be the aim in practice to reduce leakage to a minimum by making the leakage circuits of very great resistance compared with the direct circuit.

Effect of Heat on Magnets.—If a permanent steel magnet is heated it gradually loses its magnetism, till when at a bright red it seems to lose it altogether. Nickel also loses its magnetic properties when heated, while cobalt does not. If a piece of iron is rapidly magnetised and demagnetised it becomes hot, as if the magnetisation caused internal friction. Thus it may be said that heating an iron or steel magnet increases its resistance. We have already seen that heating the conductor of a conductive circuit increases its resistance, so that this property seems common to both the conductive and the magnetic circuits.

Interactions of Fields.—The interactions between the magnetic fields of conductors have been described.
between the fields of conductors and the fields of magnets. Let NS, Fig. 35, represent a magnet. The direction of action of the loop of force is from N to S; and if iron filings are put into the field they will form a polarised chain from N to S. The circuit is through air, and has a certain resistance. If now we bring another bar of magnetic material, such as iron, into the vicinity of the field, as in Fig. 36, the resistance of the magnetic circuit will be lessened, if the circuit passes as N to S1, N1, S. In fact, we make a path of less resistance through the iron, and immediately the loops follow the law, and go through the circuits inversely as their resistance. All the loops will not pass through S, N, only the number agreeing with the law enunciated. The remainder still go through the shunt circuit presented by the air path. We have previously agreed to the convention that the pole of a magnet, where the loops leave, is the N pole, and where they enter it is the S pole. The loops enter at S1, owing to the initial directive action of N, and leave at N1; therefore, as S1, N1 now possesses all the properties of a magnet, we say it has been magnetised by the influence of N, S. In electrical language, any conductor, magnet, or magnetic substance acted upon by the field of any other conductor or magnet, is said to be acted upon by induction. The action is said to be inductive action.

Thus the bar S1, N1, is said to be magnetised by induction. A magnet pole acting upon a magnetic substance induces in the latter a pole of opposite polarity to itself. A north pole induces a south, and a south pole induces a north.

Let NS, N, S1, Fig. 37, represent two bar magnets of about equal strength. Bring them into proximity so that their fields interact. Each magnet is surrounded by its chains of polarised particles, and the attempt to bring the magnets together means the attempt to put the two fields into the same space. If each field could be indicated by iron filings it would be attempting to put two lots of filings into the same space, which of course is a physical impossibility. If we agree upon the convention that two loops of force cannot occupy the same space no more than can two chains of iron, the whole matter becomes clear. There is a resistance of one field to the introduction of the other. The term repulsion has been given to this resistance, and two similar poles are said to repel each other. This repulsion, then, is of the same nature as the resistance offered to matter being put into the same place as other matter. However near the poles may be, there is no action between magnets except when their fields interact. In many cases, however, it assists calculation to consider this resistance as due to a repulsive force. If the fields of two such magnets are made to interact, the strength of each magnet is weakened, as may easily be shown by the explanations given. If one magnet is considerably more powerful than the other, then the polar chains of the weaker one are reversed by the stronger, and the weaker magnet is magnetised in the opposite direction to what it was originally, the pair then exhibiting similar phenomena to the pair in Fig. 38.

Let N1, S1, NS, Fig. 38, be two magnets of about the same strength brought into proximity so that their fields interact, but with opposite poles towards each other. The action of the pair is to merge the two circuits into one, the one magnetic circuit having a less resistance than either of the two separate. The tendency of all magnetic loops is to make themselves as short as possible, so the tendency of the circuit is now to shorten itself, and this can only be done by the bars getting closer together. Let A1, Fig. 39, represent a magnet with its chain of polarisation as shown, and B1, a similar magnet. If the opposite poles are brought near, it will be seen that the polarised particles can satisfy each other—that is, be so arranged that the + (shaded) pole of one is in contact with the - (unshaded) pole of the next, when the line of polarisation passes direct from + pole of A1 to - pole of B1, making A1 and B1 parts of one magnetic system. The tendency to shorten the lines tend to bring A1 and B1 into close contact, or make the system like that in
Fig. 40, where N S and N₁, Fig. 41, were the original magnets. This tendency gives rise to the phenomena of attraction, whence, in short, the laws have been promulgated—

1. That unlike poles attract.
2. That like poles repel.

Both these properties are of great service in practice.

We have now to briefly consider the interaction of conductors and of magnet fields.

If a conductor is brought into a magnetic field, a number of the magnetic loops pass around the conductor. It has been stated that the magnetic loops of a conductor are caused by the current; the reverse action also takes place, and magnetic loops passed around a conductor induce a current in that conductor. Further, just as the number of loops is proportioned to the current, so the current is proportioned to the number of loops. If a number of magnetic loops encircle a conductor, a temporary current is set up in the conductor in a certain direction; if the number of encircling loops be diminished an equivalent current is set up, in direction the reverse to the original current. If the whole number of loops be taken away, the reverse current is equal to but opposite in direction to the original current. If the number of loops is added to, the current set up is in the same direction as the original current. A continuous current can only be obtained by continuously varying the number of loops passed around the conductor. A continuous current always in one direction could be obtained if the number of loops passed round the conductor could be continuously increased. It is customary to speak of the current or the pressure that regulates the current as due to the number of lines or loops cut per second by the conductor, and one volt pressure is obtained in a conductor when the conductor cuts 100,000,000 loops of force per second. The usual method of obtaining a current is to bring a conductor into as strong a field as possible, then to take it out again. This action gives first a current in one direction, then an equal current, but in the opposite direction. Apparatus, however, is used so that these reversed currents may, if required, appear at the point where they are to be utilised, in the same direction.

The action of a magnetic field upon a conductor is to alter the electrical pressure of the conductor, and so obtain a current. If a current already exists in the conductor, the action of the field will be either to augment or to decrease the current according to the direction of the original current. If it is in the same direction as that due to the field, we get increase; if in the opposite, we get decrease.

Lastly, we have the action of a conductor field upon a magnetic substance or upon a magnet. If instead of the open coil, Fig. 31, we make our turns of wire around a piece of iron, Fig. 42, and send a current through the wire, the iron core is in the magnetic circuit, and becomes a magnet. If the viewer is looking at one pole of the magnet, and the current in the surrounding coil is in the same direction as the hands of a watch travel, he is looking at the south pole. The direction of the magnetic loops is in at S, out at N, the current in the coil being in the direction shown by the arrows. The resistance of the magnetic circuit is lessened by bending the coil till the two poles are near each other, as in Fig. 43. If a core of steel is used instead of a core of iron, the steel may be made into a permanent magnet, whereas the iron (and the more completely so the softer it is), when the current is stopped, loses its magnetic properties, though even with the softest iron a little magnetism always remains—termed residual magnetism.

There is one phenomena connected with field interactions of great use in practical work. It is the action of a small magnet in the magnetic field of a conductor. To understand this action, it must be remembered that if a magnet and a conductor are parallel to each other, their fields will be at right angles. Suppose D, Fig. 44, represents a magnet with polarised loops as shown. If these polarised loops are brought within the influence of another polarising force, the latter will try
to polarise in its own direction. If the new polarising force be at right angles to the original, the action of the force will be to polarise the particles in a direction at right angles to their original direction. This is what happens with a small magnet in a conductor field, so that if N S, Fig. 45, is brought into the field of C, the

![Fig. 45.](image)

stronger field C tends to polarise the loops of N S in the direction in which its own loops are polarised. As the magnet N S is itself a chain of polarised particles, its direction is influenced, and the result is that a magnet so brought into a conductor field tends to set itself or to be placed in a position at right angles to the conductor. If we assume that two forces in different directions are acting on material particles, B A, Fig. 46, we know that the particles will tend to a direction which is the resultant of that of the forces, and this direction in the case under consideration will tend to move, in accordance with the foregoing considerations.

The interactions of the greatest use in electrical engineering are:
1. Those between a magnetic field and a conductor, which give the basis of dynamo action.
2. Those between conductor fields and conductors, which give the basis of transformers.
3. Those between conductor field and magnets, which give the basis of many of our measuring instruments.

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CHAPTER IV.

THE INDUCTIVE CIRCUIT.

It is customary to view the inductive circuit as something altogether different from the conductive, whereas the one is in reality but a modification of the other. The modification introduces more prominently certain phenomena which are important, and have now to be considered. Induction is a term used to denote a condition which in different circumstances seems altogether distinct from what it does under other circumstances, yet a closer examination will show the similarity. There can be no flow of current without difference of electrical pressure, but there can be difference of electrical pressure without current. The former case, difference of pressure with current, exists in the conductive circuit; the latter case, difference of pressure but no current, exists in the inductive circuit. We have said electrical apparatus is used for producing electrical pressure. It may aid the imagination in some cases if we look upon the apparatus as having a double object, raising pressure on the one side and proportionately decreasing it on the other. Of course the assumptions previously made ought to lead to this view, for as there is no introduction of electricity into a circuit, the increase of electrical pressure in one direction naturally means that if measured in the opposite direction the pressure is below the maximum. Thus we get two conditions the counterpart of each other, a quantity of electricity on the one side under more electrical pressure, an equal quantity on the other side under less electrical pressure. The lifelong object of electricity in these different states is to resume the normal condition, or the condition of a normal pressure when no electrical phenomena are indicated.

We can now represent the simple inductive circuit, Fig. 47. Suppose a source, S, of electrical pressure, and conductors, A and B, separated by the air space, D. Suppose, further, the pressure to be increased in the direction of A, and diminished in direction of B, then when contact is made with the source we get a momentary rush or current in direction A, and as it were a slight heaping up of the electricity in A and a corresponding diminution in B. This heaping up, accumulation, or charge, as it is called, shows itself principally at the surfaces of A and B, immediately opposite, or the electricity in unlike conditions of pressure gets as near together as possible.
The quantity so accumulated at the ends of wires is extremely small, but it is easy to arrange the circuit so that quantities measurable by our instruments can be dealt with. First, however, it may be wise to point out that these two electrical conditions are fully recognised.

If the apparatus we use increases the pressure in one direction, this has the same effect as diminishing it in another, hence the electricity appears manifested to us in two different conditions. In the olden days one electricity was spoken of, the phenomena being said to be due to a surplus or to a want of electricity; subsequently two electricity were named; still later the conditions were simply termed positive and negative, and symbolised by + and −. These symbols are very suitable and we shall adopt them, using + to symbolise electricity at the point of higher pressure, and − to symbolise it at the point of lower pressure. It will at once be seen that if the pressure is taken away the electricity assumes its normal condition, when it is not manifest to our instruments. Thus only in its abnormal state is electricity manifest to us, or useful for any purpose for which it is desirable to use it. It is convenient sometimes to suppose the apparatus raises the pressure on the one hand, and lowers the pressure on the other to equal degrees, just as pumping water from a cistern both raises and lowers, though only in equal degrees under certain conditions.

If the normal electrical condition algebraically be equivalent to 0, this is represented by the sum of the positive and negative conditions. If \( x \) represents the electrical pressure in any circuit + \( x \) is exactly equal to − \( x \), or in another way a pressure of 10 in one direction is equivalent to a diminution of 10 in the opposite direction, as +10 − 10 = 0, the normal condition of pressure. We cannot by any possible device obtain a condition that more pressure is obtained in one direction than depression in the other. This is the same as saying, like the old books, whenever + electricity is generated an equal quantity of electricity is generated at the same time.

The statement, “a heaping up of electricity,” is not scientifically accurate. What takes place is the heaping up or accumulation of electrical energy. Just as in the conductive circuit \( C \times E \) represents electrical energy, so in the inductive circuit the energy may be represented by \( A \times E \), where \( A \) represents the electricity accumulated under a pressure, \( E \).

Simple Inductive Circuit.—A simple inductive circuit may be arranged as in Fig. 48. Let \( S \) be the source of electrical pressure, \( A \) and \( B \) wires joining the terminals of the source with the parallel conducting surfaces or plates shown in section \( P \) \( P \), at a distance from other conductors. The air space between \( P \) and \( P \) forms the dielectric, non-conductor, or inductive resistance. If the distance between \( P \) and \( P \) be taken as the length of the resistance, and the surface area of the opposing surface of one of the plates as the sectional area of the resistance, then, just as in the conductive circuit, the resistance varies directly as the length of the conductor and inversely as its sectional area, so in the inductive circuit the resistance varies directly as the length and inversely as the sectional area of the dielectric. In other words, if you double or treble the length of the dielectric, you double or treble its resistance, while if you double its sectional area you halve its resistance. This is symbolised by

\[
R \approx \frac{L}{S}
\]

where \( R \) = resistance of dielectric, \( L \) its length, and \( S \) its sectional area. In both circuits, then, we have similarly the source of electrical pressure and resistance of circuit. The result of electrical pressure in the conductive circuit is current, in the inductive circuit it seems to be accumulation on the surfaces of the opposite conductors. We say "seems" because the probable action is at the surface of the dielectric in contact with the conductors, or in the dielectric, and not on the conductors. In this case, however, the use of the popular expression will do no harm.

The idea of accumulation involves that of density per unit area, and if the plates are, throughout their surfaces, at the same distance apart the same source accumulates or charges the opposite surfaces to the same density. The quantity accumulated, or the total charge, will evidently be the density per unit area × number of units of surface. It will now be seen that accumulation in the inductive circuit is analogous to current in the conductive circuit, and that the same laws apply to both.

\[\text{Current} \times \text{resistance} = \text{electrical pressure.}\]

Or \( C \times R = E \).

\[\text{Accumulation} \times \text{resistance} = \text{electrical pressure.}\]

Or \( A \times R = E \).

**Inductive Resistance.—Series.—Multiple Arc.—Inductive Resistances are added in series just as conductive resistances. Thus Figs. 49 and 50 show two resistances**
in series; Figs. 51 and 52 show three resistances in series. In either case the length of dielectric has either been doubled or trebled, and the total resistance.

\[
R = R_1 + R_2.
\]

Or in the second case \( R = R_1 + R_2 + R_3 \).

If \( R_1 = R_2 = R_3 \), etc., then \( R = nR_1 \).

In the conductive circuit the practical effect, as far as total resistance is concerned, of adding conductors in multiple arc is the same as if the sectional area of the conductor is increased. Thus the resistance of the circuit, \( R \), Fig. 53, would be halved either by adding, in multiple arc, another similar conductor, or doubling the sectional area of \( R \). Similarly, in the inductive circuit the practical effect of the addition of resistances in multiple arc is to increase the sectional area, and correspondingly to decrease the resistance.

Thus, if, in Fig. 54, \( P \) and \( P_1 \) be the opposing conductors and \( R \) the inductive resistance, and if \( P \) and \( P_1 \) be increased to double size, as shown by the dotted lines in Fig. 55, or a similar resistance be added as shown in Fig. 56, the total resistance, \( R \), will be

\[
R = \frac{R_1 R_2}{R_1 + R_2}
\]
as in the conductive circuit, for let the respective resistances be \( R_1 \) and \( R_2 \), and the pressure be unit pressure between the surfaces, and let the joint or total resistance be \( R \), then:

Accumulation on \( P \) or \( P_1 = \frac{1}{R} \)

\[
S \text{ or } S_1 = \frac{1}{R_2}
\]

Total accumulation on \( P \) and \( S \), or \( P_1 \) and \( S_1 \) = \( \frac{R_1 + R_2}{R_1 R_2} \); but as accumulation is inversely as resistance \( R = R_1 R_2 \).

Distribution of Charge.—It has been stated that in the conductive circuit the current is increased when a new path is inserted into the circuit, and the total current distributes itself inversely as the resistances; so in the inductive circuit the charge or accumulation is increased by the insertion of a new inductive path, and the total charge distributes itself inversely as the resistances. Thus in Figs. 55 or 56 the addition of plates, \( S, S_1 \), equal to \( P + P_1 \) with \( R_2 = R \), pressure remaining constant, leads simply to doubling the charge because the resistance is halved, the quantity and density on \( P \) or \( P_1 \) being equal to quantity and density on \( S \) or \( S_1 \). If, however, \( R_2 \) is different from \( R_1 \), as in Fig. 57,

\[
\frac{Q}{Q_1} \text{ represent the new opposing conductors, the total accumulation will be increased because the total resistance is lessened. Suppose in this case } R_2 = 2 R_1 \text{, we may represent}
\]

\[
R = \frac{R_1 R_2}{R_1 + R_2} = \frac{2}{3}
\]

that is, the resistance of the original circuit, \( R_1 = 1 \), is now by the addition of \( R_2 \) reduced to \( \frac{2}{3} \), and the charge will therefore be correspondingly increased. And if \( 10 \) represents the old quantity accumulated, and \( x \) the new quantity,

\[
\frac{\text{New resistance}}{\text{Old resistance}} = \frac{\text{Old charge}}{\text{New charge}} = \frac{\frac{2}{10}}{1 \frac{x}{3}}
\]

whence \( x = 15 \).

In symbols, if \( Q = \text{old quantity and } Q_1 \text{ new quantity accumulated,}
\]

\[
\frac{R_1 R_2}{R_1 + R_2} : R_1 : Q : Q_1
\]
This new charge is distributed inversely as the resistances—that is, 10 parts with resistance \( R_1 \) and 5 parts with resistance \( R_2 \). It will be seen that no change has taken place as regards the charge on \( P \) or \( P_1 \), and this will be found to hold good whatever branch resistances may be added to the circuit. Similarly, in the conductive circuit, it has been seen, the adding of parallel, branch, or shunt circuits with pressure remaining constant, does not affect the current through the original circuit. If the opposed conductive surfaces have at all points the same inductive resistance between them, the distribution of the charge is uniform over the surfaces. If, however, as is frequently the case, the resistance is not uniform, then the distribution is not uniform. A simple diagram will illustrate this. Let \( S \), Fig. 58, represent the source, one pole of which is connected with the conductor, \( A \), the other with the wall of the room, \( B \). The conductor, \( A \), is insulated from the room, and thus can receive a charge from the source, \( S \). Let air be the dielectric. The dielectric resistance between the points \( C \) \( D \) will be much less than the resistance between the points \( E \) \( F \), hence the charge upon unit area \( C \) will be correspondingly greater than the charge on unit area \( E \). Experiments have often wondered why certain results did not agree with theory, and many a young student has forgotten that his body near a piece of apparatus causes a distribution of charge different to what would be if the body were not there.

**Short Circuits.**—When the resistance of the conductive or of the inductive circuit is decreased to a small quantity, the current or the accumulation is enormous. An examination of the formula will show that theoretically any amount of current or accumulation can be had with any pressure, however small. Anyone who understands division in arithmetic will easily understand our meaning. Thus, suppose we have to divide any number—say 5—by any other number greater than unity, the answer will be less than 5; it is exactly \( \frac{5}{2} \) when we divide by unity, but when we get on the other side of unity and divide by numbers less than unity the answer is greater than 5.

Take these examples:

\[
5 \div 2 \text{ or } \frac{5}{2} = 2.5.
\]
\[
5 \div 1 \text{ or } \frac{5}{1} = 5.
\]

Thus in \( C = \frac{E}{R} \) or \( A = \frac{E}{R} \) whatever pressure \( E \) may indicate, the current, \( C \), or accumulation, \( A \), may be as great as we please provided we make \( R \) in each case small enough.

It is this short-circuiting in practical work that leads, as we have before said, to great dangers. Whether the original circuit be conductive or inductive the result of a short-circuit is the same, the passage of a large current through a small resistance.

**Specific Inductive Resistance.**—Faraday found that by substituting another gas for air as the dielectric the resultant charge was unaltered, and he also found for all the solid and liquid dielectrics he experimented with a greater capacity for accumulation than with gases. He thus introduced the term specific inductive capacity. It would now seem preferable to look upon all gases as having the same resistance, and solids and liquids as having different resistances. If the resistance of unit length and unit sectional area of air be taken as the unit, then the resistances of other insulators compared with this might be termed their specific inductive resistances.

**Quantity and Capacity.**—The unit of quantity is an ampere per second, and is called a Coulomb. The capacity of a conductor is measured by the number of coulombs of charge that can be given to one conductor with a volt pressure between that conductor and the opposing conductor. Thus, the capacity of \( P \), Fig. 59, is the number of coulombs upon it when there is a difference of pressure of a volt between \( P \) and \( P_1 \). The unit of capacity is called the Farad.

The capacity of a single pair of plates is small, and to obtain a greater capacity in practice a series of insulated conductors are arranged so that each alternate conductor is connected to its own terminal, as in Fig. 60.

This apparatus is called a condenser, and is frequently made of sheets of tinfoil, separated by sheets of thin paper coated with paraffin wax. If the conductors are separated by air, we have an air condenser. If \( A \) is the surface area of one of the sets of conductors in
square inches, and \( d \) the distance in inches between
them—that is, the length of the dielectric—then the capacity in farads is
\[
F = \frac{A}{10^{12} \times 4.452 \times d}.
\]

Condensers are usually made of so many millionths of a
farad, or micro-farads, capacity, and the above formula
becomes in micro-farads (M.F.)
\[
(M.F.) = \frac{10^6}{10^{12} \times 4.452 \times d}.
\]

If the measurements are in square centimetres and
centimetres, these formulas become respectively
\[
F = \frac{A}{10^6 \times 1.131 \times d},
\]
and
\[
(M.F.) = \frac{10^6}{10^6 \times 1.131 \times d}.
\]

If, instead of air, a dielectric of greater specific
inductive capacity be used, then these formula must be
multiplied by the "specific inductive capacity" to give
the capacity of the condensers. Thus, if porpafine wax is
used, this having a specific inductive capacity of about
2, the formula
\[
F = \frac{A}{10^{12} \times 4.452 \times d}
\]
becomes
\[
F = 2 \times \frac{A}{10^{12} \times 4.452 \times d}.
\]

Prof. Ayrton gives the following table of specific
inductive capacities:

<table>
<thead>
<tr>
<th>Substance</th>
<th>Specific Inductive Capacity</th>
<th>Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum, air at about 0.001</td>
<td>0.94 about.</td>
<td>Ayrton.</td>
</tr>
<tr>
<td>millimetres' pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum, air at about 5</td>
<td>10.9985</td>
<td>Ayrton.</td>
</tr>
<tr>
<td>millimetres' pressure</td>
<td></td>
<td>Boltzmann.</td>
</tr>
<tr>
<td>Hydrogen at about 760</td>
<td>10.99641</td>
<td>Boltzmann.</td>
</tr>
<tr>
<td>millimetres' pressure</td>
<td></td>
<td>Ayrton.</td>
</tr>
<tr>
<td>Air at about 760 millimetres'</td>
<td>10.9967</td>
<td>Taken as the standard</td>
</tr>
<tr>
<td>pressure</td>
<td></td>
<td>Boltzmann.</td>
</tr>
<tr>
<td>Carbonic Dioxide at about 760</td>
<td>10.9968</td>
<td>Ayrton.</td>
</tr>
<tr>
<td>millimetres' pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olefiant Gas at about 760</td>
<td>1.000658</td>
<td>Ayrton.</td>
</tr>
<tr>
<td>millimetres' pressure</td>
<td></td>
<td>Boltzmann.</td>
</tr>
<tr>
<td>Sulphur Dioxide at about 760</td>
<td>1.00097</td>
<td>Ayrton.</td>
</tr>
<tr>
<td>millimetres' pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paraffin Wax, Clear</td>
<td>1.92</td>
<td>Schiller.</td>
</tr>
<tr>
<td></td>
<td>1.96</td>
<td>Wülfler.</td>
</tr>
<tr>
<td>Paraffin Wax, Milky</td>
<td>2.82</td>
<td>Gibson and Barley.</td>
</tr>
<tr>
<td>Indiarubber, Pure</td>
<td>2.84</td>
<td>Boltzmann.</td>
</tr>
<tr>
<td>&quot; Vulcainised</td>
<td>2.84</td>
<td>Schiller.</td>
</tr>
<tr>
<td>Resin</td>
<td>2.55</td>
<td>Schiller.</td>
</tr>
<tr>
<td>Ebenite</td>
<td>2.56</td>
<td>Wülfler.</td>
</tr>
<tr>
<td></td>
<td>3.15</td>
<td>Boltzmann.</td>
</tr>
<tr>
<td>Sulphur</td>
<td>2.56 to 3.21</td>
<td>Wülfler.</td>
</tr>
<tr>
<td>Shellac</td>
<td>3.35 to 3.73</td>
<td>Boltzmann.</td>
</tr>
<tr>
<td>Gutta percha</td>
<td>4.2</td>
<td>Wülfler.</td>
</tr>
<tr>
<td>Mica</td>
<td>5</td>
<td>J. Hopkinson.</td>
</tr>
<tr>
<td>Flint Glass, Very light</td>
<td>6.57</td>
<td></td>
</tr>
<tr>
<td>&quot; Light</td>
<td>6.85</td>
<td></td>
</tr>
<tr>
<td>&quot; Dense</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>&quot; Double extra dense</td>
<td>10.1</td>
<td></td>
</tr>
</tbody>
</table>

Prof. Ayrton gives the following table of specific
inductive capacities:

Leyden Jar.—Condenser.—The original form of the
condenser was that known as the Leyden jar so named
after the town of Leyden, where it was accidentally dis-
covered by Muschenbroek and Cunius in 1746. The
Leyden jar is usually a glass jar coated inside and out-
side to about three-fourths or rather more of its height
with tinfoil. Fig. 61 shows a sheet of glass, A B,
coated on both sides with tinfoil, A A, while Fig. 62
shows the coated glass in the form of a jar, A B form-
ing the external and internal coatings of tinfoil. The
conductor from B can be connected to one terminal of
source through the knob and portion outside the jar.
The charged condenser contains a store of electrical
energy
\[
= \frac{F \times E^2}{2 \pi} \text{ foot-pounds.}
\]

Some writers have suggested the storing up of electrical
energy by means of huge condensors, like gas is stored
up in gasometers. Perhaps a little consideration of the matter would
show that the idea is not feasible, for it
can be shown that one-half the
energy expended in charging the
condenser will be lost when the
charge is obtained from a source,
whether battery or dynamo, with the
electrical pressure, or potential, con-
stant. If the pressure of the charging
source could be continuously in-
creased in proportion to the decrease of
pressure from the condenser in
discharging, we should get minimum
loss. Besides loss, the space required
for the condensers would be very large.

Suppose, for example, a source of E volts be used to
charge a condenser of F farads, then, as above, the
store of energy
\[
= \frac{F \times E^2}{2 \pi} \text{ foot-pounds.}
\]

Let \( Q \) = charge of condenser in coulombs,
\[
Q = FE.
\]

The total work done by the source
\[
= 7375 \ Q \ E \ \text{ foot-pounds.}
\]

Hence loss \( = (7375 - 37) \ E^2 \ \text{ foot-pounds,}
\]
or one-half the energy expended.

We have thus briefly indicated the salient features
which have to be applied in practice concerning the
three circuits.

Each special portion of the book will expand into
greater detail the features to be applied in the specific
application under discussion.
25 H.P. RECKEZAUN MOTOR—4-SIZE.
25 H.P. RECKENZAUEN MOTOR—4-SIZE.
CHAPTER V.

ELECTRO-GRAphICS.

It is essential to the electrical engineer that he should be able to rightly interpret the graphic representation of physical phenomena, as it is for the mechanical engineer to interpret the diagram given by a steam-engine. A little curve speaks clearly and plainly to the mechanical engineer, telling him at a glance almost as much as could be written in several pages, and enabling hundreds to read and to understand what is taking place, although if the information was put before them in words and figures it would remain incomprehensible. The use of graphic methods in electrical engineering is increasing, and the introduction of these methods, more particularly to phenomena connected with dynamos and motors, has largely led to the astounding increase of our knowledge about such apparatus in a short time. It may be said that Dr. J. Hopkinson, F.R.S., in his papers before the Institution of Mechanical Engineers, in April, 1879, and April, 1880, first effectively used the system as an instrument of research, and the remarks of Mr. R. E. B. Crompton during the discussion of the second paper conclusively show how soon its value was acknowledged in practice. Mr. Crompton said, "If Dr. Hopkinson's diagram was correct, as no doubt it was, the problem was solved which had perplexed him for a long time—namely, to find out the point at which to regulate the lamps in order to get stability of light."

A full and complete knowledge of graphical methods requires an extended knowledge of mathematics, but very much may be done by men who have little or no mathematical skill. A man who can properly use a pair of compasses and a scale of lengths will frequently be able to solve problems of a certain class, for all practical purposes, as satisfactorily as the more accomplished mathematician. In many cases a plotted curve speaks more plainly and tells more to the untrained mathematician than the equation to that curve, be it simple or be it complex. Within certain limits a curve can be interpreted by everyone. It must not for a moment be supposed that the non-mathematician can ever attain to the position of the mathematician either in accuracy or extent of interpretation. The former can do much, but the much is very limited compared with that of the latter. As has been stated, the symbolisation and the solution of problems arising in the mechanical arts by means of lines and curves—that is, by graphical methods—is very extensive, so that the application of the system to electrical problems was perfectly natural. Although Dr. Hopkinson may be taken as introducing the system to the student so far as dynamos and that class of electrical apparatus is concerned, it will be found that this system has long been extensively used in discussing problems connected with cable work. It is only necessary to consult the writings of Latimer Clark, F. C. Webb, H. R. Kempe, and others who have written on submarine cables and their testing to see this. We imagine that the great value of the system is because it pertains to the concrete rather than to the abstract.

Although the title of this chapter is Electro-Graphics, it is intended to indicate certain directions wherein books on special branches of mathematics should be consulted, rather than to enlarge upon the subject.

It is impossible to understand the references made by writers on dynamos without an elementary knowledge of trigonometrical ratios. Take the case of the induced electromotive force in a one-coil armature, which is "proportional to the sine of the angle through which the coil has turned." Simple as this statement is to the initiated, it is incomprehensible to the uninitiated except it be accompanied by a graphic representation of a "curve of sines." Let us examine this simple statement—

In Fig. 63, let $A B$ be a straight line. Upon $A B$ place another straight line, $A D$, equal to $A B$ in length, the end $A$ of $A D$ resting exactly upon the end $A$ of $A B$.

Rotate $A D$ around $A$, taking up the position shown at $A D$.

From $D$ drop a perpendicular line on to $A B$, cutting $A B$ at $C$.

The rotation of $A D$ has caused the opening, or angle $B A D$, between the two lines, $A B, A D$.

No matter how long or how short $A B, A D$, the lines $A B, A D, A C, C D$, etc., all have a constant proportion to each other as long as the angle $B A D$ remains unaltered.

If, however, $A D$ be rotated further, say, to $A D_1$, the proportion of these lines to one another has altered. This will easily be seen, for $C D$ becomes $C_1 D_1$, a much
Missing Page
But the forces may neither act together nor exactly opposite, but at any angle. Any elementary book on statics will show that the resultant of any two such forces acting at a point may be represented in magnitude and in direction by the diagonal of the parallelogram, of which the lines representing the two forces form adjacent sides. Let A B, A C, Fig. 69, represent forces of 4 lb. and 3 lb. respectively acting in the directions A B, A C. The resultant is found by completing the parallelogram A B C D, by drawing through C the line C D parallel to A B, and through B the line B D parallel to A C.

Join A D. Then A D represents the resultant of the force A C, A D in direction and in magnitude—that is, the same effect would be obtained if A C and A D were replaced by a force represented in direction and in magnitude by A D. If A B, A C act at right angles to each other, and be drawn to scale, A B = 4 units, and A C = 3 units, then A D will on the same scale measure 5 units. For the angle A B D being a right angle,

\[ A B^2 + B D^2 = A D^2 \]
\[ 4^2 + 3^2 = A D^2 \]
\[ \sqrt{25} = 5 = \sqrt{A D^2} = A D. \]

The resultant of two forces acting at any other angle than a right angle may be similarly represented, though in many cases the calculation is not so simple. Take as an example:

Two forces represented by 12 lb. and 15 lb. acting upon a point at an angle of 60 deg., required to find the magnitude and direction of the resultant.

1st. Graphical solution, Fig. 70.

\[ \begin{align*}
\text{Draw } A B & = 15 \text{ units of any convenient scale.} \\
\text{Make the angle } B A C & = 60 \text{ deg.} \\
\text{Make } A C & = 12 \text{ units of same scale as } A B. \\
\text{Through } C \text{ draw } C E \parallel A B, \text{ and through } B \text{ draw } B E \parallel A C. \\
\text{Join } A E. \text{ Then } A E \text{ is the resultant of } A B, A C, \text{ and if measured off on the same scale as was used in}
\end{align*} \]

drawing A B, A C will be found to be 23 2-5 parts of that scale. The angle B A E will be found to measure very nearly 26° 20'. The resultant force then is 23 2-5 lb.

2nd. Calculation:

\[ A E^2 = A B^2 + B E^2 - 2 \cdot A B \cdot B E \cdot \cos 120 \text{ deg.} \]
\[ = A B^2 + B E^2 + 2 \cdot A B \cdot B E \cdot \cos 60 \text{ deg.} \]
\[ = 15^2 + 12^2 + 2 \times 15 \times 12 \times 0.5. \]
\[ = 549. \]
\[ A E = \sqrt{549} = 23.43. \]

An answer which differs from the preceding one only by '03, or \( \frac{1}{32} \).

If more than two forces act upon a point, their resultant may be found by first finding the resultant of two of the forces, then of two more, then the resultant of these resultants, and so on.

Moment of Forces, Couples, Torque.—Forces may not act at the same point on a body, Fig. 71.

\[ \begin{align*}
\text{Let the two forces } P \text{ and } Q \text{, represented in magnitude and direction respectively by } A B, C D, \text{ act respectively at the points } A \text{ and } B \text{ on a body. The resultant of these forces could be found. Also the point at which it acts, graphically thus—Join } A C. \text{ Produce } DC, BA \text{ to meet at the point } E. \text{ Along } EC \text{ take } E D_1 = CD, \text{ and along } EA \text{ take } E B = AB. \text{ Complete the parallelogram } E B_1, B D_1. \text{ Join } E R. \text{ Produce } E R, \text{ cutting } AC \text{ in } F \text{ and make } FR_1 = ER. \text{ Then } FR_1 \text{ represents the resultant of } A B_1, C D, \text{ and } A B_2, C D \text{ may be replaced by the single force } FR_1 \text{ acting at } F. \\
\text{From } F \text{ draw } FM, FM_1 \text{ perpendicular to the direction of the forces } A B_1, C D \text{ respectively. It is found that the force } P \text{ represented by } A B \times FM = \text{the force } Q \text{ represented by } CD \times FM_1, \text{ or shortly, } P \times FM = Q \times FM_1. \\
\text{These products are termed the moments of the forces.} \\
\text{If the body acted upon be reduced to a rigid line } AC, \text{ } A C \text{ is called a lever, and the point } F \text{ its fulcrum.} \]
the force \( P \) alone were to act on the body at the point A, or, say, on the lever, it would evidently twist the lever about the fulcrum, and \( Q \), acting alone at C, would twist the lever about the fulcrum in the opposite direction. When two equal and opposite parallel forces act at different points of a rigid body in the same plane, their effect cannot be obtained by a single or resultant force, and their tendency will be to twist the body in the direction of the plane in which they act. Thus \( P \), Fig. 73, acting on A in the direction \( A P \), and \( P \) acting on B in the direction \( B P \), will twist the body round in the direction \( B A P \) or \( A B P \).

![Fig. 72](image)

The term Couple is applied to such a system of forces.

The product of one of the forces and the arm of the couple is called the moment of that couple. Thus \( P \times AB = \) moment of the couple represented in Fig. 72. This applied to a magnet gives the magnetic force at the N pole or at the S pole \( \times \) the length of the axis of the magnet as the moment of the magnet.

This moment is a measure of the tendency of the couple to twist the body on which it acts, and it is customary to indicate a couple by its moment.

A couple tending to twist a body in the same direction as the hands of a watch is termed a positive couple; if in the opposite direction, a negative couple. The term "torque" is generally used by electrical engineers instead of "moment of couple," "statical-moment," or "turning moment."

The product of two quantities can be represented by an area.

This kind of graphic representation is principally due to Prof. Silvanus Thompson. An example, taken from his well-known book, will show the excellence and the simplicity of his work. It relates to the efficiency of motors. Let \( AB \), Fig. 73, represent the electromotive force, \( E \), of the electric supply. On \( AB \) construct the square \( ABCD \). Draw the diagonal \( BD \). From B along \( BA \) measure \( BF \), representing on the same scale the counter electromotive force of the motor.

![Fig. 73](image)

Through \( F \) draw \( FGH \) parallel to \( BC \), and through \( G \) draw \( KGL \) parallel to \( AB \) or \( DC \). The actual electromotive force producing a current is the difference between the electromotive force of the supply and the counter electromotive force of the motor. Let the latter \( = e \). The difference is \( E - e \), which may be represented by \( AF, KG, DH, KD, GH, \) or \( LC \). The electric energy put into the motor per second is \( C^2R = EC \); and as \( C = \frac{E - e}{R} \), where \( R = \) total resistance in the circuit, \( C \) is represented in the diagram by \( \frac{FA}{R} \), for \( FA = AB - BF = E - \epsilon \). The energy expressed thus may be written \( \frac{E(E - \epsilon)}{R} \).

The work converted by the motor is

\[ \frac{e(E - \epsilon)}{R} \]

but \( R \) is constant, so that these values may be written respectively \( E(E - \epsilon) \) and \( e(E - \epsilon) \).

Now the product \( E(E - \epsilon) \) is represented by the rectangle \( AFDH \), for \( AD = AB \) representing \( E \); and \( AF \) represents \( E - \epsilon \).

While the product \( e(E - \epsilon) \) is represented by the rectangle \( GLCH \), for \( GL = FB \) represents \( e \), and \( GH = GK = AF \) represents \( E - \epsilon \).

These areas, then, are proportional to the work expended and recovered, and when shaded, as in Fig. 74, exhibit very clearly these proportions.

It will be seen that the construction of such diagrams is very simple, but when carefully constructed can be made to give considerable information to those who might be unable to understand analytic treatment.

The Use of Co-Ordinates.

The third kind of graphic representations to which we shall briefly allude are those in which it is usual to define the position of a line by referring to its distance from two other lines generally at right angles to one another in the plane of the paper. The branch of mathematics that treats this subject fully is termed co-ordinate geometry. As an instrument of research the co-ordinate theory is unequalled for power and facility. Assume that lines, whether straight or curved, are made up of a series of points. It will be best to consider first the position of a point in a plane, then to consider series of points or lines.
Draw two lines at right angles \( \overline{XOX}', \overline{YOY}', \text{Fig. 75.} \)

These are called the co-ordinate axes, or, briefly, \( \text{co-ordinates}. \) Usually only one quadrant is required, \( \overline{XOY}. \) The point \( O \) is said to be the origin of the co-ordinates, lines measured along \( \overline{OX} \) are named the abscissae, and along \( \overline{OY} \) the ordinates, while \( \overline{OX} \) and \( \overline{OY} \) together are called the co-ordinates, \( \overline{XOX}', \overline{YOY}' \) are the co-ordinate axes, here rectangular, but not necessarily so. The position of any point \( P \) in the same plane as the co-ordinate axes is fixed if we know its distance from the co-ordinates. A further convention is that all ordinates above \( \overline{XOX}' \) are reckoned +, all below −, while all abscissae to the right hand of \( \overline{YOY}' \) are reckoned +, all to the left hand −. If, then, the point \( P \) is in the first quadrant, and its abscissa, the line \( PN, \) drawn through \( P \) parallel to \( \overline{OX}, \) and its ordinate, \( PM, \) drawn through \( P \) parallel to \( \overline{OY}, \) both ordinate and abscissa are positive. If the point \( P \) were in the second quadrant the ordinate would be + and the abscissa −; in the third quadrant both would be −, and in the fourth the ordinate would be − and the abscissa +. Thus the position of \( P \) can be rigidly defined. It is usual to describe the abscissa by the letter \( x \) and the ordinate by \( y, \) so that taking \( P \) as in the diagram \( PN=OM=a;\ PM=ON=y.\)

The point whose co-ordinates are \( x \) and \( y \) is simply denoted by \( (x, y). \) When a point is given, and its co-ordinates are consequently known, the known quantities are generally represented by \( a, b, \) etc.

Thus, if \( x=a \) and \( y=b, \) to find the point we measure off \( OM=a \) divisions of the scale in which \( a \) is given, and \( ON=b \) divisions of the same scale, then drawing \( MP \) parallel to \( \overline{OY} \) and \( NP \) parallel to \( \overline{OX}. \) The intersection of the lines denotes the position of the point. The following numerical examples give points in each quadrant (Figs. 76, 77, 78, and 79):

1. \( x=3, y=4 \)
2. \( x=-3, y=4 \)
3. \( x=-3, y=-4 \)
4. \( x=3, y=-4 \)

This representation of the position of a point in a figure drawn to scale is called \textit{plotting} or \textit{constructing} the point. We often, however, know something about points, but not enough to determine them. In this case the point can take any one of a series of positions, and yet its co-ordinates satisfy the conditions imposed upon them. Thus let \( x=0. \) This tells us simply that the distance of the point \( P \) from the axis of \( Y, \) is nothing; in other words, that the point lies somewhere on \( \overline{OY}. \) Similarly, \( y=0 \) tells us that the point lies somewhere on \( \overline{OX}. \) If \( x=a, \) it means that the point \( P \) is distant \( a \) unit from \( \overline{OY}, \) and that it is somewhere in a line drawn parallel to \( \overline{OY}, \) distant \( a \) units from it.
Again, if \( z = y \), we see that the co-ordinates of \( P \) are always equal, and of the same sign. The point to satisfy these conditions is anywhere on the line \( AB \), which bisects the angle \( XOY \), Fig. 80, and no point not on this line can fulfil them. If the point lies on the part of the line in the angle \( XOY \), its co-ordinates are equal and positive; if on the part in the angle \( XOY_1 \), they are equal and negative.

![Fig. 80.](image)

This series of positions which a point can occupy while its co-ordinates satisfy a given equation, is called the locus of that equation. The word curve is used here to indicate any geometric locus, whether a curve, a straight line, or an isolated point. Consider a little further Fig. 80. Each point in \( AB \) is equally distant from \( OX \) and \( OY_1 \), a property which (remembering the distinction between positive and negative directions) no other point in the plane possesses. Now, the distances of a point from \( OY \) and \( OX \) are the co-ordinates \( x \) and \( y \) of that point, and, therefore, the equation \( x = y \) expresses algebraically the distinctive property of points on \( AB \), or, as we may say, of the line \( AB \). This equation, therefore, is called the equation of \( AB \). Hence we define the equation of a curve as:

The equation of a curve is the expression in an equation of the relation which exists between the co-ordinates of every point of that curve, and of no other points.

This equation expresses some law which governs the changes of the co-ordinates of \( P \), and controls the part of \( P \) in the plane: hence a curve that is drawn at random is not the locus of any equation, for, to repeat, the locus of the equation must be a curve governed by some law. We have then two cases:

I. A curve governed by some law, which curve has its corresponding equation.

II. A curve not controlled by any law, which curve has no corresponding equation.

When the curve is the locus of an equation, if the equation is given, we can construct or plot the curve by determining the position of a number of points in the curve, and joining these points, or we can experimentally determine a number of points, and thus plot the curve, and, if any, obtain the corresponding equation.

Let us plot the curve whose equation is \( x - y + 2 = 0 \).

If we choose any arbitrary value for \( x \), we can find a value for \( y \), which, together with the chosen value of \( x \), will satisfy the equation. These values—viz., the arbitrarily chosen one and the one found—are therefore the co-ordinates of one point of the locus of the equation. A second chosen value for \( x \) enables us to find another value of \( y \), and these are the co-ordinates of another point of the locus of the equation, and so on.

If we choose \( x = 1 \), then \( y = 3 \), in order that \( x - y + 2 = 0 \), therefore \( (1, 3) \) is a point of the required locus. Again, if \( x = 2 \), then \( y = 4 \), and \( (2, 4) \) is a point of the required locus. Similarly \( (4, 6), (8, 10), (0, 2), (-1, 1), (-2, 0), (-3, -1), (-5, -3), (-8, -6) \), are points of the locus. Plotting these points, we see, Fig. 81, they all lie in a straight line, and from this we infer that the equation \( x - y + 2 = 0 \) represents a straight line, which cuts \( OY \) two units above \( O \), and \( OX \) two units to the left of \( O \). It saves a good deal of time and trouble if ruled paper, especially prepared for this purpose, is used for plotting work.

![Fig. 81.](image)

Let us plot the curve whose equation is \( y^2 = 4x \). In this equation:

\[
\begin{align*}
&\text{if } x = 0 \quad y = 0 \\
&\text{... } x = -\frac{1}{2} \quad y = \pm 1 \\
&\text{... } x = \frac{1}{2} \quad y = \pm \sqrt{5} = \pm 2.24 \\
&\text{... } x = 1 \quad y = \pm 2 \\
&\text{... } x = 2 \quad y = \pm 2 \sqrt{2} = \pm 2.82 \\
&\text{... } x = 3 \quad y = \pm 2 \sqrt{5} = \pm 3.46 \\
&\text{... } x = 4 \quad y = \pm 4 \\
&\text{... } x = 5 \quad y = \pm 2 \sqrt{5} = \pm 4.48 \\
&\text{... } x = 6 \quad y = \pm 2 \sqrt{6} = \pm 4.90
\end{align*}
\]

and so on.

If we choose a negative value for \( x \), we obtain an imaginary value for \( y \), which leads to the conclusion that \( x \) has no negative value—that is, that there are no points on this locus with negative abscissa, no points, to the left of \( OY \). Again, each abscissa has
two ordinates, each of which satisfies the equation, from which we infer that from every point above OX there is a point symmetrically situated below OX. Further, it is evident that as \( x \) increases so also \( y \) increases. There can be no limit, therefore, to the extent of the curve to the right of OY. Fig. 82 shows this curve.

We have seen that straight lines can be used to represent quantities—that if a line 1m. long represents 1 bushel of corn a line 10in. long will represent 10 bushels of corn; so if a line 1 unit (any unit on any selected scale) represent 1 ohm resistance, then a line \( n \) units will represent \( n \) ohms resistance; or if 1 unit represents 1 volt, or 1 ampere, \( n \) units will represent \( n \) volts or \( n \) amperes. Thus, lengths upon the co-ordinates are made to represent ohms, volts, amperes, revolutions of armature, ampere-turns, resulting magnetism, or whatever is required for the investigation in hand. The consideration of a few simple examples will enable the reader to see how useful this kind of representation can be made. Let OX, Fig. 83, represent resistance, and OY electrical pressure or electromotive force. Let the end, X, of the resistance, OX, be connected to earth, so that at the point X we get zero pressure. Join YX. In OX take any point, A, and through A draw AB parallel to OY; then AB will represent the electrical pressure at the point A. It can be shown that YB bears the same proportion to BX as OA does to OX; so that if we know the fall of electrical pressure between YB we know the resistance OA, if we know that of OX. Suppose OY = 50 volts and OX = 500 ohms. By drawing through B the line BC, parallel to OX, on to OY, and measuring YC, we find YC is 2-5ths of OY, and therefore represents a loss of 20 volts; OA therefore represents 2-5ths of 500 ohms, or 200 ohms. The resistance represented by A X = 300 ohms, and the pressure at A = 30 volts. Similar measurements might be made at any other point in OX or OY.

Suppose we desire to show the relation between armature speed and electrical pressure. Let OX, Fig. 84, represent the revolutions per minute, and OY the pressure. The curve shows clearly the relation called the characteristic curve possesses the most importance to the student of dynamos. Let the machine under consideration be a series-wound machine, run at constant speed with a load varying from the largest to the smallest that the machine will carry without injury. Measure for each resistance the difference of pressure or potential at the terminals, and the current. Let the currents be represented along OX, and the pressures along OY. The intersection of
25 H.P. BECKENBAUM MOTOR—⅓ SIZE.
the horizontal and vertical lines which represent the current and the pressure give a series of points, which when joined give the curve called the characteristic of the machine. In Fig. 85, let O A B C represent such a curve, and the interpretation of its peculiarities is the object of the construction. The curve shows that when the currents are small the pressure increases rapidly, and as this part of the curve is almost or quite a straight line, the pressure and current increase in the same proportions. When the current has increased to a certain value in the diagram indicated at or about the point A, the pressure increases less rapidly, and soon reaches its maximum limit, past which it will probably slightly decrease. Now the practical value of having such a curve as this depends upon the ability to interpret. The complete interpretation can only be understood after a course of study of the dynamo, but sufficient can perhaps be said here to indicate the enormous value of such curves, and to induce the student to closely examine all that may be said about them. The curve given is that known as the external characteristic of a series dynamo. It has already been mentioned that the electrical pressure of the machine increases pretty uniformly according to the number of revolutions. Here we have assumed the revolutions to be constant. Part of the pressure generated is used to overcome the resistance of the armature itself, the remaining part—viz., the difference of pressure or the difference of potential at the terminals of the dynamo—is that available for use in the external circuit. The characteristic curve can take into account the total pressure, or, that available in the external circuit only. From the curve given we should infer putting other considerations aside, that this machine would not be run to the best advantage if run for pressure or current less than those indicated by point A; neither should it be run much, if any, beyond point B, as that is the maximum point for pressure. Further, for value of currents between A and C, the machine gives nearly constant pressure for different loads. Of course, the nearer the curve A C is to a straight line the more constant the pressure. If, therefore, it is desired to construct a machine to give a constant pressure, it is necessary to have one that gives a characteristic with A C as nearly a straight line as possible.

How comes there to be such a sharp bend in the curve at A? Before answering this question let us see how the total characteristic is obtained.

Assume, though of course in an actual case the resistance would be measured, the resistance of the armature to be .5 ohm.

To drive 5 amperes through .5 ohm requires 2.5 volts.

\[
\begin{array}{c|c|c}
\text{ampere-turns} & \text{resistance of magnetic circuit} \\
\hline
5 & \frac{2.5}{.05} = 50 & \frac{5.0}{.05} = 100 & \frac{5.9}{.05} = 118 & \frac{5.5}{.05} = 110 & \frac{5.0}{.05} = 100 \\
\end{array}
\]

From O, Fig. 86, draw the line O I at an angle with O X, whose tangent is \( \frac{1}{5} \)—that is, the numerical value of amperes = in this case \( \frac{2.5}{5} \) or \( \frac{5}{10} \). The ordinates of this line represent the pressure or electromotive force or volts lost in the armature. Add the ordinates of O I to the corresponding ordinates of OABC, and we get a series of points which, when connected, give the curve O T. Then the length of ordinates from O X to O T gives the total voltage induced, or the curve O T may be called the total characteristic. In practice account must be taken of the rise in temperature causing an increased resistance in the armature, so that the real loss in volts is greater than is depicted in this diagram.

To return to the question, How comes the bend in the curve at A? It has been stated that a current through a coil around a core of soft iron evokes magnetic lines or loops of force. We have seen, p. 23, that

\[
\text{Number of loops} = \frac{\text{ampere-turns}}{\text{resistance of magnetic circuit}}
\]

that is, if the resistance of the magnetic circuit remained constant, the number of loops would vary directly as the ampere-turns, but the resistance is not constant. It increases with the magnetisation, and after a time the sending of additional current through the coil does not increase the number of loops or force through the iron core. When the magnetism of the iron core does not respond to the increase of current, the iron is said to be saturated. In a series-wound machine the magnetic field, in which the armature revolves, increases rapidly in strength till the iron of the field-magnets is saturated. The portion of the curve O A shows the condition while the core is not saturated. An increase of the current in the series coils after A is reached—that is, when the iron is saturated—has little effect in increasing the magnetism, and therefore the pressure.

Just as we have drawn the characteristic between pressure and current, in the same way characteristics
of the compound no short-circuited.

The characteristc curve can be obtained for any two varying quantities which depend upon each other, and for only two.

**Fig. 87.**

Of course the curves obtained from a series machine are altogether different from those obtained from a shunt or a compound machine. To obtain similar diagrams to those above given in a series machine, the armature speed must be kept constant. First, with terminals open, there is no current in the external circuit, therefore none in the field-magnet coils, therefore no magnetisation and no magnetic field. Connecting the terminals by a large resistance, a small current is obtained; reducing this resistance, we get a larger and a larger current, and a stronger and stronger magnetic field, till the point of saturation is reached. With a shunt machine, on the contrary, when the terminals are open, the whole current goes through the shunt coils, the field-magnets are excited to their highest point, and we get maximum pressure.

The general characteristic for current and pressure of a shunt machine for different resistances is shown in Fig. 87. Let Ox represent current, and Oy pressure. Starting with open resistance between the terminals, the machine gives its maximum pressure OE and no current. Putting in a very large resistance and gradually decreasing it, we get more and more current with the pressure falling. The first part of the curve EABCO is almost a straight line, and during this part of the curve the fall of pressure is proportional to the current as the resistance decreases. At A the pressure commences to fall more rapidly, and at B still more rapidly, till at C the maximum current OC1 is reached. If we decrease the resistance past C continuously till the machine is short-circuited, the pressure and the current both fall till, when short-circuited, both are at zero. The curve shows graphically what is known as all after a moment's thought, that maximum pressure is when the machine is run on open circuit—that is, when all the current goes to excite the field-magnets, and no current to the external or working circuit; that when no current goes into the shunt circuit, there is no field, and consequently no pressure and no current. This happens when the machine

**Fig. 88.**

is short-circuited. The curve shows there is a maximum current = OC1, and if the armature will stand this maximum current no alteration of the external circuit will injure the machine. In practice, however, no one runs a shunt machine between C and O—it would be very uneconomical. The best machines would be limited to a part of EAB. If any part of EAB was perfectly straight, then the current might be varied at will within the limits of that straight part without alteration of pressure. The inclination of EAB is due to the resistance of the armature, some part of the pressure being used to overcome this resistance. If the armature had no resistance a portion of the curve, say EA, would be horizontal, and then we could have current varying, as mentioned before, with constant pressure. But this part of the subject will be fully treated hereafter. It will be sufficient to say here that the difficulty indicated was avoided or neutralised by the introduction of compound winding, or of the compound dynamo. The characteristic of the compound machine should be a combination of the charac-
characteristics—the resultant characteristic, we might call it, of the series and shunt machines.

In the characteristic of the series machine the pressure rises in a regular manner, in the characteristic of the shunt machine it falls in a regular manner—hence, by a proper combination of the two the action may be to keep the pressure constant. In other words, we have only to design the windings of the shunt and series coils so that the action due to the series coils in increasing the magnetism of the field-magnets shall be just equal to the action of the shunt coil in diminishing that magnetisation. The resultant action will give constant pressure, or potential, within certain limits. We can show what we mean by a diagram, Fig. 88. Let OB represent the rise of pressure due to the series coils and EA the fall of pressure due to the shunt coils.

If OB rises in the exact proportion as EA falls, the pressure will be represented by the straight horizontal line EA, and up to that limit the current can vary without variation of pressure. It can be shown that a compound machine should only be used in such parts of EA, OB as are nearly straight lines; also that the bend of the curve EA at A, is due principally to saturation. Thus we learn that a compound machine should be run below the saturation point. Sufficient has now been said to prove our contention that the whole subject of electro-graphics is of the utmost importance, and although the reader may start without much mathematical skill, there is no reason why, with careful attention, he should not be able to plot and interpret diagrams to such an extent as to be of very great service to him in practical work.

CHAPTER VI.

THE CENTRAL STATION.

The very name central station indicates its importance. Here the electrical engineer’s work is collected, and here most of his troubles begin. The electrical energy which has to be distributed over a large or a small area must be generated in large quantities; and at a convenient point, in order to make its commercial production possible. This means the collection of large masses of machinery upon that spot, and the provision for their due maintenance and work.

Position, Initial Cost, and Cost of Maintenance.

In most cases the cost of maintenance, which, for the moment, may be taken not merely to imply the keeping of the machinery in repair and in working order, but to include the cost of the fuel, water, and other materials required in the daily work, is of far greater importance than initial cost. In choosing a site, therefore, for a central station, it is necessary to consider the position in regard to the cost of obtaining the requisite daily supplies. Thus one site may cost a thousand pounds more than another, yet by utilising the nearer site a saving of a hundred pounds a year on cartage may be effected. It will be better to pay the higher sum once than to pay the higher cartage, which affects the working expenses as long as the station runs.

Another consideration of great importance in the selection of a site is the room for extension. During the discussion of a recent paper on central stations, a speaker remarked, “I think I speak advisedly when I say that almost every central station man throughout the country has, upon finding his station too small, enlarged it to meet the requirements of all time, got it quite completed, and found it was still too small.” Again, the position selected will depend largely upon the system adopted, whether the system be the generation of high pressure or the generation of low pressure. It will be seen, then, that the selection of a site is not so simple a proceeding as it may sometimes seem. It is not the seeking of a vacant plot of ground in a populous part. A vacant plot in the very midst of a population anxious to obtain light and power may not be so economical as a plot at some distance, or on one side of the area of distribution. The selection of a site for a large central station is, however, more of a financial problem of a complex character than a purely engineering problem.

The Building.

The style of building will depend upon the part of the world where it is erected, and the available building materials in the district. It is not our intention to enter into any discussion as to the value of brick, stone, iron, or wood, or thickness or height of walls, but, like Franklin, being fully imbued with the idea that the foundation is the most important part of the building, a subsequent chapter is devoted to a brief survey of the factors that enter into the making of a good foundation. As steam will probably constitute the principal power for driving dynamos, and as the best steam engines will be constant sources of worry and trouble if their foundations go amiss, although the engines themselves may be excellent in every sense of the word, the wise engineer will pay the most careful attention to all that concerns his foundations. Then, again, comes into consideration the system employed and the insulation of the dynamos. Surely too little attention has been
paid to the use of insulating material in foundations. Vibration, and especially when the station is in the vicinity of residential houses, has to be considered, as has noise, and the transmission of both noise and
vibration depends largely upon the suitability or unsuitability of the foundations. Of course the walls and roof must be erected with due consideration of the duties they have to fulfil.
Fig. 91. — Mentmore.—Section through Engine Room.

Fig. 92. — Mentmore.—Section through Boiler Room.
The arrangement of the machinery in the building is a test of an engineer's abilities. The plans of one engineer will be far preferable to those of another under the same conditions. There is no royal road to success. The younger generation must learn from the experience of the older—hence too much cannot be known of how others have solved the problem as presented to them. The conditions of each separate installation will have to be studied and arranged for. So far as we can we shall aid the engineer by giving examples of installation arrangements over as wide and varied a field as possible. We may here refer to the arrangements made at one or two typical installations to show the great divergency of requirements. One station mentioned is a large central station, the other is a small isolated station for a gentleman's mansion. The Edison Brooklyn station may be termed a representative station for lighting large towns. The engines in this station are upon the ground floor, the dynamos on the floor above. Of the latter there are 24, each with a capacity of 750 amperes and 140 volts. Through the centre of the dynamo-room runs an electrical gallery where the electrician controls the switch arrangements. The longitudinal section and the plan, Plates N and O, show clearly the whole arrangement.

Figs. 90, 91, and 92 show the arrangements at the Earl of Rosebery's mansion at Mentmore. This is a private installation, carried out by Messrs. B. Verity and Sons, and is similar to many other stations erected for supplying private mansions or isolated buildings. The illustrations show plans and sections of boiler and engine rooms. The measurements are given, so that further explanation is unnecessary.

CHAPTER VII.

FOUNDATIONS CONSIDERED PRACTICALLY.

The importance of substantial and enduring foundations to heavy buildings, and especially such buildings as are to contain heavy machinery, cannot be overstated; yet, in practice, frequent failures occur because due attention is not paid to this matter. The precise relation of the loaded superstructure to the nature and extent of the stability of the substratum should be the fundamental principle in determining the most suitable class of design of foundation to employ, the character of the provisions and precautionary measures which should be adopted, and as well should command the requisite degree of attention to all important practical details during the execution of the work which would ensure its sufficiency in all respects, and hence its permanency. Foundations should not be liable to be affected injuriously by frost, water, air, weather, or other source of disturbing action, whether mechanical or chemical in its nature, and consequently should be immovable by any other conditions to which they will be subject in the ordinary course of events. Displacement of foundations may occur vertically or horizontally—the one by compressive yielding of the subsoil, in which, however, there is more or less lateral displacement amongst the substances composing the substrata; the other by the sliding over one another of the layers, which lie, obliquely of different bands of overlying, interlying, or parting soils. The natural soil in situ is not always substantial, and is very frequently deceptive and irregular in thickness, compactness, cohesion, etc., at different parts of a foundation site, and especially so when in the vicinity of existing or old waters of rivers, morasses, estuaries, lakes, etc., which may have left indications of its character on the surface, or all may be concealed in subterranean forms only, and therefore be the more likely to prove dangerously insidious.

All structures built of masonry, in stone or brick horizontal courses, laid with yielding mortar bed-joints, must settle to some extent in height depending upon the frequency and thickness of the bed-joints occurring in the work. And likewise all soils are more or less compressible. Hence, in all cases subsidence of the soil to some extent is unavoidable, but by judicious treatment it can be greatly minimised and equalised in both cases, instead of being exaggerated and distorted, as frequently happens by neglect of intelligent treatment and adaptation. Foundations are either (1) natural, or (2) artificial, considered in a restricted sense of the term, which implies in one case the natural virgin solid stratum of soil, rock, etc., in situ, which underlie the expanded footings base, and which may of itself be of sufficient depth and compactness to support the building when ultimately loaded if it be a ware or store house, or in the case of mills, factories, workshops, etc., with full equipment of going machinery. The methods and expedients resorted to for the purpose of rendering permanent the stability of the natural soil by preventing lateral movement or escape of any part of the supporting substance when of a semi-fluid character, such as sands, clays, etc., and by adequately increasing the supporting area when the strata consists of soft or loose materials by means of a monolithic bed.
of concrete, must be studied in the case of natural foundations.

In the other case examination should be made of all the devices which have for their object to provide, by artificial means, a reinforcement of the natural bearing capacity of soft soil by consolidation, by studding it with piles, or by providing skeleton supports, as timber or iron (screw) piles, sand or concrete piers, penetrating the soft soil to reach the lower solid strata, or constructing gridirons of iron or steel beams embedded in concrete.

The first consideration must be drainage. In districts where there is no town drainage system available with which to connect and relieve the foundation excavations and trenches, of water accumulations from rain, or from water surcharging adjacent lands, which should be collected in a receptacle in a convenient position for being discharged, etc., by "grapes" (small channels branching in different directions), adequate provision should be made in advance, either by temporary outlets, pumps, etc., as any flooding or submerging of the foundation area or trenches should be avoided. Surface waters should be prevented from entering the excavations and trenches. The foundation strata for all important structures should be thoroughly tested either by deep trial pits at different parts of the foundation site, or by wrench auger borings, by which samples of the various soils passed through are brought up for examination at convenient intervals.

Foundation strata are sometimes tested by applying to a limited area of the footing base a sufficient unit pressure per square foot, by means of loading a framework with heavy weights of iron, stone, etc., to adequately represent the ultimate unit load to be imposed by the building, etc., with exact observations and notes of the time-measured subsidences which it produces. It should be observed that an ordinary rectangular arrangement of testing frame, with four supporting areas at the four corners, is liable to give confusing results if the points of application, and amounts of the weights, and the leverage of their action at all times upon the supports, produce not equal moments. As this would be practically unavoidable in case of undue subsidence of any one of the four supports, which would throw an uncertain surplus proportion of the load upon the two diagonals of the remaining three supports, it is preferable to have only three supports in triangular arrangement.

The site of foundations may, by these means, be discovered to require precautionary treatment in the manner already alluded to, or protection from the action of a high-water level of water-bearing beds, or running waters, underground springs, which may be the outlets of natural reservoirs of a distant locality which may retain water above the level of the outfall in proportion as the capillary action and the friction amongst the particles in passing through the interstices of the permeable strata exceeds the hydrostatic pressure of the accumulating rainfall, whereby several feet deep of water may occur at certain seasons. In the body of extensive hills of permeable surface strata, as sand, oolitic freestone, fissured limestone, chalk, etc., natural reservoirs of water are heaped up, as it were, above the level of outlet, having a varying curvilinear surface rising from the outlet, and accordingly there are cases of wells occurring on chalk hills, many miles from valleys, which have a water level 40ft. or 50ft. higher in spring than in autumn. Such conditions prevailing on a site might prove a matter of very serious import, as may readily be imagined. The presence of quicksands, more or less saturated, when underlying the surface strata, are thus discoverable. Stagnant, intermittent, or permanently waterlogged areas adjacent to the site may by intermediate geological features well up from time to time, as "land tides," by the action of which the supporting or lateral materials, which may include water itself, naturally present, of the foundations may be disturbed or dissipated. Such cases require special expedients, such as sheet-piling, puddled clay trenches, etc., for effectually retaining the supporting materials immovable. Sheet-piling alone is insufficient for this purpose when the substratum is "waterlogged." All rocks and earths being more or less porous are liable to be permeated by water from rain, etc. In some geological local conditions intermittent "welling up" may occur at a considerable distance from the immediate source of the supply or "catchment basin." Intervening "dykes," "faults," etc., may either, according to circumstances, have the effect of precipitating or of temporarily preventing the access of distant ground waters. Hill slopes and valleys are thus frequently affected when the strata dip towards the site. A knowledge of the surface geology of the district, the strike or trend and inclination of dip, etc., of the strata, their superposition, the kinds and character of rocks and other soils to be encountered in excavating foundation trenches, cellars, etc., their outcrop, water-bearing capacity, and other prevailing accidental and incidental circumstances which have more or less effect upon the permanence and stability of the work should be obtained from proper sources, or by the methods known as "field geology."

Ridges and escarpments consist mainly or partly of water-bearing beds, of limestone, chalk, sandstone, etc. The softer clays being more readily denuded, gravitate to the lower grounds. Strata generally dip towards and pass underneath the higher grounds; the beds are not often found quite horizontal. The anticlinal strata, like Δ, are more readily denuded than the synclinals, like letter V, hence the latter remain while the higher intervening anticlinals are washed away, leaving valleys occupying the sites of the pre-existing hills, and escarpments of trough-like beds underneath the present ridge. Water levels will rise in them to the top of the exposed outcrop or escarpment of the impervious strata, and escape in perennial or intermittent springs, according to the extent and capacity of the underground reservoir formed by the impervious bed. It is preferable to divert springs and water channels than to dam them out from founda-
tions. Damming out of springs or surcharging waters from underground basements and deep cellars and areas requires very carefully executed puddled walls and bottom without any breaks, or walls and basement or cellar floors should have an impervious coat of good hydraulic cement or asphaltite, etc. Hence the same geological knowledge that is required to obtain water supply by easiest means is also available for devising the readiest expedients for discovering its presence or dispersing it. In the reverse geological conditions, an impervious surface sheds rain and surface water to, and received by, lower pervious surface beds. When pervious beds are sandwiched between impervious beds, they are in a condition to act as a syphon in conveying underground waters to considerable distances underneath valleys and undulating ground when it is required in connection with the excavation of foundation trenches, cellars, or deep areas, etc., to pump the water from water-logged ground in the neighbourhood of existing buildings. It is unsafe in most cases to use a steam pump to keep the water low to permit of work of continued excavation, or of construction of concrete, stone or brick masonry, etc., as the sudden withdrawal of a large quantity of water may deprive neighbouring foundations of its supporting property, and thereby cause injurious settlements of these buildings.

From a failure to acquire some or all of such preliminary information, a sound and capable substratum has been frequently known to be rendered insecure by blindly cutting the excavations, trenches, etc., too deep into a stratum already sufficiently limited in thickness.

Characteristics of Sites as regards Soils, Rocks, etc.

Differences in the character of the soils of the subjacent strata in foundations produce corresponding differences in the amount of resulting settlements of the future building, and, hence, if they vary in different parts of the site instead of being of homogeneous composition, and of equal thickness and compactness throughout, which is rare in extensive and occasionally so even in moderate sized sites, proper expedients must be adapted to improve its bearing power in those parts which are the more compressible, and thus ensure equal stability throughout, or by a corresponding enlargement of footing areas, or by deepening the trenches to reach a more solidified condition in the underlying layers when such is to be found, by drainage of surcharging waters, by spreading layers of sand, gravel, broken stone, concrete, etc., of sufficient thickness, by ramming, pinning, or grouting in the case of coarse, loose gravel substrata.

The earths met with may have characteristics which render them of commercial value in certain localities, or they may be of present utility in connection with the building, or, on the other hand, they may have qualities to be guarded against in building operations, or such as may render a site for certain purposes extremely undesirable. Rock seldom covers uniformly the entire area of a foundation site. Sand, gravel, clay, silt, mud, etc., may occupy the remainder; the rock may ledge or berne up at one side or end of a site, or even under one side of some of the walls only. The surface of the rock may have large cavities, sand or potholes, or the strata may be inclined, upturned, inverted, dislocated, or may have large deep fissures filled with loose parting bands or beds of sand, gravel, and clay, which the superincumbent weight of soil, or the presence of water, or the action of the weather, may displace in the course of time.

In the occurrence of successive beds, or layers of soils, the larger stones, or particles of matter, are usually found in the lowermost positions in the series; thus the successive beds of boulders, gravel, sand, silt, mud usually occur in the order named when enumerated upwards. The beds are thus formed by the action of water, or sometimes by that of wind, but in the latter case are less regular. In the former mode there is a considerable approach to parallelism amongst the successive layers, but with less exactness than occurs in the cleavage planes of sedimentary deposits in most cases, when they are said to be "conformable." Strata deposited by water contain fossil remains of animals and plants embedded in them while they were soft. Metamorphism by heat, chemical action, or pressure, generally destroys those organic remains, and produces crystalline structure, but it leaves the stratification undisturbed. Stratum may thin out in places where there has been a previous deposit at a higher level. As a rule, the lowest strata are the oldest, except when they have been tilted over, inverted, etc., in limited areas by great natural convulsive agencies.

In situations where large cavities, fissures, ravines, in rock sites, etc., occur, sound hard-setting concrete should be freely used in a manner to ensure permanency and avoid future subsidences when the full weight of structure is imposed upon it. All kinds of rock, or, indeed, the same kind of rock in different situations in a quarry or districts, are not equally permanent.

When the laminae or beds lie obliquely to each other, as when produced by the action of tidal currents, it is called "false bedding"; or when the strata are "unconformable," i.e., the lower strata have been bodily upturned or overturned, and succeeding strata are deposited upon the upturned edges, with each of the successive strata overlapping the one beneath, whereby special conditions endangering instability may prevail. When there occur large cavities in the surface of rocks it is difficult to fill it up as solidly as the rock itself, so as to proceed with the masonry work, etc., without waiting until it is set perfectly hard. In favourable conditions anchoring can be usefully resorted to; but all such preparatory work should be done as far in advance as possible to ensure the least subsidence. The most recent and superficial strata deposits, which consist of sands, gravels, clays, boulder clay, silt, mud, etc., which generally overlie the igneous and stratified rocks, are composed of rock materials more or less ground up, weathered, and decomposed. It may be either alluvial, as produced by the action of existing or recent waters, wind, rain, and weather, or may be detritus, or northern
glacial drift, to which the name diluvium was formerly applied on the assumption that it was produced by the historic deluge, but is now referred to subsequent agencies of the glacial period, when the northern hemisphere, down to between the 40th and 50th parallels, was covered with ice, or to the action of extraordinary currents of water, or to submarine earthquakes, etc. The drift is usually composed of mixtures of abraded rocks, boulder clay, earth, stones, boulders, etc., brought from the north by ice drifts, and sands, marls, loams, gravels, etc., which have been more recently deposited by overflowing water. The former occupy the more extended districts. These drift deposits usually cover the older solid rock formations which occur in alternating rock layers, various in kind, thickness, and extent, but always in regular if not in constant sequence. These layers are rarely horizontal, but incline or dip with various slopes, and may strike in the same or in different cardinal directions, according to the character of the disturbing agencies by which they have been affected by upheaval of old sea, lake, valley, etc., beds, and which may have been subsequently partly eroded by floods or the depression of pre-existing mountains. By such agency the (1) primary and lower strata in the natural order of formation of igneous or unstratified rocks, such as granite, traps (varieties of dolerite or basalt, etc.), have been brought to the surface. Rocks are classified according to the nature of the prevailing mineral constituent, as siliceous (flinty), argillaceous (clay), calcareous (carbonate of lime). They are composed chiefly of quartz (silica and oxygen), felspar, which is of several family varieties (potassium, which may be replaced by sodium, or by calcium, aluminium, silicon, and oxygen), and mica, a glittering substance, composed of the same elements, commonly called clay and flint, with magnesia and oxide of iron, but of different ratios of combination, with the addition of iron and magnesium. Granite proper has the minerals disposed in granular irregular aggregation. Granites are in varieties of grey and red; that in which the minerals are aggregated in more or less parallel layers, and which is stratified, as gneiss. In some varieties of granites, as found in Aberdeen, etc., called syenite (from the island Syene in Egypt), hornblende replaces the mica. Hornblende is a dark crystalline substance composed of flint, alumina, magnesia, and black oxide of iron. Syenite does not split well. When granite contains large distinct crystals of felspar, it is the porphyritic variety. When quartz is disposed in parallel lines it is graphic granite. Schists are composed of finer mineral grains disposed in a laminated arrangement, indicating a tranquil sedimentary deposit, parallel to the lines of stratification, as in slates, flagstones, etc., or may be foliated, as in the crystalline variety, whereby the alternating layers of different minerals of which gneiss and other metamorphic schists are composed.

The sedimentary or stratified rocks are composed of the fragments of pre-existing rock formations, either in the form of gravel, sand, clay, etc., or these materials consolidated. The more complex the com-
notwithstanding these points of resemblance the wash may overlie a treacherous bed of quicksand, or, perhaps, peat, silt, etc. In extensive alluvial flat areas ancient river sites may exist, parts of which, in some instances, have been covered over to any depth up to even 100 ft., with probably only a comparatively shallow compact crust overlying a deep bed of soft silt.

Clays and shale, mud, ooze, etc., are of so numerous a description, each varying in composition and characteristics—very widely varies from slate or shale to soft oozing mud, but none possessing perfect compactness, and all more or less alterable in elasticity and fluidity by air, moisture, of which it is very retentive, etc.—that it is regarded as the most treacherous and troublesome of all strata for a foundation. The London blue clay is no exception. It and other clays expand with such enormous force as to crack and crush large scantling timbers and the struts used in shoring up the sides of excavations. If a compact dry bed of clay be covered with concrete, and be sufficiently below the surface, it may make a safe foundation. Silicate of alumina is the basis of all clays. They usually contain oxide or sulphide of iron, or some carbonaceous matter which imparts a dark bluish-grey colour. Some clays are calcareous, and contain septaria, masses of impure carbonate of lime, and sulphate of lime (selenite), as in the London clay, Reading or mottled clay, and Oxford clay. The pure clay is the China clay, and is derived from decomposed granites and other felspar bearing rocks, but generally clays are largely admixtures with various impurities. It is fullers earth with an excess of silica. Loam, with a certain proportion of fine sand, as brick earth. Shale is clay and marl hardened and laminated; if mica is present it is micaceous, carbonaceous if carbonaceous or bituminous matter present. Marl is clay that contains a considerable proportion of lime; if it is hardened, indurated, it is marl rock, which decomposes on exposure to the weather. The varied colouring of clay is due to iron in various states of oxidation, and to organic matter—the latter imparting colours varying from light grey to black. The iron imparts red, yellow, brown, and purple. Fireclay contains an excess of silica. Beds of blue marl, though tough and hard, do not afford a good foundation stratum.

When the excavation, either for cellars or footing trenches, is made in compact soil, short rough boards, called "poling boards," are laid vertically against the excavated sides at intervals on the opposite sides, and kept in place by cross struts. When the ground is loose, the poling boards, 2 ft. to 3 ft. long, are placed close together, and kept in place by stout horizontal planks called "wales," which are kept apart by square timber struts of scantling suited to the width of the cutting. This operation is repeated lower down as the excavation proceeds. If it be a cellar, the sides must be sustained by raking shores footed upon the excavated bottom. In very loose unstable soils, as sloppy clays, dry sand, etc., long poling boards are placed horizontally, and strutted. As the excavation gains depth, short vertical wales can be laid across several of the horizontal poling boards, and thus release some of the struts to be used lower down.

All excavations for footing trenches should be 6 in. wider on each side than the figured width of the footing base, and should be made perfectly level in one plane, or, if on rising ground, in as long benches or steps as the gradient will admit of. It is advisable to make the step, or rising face of the bench, in the lower one-third point of a bay under voids, to avoid any sliding of the face of the soil terrace by the pressure of the solid pier footing if placed too near the edge of the bench. Trenches for drains to be 1 ft. wider than the diameter of the pipes. Deep trenches should be 2½ ft. to 3 ft. wide, and 4 ft. wide if over 8 ft. deep.

Underfooting.—The trenches are sometimes filled to a depth of 3 ft. or 4 ft. or more, with layers of broken stone, gravel, sand, and concrete, well rammed in convenient layers. The soil may thereby be greatly compacted, and the ultimate subsidence of the building greatly reduced. Where concrete is used it should be made of good hard-setting lime or hydraulic cement, so that it may become and act as a monolithic structure, as otherwise it will not spread the pressure of the footing base over a larger area as intended.

Increase in Bulk of Excavated Material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Increase in Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth and clay (before subsequent subsidence)</td>
<td>1/6 more</td>
</tr>
<tr>
<td>Sand and gravel, or earth and clay, after subsidence</td>
<td>1/3</td>
</tr>
<tr>
<td>Chalk (depends on the shape and ruling)</td>
<td>1/3</td>
</tr>
<tr>
<td>Rock (which they make in the heap)</td>
<td>1/3</td>
</tr>
</tbody>
</table>

Loose soils compress into less space than occupied in their natural deposition. Thus clayey earth occupies about one-tenth part less volume in embankment than before digging, gravelly earth one-twelfth less. Rock in large pieces about five-twelfths more. Rock in small pieces about three-fifths more. Light sound earth occupies about the same space.

Estimating.—Cost depends upon the nature and stiffness of soil and depth of the excavation, for each throw up or staging of 6 ft., when the stuff is not carted or derricked out. In loose ground a man can throw up about 10 cubic yards per day of 10 working hours. In stiff clay or firm gravel about 6 yards. In hard ground, where picking is required, 4 yards. Three men will remove 30 yards of earth to a distance of 20 yards in a day.

Excavating is measured and priced by the cubic yard. Carting is charged by the single or double load—the single load of sand, earth, rubbish = 1 cubic yard.

When the footing courses are laid and the foundation wall will be set forward, the mortar joints properly set and the work dry, the filling in should be done by careful ramming of the earth in the trench round the footings.

Foundation Drainage.—Should the conditions require water to be carried away from the footings, either drain
tiles or broken stone, covered with slate or with small slabs, should be laid outside the footings for this purpose before the refilling is proceeded with.

**Protection from Surface Water.**—When the ground is levelled up against the walls it should slope down from the wall to shed off the surface water, and prevent its penetrating to the foundation walls, or other needful precautions should be adopted for the purpose. Stone has about three times the capacity of conducting moisture that brick has. Wall plaster is about one-fifth less than brick, wood is one-fourth that of plaster.

**Design of Footing Courses.**

As the enduring safety of a building depends upon the adequate apportionment of the footing base, it necessarily demands very careful attention in design and execution. The area of the base of the foundation footing should be proportional to the bearing capacity of the strata upon which the ultimate loads are to be imposed. In this connection there are three important considerations which are essential in all foundations:

1. The area of the base of the foundations should be so extended as to impose only a safe unit of pressure of the loaded structure upon the subsoil suitable to its bearing capacity.

2. That the centre of the footing area should coincide with the centre axis of the loaded pier wall, i.e., the foundation area should support its load centrally, whether on the continuous or on the isolated principle.

3. That the upper surface should be made truly horizontal, in one plane where possible, and where rising or hilly ground occurs, the number and extent of the planes, or benches, should be regulated by the amount of inclination. It is advisable to make the face of the step, or rising of the bench, in the lower one-third of a bay, i.e., underneath the voids, so as not to endanger any sliding of the face of the soil at the change of level, by the pressure of the solid pier footing if placed too near to the edge of the raised bench. If the difference in level of these benches be considerable, it may be necessary, in compressible soils, to allow additional extension of the footing base to correspond with the added weight of the extra depth of foundation walls, etc. In all benching, or stepped, foundations, the walling and footing courses should be of thick stones, and the joints should be very closely laid in hard-setting mortar or cement, to ensure as far as possible that the entire extent of the structure shall subside equally. Similar precautions should be observed when one portion of a building is higher than other adjoining parts.

Also when only a portion of the site is covered by solid rock, for it seldom occurs that rock, or equally solid portions, extends all over the entire building area of a site, and hence some portions of the structure require to be supported upon, it may be, loose gravel, clay, or other material of a very different character and bearing capacity. The surface of the rock if hard may be weather-worn, exposing more or less sloping smooth surfaces on which it would be unsafe to build without resort to some effectual method to prevent sliding or canting of any portion of the structure. In such cases it is usual to chisel out steps, checks or channels, etc., to hold dowels, keys, etc., as there are many circumstances in which blasting operations would not be permissible. In some rocks there occur sand, or pot holes, or pockets, which may so occur as to be utilised for this purpose. In the softer rocks the surfaces may be loose and disintegrated, all of which should be carefully removed. Large mass boulders may occur in the way of the footings, and if not judiciously treated may incur possibilities of unequal settlement, it may require to be considered as a part rock foundation. Irregularities occurring in firm ground should be levelled up with concrete.

**The Principles of Footing Courses, Continuous v. Isolated.**

The fenestrated bays of buildings, by which void is placed over void and solid over solid, naturally resolves the wall into impost and spandrels. The portions of the solid wall intervening between the bays act as piers. Yet, in violation of this very evident principle of design of foundation, many architects and builders give to this spandrel or bay portion of the wall the same width of footing base as to the pier portion, though, in the majority of instances, it does not support the one-twentieth part of the weight of the loaded wall per foot run in comparison with that sustained by the intervening piers. The part of foundation underneath the bay or spandrel supports merely that lowest part of wall which lies immediately underneath the lowest void or window opening; all the remaining part of the wall above and vertically between the voids which forms so many spandrels is imposed upon the piers, one-half upon the pier on each side of the void. The frequent result of this violation is to be seen all over London as well as in the provinces in disfiguring cracks, broken walls, sills, spandrels, window arches, lintels, stone storey courses, or other horizontal stone bands, mouldings, corners, widely opened stone joints, etc., and in many cases where it does not appear its salvation is due rather to the extra strength given to the masonry, or to the incompressibility of the substrata, concrete, hoop iron bond, etc., rather than to design upon the proper principle.

The footing base of ordinary foundations are of the same continuous width throughout for the main walls of the building, but the footings of fenestrated walls designed on the isolated principle would have, for voids in vertical tiers and equidistant horizontally, indents in the plan of the footing base nearly equal to the width of and immediately underneath the spandrel bays, upon both the inside and the outside of the wall. The fact of the weight of the spandrels being transferred to the impost of the intervening pier walls requires that the footing base underneath the impost should extend sufficiently in the shape of a "return" under the sides of the bays to equalise the insistent pressure upon the subsoil.
Off-Sets of Masonry Footings.

The area of the foundation having been determined and its centre having been located with reference to the axis of the load, the next step is to determine how much narrower each footing course may be than the one next below it. The projecting part of the footing resists as a beam fixed at one end and loaded uniformly. The load is the pressure on the earth or on the course next below. The off-set of such a course depends upon the amount of the pressure, the transverse strength of the material, and the thickness of the course.

To deduce a formula for the relation between these quantities, let

\[ P = \text{the pressure, in tons per square foot, at the bottom of the footing course under consideration;} \]

\[ R = \text{the modulus of rupture of the material, in pounds per square inch;} \]

\[ p = \text{the greatest possible projection of the footing course, in inches;} \]

\[ t = \text{the thickness of the footing course, in inches.} \]

The part of the footing course that projects beyond the one above it, is a cantilever beam uniformly loaded. From the principles of the resistance of materials, we know that the upward pressure of the earth against the part that projects multiplied by one-half of the length of the projection is equal to the continued product of one-sixth of the modulus of rupture of the material, the breadth of the footing course, and the square of the thickness. Expressing this relation in the above nomenclature and reducing, we get the formula

\[ p = \frac{t}{2} \sqrt{\frac{R}{41.6 P}}. \]

or, with sufficient accuracy,

\[ p = \frac{1}{3} t \sqrt{\frac{R}{P}}. \]

Hence the projection available with any given thickness, or the thickness required for any given projection, may easily be computed by the latter equation. Notice that, with the off-set given by the above formula, the stone would be on the point of breaking.

The margin to be allowed for safety will depend upon the care used in computing the loads, in selecting the materials for the footing courses, and in bedding and placing them. If all the loads have been allowed for at their probable maximum value, and if the material is to be reasonably uniform in quality and laid with care, then a comparatively small margin for safety is sufficient; but if all the loads have not been carefully computed, and if the job is to be done by an unknown contractor, and neither the material nor the work is to be carefully inspected, then a large margin is necessary. As a general rule, it is better to assume, for each particular case, a factor of safety in accordance with the attendant conditions of the problem than blindly to use the result deduced by the application of some arbitrarily assumed factor. The following table is given for the convenience of those who may wish to use 10 as a factor of safety:

<table>
<thead>
<tr>
<th>Kind of Stone</th>
<th>R, in lb.</th>
<th>Off-set for a Pressure, in tons per square foot, of</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>per square inch</td>
<td>on the Bottom of the Course, of</td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td>1,500</td>
<td>2-9</td>
<td>2-1</td>
</tr>
<tr>
<td>Limestone</td>
<td>1,500</td>
<td>2-7</td>
<td>1-9</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1,200</td>
<td>2-6</td>
<td>1-8</td>
</tr>
<tr>
<td>Slate</td>
<td>5,400</td>
<td>5-0</td>
<td>3-6</td>
</tr>
<tr>
<td>Best Hard Brick</td>
<td>1,500</td>
<td>2-7</td>
<td>1-9</td>
</tr>
<tr>
<td>Hard Brick</td>
<td>800</td>
<td>1-0</td>
<td>0-8</td>
</tr>
<tr>
<td>Concrete</td>
<td>(1 Portland</td>
<td>10 days</td>
<td>(3 pebbles) old</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>150</td>
<td>0-8</td>
</tr>
</tbody>
</table>

To illustrate the method of using the preceding table, assume that it is desired to determine the off-set for a limestone footing course when the pressure on the bed of the foundation is 1 ton per square foot, using 10 as a factor of safety. In the table, opposite limestone, in next to the last column, we find the quantity 1-9. This shows that, under the conditions stated, the set-off may be 1-9 times the thickness of the course.

If it is desired to use any other factor of safety, it is only necessary to substitute for R, in the preceding formula, the desired fractional part of that quantity as given in the second column of the above table. For example, assume that it is necessary to use limestone in the foundation, and that it is required to draw in the footing courses as rapidly as possible. Assume also that the pressure P on the base of the foundation is 2 tons per square foot. If the limestone is of the best, and if it is laid with great care, it will be sufficient to use 4 as a factor of safety. Under these conditions the equation gives

\[ p = \frac{1}{3} t \sqrt{\frac{R}{P}} = \frac{1}{3} t \sqrt{\frac{2 \times 1500}{2}} = 2-3t. \]

That is, the projection may be 2-3 times the thickness of the course.

Strictly, the above method is correct only when the footing is composed wholly of stones whose thickness is equal to the thickness of the course, and which project less than half their length, and are also well bedded. The values in the table agree very well with the practice of the principal architects and engineers for hammer-dressed stones laid in good cement mortar.

The preceding results will be applicable to built footing courses only when the pressure above the course is less than the safe strength of the mortar. The proper projection for rubble masonry lies somewhere between the values given for stone and those given for concrete. If the rubble consists of large stones well bedded in good, strong mortar, then the values for this class of masonry will be but little less than those given in the table.

If the rubble consists of small, irregular stones with Portland cement, the projection should not much exceed
that given for concrete. If the rubble is laid in lime mortar, the projection of the footing course should not be more than half that allowed when cement mortar is used.

Notice that drawing in the footing courses decreases the area under pressure, and consequently increases the pressure per unit of area; hence the successive projections should decrease from the bottom towards the top.

Foundations for Steam Engine Beds, etc.

Foundations for beds of steam engines and other stationary motors, and for alternating and revolving or percussing heavy machinery, tall chimney shafts, towers, etc., should in all cases be laid quite independently of all walls of buildings, and be in no wise attached thereto.

Elastic Foundations for Engines or Machines.

Such foundations require complete isolation of constructions, with the object in view of deadening shocks, avoiding transfer of vibrations, and of lessening the incessant noise which often constitute a legal nuisance, involving litigation for its abatement. This problem has had many solutions offered, but none entirely satisfactory and generally applicable. Neither rigid foundations nor the interposition of elastic bodies has succeeded, though this latter direction promises well. The holding-down bolts of the engine or machinery bed transmit vibrations to the parts bolted to them. A recent experiment at an electrical station by M. Juppont has proved the value of judicious methods of introducing elastic bodies. It consisted of placing in a rectangular excavation of suitable depth two sheets of plate-iron having a series of discs of caoutchouc between them, causing isolation, placed upon a platform laid upon the bottom, and having a platform rivetted to the top plate to prevent deformation. Upon this upper platform the foundation proper was erected, having a clear trench all round it, with provision for bolts and space for cleaning, etc. The mass of the foundation need not be of masonry, and may with advantage in certain cases be replaced by a caisson filled with sand. The steam and exhaust pipes were wound in a spiral at their top part to give elastic accommodation without forcing the joints. The amplitude of oscillation was eight millimetres, but no vibration was communicated outside of the trench.

Suspended Foundations for Machines.

A sugar refinery in Philadelphia, U.S.A., has several steam engines distributed all over the building, and upon different storeys, some being upon the second and third floors. Some of these engines were bolted to iron girders, or heavy beams, and some of them ran smoothly and silently, while others of them produced vibration and disturbing "rattle." To correct this "rattle," as an experiment, the mass of the engine foundations was suspended from the bottom of the engine, whereby, in consequence of the inertia of the weight of the mass suspended, the vibrations and "rattle" were absorbed.

Strength and Stability.

Strength and stability of masonry begin with the foundations, and hence it is essential to give early attention to the actual conditions of the mode upon which the stability of masonry structures depend. It is often erroneously treated as a mere question of the simple moment of resistance against overturning, which is thus made to depend upon the assumption that the leverage resistance of the entire actual width of the footing base, out to the extreme edge of the toe, is supposed to be effective, thus treating the footings and wall as an entire, perfectly rigid monolith, like a piece of solid iron. But no masonry wall of ordinary building materials and structure possesses this unattainable degree of incompressible and tenacious strength, sufficient to support its entire weight and imposed loads, upon only one mere edge of its footing base. Indeed, the generality of walling does not possess any appreciable extent of reliable cohesion, and the measure of its strength is mainly derived from the weight and frictional resistance to displacement, which the blocks of stone, etc., of which it consists, exert upon each other. But, in practice, the mode of overturning involves three general cases. Thus: (1) If we consider the case of the overturning of a wall of ordinary construction of brick footing consisting of two bottom courses, and to be tilted, or canted over, experimentally by a horizontal force, as wind pressure, whereby the centre of gravity of all its weight is vertically over the extreme outside edge of the footing base, thereby depressing it into a yielding soft subsoil—in order to preserve stability in such a case, the resultant of the weight acting vertically, and the wind pressure acting horizontally, multiplied by their respective leverages, are adjusted so as to pass within the middle half width of the footing base, i.e., a full quarter of the width inside of the toe. (2) If the subjacent soil or bed be of solid rock, and the walls were similarly canted over (a), the edge of the toe would be crushed backwards until the area of support would be enlarged equivalent to the crushing resistance of the brick, assuming them to act as a monolith, or (b) a vertical section of the toe would be ruptured by shearing at some critical inside point, or (c) by the cross rupture of the bricks and by simultaneous opening of the corresponding back joints of the underside of the base. (3) If the footings remain rigid as well as the subjacent foundation bed, then overturning takes place by the opening at a critical point in the height of vertical section of a horizontal joint on the windward side of the wall, which is thus said to be in tension.

In view of these actual modes of operation of the active forces and of the building materials in the act of overturning, and the application of the corresponding principles to determine the stability of walls, there are two obvious provisions which the design of walling should contemplate.

1st. It is evident that for a high masonry structure it should be designed for a convenient safe limit of crushing pressure upon the materials, instead of for a
merek overturning leverage moment—overturning taking place if the deviation of the resultant of the horizontal and vertical moments be half the thickness of the wall from its centre on plan.

2nd. When the adhesion of the mortar is not sufficient to be considered, the windward joints would be in tension, and have a tendency to open if the resultant of the moments of the vertical and horizontal forces acting at any joint in the height deviates from the centre of that joint by only one-sixth of the thickness of the wall. This would occur before the leeward edge of the joint would have any tendency to be crushed.

Building Materials.—Stone.

The position of the occurrence of rock beds in quarries or quarry sites to be opened, suitable for building stone, requires practical skill to discover its precise value. The appearance and qualities of the same kind of stone, and even that from the same quarry, vary as successive beds or layers are reached, the deteriorated and less compact forms lying at the top; the more dense but “green,” i.e., soft and containing moisture called quarry sap, lie towards the bottom, or further from the surface. These latter, however, harden upon exposure to the atmosphere, the moisture coming to the surface in the form of a hard crust, which makes it more expensive to work.

The position in a quarry of the best beds or stratum for furnishing stone of a quality and characteristics suitable for exterior building purposes is of importance to be specified for use in an intended building, otherwise a stone of identical appearance, but possessing inferior weathering characteristics, may be substituted without the possibility of present detection. In quarries of different kinds of stone, and in different localities, the successive beds of the same stone are known by different names.

Thus, in a quarry of Portland stone, the best bed of which is one of the most durable of stones, the succession and names of the beds will be somewhat thus in the downward order, until the useful bed, No. 11, forming the upper beds of the oolitic limestone series, is reached about 30ft. below the surface:

1. The vegetable mould, with various debris of rock admixture on the ground surface.
2. Clay and shingle from debris of purbeck (freshwater) limestone, which is only one of a series of limestones, clays, shales, and sandstones, of which the purbeck beds consist, which is divided into an upper, a middle, with cinder beds, a lower series, with dirt beds. The dirt beds being dark-coloured loam like, which are interstratified with oolitic limestones and sandstones of Portland.
4. Bacontier, with layers of stone.
7. Dirt bed, with fossil trees.
11. Roach (true), 2ft. or 3ft. thick. A useful weather stone, a conglomerate of fossils cemented together by carbonate of lime; cavities, large and small, are very numerous in it. It is distinguished by the shell-cast, known as the “Portland screw,” which is peculiar to this bed only.
12. Whitbed, 8ft. to 10ft. thick, fine even grained, one of the most durable building stones in England, and is the most valuable of the Portland quarries. It consists of fine oolitic (roe-like) grains durably cemented together with a hard, crystalline material, and interspersed occasionally with shelly matter.
13. Curf or kerf, flinty. A bastard roach surmounted by a layer of rubbish.
14. Curf and basebed or bastard roach.
15. Basebed, a substantial stone 5ft. or 6ft. thick. This, with the bastard roach or basebed roach, are very similar in appearance to the true roach and whitbed, but they do not weather well, and therefore are only fitted for inside work, or where only exposed to varying conditions in foundations.
16. Flat beds or flinty tiers.

The true roach is remarkably tough and strong, weathers well and resists the solvent action of water; is a very light brown colour.

The first eight numbers are excavated with shovel and pick, 9, 10, and 11 require to be blasted, 12 to 16 are quarried by wedges and lever bars. Though Nos. 11, 12, 13, 14, and 15 can hardly be distinguished from each other, even by the most practised eye, and are, as stated above, very different in characteristics, while their chemical composition is almost the same, and consists of (in 100 parts) silica, 1-20; carbonate of lime, 95-16; carbonate of magnesia, 1-20; iron and alumina, 0-50; water and loss, 1-94; and a trace of bitumen.

The quality of resisting the deteriorating influences of the atmosphere, rain, dampness, alternate wet, dry, sun, frost, etc., is of the utmost importance. The durability depends upon its physical properties and structure as well as upon the chemical composition of its mineral constituents. The nature of the substance which cements the minerals together in the rock mass, to be durable, should be solid and in a half crystalline state. Thus some durable sandstones are rendered so by having a cementing matrix chiefly of silica, but when the matrix contains alumina, the principal ingredient of clay or lime, the sand stone is less durable, and may even be very perishable—the least durable being in an earthy powdery state. The durability is also affected by the nature of the exposure which the position of the stone in the building subjects it to. A “weathering” exposure subjects it to the deteriorating effects of the weather, consisting of alternations of rain, dew, wind, sunshine, frost, etc., with all their attending concomitants, as well as the destructive chemical action of the atmospheric gases, acids, etc., especially of those peculiar to large and manufacturing cities, sea coasts, etc. The action of the freezing of the water absorbed into the pores of the stone, carbonic acid, both the natural and that of artificial production in the air, sulphuric and hydrochloric acids in rain, nitric acid, all act rapidly in effecting de-
composition either of the mineral constituents, or of its cementing materials, if of carbonate of lime or of magnesia, alumina, etc. The oxygen of the air acts upon the iron salts in the stone. The sulphurous and other waste acid products of factories of different kinds, as of bleach works, chemical works, etc., send forth clouds of acid-laden fumes that are quickly destructive of the structure of stone. The crystallisation in the pores of the stone of the sulphates thereby formed produces fracture by expansion, whereby large flakes and surface fragments are loosened. Rain that is absorbed in excess by capillary action on the lower horizontal surfaces or undersides, as in softs of lintels, arches, cornices, etc., by solvent action and by expansion is destructive. These are the trying positions to give particular attention to when investigating the durability of different kinds of stone, whether they be in a building, or strewn about a quarry, stoneyard, etc. Building stone is less destroyed in a dry than in a rainy climate, or on the side of a building exposed to the prevailing rains and sheltered from the sun and from drying winds. Light winds dry out dampness and distribute dust, which by accumulation retains moisture, while high winds force farther into the pores any surface dampness, dust, etc., besides, by blowing forcibly about heavy sharp dust particles, producing a wearing action. Sudden variations of cold and heat, by producing alternating contraction and expansion of the different substances of the composition, which may have differing expansion units, are also destructive. Quoins, corner, or arris stones, when exposed to different degrees of heat on their different faces, are liable to crack, from the unequal expansion and contraction thereby caused. Exposure to continuous dampness, as in foundations, may subject stone to the action of mineral salts in the local underground waters, where it is employed, and if frost penetrates to it, deterioration is hastened. Frost penetrates damp solid earth deeper than dry porous soils; it will also follow iron, which acts as a conductor.

Physical structure contributes greatly to the durability or otherwise of stone. Thus, chalk and marble have the same chemical composition (pure carbonate of lime), but are of different structures. Marble, especially when polished, will endure much longer than chalk. Hence stones which are crystalline in structure, as marbles, granites, etc., "weather" better than the non-crystalline varieties, as slaty stones, or the granular class, as chalk, limestone, sandstone, etc. Porous stones absorb moisture more largely than close-grained dense stones; and hence acid-charged dampness, as rain, etc., and the freezing of the moisture in the pores tends to disintegrating and rupturing the structure of the stone.

When both the mineral grains and the uniting substance are alike durable, the rock partakes of their durable characteristics; but when the mineral grains easily decompose, while the cementing substance remains, the structure becomes porous. If, on the other hand, the cementing material is dissolved, the mineral grains separate. Stones often contain soft patches and inequalities of structure or of chemical composition, which are frequently indicated by blotched or mottled colour, when the one part will wear or weather away faster than the other, leaving the projecting portions exposed to catch accumulations of dust, rain, etc., and hasten decay. Lichens and other mild growths upon the faces of stone tends to deteriorate it, notwithstanding that for sandstones they are sometimes accounted a protection from the mechanical action of the weather.

The best stones absorb the least water, and are therefore the less liable to the expansion of being frozen in the pores of the stone, by which it is disintegrated. Thus, in 24 hours, trap and basalt will only absorb up to about one-fifth per cent. of their volume. Good granites, half per cent.; indifferently granites, 1 to 3 per cent.; the harder sandstones, less than 7 per cent.; those of a very durable kind, 8 per cent.; moderately durable sandstones, 10 per cent.; very bad sandstone, 20 per cent. of its volume. Limestones vary from about 8 per cent. upwards; Portland, very durable, 13 per cent.; Ancaster and Roche Abbey, durable, 16 to 17 per cent.

A few fresh thin chips of the stone to be tested, immersed for several hours in rain-water, will, when afterwards shaken up, show by its milky or murky appearance to what extent the constituents of the stone are not stable. When the chippings are broken off the stone should be thoroughly damp.

A solution of about 1 per cent. of sulphuric and hydrochloric acids will suffice to indicate the behaviour of a stone subject to a city atmosphere; or a few drops of acid upon a stone will produce effervescence if carbonate of lime or of magnesia be present in large proportions. But the observation of how similar stone has worn is a test of the greatest value.

Hard stone should always be put where exposed to rubbing, as in jams and sills of doors, pavements, exposed quoins and parts of arrises, plinths, etc., also where they receive dripping water, the running water of rivers, shore waves, etc. Hard stone, however, may be chemically inferior, and may not weather as well as a soft stone. The granites have about three times the hardness, or resistance to abrasion, that the hardest sandstones possess, about 10 times that of marble, and about 80 times that of soft limestone, as the Bath stone used for inlay of walling, etc.

Tough stone is not liable to splinter and crack, and is of importance in places where bolted to machinery, especially that which has a percussive action.

Strength, stress, is usually denoted by the ability to resist great compressive stress or weight. Although stone in its ordinary position in overlapping courses and crosslapping bond is subject principally and in the normal conditions to equal and uniformly distributed pressure and likewise to equal subsidence, but it is very liable, not only during construction, but afterwards, to be severely affected by unequally distributed or eccentric pressures, producing oblique acting or cross stresses, in which its cohesive properties of resis-
SECTIONAL ELEVATION.

DAVEY-PAXMAN'S ESSEX BOILER.
SECTION ON LINE ABCD.

DAVY-PAXMAN'S ESSEX BOILER.
tance, more than its shearing strength, are subject to critical stress, and which is equivalent to tensile action upon the material of the stone, as in unequal settlements of different portions of the building or of the wall, or of the facing and backing portions, vibratory or oscillatory motion of machinery. In some such cases the outside edges are pinched off in large flakes. The ample dimensions usually given to walls, and even to piers in ordinary sizes of buildings, will never likely subject the stone to an unsafe pressure simply, as the weakest sandstones which would be admitted to a building will safely bear even 10 tons per square foot of area of horizontal section. It is in only in some of the piers or columns of a few medieval churches or large Gothic buildings that 10 tons per square foot is exceeded. When a heavy weight is concentrated upon only a small part of the surface of a block of stone, its full nominal strength is reduced, as when an iron column stands on a stone base, or the end of an iron girder rests upon a bonding stone, and only covers half the block, its effective resistance is only about two-thirds of its nominal strength, and if the column base only occupied one-quarter of the surface of the stone block, its effective resistance would be reduced by one-half. This is very important to bear in mind. For engine bedding a heavy stone is essential, also for retaining walls, or where subject to the action of tide waters.

It is important to the durability in the wall of all stone (except the unstratified and unlauned varieties) that it should be laid in the wall in the position corresponding to that of its original deposit in the rock formation in the quarry, whether the layers have been subsequently tilted or inverted or not—i.e., with the direction of its structural natural layers or lamine in a horizontal position—otherwise, if laid perpendicularly, the edges of the layers will be turned upwards, and will the more readily receive and retain dampness between them, whereby the disintegrating acids, frost, etc., will scale off the face laminate, and the stone be thus disfigured and further exposed to rapid deterioration.

Brick. London bricks are nominally 9in. by 4½in. by 2½in., but really only about 8½in. by 4½in. by 2½in. to 2¾in.

"Rubbers," or "cutters," are made of washed clay, freed from lumps and pebbles, and of a uniform composition, and only burnt sufficiently to admit of cutting, carving, rubbing, moulding, to any required design of architectural features. The best kind is burnt to a point just short of vitrification. Inferior kinds are less burnt, or under burnt. Rubbers, however, are not so durable as "purpose-made" bricks, which are moulded to any required shape, and sufficiently burnt.

"Facing," for fronts, are the best selected of the clamp or kiln production, combining uniform colour, sufficient burning, perfect in shape, sound and free from pebbles or lumps and flaws of any kind. Each district and each brickfield has its own quality of production.

Common bricks are "unwashed," and frequently of very unfit clay, carelessly treated, unequally burnt, brittle, cracked, and generally unsound, soft, and unfit for house building of any structural importance. They are, however, classed into shipper's, the best, next stocks, grizzles, rough stocks, and place bricks.

Malms, originally made from the malm clay which in early times was found in the neighbourhood of London, and corresponds to that which is suitable for hop-growing districts. The present so-called malms consist of tempered clay with cream of lime, or about one-sixteenth part of ground chalk in pulp, and breeze (or refuse cinders) incorporated before moulding. The methods and care in the manufacture differ in different brickfields and districts, with corresponding varieties in the qualities and grades of production.

Good bricks should be free of cracks, and pebbles of lime, however small, which slake on being wet or in wall and burst. They should also be free of lumps and pebbles of other rock, which cause unequal expansion and contraction, and have a good even shape edge unbroken, with ordinary roughness of bed surface (both upper and lower sides) for adhesion of mortar, shew a glassy fractured surface, give a clear sharp ring when struck together. The length should be 2 breaths + a mortar joint of ⅜in. to ⅜in., according to the kind of the brick and brickwork, × 2¼in. thick, weigh about 7½lb. It is well to remember that a ⅜in. thinner brick than 2½in. will require an extra course in every 20 courses, say, in every 4ft. 6in., if laid with a ⅜in. bed-joint.

Masonry Walling. Uniformity of construction of walls is necessary to impart the utmost strength, by ensuring uniformity of subsidence during construction, and stability when exposed to the action of excessive heat when the building is on fire.

When there is an exterior facing of ashlar, backed internally by rubble or brickwork, there is a diversity of subsidence in proportion to the difference in the number and thickness of the mortarbed joints in the ashlar and in the backing, and when a fire occurs in such a building the walls crack and rend by reason of the difference of the expansion units of the two classes of materials, and endanger the safety of the entire building. Ashlar as usually constructed has never a thorough bonding, but may have a three-quarter bond stone nominally, but which in practice often falls far short of three-quarters of the thickness of the wall, and be merely an angular point of overlap. These bond stones ought to be sufficiently distributed in every few courses, depending on their height, and on the duty of the wall.

Facing brick, backed with common "stocks," will not be conformable in height of courses, as it may require, say, eight of the facing bricks to correspond with seven courses of the stocks. Thus, if stocks laid up four courses to the foot high, and that facing brick laid up ¾in. less in each course—i.e., each course of facings would lay up 2¾in., and so on for other differences—
would, therefore, only be in such a case at every eighth course that a heading course could be laid with which to cross-bond the facing with the backing. Such a heading course, however, is not laid as in common brickwork, but merely an inside corner is clipped off the face brick, which is usually laid in Flemish bond—i.e., alternate header and stretcher in each course, breaking joint—but the header is false and only a half brick, a corner of the backing brick projects into the clipped space of the facing, like a king closer, which makes it a very imperfect bond and a necessarily weak wall. It especially becomes weak in narrow piers, when closers are required in each header course, so as to bring the header to break joint in the centre of each stretcher, a three-quarter bat being required in each stretcher course, whereby the opportunity for bond is proportionately lessened. In Flemish bond the closer and three-quarter bat would both occur in the same course, but break joint in the alternate courses. When the width of the pier suits the working in of a certain number of whole bricks better bonding is secured than if otherwise, when there is more clipping of bricks necessarily resorted to. English bond is composed of all header and all stretchers alternating in the successive courses, but there are varieties in the methods of laying both the Flemish and English bonds.

When the number and thicknesses of the external and internal bed joints are unequal, the backing should be laid in Portland hydraulic cement, or quick-setting blue lias lime mortar, properly gauged with sharp sand, free of loam, dust, or clay.

For mills, factories, or where machinery is employed, in order to localise and absorb the vibratory action of driving shafting and of machines distributed through a building on several of its upper floors, deep pilasters or piers should be built with light bonded walls of whole brick between them in the nature of panels. This method is effectual in imparting a longer life to machinery as well as to the building, and minimises the expense of repairs in both. Besides this arrangement, it is likewise essential that equally balanced foundations for walls or piers should be constructed in order to preserve the true level of the building in all its parts throughout its extent, so that shafting and connected machinery and power engines may be laid with all probability of retaining an accurate level, without which it is impossible to work smoothly.

No outside wall of ordinary rubble should be less than 16 or 18 inches thick. Some slaty districts produce a flag or rag stone, which will quarry in regular layers of only a few inches thick. Walls built of these could be laid up of less width, if not too high—i.e., 14 to 16 times its width without intermediate tie beams, etc.

Hollow walls, with a vertical air cavity of 2in., are sometimes built to keep basements and cellars dry; but, in order to be effective, they should be very carefully executed, and no mortar allowed to drop between, which in ordinary work, and without a special precautionary device, is practically impossible. As a means of preventing it, iron tubes, wrapped round with hay bands, are sometimes resorted to. These rest on the last bond ties in the cavity, and are moved out before the next row of bond ties is laid. There are several forms of cast-iron wall ties, with claws and turned-up ends and a rising bend to cross the cavity, to prevent damp passing along it by obliging it to ascend, which gravitation will prevent. The cavity must be commenced at the horizontal damp course, and be made continuous round the corners and angles, and brought close up to the reveals of all openings. There should be weep holes provided at bottom of the cavity, to carry off any injected moisture and to afford ventilation.

In surcharged sites, underground basements and cellars may require damp-proofing all underneath the floor and all round the walls up to and above the highest water level of the district waterlogged. Hygeian rock asphalt is considered one of the best waterproofing materials for underground walls. It is poured in a molten state into a ¾ in. continuous open vertical joint, left in the thickness of the work at every third or fourth course as the wall rises. It sets hard, and strongly combines the inside and outside portions into one compact wall, greatly increasing its strength, and rendering it perfectly waterproof.

**Masonry Footing Courses.**

The metropolitan by-laws require at least 6in. thick layer of concrete spread over all building sites, unless of gravel, sand, or natural virgin soil.

Foundations of walls of houses to have not less than 9in. thick layer of concrete extending 4in. beyond each side of the footings, unless the site be on a natural bed of gravel, in situ, does not apply to a building to be used as a stable or shed, provided such be not used for public assemblies or entertainments, or as dwelling or sleeping places. Therefore workshops, etc., which may have in confined employment large numbers of persons for 12 hours in the 24, are curiously exempted, whatever may be the insanitary conditions of the site.

When the substratum consists of solid rock, or a thick bed of gravel, dry sand, or gravel and sand, the footings may consist of two courses in each inset. The header course should be above, and the stretcher course laid below, all overlying courses should carefully break joint with the course immediately beneath it. It is usual to make the insets (in the act of laying the bricks) ¼ brick = 2¾in. When the insets consist of one course in each inset, the lower tier usually consists of a header and a stretcher, but it would be better to have two header courses with a stretcher between them. When the substratum is of compressible soil, large thick sound stone flags, as used in Yorkshire, etc., sometimes called “landings,” or a thick bed of sound concrete of Portland cement (see under Concrete), should be used to impart a monolithic character under the imposed pressure. But in the absence of such provision the thickness of brickwork under the toe of the footing should be increased very much more than is commonly done on compressible subsoils. According to experiments by
J. H. Apjohn, R.E., at Akra, Indian Government brickworks, Calcutta, four courses of brickwork under the toe of splayed pier footings cracked badly with 1½ tons per square foot of area on a soft alluvial soil, and he recommends that for similar soils to those experimented on, in order to sustain a pressure safely of 1 ton per square foot, the thickness at the toe of the footing should be at least 11½.6in., or, say, six courses of brick. Any rupture under the toe by shearing, or opening of the back joints, means a lessening of the area of the bearing surface, and a consequent liability to an excessive subsidence of the wall or pier.

Bricks should be hard burned, well shaped, whole and sound, laid in strong hydraulic lime, mortar, or Portland cement, with all the joints and vacuities solidly filled.

The Staffordshire blue bricks (with rough surface), which are proof against the chemical decomposition of damp soils or ground waters, and are of the utmost strength, should be more used in footings than they are.

Failures in footings are always expensive to remedy, and destroy the value of a building; and therefore strong, sound materials of sufficient section should be employed, and only the best hydraulic lime or cement used.

Concrete.

What is called the "aggregate" is of broken brick, slag, or stone (to pass through a 1½in. to 2½in. ring); burnt clay, gravel, ballast, breeze (refuse coal cinders), are also used. There should be no adhering dust or mud coating, which prevent the adhesion of the cement. Shingle, or round smooth pebbles, are not so desirable.

Sand is requisite to fill the voids, and is desirable for improving the strength, and is necessary to make it waterproof.

It is more economical to have stones in relative quantities broken to different sizes, so that the smaller ones will nearly fill the voids of the larger. The nett voids for different sizes are as follows:

<table>
<thead>
<tr>
<th>Void</th>
<th>Cubic Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ft</td>
<td>8</td>
</tr>
<tr>
<td>1½ ft</td>
<td>10</td>
</tr>
<tr>
<td>2 ft</td>
<td>12</td>
</tr>
</tbody>
</table>

When the concrete is required in large thick masses, the centre portion, or core, is often made with large pieces or chunks of stone or old bricks.

The proportions of the ingredients in any particular case depend on the composition of the aggregates, without estimating the sand. Thus, for shingle 1 cubic yard would require 2 cubic feet of Portland cement, 8 cubic feet of sand, and 7 or 8 gallons of water, which should always be clean, and not muddy. For ballast, 1 cubic yard, having already 4½ cubic feet of sand mixed in it, would require 4 cubic feet of cement, 3 cubic feet of sand, and 8 gallons of water, and so on.

Ordinary proportions are 1 part of Portland cement to 6 or 8 parts of gravel, according to the coarseness of the gravel and the compressibility of the soil underneath, which, by irregularity, may need a larger factor of safe strength.

The materials are mixed in a dry state upon a boarded platform, then tempered with the water, sprinkled over gradually, then the whole turned over three times. It is then laid in the footing trench, 10in. to 12in. deep, in horizontal layers in convenient lengths, boarded or stopped off so that it can be rammed before any setting takes place. The space to be thus filled at a time should correspond with the quantity in the batch made each time—one should be kept mixed over night, or even over meal hour. The top and end of each layer should be swept clean, and the exuded skin removed by a pick, etc., as it would prevent adhesion of succeeding layer. To ensure proper adhesion between layers, it may be necessary to give the lower one a thin coating of fresh cement just before applying the over layer. When hydraulic lime is used instead of Portland cement, it should be ground, and not be used as sent from the limekiln.

Mortar.

Fat limes should not be used, but being cheap and expeditious in slaking tempering, they are preferred by workmen and contractors, notwithstanding their known unfitness for mortar to be used in damp situation as for foundations. In dry positions only a thin outer crust or edge of the joint sets and becomes dry, the interior remaining soft, and meanwhile all the weight of super-structure rests upon these dry outer edges of the joints. In brickwork this same cause produces fracture of heading courses, leaving the wall liable to split up and the outer to be detached from the inner face. Moderately hydraulic lime or Portland cement should be used in all ordinary foundations below the damp-proof course, not only for the masonry, but also for the concrete bedding.

For foundation masonry, etc., exposed to water or to water-logged soil, only a strongly hydraulic lime or heavy Portland cement should ever be used, as alone possessing enduring strength.

General Safe Bearing Power of Soils, etc.

(The factor of safety being 3 to 4)

Rock, the hardest in thick layers or strata in native bed, has been loaded with 200 tons per square foot.

Gravel and coarse sand, the particles well cemented together with clay, protected from water... 4 to 6 tons

Sand, well compacted and not liable to lateral disturbance... 8 " 10 "

Sand, clean, dry... 2 4 "
Clay in thick beds and always dry ... 4 to 6 tons
Clay moderately dry ... 2, 4
Clay, Central Illinois, U.S.A. without appreciable settlement ... 1\frac{1}{2}, 2
Clay, soft ... 1, 1\frac{1}{2}

The stability of clay is increased by admixture of sand and gravel.

Alluvial soil, quicksand, according to dampness, etc. ... \frac{1}{2}, 1

Tall chimney shafts, towers, steeples, etc., should impose a less unit of pressure on substratum than ordinary buildings because of wind leverage range.

**Examples of Loads on Foundation Soils.**

Blue clay mixed with sand and water ... 1 to 1\frac{1}{2} ton.
Yellow sandy clay ... 2, 2\frac{1}{2}
Compact clay ... 1\frac{1}{2}, 0
Compact clay, stony ... 5\frac{1}{2}, 0
Clay and sand ... 3, 9
Alluvial soil and quicksand ... 0\frac{1}{2}, 0\frac{1}{4}
Unstable sand ... 12, 0
Compact sand with slight mixture of clay 2\frac{3}{4}, 2\frac{1}{4}
Wet sand, not very compact, cracked with 4, 0
Compact gravel and sand ... 7\frac{1}{2}, 8
Coarse gravel ... 4\frac{3}{4}, 0

A thin hard layer of clay resting on soft mud which overlies a stratum of quicksand 1\frac{1}{2} to 2 tons, which produces subsidence of 1 in. per ton in a year.

London clay, blue, 1\frac{1}{2} to 2 tons; red ... 4 to 6 tons
Blue clay \frac{1}{2} to \frac{1}{2} fine sand and \frac{1}{2} water, weighing 80 lb. to 100 lb. per cubic foot 0, 2
Yellow clay mixed with sand ... 0, 2\frac{1}{2}
Stiff clay when kept dry, 4 to 6 tons, but same clay saturated ... 1\frac{1}{2}, 2
Light structures with heavy running machinery or rolling loads should have a minimum unit of pressure.

Heavy structures with quiescent loads may have maximum unit pressure.

**Laws of Subsidence in Alluvial Soft Soils.**

1. When the pressure upon the soil increases in an arithmetical ratio the subsidence increases in a geometrical ratio.

2. When the depth of the foundation from the surface of the soil increases in arithmetical progression the subsidence decreases according to a geometrical series.

**Small and Large Pier Subsidence.**

There is a common, but erroneous, idea that equal areas of foundations should sustain equal pressures in compressible soils, but walls subside more than piers, and large piers more than small piers transmitting equal loads per square foot of subjacent soil, because of the difference of support derived in each case from the friction of the soil upon the sides of the footings. Those, therefore, having the most perimeter in contact with the soil per square foot of horizontal area derive the most frictional support. For the same reason the greater the depth to which foundations are sunk in soil in contact with the foundation masonry the greater is the sustaining power thus derived. Thus a long wall footing has only its external and internal sides or edges exposed to contact with the soil, but a pier has all its sides. Then comparing piers, a square pier has the maximum periphery—two squares, close side by side, present a perimeter only of one-fourth less, and so on for other rectangular proportions.

Piles are of whole timber or timber poles, or spars of oak, teak, beech, elm, larch, fir, straight grained, free of bark and projections of knots, etc. Large and diagonal knots must be avoided, as they are apt to break off at these in the driving. The butt end is driven lowest; the head has a wrought-iron strap or hoop to prevent splitting while being driven by the monkey. The lower end is pointed and shod with a wrought-iron pointed shoe with flaring straps by which it is spiked to the pile. Some shoes are made with cast-iron points.

Bearing piles 9 in. to 18 in. diameter of whole timber are employed to support foundations upon soft soils, either by reaching to a hard stratum underlaying the upper soil or by the frictional support of their sides upon the contact soil; in order that piles may not bend by driving their length they should not be more than 20 times their diameter.

**Semi-Liquid Soils.**

With a soil of this class, as mud, silt, or quicksand, it is customary (1) to remove it entirely, or (2) to sink piles, tubes, or caissons through it to a solid substratum, or (3) to consolidate the soil by adding sand, earth, or stone. Soils of a soft or semi-liquid character should never be relied upon for a foundation, when anything better can be obtained; but a heavy superstructure may be supported by the upward pressure of a semi-liquid soil, in the same way that water bears up a floating body.

According to Rankine, a building will be supported when the pressure at its base is \( w h \left( \frac{1 + \sin a}{1 - \sin a} \right)^2 \) per unit of area, in which expression \( w \) is the weight of a unit volume of the soil, \( h \) is the depth of immersion, and \( a \) is the angle of repose of the soil. If \( a = 5 \) deg., then, according to the preceding relation, the supporting power of the soil is 14 \( w h \) per unit of area; if \( a = 10 \) deg., it is 20 \( w h \); and if \( a = 15 \) deg., it is 29 \( w h \). The weight of soils of this class, i.e., mud, silt, and quicksand, varies from 100 to 130 lb. per cubic foot. Rankine gives this formula as being applicable to any soil; but since it takes no account of cohesion, for most soils it is only roughly approximate, and gives results too small. The following experiment seems to show that the error is considerable: "A 10 ft. square base of concrete resting on mud, whose angle of repose was 5 to 1 (\( a = 11.3 \) deg.) bore 700 lb. per square foot." This is 2\( \frac{3}{4} \) times the result by the above formula, using the maximum value of \( w \).
CHAPTER VIII.

STEAM BOILERS.

BOILER is a closed vessel, which contains partly steam and partly water. Steam is produced by applying heat to the water, whereby the temperature of the water rises, becoming greater and greater the more heat is added. It is only one part of the heat, the sensible heat, which is spent in raising the temperature of the water; the rest of the heat, the latent heat, is spent in changing the molecular state of the water into that of steam. Therefore, starting with cold water in the boiler, the heat generated by the fire will first raise the temperature of the water, and then after some time, we shall find that the hand of our pressure-gauge will begin to move, indicating that the pressure of the steam within the boiler has become greater than the pressure of the atmosphere outside the boiler. If we continue applying heat, the pressure of the steam will become so great that it lifts the safety-valve, thus telling us that we have reached the maximum pressure at which our boiler ought to be worked.

The temperature of the water in the boiler will rise with the pressure, but if we keep the pressure constant the temperature will also keep constant. The relation between temperature and pressure of steam, generated in a boiler, has been determined by very accurate experiments by the French philosopher Regnault, and the result, of these experiments are shown in the table given below.

Suppose we have a cylinder with a tight-fitting piston, and that on the one side of the piston we have steam, in direct connection with a boiler, at a certain temperature, and on the other side of the piston we have a perfect vacuum; then the pressure, in pounds per square inch, by which the piston is pushed along in the cylinder, is called the absolute pressure of the steam, and will in this book be denoted by \( P_a \). If, instead of a perfect vacuum, we had the atmospheric pressure—i.e., 14.7 lb. per square inch—on the piston, then the pressure, by which the piston would be pushed along, is called the effective pressure of the steam, and will be denoted by \( P_e \). In both cases we must imagine that there is no friction between the piston and the cylinder.

Steam, as generated in an ordinary steam-boiler, is probably never perfectly dry, but contains suspended water which has been carried away by the steam, just at the moment it left the water from which it is generated. We can, however, dry the steam by carrying it into a closed vessel, which is connected by a pipe to the steam-room of the boiler, and there heat it. We shall then find that the temperature of the steam will remain the same as that in the boiler, as long as the steam contains suspended water. Just when the last drop of suspended water is evaporated, the steam being perfectly dry, it is said to be dry saturated steam, whereas the steam in the boiler is called saturated steam simply.

If we continue to apply heat to the steam after it is dried, we shall find that its temperature will rise, and the steam will expand; steam in this condition is called superheated steam. The pressure of the superheated steam will, of course, remain the same as that of the steam in the boiler, on account of the connection with the boiler. It is evident that the mass of the superheated steam contained in the small closed vessel, will be smaller than that of the dry saturated steam which the vessel previously contained. We may therefore say that dry saturated steam is steam of maximum density, and that its temperature is the lowest possible of steam at a particular pressure.

It is of importance to engineers to know the volume, in cubic feet, of one pound of steam—i.e., the specific volume of steam; and also the mass in pounds of one cubic foot of steam—i.e., the density of steam. The former will be denoted by \( v \), and the latter by \( w \). They both vary with the pressure, and some of their values are given in the annexed table, together with the corresponding pressures and temperatures.

| TABLE SHOWING RELATION BETWEEN PRESSURE, TEMPERATURE, SPECIFIC VOLUME, AND DENSITY OF DRY SATURATED STEAM. |
|---|---|---|---|---|---|---|---|
| \( P_a \) | \( t \) | \( v \) | \( w \) | \( P_a \) | \( t \) | \( v \) | \( w \) |
| 15 | 213 | 25.87 | 7387 | 100 | 327.4 | — | — |
| 20 | 228 | 19.74 | 9306 | 110 | 342.5 | — | 2896 |
| 25 | 240 | 16.91 | 9625 | 120 | 371.1 | — | — |
| 30 | 250 | 13.49 | 9741 | 130 | 374.7 | — | — |
| 35 | 259 | 10.30 | 9071 | 140 | 352.8 | 3.177 | — |
| 40 | 273 | 8.37 | 8441 | 150 | 395.1 | — | — |
| 45 | 274.3 | — | | 160 | 393.3 | — | — |
| 50 | 280.9 | 8.347 | 1108 | 170 | 388.1 | 2.645 | 3780 |
| 55 | 287 | — | — | 180 | 372.8 | — | — |
| 60 | 292.3 | 7.037 | 1241 | 190 | 377.3 | — | — |
| 65 | 297.8 | — | — | 200 | 381.6 | 2.270 | 4204 |
| 70 | 302.7 | 6.090 | 1624 | 210 | 385.5 | — | — |
| 75 | 307.4 | — | — | 220 | 389.7 | — | — |
| 80 | 311.8 | — | — | 230 | 393.5 | — | — |
| 85 | 316 | — | — | 240 | 397.2 | — | — |
| 90 | 320 | 4.810 | 3079 | 250 | 400.8 | 1.941 | 5432 |
| 95 | 323.9 | — | — | 260 | 404.3 | — | — |

We have now to consider the quantity of heat required to raise the temperature and to evaporate the water in our boiler. This has also been most accurately determined by Regnault, and the result of his experiments is, that the amount of heat, \( H \), required to raise the temperature of one pound of water from 32 deg. F. to \( t \) deg. F., and then evaporate it at that temperature, is

\[
H = 1082 + 0.305 t \quad \ldots \quad \ldots \quad \ldots \quad (1)
\]
H is called the total heat of evaporation of water, and is expressed in British heat units. We must remember that a British heat unit is the amount of heat requisite for raising the temperature of one pound of water from 32 deg. F. to 96 deg. F., at a pressure of one atmosphere. The temperature of the feed-water which we pump into our boiler is never as low as 32 deg. F., but is, say, $t_1$ deg. F.; we have, therefore, only to raise the temperature of the water from $t_1$ deg. to $t$ deg., and the heat we have to apply, in order to turn one pound of feed-water into steam, will be

$$H - (t_1 - 32) = 1114 + 0.305 \times t - t_1 \ldots (2)$$

The temperature of the water in the different classes of boilers varies from about 300 deg. F. to 390 deg. F.; the total heat of evaporation will therefore vary between 1,173 and 1,200 heat units, or less than 3 per cent. The heat required for producing a certain amount of steam, will therefore practically be independent of the pressure to which the steam has to be raised.

Combustion and Fuel.—We have now to consider the best way of producing the heat which is required for our boiler. For this purpose we burn fuel. Generally speaking, burning or combustion is a rapid chemical combination, but the only kind of combustion which is used to produce heat for driving steam-engines, is the combination of the constituents of various kinds of fuel with the oxygen which is contained in the atmosphere.

The chief combustible constituents of fuel are carbon and hydrogen. Of these, hydrogen is the best; for one pound of hydrogen will, by burning with oxygen, develop 62,030 heat units, whereas one pound of carbon, when completely burnt, will only develop 14,500 heat units.

Sulphur is also often met with in ordinary fuel, but the heat developed by burning it is comparatively small, and the product of combustion is bad for the boiler.

The heat developed by the complete burning of a fuel is called its total heat of combustion.

As one pound of water at 212 deg. F. requires about 966 heat units for its complete conversion into dry saturated steam, it is evident that one pound of hydrogen by its combustion with oxygen can completely evaporate $\frac{62,030}{966} = 64$ lbs. of water at 212 deg. F. The number 64 is called the evaporative power of hydrogen. If we therefore say that the evaporative power of ordinary coal is 15, we mean, that if all the heat produced by the complete combustion of one pound of this coal could be made useful, it would be able to evaporate 15 lbs. of water at 212 deg. F. In practice, however, this result is impossible, because the combustion cannot be perfectly completed, nor can all the heat be made useful. It is, however, of great importance to know the total heat of combustion of a fuel, in order to judge whether a furnace is well constructed or not.

The available heat of combustion of a fuel, when burnt in a boiler-furnace, is that part of the total heat of combustion which is actually absorbed by the water, and the efficiency of a boiler for a certain kind of fuel, is the ratio of the available heat to the total heat, when the given kind of fuel is burnt in the boiler-furnace. We shall see later on that one boiler may be more efficient for one kind of fuel than for another; and it may also be more or less efficient for the same kind of fuel, according to the way the firing and the boiler on the whole are managed.

The following are the principal causes why the available heat is smaller than the total heat of combustion:

1. By careless stoking and handling of the fuel with the shovel, part of the coal is made to break into small pieces, which will fall through the openings between the firebars.

2. To prevent this waste of unburnt fuel, (a) the coals should be thrown evenly over the fire with the shovel, and (b) the layer of fuel should not be so thick as to make it necessary to stir the fire from above. (c) The firebars should be cleared from below, (d) the ashes should be riddled, and the small coals should be thrown on the fire again.

3. If the supply of air to the fire is insufficient, a waste of fuel will take place in the form of smoke, which is fuel in waste state. It is therefore of great importance to produce a necessary draught in the furnace. In the annexed table, $W$ denotes the mass of one cubic foot of fuel, $H_t$ the total heat of combustion per pound of fuel, and $A$ the mass of air, in pounds, which is theoretically required for the complete combustion of one pound of fuel. It is, however, necessary to furnish an additional supply of air for carrying away the gaseous products of combustion at the moment they are formed, in order to give free access of air to the fuel.

4. The greater the velocity of the air and the smaller the fuel, the smaller is the additional air required for dilution. It has been found in practice, that the amount of additional air to be supplied to a boiler-furnace with ordinary chimney draught, must be equal to the amount of air required for the complete combustion of the fuel. The total amount of air required per pound of bituminous coal will therefore be 22lb.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>W</th>
<th>$H_t$</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood, dry</td>
<td>25</td>
<td>5,900</td>
<td>5-5</td>
</tr>
<tr>
<td>Peat, dry</td>
<td>20</td>
<td>7,750</td>
<td>6-0</td>
</tr>
<tr>
<td>Bitum, coal</td>
<td>37</td>
<td>10,000</td>
<td>11</td>
</tr>
<tr>
<td>Coal, dry</td>
<td>35</td>
<td>11,500</td>
<td>10-1</td>
</tr>
<tr>
<td>Coke</td>
<td>25</td>
<td>12,800</td>
<td>11</td>
</tr>
</tbody>
</table>

(3) In order to produce a draught in a boiler-furnace by means of a chimney, the gases which escape by the chimney must have a high temperature—hence a considerable loss of heat.

(4) Waste by Radiation of the Incandescent Fuel.—According to Peclet, the heat radiated from incandescent fuel is, from wood 0-23, and from coal and coke 0-5 of the total heat of combustion.
STEAM BOILERS.

For this reason it is of the greatest importance that the firebox of the boiler should be constructed in such a manner, that the radiated heat is carried into the furnace and made useful. This is generally done in two ways—viz.: (a) The firebox and ashpit are contained within the boiler, whereby all the radiated heat will be intercepted by the boiler, and is thus made useful; (b) the firebox and ashpit are outside the boiler. In this case the firebox is built of brickwork lined with firebrick. As both are bad conductors to heat, the temperature of the firebrick lining will be very high. The heat will therefore be given to the gases which strike the lining, and thus carried into the furnace; the greater part of the heat radiated down to the ashpit will be made useful in heating the fresh air while it is passing through the ashpit to the grate.

To prevent heat from radiating through the holes in the fire-door, it is usual to fix a plate to the inner side of the door; the heat absorbed by this plate will partly be carried into the furnace by the air entering through the holes.

(5) Some heat will be carried away through the brickwork, although this is a bad conductor. As the boiler cannot altogether be covered with good insulators, some heat will be lost through the naked parts of the boiler.

Practical Determination of the Available Heat of Combustion.—The fuel should be burnt in a well-constructed boiler, and the water should either be evaporated under the pressure of the atmosphere—i.e., the generated steam should be allowed to escape into the air—or else the steam should work a steady-running engine. Variations in steam pressure in the boiler should be avoided.

Before starting the experiment, the fire must be in the normal condition, and the height of the water in the boiler, as well as the temperature of the feedwater, must be noted. The firing should then be kept up very regularly, and the masses of the coal and feedwater are measured. The experiment is then carried on in this manner for several hours. In finishing the experiment, the fire must be kept in exactly the same condition as when the experiment began, and the height of the water in the boiler must also be the same.

Let the mass of feed-water evaporated be F, and its temperature be \( t_f \), the temperature of the steam be \( t \), and the mass of the coal consumed be C, then the available heat of combustion, \( H_a \), of 1 lb. of fuel, will be

\[
H_a = \frac{F(1114 + 305t - t_f)}{C} \quad \ldots \quad (3)
\]

In order to find the relative available heat of combustion of various kinds of fuel, these must be burned in the same furnace and under the same conditions. In the same way we can find the relative efficiency of various kinds of furnaces, by burning the same kind of fuel in the furnaces to be examined.

These experiments, however, will not give a useful result, unless the following precautions are taken:

1. That the engine must be worked at constant speed and power.
2. That the firing is kept up very regularly, and the same amount of coal is burnt in the same interval of time.
3. That the temperature of the feed-water is constant.
4. That the steam-room of the boiler be large enough to avoid variations in steam pressure, as it is otherwise difficult to observe the exact height of the water in the boiler. A small steam-room also causes water to be carried over to the cylinder by the steam, whereby the exact quantity of water evaporated cannot be measured.

By the temperature of the fire is understood the temperature of the gaseous products of combustion and the additional quantity of air with which they are mixed. The temperature of the fire can be measured by means of a pyrometer, but it can also be calculated approximately. The mean specific heat of the products of combustion, including air and ashes, may be taken as 0.24; the total amount of air required to burn one pound of fuel, when the draught is produced by means of a chimney, is 2 A, the temperature of the fire will therefore be

\[
t = \frac{H_a}{0.24 (2A + 1)} \quad \ldots \quad (4)
\]

The values of \( H_a \) and A to be taken from table on preceding page.

If the air be supplied at a temperature of \( t_f \) deg. F., then the temperature of the fire will be \((t + t_f) \) deg. F.

General Description of Steam Boilers.

As fuel, coal, coke, wood, and peat have been chiefly used, but in later years liquid fuel has been introduced, especially in Russia and in America. The right fuel to be used at any locality is that of which the ratio between the total heat of combustion and the price is a maximum, with due consideration to the fact that the boiler must be constructed to suit the fuel. Thus in certain parts of Central America rosewood is burnt under the boilers. In Cuba the refuse of sugar-cane is used. According to Messrs. Babcock and Wilcox, their boilers at the Chicago cable railways are worked regularly on the offal from the stables of the horse-roads, a very small proportion of coal being used to keep it alight. “Slack” is also often burnt under boilers with economy.

The heat which is contained in the gaseous products of combustion, which latter hereafter will be called the gases, is conveyed from the firebox to the boiler. This is done by letting the gases pass through the flues on their way to the chimney. These may be external, and are then partly bounded by the outside of the boiler-shell, and partly by the brickwork surrounding the boiler; or else they may be internal, and are then wholly contained within the boiler.

That part of the boiler-surface which is in contact with the gases is called the heating-surface, and it is through this that the heat of the gases is communicated to the water. The temperature of the gases will thus diminish in proportion as the heating-surface is increased, and will reach the chimney at a temperature which is
higher than that of the boiler, but will approach it the
closer, the greater the heating-surface. The chimney
not only carries away the gases, but also produces a
draught by means of the high temperature of the gases.

We have seen that the total heat of combustion of
one pound of good coal is about 15,000 heat units. The
temperature of the fire will therefore be

\[ t = \frac{15,000}{24 \times 28} = 2,700^\circ \text{F.} \]

and the heat-waste will be, taking the temperature of
the chimney as 500 deg. F.,

\[ 24 \times 28 \times 500 = 3,000 \text{ heat units,} \]
or 20 per cent. of the total heat produced by the com-
plete combustion of the fuel. In order to diminish
this heat-waste, the combustion must be completed
with as small a quantity of air as possible.

The Fireplace of a boiler consists of three parts—viz.:
(1) the grate on which the fuel is placed; (2) the fire-
box, above the grate, in which the constituents of the
fuel are burnt; and (3) the ashpit, below the grate,
into which the ashes fall and the supply of air is
admitted.

The grate is composed of firebars, which support
the fuel, and open spaces between the bars for the
admission of the necessary air to the fire. The firebars
are made of cast iron, in length from 2ft. to 3ft.
Their thickness diminishes towards their lower edge, in
order to admit of the free entrance of air and the better
escape of the ashes. At each end, as well as at the
middle of the bar, are projections whereby the bars
are kept apart, leaving the proper spaces between them
for the admission of the air. The firebars are laid on
the cross bearers. It is necessary to allow an end play
for the expansion of the bars: this play is generally 0\'02
of the length of the bar.

For the purpose of saving time when removing the
bars, they are often cast in pairs; this is hardly a good
plan, as the two bars seldom expand equally, and will
therefore bend, leaving uneven spaces between them.

The surface of the grate is either horizontal or, more
usually, a little inclined towards the back. The length
of the grate must never be more than 7ft. and the width
not more than 5ft., in order to make the firing easy.
When the grate is placed in an internal flue, then the
width is determined by the diameter of the flue. The
total open space between the firebars should be

For coal and coke from \( \frac{1}{4} \) to \( \frac{1}{2} \) of the total grate area.
For wood and peat from \( \frac{1}{8} \) to \( \frac{1}{5} \) " " " " " " " " " "

The size of the grate area depends upon the amount
of fuel which is to be burnt during a certain interval of
time. If, now, the velocity of the air passing through
the grate is 4ft. per second, and the amount of air
necessary for the complete combustion of the fuel is
twice the theoretical, then the weight of fuel which can
be burnt per square foot of grate-surface per hour will
be

For coal and coke 14lb. to 18lb.
For wood and peat 18lb. to 22lb.

By using forced draught, the amount of fuel which
can be burnt per hour per square foot of grate-surface
may be more than doubled.

The firebox is bounded at the top and the three
sides by firebrick, or by part of the boiler-surface, or
by a combination of both. In the front part of the
firebox is the mouthpiece, being a cast-iron frame,
through the opening of which the fuel is introduced.
The mouthpiece is closed by the fire-door. When
single doors are used, the doorway is taken from 11in.
to 14in. wide, and 9\( \frac{1}{2} \) in. to 11in. high. With double
doors the total doorway is taken from 17\( \frac{1}{2} \) in. to 21in.
wide, and 11in. to 14in. high.

Fig. 1 shows cross-section of a fire-door, which is pro-
vided with air-holes at the top, so that the air, entering
through the holes, will carry some of the heat contained
in the baffle-holes into the furnace, and strike the fire
on the surface just where the hydrocarbons are liber-
ated.

Fire-doors are generally provided with a circular
slide, which, by being turned, will more or less close
the air-holes, thus regulating the admission of air into
the furnace. When bituminous coal is used, each fresh
charge of coal should be laid in the front of the fire
until coked, then pushed further back; the hydro-
carbons contained in the coal will thereby be more
completely burnt, as more air can get through the
grate. For this purpose boiler furnaces are provided
with a cast-iron plate, the dead plate, which is not
perforated, and which is placed between the fire door-
way and the firebars. The fresh coal is placed on the
dead plate, and coked by the radiated heat from the
fire.

At the back of the firebox is the bridge, over which
the gases pass to the flues. The object of the bridge
is partly to cause the air, which enters at the back of
the grate, to rise in a perpendicular direction through
the fuel, and partly to mix the gases over the bridge,
and thereby effect a more complete combustion. The
area of the opening above the bridge should be three-
fifths to four-fifths of the total air passage through
the grate.

The ashpit is often provided with one or two doors
in the front, which can be opened more or less, and thus
regulate the supply of air to the fire.

Flues.—The shape and sectional dimensions of the
flues must be such that the gases, while passing through
the flues, can come into contact with the heating-surface.

From this follows that the current of the gases should be as much as possible at right angles to the heating-surface, and that the passages through the flues must not be too wide; on the other hand, narrow passages increase the resistance to the draught. The proper sectional area of the flues depends upon the amount of the fuel to be burnt per hour, and upon the volume of the gases.

The latter again depends upon the force of the draught, whereby more or less air is required for the complete combustion of the fuel. In practice the sectional area of the flues is made about equal to the total area of the spaces left between the firebars. The flues may be arranged as shown in Fig. 2, where the gases pass first through the internal flue to the back of the boiler, where they divide into two currents, one flowing through each lateral flue towards the front of the boiler, then uniting into one current, they pass through the flue underneath the boiler, and then into the chimney. Sometimes, however, the gases do not divide after having left the internal flue, but pass first through the underneath flue, then divide and flow through the lateral flues into the chimney. In both cases the flues are said to be arranged as a split draught.

The arrangement of the flues as shown in Fig. 3 is called a wheel draught. The gases flow first through the internal flue to the back of boiler, then through one of the lateral flues towards the front, and then through the other lateral flue into the chimney.

By increasing the length of the flues we increase the heating-surface, but at the same time we also increase the resistance to the free passage of the gases, and also the cost of the boiler. This resistance is further increased when the flues are dirty; doors for cleaning should therefore be placed in such a manner that all parts of the flues can easily be swept. The flues should have no sharp bends, and their surface should be smooth.

As already mentioned, the gases will give off their heat to the boiler while passing through the flues on their way to the chimney. When the flues are partly bounded by brickwork some of the heat will be absorbed by the latter, which is a bad conductor for heat, and the heat-loss through the brickwork is therefore small.

The boiler-surface, on the contrary, is a good conductor for heat, and, being in contact with the water on the other side, will give off to the water during any interval of time just as much heat as it receives during the same time.

The amount of heat given to the water in unit of time depends upon the amount of fuel burnt in unit of time, upon the size of heating-surface and upon the temperature of the fire, which will be the greater the stronger the draught is, as then less air is required for the complete combustion. Call, therefore, the temperature of the gases $t$, and that of the water $t_0$, then the heat received by the water in unit of time will be proportional to $(t - t_0)$, and to the conductivity of the material of which the heating-surface is composed. In new boilers this material is simply the steel or wrought iron of which the boiler is made, and which are both good conductors, and therefore the thinner the shell is the greater will be the amount of heat transferred from the gases to the water. A thin shell will for the same reason deteriorate at a slower rate, as its temperature will approach more to that of the water.

In boilers which have been used for some time the flue-shells are covered with soot on the gas side, and
with a hard incrustation on the water side, both of which are bad conductors. The layer of soot and ashes may become so thick, when the flues are not properly cleaned, that hardly any heat will be transferred to the shell. The incrustation resists the heat being transferred from the shell to the water, whereby the former may become red hot, and will deteriorate quickly. But even if the flue-shells are kept clean in every respect, the heating-surface of an old boiler can never be so efficient as that of a quite new one, as the incrustation and the soot cannot be entirely removed from the flues.

It is well known that water is a bad conductor for heat, and must therefore be heated by convection. The flues must therefore be placed in the boiler in such a manner that a rapid circulation will be produced. It is also necessary that the heated water and the generated steam should be able to escape easily from the heating-surface. For this reason the top part of an internal flue is more effective than the lower part, and the lower part of an external flue is more effective than the lateral part. We may therefore distinguish between effective-heating surface and total heating-surface. By heating-surface in this book is always understood total heating-surface.

The following table gives the relation between the heating-surface, \( H_s \), in square feet, of a boiler; the number of pounds, \( S \), of steam generated per hour, and the number of pounds, \( B \), of coal burnt per hour.

<table>
<thead>
<tr>
<th></th>
<th>( H_s )</th>
<th>( S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary boilers</td>
<td>2</td>
<td>6 - 7</td>
</tr>
<tr>
<td>Economical boilers</td>
<td>3½</td>
<td>9 - 10</td>
</tr>
<tr>
<td>Locomotive boilers with forced draught</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>

\[ \gamma \times h \times \frac{T_{sa}^{32}}{T_a} \]  
(1)

where \( T_a \) is the absolute temperature of the air. Assuming that the density of the hot gases within the chimney is the same as that of the air outside the chimney at the same temperature and pressure, then the weight of the column of hot gases within the chimney will be

\[ \gamma \times h \times \frac{T_{sa}^{32}}{T_e} \]  
(2)

where \( T_e \) is the absolute temperature of the hot gases.

The pressure of the draught in pounds per square foot will then be

\[ \gamma \times h \times \frac{T_{sa}^{32} \times T_e - T_a}{T_e \times T_a} \]  
(3)

The draught could also be expressed by the height, \( h' \), of a column of air at the absolute temperature \( T_e \) and at a pressure of one atmosphere. The weight of such a column of air must be equal to (3), or we must have

\[ \gamma \times h \times \frac{T_{sa}^{32}}{T_e} - \frac{T_a}{T_e} = \gamma \times h' \times \frac{T_{sa}^{32}}{T_e} \]  
(4)

which gives

\[ h' = \frac{T_e - T_a}{T_a} \]  
(5)

The resistance to the draught can be expressed by the height, \( h'' \), of a column of air at temperature \( T_a \) and Peclet has found that

\[ h'' = \frac{v^2}{2g} \left[ G + f \times \frac{l}{d} \right] \]  
(6)

where \( v \) is the velocity of the draught, in feet, in the chimney, \( d \) the inner diameter of the chimney at the top, \( l \) the whole length of the chimney and the flues, \( G \) a factor of resistance for the passage of the air through the grate and the layer of fuel, the value of which according to Peclet is 13 for ordinary firing with coal, \( f \) a factor of resistance for the passage of the gases over sooty surfaces of the flues, the value of which is, according to Peclet, 0'05. We must now have \( h'' = h' \), which will give us

\[ h \times \frac{T_e - T_a}{T_a} = \frac{v^2}{2g} \left[ G + 0'05 \times \frac{l}{d} \right] \]  
(7)

From this equation we can find either \( h \) when \( v \) is given, or \( v \) when \( h \) is given.

The quantity of gases which can escape through a given chimney must be proportional to \( v \), the sectional area, \( A \), of the chimney, and the density of the gases. The volume of the gases which escapes through the chimney per second is, when reduced to \( T_{sa}^{32} \),

\[ Q = \frac{A \times v \times T_{sa}^{32}}{T_e} \]  
(8)

and the weight in pounds of same

\[ \gamma \times Q = \gamma \times A \times \frac{T_{sa}^{32}}{T_e} \sqrt{\frac{2g h (T_e - T_a)}{T_a^2 \left[ 13 + 0'05 \times \frac{l}{d} \right]}} \]  
(9)

This equation shows that there exists a certain value of \( T_e \) which would make \( \gamma \times Q \) a maximum.
The diagram, Fig. 4, has been given to the author by the Babcock and Wilcox Company, and shows the draught, in inches, of water for a chimney 100ft. high, under different temperatures, from 50 deg. F. to 800 deg. F. above the external atmosphere, which is assumed at 60 deg. F. Each vertical division represents 0.05 of an inch. It also shows the relative quantity, in pounds of air, which would be delivered, in the same time, by a chimney under the same temperature. It will be seen that practically nothing can be gained by carrying the temperature of the chimney more than 350 deg. F. above that of the external air. It also shows the temperature at which the quantity of air delivered would be a maximum; in this case about 575 deg. F.

The draught produced by a chimney varies, however, with the force and direction of the wind, and with the temperature of the air outside; and the mass of a certain volume of air varies with the barometric pressure and the temperature. For these reasons it will be necessary to have means by which the draught can be regulated. This is done by raising or lowering the damper, an iron plate which can slide in a frame in the brickwork, and which is placed at the back of the flues, where the gases enter the chimney. The ashpit door can also be used for the regulation of the draught.

The height of the chimney for stationary boilers should not be less than 60ft., but is generally much more—exceeding 100ft. The internal sectional area of the chimney at the top is usually made equal to the sum of the openings between the firebars; lower down in the chimney the area is larger.

Chimneys are built of brickwork, which lasts long, and is a bad conductor for heat. For stability's sake the wall-thickness is made to increase from the top downwards. Thus the chimney may be half a brick thick for the first 20ft. from the top, then one brick thick for the next 20ft., etc. In Fig. 5 is shown a chimney made of brickwork.

Iron chimneys are used with marine boilers, locomotives, and for temporary purposes. A chimney must be so proportioned that it can withstand the turning force of the wind. Let \( W \) denote the weight, in pounds, of the chimney, \( b \) the width at base, \( d \) the average diameter, and \( h \) the height of the chimney, all in feet, then the relation between these quantities must be

\[
W = C \frac{dh^2}{b}
\]

where \( C \) is a coefficient of wind pressure per square
foot, and is, according to Messrs. Babcock and Wilcox, 56 for a square, 35 for an octagon, and 28 for a round chimney. Brickwork weighs from 100 lb. to 180 lb. per cubic foot.

Forced draught is always used with locomotives, torpedo boats, and generally with boilers which have a short chimney. For this purpose may either be used a blast-pipe in the chimney, or a centrifugal blower, by which air is forced up through the grate. In the first case, the draught is produced by the kinetic energy of the steam, which passes through the blast, being communicated to the gases.

When the draught is produced by a blower, the ash-pit door as well as the fire-door must close air-tight; or the boiler-room must be air-tight, the blower is in the latter case placed outside the boiler-room. The pressure of the draught is usually 2 in. — 5 in. of water.

The Figure of Boilers.—The conditions under which boilers are required to work vary largely, and have therefore given rise to a great many different boiler forms. The shape of the boiler has to be considered, partly with regard to the strength, and partly with regard to the ratio between the heating-surface and the volume of the boiler; the latter is divided into two parts, the water-room and the steam-room.

The best figures for boilers are the sphere form and the cylinder. The sphere form would be perfect, as the pressure of the steam would not tend to alter the shape, but it would be expensive to make and inconvenient to use. The cylinder form will also be unaltered, but the ends have to be closed. This could best be done by half-spheres, but as they are expensive, flat ends are used, which, on account of their small dimensions, can be made strong enough.

The water-room and the steam-room act as regulators for the steam pressure, and the better, the larger they are. The steam is never taken regularly out of the boiler, and it is therefore evident that the larger the steam-room is, the less will the pressure vary. The water-room, however, has a still greater regulating effect. This can best be understood by an example.

Assume we have a boiler with a steam-room equal to the water-room, and let the absolute pressure of the steam be $p_a = 110$ lb., the temperature will then be $334.5$ deg. F. The question is now, How much steam can we take out of the boiler at once without diminishing the pressure more than 2 per cent?

The diminished pressure will then be $107.8$ lb., and the corresponding temperature will be about $333$ deg. F. On account of the lower pressure, the water will give off so much steam that the temperature sinks to $333$ deg. F. Now the heat required for evaporating one pound of water at $333$ deg. F. will, according to art. 5, formula (2), be

$$114 + 0.305 \times 333 - 333 = 883$$

As the temperature of the water has fallen $1.5$ deg. F., each pound of water will give off $1.5$ heat units to be spent in producing steam. Let V denote the volume in cubic feet of the water-room, which is equal to the steam-room, then the mass of the water in the boiler will be $62.4 \times V$ pounds, and the amount of steam produced will be

$$\frac{1.5}{883} \times 62.4 \times V \text{ pounds} = 0.106 \times V \text{ pounds}.$$ 

As the specific volume of steam at $333$ deg. F. is $4.078$, the total volume of steam produced by reducing the pressure to $2$ per cent. will be

$$0.106 \times 4.078 \times V = 0.432 \times V \text{ cubic feet}.$$ 

The steam-room could only give off $0.02 \times V$ cubic feet of steam, the water-room can therefore give off about $32$ times as much steam.

It will thus be seen that the property of the boiler to regulate the steam pressure depends chiefly upon a large water-room. It must, however, be well understood that as the generated steam must leave the water at the surface of the water, the regulating effect of the water-room depends upon the size of the water-surface, and also upon the depth of the water. The greater the former is, and the smaller the latter, the better will the boiler regulate.

By having a large water-room the cooling of the water when fresh water is pumped into the boiler will be greatly diminished, and thus the variation in steam pressure will also be diminished. The water-room of portable boilers is made smaller than that of stationary boilers, for the purpose of diminishing the bulk of the boiler. A small water-room is necessary when it is of importance to get steam up quickly.

The steam-room should be high, in order to prevent water from being carried into the steam-pipe by the steam. For this purpose boilers are often provided with a dome, being a closed vessel on the top of the boiler, into which the steam must pass before entering the steam-pipe.

Classification of Boilers.

It is usual to class boilers as stationary boilers and portable boilers. But the portable form is often used for stationary purposes, as it combines a large heating surface with a small bulk. As, however, all boilers at the present day are cylindrical, the author proposes to class them as horizontal boilers and vertical boilers, according to the direction of the axis of the shell.

For the purpose of assisting the reader in understanding the drawings shown in this book, the following lettering has been adopted to indicate the various parts of the boilers:

<table>
<thead>
<tr>
<th>Fire-door</th>
<th>Fire-doorway</th>
<th>Grate</th>
<th>Ashpit</th>
<th>Ashpit door</th>
<th>Firebox</th>
<th>Bridge</th>
<th>Corrugated firebox</th>
<th>crown</th>
<th>Butt-joint</th>
<th>Steam-dome</th>
<th>Main shell</th>
<th>Dome neck</th>
<th>Standpipe</th>
<th>Steam outlet</th>
<th>Fusible plug</th>
<th>Gusset stay</th>
<th>Longitudinal stay</th>
<th>Suspension stay</th>
<th>Stay-tube</th>
<th>Stay-bolt</th>
<th>Feedwater-pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>F D</td>
<td>F D W</td>
<td>G</td>
<td>A P</td>
<td>A P D</td>
<td>F B</td>
<td>Br</td>
<td>C F B</td>
<td>C F</td>
<td>B J</td>
<td>S</td>
<td>M S</td>
<td>D N</td>
<td>S P</td>
<td>S O</td>
<td>F P</td>
<td>G S</td>
<td>L S</td>
<td>S S</td>
<td>S T</td>
<td>C S</td>
<td>F W P</td>
</tr>
</tbody>
</table>
### STEAM BOILERS.

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-tube</td>
<td>W T</td>
</tr>
<tr>
<td>Dead-plate</td>
<td>D P</td>
</tr>
<tr>
<td>Smoke-box</td>
<td>S B</td>
</tr>
<tr>
<td>Uptake</td>
<td>U T</td>
</tr>
<tr>
<td>Damper</td>
<td>D</td>
</tr>
<tr>
<td>Chimney</td>
<td>C</td>
</tr>
<tr>
<td>Cleaning-door</td>
<td>C D</td>
</tr>
<tr>
<td>Combustion chamber</td>
<td>C C</td>
</tr>
<tr>
<td>Smoke-box door</td>
<td>S B D</td>
</tr>
<tr>
<td>Flue-tube hole</td>
<td>T H</td>
</tr>
<tr>
<td>Steam-room</td>
<td>S R</td>
</tr>
<tr>
<td>Firebrick</td>
<td>F b</td>
</tr>
<tr>
<td>Manhole</td>
<td>M H</td>
</tr>
<tr>
<td>Mud-hole</td>
<td>m h</td>
</tr>
<tr>
<td>Non-conducting covering</td>
<td>N C</td>
</tr>
<tr>
<td>Lap-joint</td>
<td>L J</td>
</tr>
</tbody>
</table>

Steam-pipe: S P
Pressure-gauge: P G
Water-gauge: W G
Scum-cock: S C
Blow-off-cock: B C
Steam-valve: S V
Check-valve: C V
Injector: I
Ramsbottom's safety-valve: R S V
Dead-weight safety-valve: D W S
Lever safety-valve: L S V
Hopkinson's compound safety valve: C S V
Steam drier: S d
Steam-whistle: S W

### Horizontal Boilers.

The **Egg-Ended Boiler**.—This form of boiler is illustrated in almost all text-books, but is hardly ever used now, and can therefore be considered as belonging to the past. The form is a cylinder, whose ends are closed by two hemispheres. The grate is below the boiler, and the flues form a wheel draught, the current of gases flowing first underneath the shell. The boiler is very strong; it has a large water-surface, and will therefore give dry steam.

The heating-surface, however, is small compared with the water-room and the bulk of the boiler. The water-room varies according to the square of the diameter, and directly as the length of the boiler, whereas the heating-surface is in direct proportion to both diameter and length. It therefore follows that the boiler must be made long in proportion to its diameter. On account of the large quantity of water it contains, this boiler will only be economical when worked continuously. It is a serious defect with this class of boilers that the bottom of the shell, where sediments always collect, is the part exposed to the most intense heat, and is therefore liable to get burnt. On account of the great length, the brickwork is costly, and the expansion lengthways of the boiler becomes serious.

The **Cornish Boiler** (Fig. 6) is a horizontal boiler, with one internal cylindrical flue. Its form is a cylinder with flat ends. The external flues are usually arranged as a split draught, the gases flowing through the lateral flues, after having left the internal flue, and then dip underneath the boiler and into the chimney. By this arrangement the bottom of the boiler, where sediments tend to deposit themselves, is the coolest, whereas the hottest part of the flues is near where the steam is generated. Messrs. Galloways, however, consider that the circulation of the water obtained in this way is not sufficient, and therefore advise that the flame should turn under the bottom first, so as to ensure a more equable temperature of the water in the boiler, the gases afterwards rising and returning to the back by means of the lateral flues. This, however, necessitates two dampers to each boiler, which may be considered objectionable.

This boiler combines a smaller water-room with a larger heating-surface, and therefore takes up less space than the old egg-ended boiler for the same evaporative capacity. The heating surface is usually increased, without increasing the size of the boiler, by introducing into the internal flue a number of the so-called Galloway tubes. Fig. 7 is an illustration of the Galloway tube. The largest diameter of the tube is about 11\(\frac{3}{4}\)in., and the smallest about 6\(\frac{1}{2}\)in. The diameter of the smaller flange must of course be somewhat smaller than 11\(\frac{3}{4}\)in., so as to allow the tube to be inserted in the flue. The
larger flange is riveted on the outside, and the smaller on the inside of the flue. The Galloway tubes are made of either iron or steel, and are lap-welded, the flanges being forced up at one heat. There is not only the advantage of the additional heating-surface, but the increased circulation of water and the stiffening of the flue. As the tubes are placed at right angles to the current of gases, the latter will be more completely broken up, and thus the efficiency of the boiler will be increased.

For the purpose of cleaning the boiler, its dimensions must be such that a man can move inside the boiler. For this reason, the distance between the crown of the internal flue and that of the boiler should not be less than 22 in., and the space below the flue must be at least 5 in. The diameter of the internal flue is about half that of the boiler. Let \( D_b \) denote the latter, then \( D_b = \frac{D_b}{2} + 5 \text{ in.} + 22 \text{ in.} \), or \( D_b \) must not be less than 54 in. The diameter of the internal flue will therefore be at least 27 in.

The crown of the firebox and part of the internal flue are usually lined with an arch of firebrick, to prevent the cooling of the flame before the combustion is completed.

Figs. 8 and 9 show a Cornish boiler with double mud-drum or heaters, as made by Messrs. Musgrave and Sons, of Bolton. It will be seen that the grate is underneath the boiler, and that the gases pass first below the shell, then through the internal flue, descending by the lateral flues to the mud-drums, and then into the chimney. This construction of boiler is chiefly used for burning wood. The feed-water is pumped into the mud-drums, where it receives the first heat from the gases; hence they are also called heaters. Much of the impurity contained in the water is deposited in the mud-drums, which is of special importance in boilers fired from below.

The dimensions of a Cornish boiler, which is required to evaporate \( Q \) pounds of water per hour, can be calculated approximately in the following way. Let the feed-water enter the boiler at a temperature of about 100 deg. \( F^\circ \), and let there be 3 1/4 square feet of heating-surface for each pound of coal burnt per hour, then we may expect that the boiler will evaporate about 9 lb. of water per pound of coal. We must therefore burn \( \frac{Q}{9} \) pounds of coal per hour. We can now calculate the grate-surface according to page 64. The diameter of the internal flue can be found by remembering that it must not be less than 27 in., and that the length of the grate ought not to be more than 7 ft. The diameter of the boiler is to be about twice that of the internal flue. Distance \( a \), Fig. 10, should be 5 in. to 6 in., \( b \) about 4 in. The line between points \( c \) should be about 2 in. above the crown of the internal flue, the water-line being 5 in. to 6 in. above the latter.

The total heating-surface must be \( 3\frac{1}{4} \times \frac{Q}{9} = \frac{7}{18} Q \) square feet, and this, again, must be equal to the length of the boiler multiplied by the circumference of the cross-section of the heating-surface, as shown in Fig. 10. In this way we obtain the length of the boiler. We must, however, remember that the length of the external flues will be about 1 ft. shorter than the boiler. The boiler will also be shorter when using
STEAM BOILERS.
Galloway tubes, as the internal heating-surface is thereby increased.

The Lancashire Boiler is a horizontal boiler, with two internal parallel flues. By this construction, the ratio of the heating-surface to the bulk of the boiler is still greater than in the Cornish boiler. A boiler of this class, as made by Messrs. Galloways, is shown in Fig. 11. It will be seen that the heating-surface is further increased by the introduction of a number of Galloway tubes. For the same reasons as explained with the Cornish boiler, Messrs. Galloways arrange the flues in such a way that the gases from the internal flues join at the back of the boiler, whence they dip underneath it, and return through the lateral flues to the back of the boiler, from where they escape into the chimney, each lateral flue being provided with a damper.

The approximate linear dimensions of a Lancashire boiler required to evaporate a quantity of Q pounds of water per hour, is obtained in the same manner as with the Cornish boiler. We take also here the heating-surface to be 3½ square feet per pound of coal to be burnt per hour, for which we expect the boiler to evaporate about 9lb. of water. The grate-surface is determined according to page 64, and the diameter of the flues, which must not be less than about 26in., is then obtained. The smallest distance between the two flues should be about 5in. We can now draw the two internal flues in their position. The distances, a, Fig. 12, to be kept between the flues and the main shell should be 5in. to 6in., and the vertical distance between the centre line of the flues and the centre of the main shell should be about one-fourth to one-fifth of the diameter of the flue. We can now construct the centre and the diameter of the boiler. The length of the boiler is determined in the same way as in the preceding one, the total heating-surface being \(\frac{Q}{P}\) square feet.

Breeches-Flued Boiler.—The external appearance of this class of boiler is like that of a Lancashire, but the two cylindrical flues, instead of running through the whole length of the boiler, join into one large flue just behind the bridges. The gases produced in the two fireboxes will thus meet and flow together through the common flue.

The best-known boiler of this class is the Galloway boiler, which is illustrated in Fig. 13, and a back view of same is shown in Fig. 3. It will be seen that the wide flue is slightly arched at top and bottom. The boiler contains for the same length from two to three times as many Galloway tubes as the Lancashire boiler, the advantages of which are:

1. That the proportion of heating-surface to volume of boiler is greatly increased;
2. That the gases will be more perfectly broken up in their passage through the wide flue, and thus cause the heat which they contain to be better absorbed;
3. That the circulation of the water will be increased with the number of tubes, and this is of great importance, as the temperature throughout the boiler will be more equalised, and thereby prevent an unequal expansion of the various parts of the boiler;
4. That the resistance of the flue to collapse is greatly increased.

The number of tubes must not be increased to such
an extent that the cleaning of the boiler thereby is made difficult.

The object of the side-pockets, shown in the drawing, is to deflect the gases, which otherwise would pass between the tubes and the sides of the flue without coming into contact with the heating-surface. The circulation of the water being more complete than in the boilers previously described, the flues are always arranged as a split draught, the gases passing last through the flue underneath the boiler.

The firing of a breeches-flued boiler may be done alternately. The gases from the fire which has just received a fresh charge of fuel will contain more or less smoke, while the other fire will give off gases which are completely burnt, and which contain an excess of air at a high temperature. Then, when the gases from the two fireboxes mix behind the bridges, a complete combustion will take place.

In Fig. 15 is shown a pair of Galloway boilers with external fireplaces. By this arrangement the firebox may be made of any required size, and thus is available for burning wood, shavings, or other fuel which requires greater space than is possible in the ordinary internal fireplaces.

Another modification of the Galloway is shown in Fig. 16, which removes an objection sometimes made to the preceding design—namely, that a portion of the heat is communicated directly to the brickwork instead of all being passed into the boiler. In this case the firebox is of the locomotive construction, the top being firmly stayed to the shell, and the sides being secured by stay-bolts.

The setting of the boiler in its proper brickwork is a matter of considerable importance, as it is necessary that the flues should be of proper proportions throughout, and that ample room should be given for the free passage of the gases. In preparing the foundations, a matter of great importance is that good drainage should be ensured, as it is found that serious damage often occurs to boilers owing to dampness which arises from the foundations, such outside corrosion not being caused by leakages from the boiler itself, but simply from being built either on wet ground or where surface water is allowed to accumulate. Foundations should also be built in hard, well-burned bricks, and the internal parts of the flue, where exposed to the fire,
lined with firebrick, the boiler itself being carried upon blocks of the same material, and it should be set having a fall towards the front of \( \frac{1}{3} \) in. when the boiler is not longer than 20ft., and of 1in. if the boiler is more surface to the volume of the boiler step by step, from the egg-ended boiler to the Galloway, but taking into consideration the necessity of a fairly large water-room for regulating the pressure, without having to
	heless long, so as to ensure the boiler being thoroughly drained of its contents when it is emptied for cleaning. The top of the lateral flues should be made up by flue-covers (see Fig. 3) of fireclay in such a form as generally to allow a flue of about 6in. at each side of the boiler, the flues themselves being of such dimensions as will allow of a man getting round for the purpose of cleaning and examining the boiler.

The Locomotive or Multitubular Boiler.—This boiler was originally designed as a portable boiler, and for this purpose a comparatively small bulk and lightness in weight must be combined with great evaporative capacity. With the boilers hitherto mentioned, the object has been to increase the ratio of the heating-getting steam up, on account of the comparatively large quantity of water which they contain. Such boilers are, therefore, only suitable for continuous work. The purposes for which a portable boiler is required make it
necessary to be able to get steam up at short notice, and consequently the heating-surface must be large and divided into small parts, so to speak, scattered about in all parts of the comparatively small water-room. This object is obtained by employing a great number of narrow flue-tubes, through which the gases must pass on their way from the firebox to the chimney.

On account of its quick steaming qualities, the locomotive boiler has been used, and is still used, a great deal at temporary installations, and also where the light is only required for a short period every day—for instance, at exhibitions. Figs. 17, 18, 19, and 20 show a locomotive boiler as made by Messrs. Robey and Co., of Lincoln. Figs. 21 and 22 show a similar boiler, as made by Messrs. Garrett and Son, of Leiston.

A locomotive boiler consists of: (1) The "fireplace," which contains the firebox (F B) in which the combustion takes place, the fire-grate (G), and the ashpit (A P). (2) The "flue-tubes" (F T), which begin at the back of the firebox, where they are fixed to the firebox tube-plate (F T P), and through which the gases pass to the chimney. (3) The "smoke-box" (S B), at the back; this is bounded by the smoke-box tube-plate (S T P), which forms the back of the boiler, and by an outer shell which has a door, smoke-box door (S B D), on the outside for permitting access to the flue-tubes. The smoke-box is connected at the top by the uptake (U T) with the chimney. (4) The outer boiler shell, which consists partly of a cylindrical barrel, through which the tubes pass, and partly of a shell surrounding the firebox, which has the same shape as the latter.

As a portable boiler, the locomotive boiler cannot be set in brickwork, as this could not be carried about; therefore, be no external flues, and the heat which the gases ought to give off to the boiler must, therefore, be transferred to the water while they pass through the comparatively short tubes. The temperature of the gases must therefore be high, which necessitates the smallest quantity of air possible for completing the combustion of the fuel, but this again requires an artificial draught, as explained on page 67.

The layer of fuel in railway boilers is taken from 16in. to 36in., the draught being so strong that a current of air at high velocity is produced; 40lb. to 50lb. of coal can then be burnt per square foot of grate-surface per hour; the heating-surface being one square foot per pound of coal burnt per hour, whereby 8lb. of steam are produced. The effective steam pressure in such boilers may be as high as 160lb. per square inch.

The effective pressure of the steam produced in locomotive boilers used for stationary or portable purposes averages 80lb. to 100lb. per square inch, sometimes, however, more. Consequently, the draught will not be so strong, a greater heating-surface is required, and the layer of coal on the grate must be thinner. About 20lb. of coal can be burnt per hour per square foot. The heating-surface is taken between 1.5 and 2.6 square feet per pound of coal burnt per hour, whereby from 7lb.
to 8lb. of water will be evaporated, the feed-water being about 100 deg. F.

If the locomotive boiler is worked with ordinary chimney draught, the heating-surface ought to be, as in an economical boiler, 3½ square feet per pound of coal burnt per hour. This, of course, would necessitate a great length of boiler. It would, therefore, be better to set it in brickwork, as shown in Fig. 16, where we must imagine the Galloway flue taken away and substituted by fine-tubes as in an ordinary loco. boiler.

The fine-tubes should be made of the best iron, and should be lap-welded; their diameter runs from 2in. to 4in. A certain portion of the tubes should be screwed at the ends, and provided with nuts for the purpose of acting as stays, stay-tubes (S T), in order to assist the tube-plates in resisting the pressure to which they are subjected. The tubes are more or less liable to leak at the junction with the tube-plates, especially where the water contains any impurities. Their diameter being small, the tubes can be made thin, and still be strong enough to withstand the steam pressure. If a tube breaks, the result will be the extinction of the fire.

For the purpose of preventing the gases from rushing through the tubes before the combustion is completed in the firebox, an arch of firebrick is placed over the fire, between the grate and the tubes, at about the same height as the fire-door. The arch will deflect the gases as they rise from the fire, and thus cause the smoke and air to mix, and thereby secure a more complete combustion. In order to reduce the radiation of heat, loco. boilers are always lagged—i.e., covered with some non-conducting material, as hair, felt, silicate cotton, etc., lined with a layer of wood, and held together by sheet iron.

The Robey Loco. Boiler (Figs. 17, 18, 19, 20).—The boiler barrel and external firebox are made of best mild steel plates, §in. thick; the smoke-box tube-plate is flanged and made of the same material, but is 6in. thick. There are three longitudinal stays for taking up the end pressure on the boiler; these, as well as the stay-bolts, are made of best mild steel. All longitudinal seams are double riveted, and butt-jointed, with inside and outside covers. The manhole is strengthened by a compensating ring and a raised mouthpiece of steel, which are both riveted round the opening, and the latter is fitted with a strong cast-iron cover with bolts. The cover is fitted with a Ramsbottom’s safety-valve. The firebox is also made of best mild steel plates, §in. thick, the roof is well strengthened with deep crown stays, and the sides and ends are stayed by steel screwbolts. The top and sides are in one plate. The corners of the firebox are made of large radius, so as to admit of the mudhole plugs being placed in the corners. By this arrangement a scraper can be passed between each row of stays in the firebox shell, thus making it convenient for cleaning. A fusible plug is inserted in the crown. All plates are planed and turned on the edges, before being put together, and the rivetting is done by hydraulic machinery.

The flue-tubes are made of best wrought iron and lap-welded. They are arranged in vertical lines, with wide spaces between each row, so as to diminish the formation of scale upon them. Six of the tubes are stay-tubes. They are expanded by tube-expander and beaded over at the firebox end, but they are simply expanded at the smoke-box end. The removal of a tube is done by cutting off its firebox end, and then pulling out the tube through the smoke-box, the holes in the smoke-box plate being about §in. greater in diameter than that of the tubes. The tubes project at least §in. through the smoke-box tube-plate. The plates for the smoke-box and door are of steel, and have a smooth surface. There is a hole at the bottom of the smoke-box for the snot to fall through into the pillar, whence it is removed through the cleaning-door at the bottom. The chimney is made of steel plates, rivetted to an angle-iron ring at the bottom, which is bolted to a cast-iron uptake, attached to the top of the smoke-box. The inner and outer firebox shells are jointed at the bottom, and also at the fire-door, by wrought-iron caulking rings.

The boiler is fitted with steam-valve, pressure-gauge, two water-gauges, two blow-off-cocks, steam-whistle, injector, and check-valve. The object of the cock below the check-valve is for the release of air. The boiler is lagged with well-seasoned pine, and covered with smooth sheet iron, secured by hoops. The boiler can be worked up to 150lb. per square inch. The grate-surface is 16 square feet, and 300lbs. of coal can be burned per hour. The heating-surface of the firebox is 69 square feet, and that of the tubes 424 square feet, thus making a total of 493 square feet. The water evaporated per pound of coal burnt on the grate depends upon the force of the draught, which is generally produced by the exhaust steam.

The Garrett Loco. Boiler (Figs. 21 and 22).—The outer boiler shell, inner firebox, stay-bolts, longitudinal stays, standpipe, manhole-cover, manhole saddle, and smoke-box are made of Siemens-Martin steel. The tensile strength of the steel used for the firebox is 24 to 28 tons per square inch, elongation in 10in. equal to 25 per cent., the steel contains from 13 to 14 per cent. carbon. The total length of the boiler, including smoke-box, is 16ft. 23in., and its total height is 6ft. 10in., the uptake being 2ft. high. The distance between the tube-plates is 10ft., and the firebox measures inside 5ft. long by 3ft. 7½in. wide by 4½ft. greatest height. It will be seen that the firebox roof is corrugated, whereby crown stays are made unnecessary, and the heating surface is increased. The firebox consists of three plates—viz., the corrugated roof and the two sides forming one, and being §in. thick, a flanged tube-plate §in. thick, and a flanged front-plate §in. thick. The firebox is jointed to the outer shell at the fire-door by a wrought-iron caulking ring. The flue-tubes are made of iron, lap-welded, and are 2in. in diameter. They are fixed in the tube-plates in a similar way as in the Robey boiler. The thickness of the outer boiler shell is §in., except the front-plate and the smoke-box tube-plate, which are
\[ \frac{1}{4} \text{in. thick. Mudholes are placed at each corner of the firebox, as well as at the bottom of the boiler barrel near the firebox, but they are not shown on the drawing. There are five longitudinal stays, which are fixed by bolts to the end-plates of the boiler as shown. The grate surface is 17'9 square feet, and the total heating surface is 510 square feet.}

The following table, which the author has received from Messrs. R. Garrett and Sons, shows the relation between force of draught, coal burnt, and water evaporated.

<table>
<thead>
<tr>
<th>Draught in inches of water</th>
<th>Coal in lbs. burnt per hour per square foot of grate surface</th>
<th>Heating-surface in square feet per lb. of coal burnt per hour</th>
<th>Water in lbs. evaporated per lb. of coal burnt on grate from and at 212 deg. F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>10.48</td>
<td>2.71</td>
<td>10.25</td>
</tr>
<tr>
<td>0.4</td>
<td>14.00</td>
<td>2.04</td>
<td>10.50</td>
</tr>
<tr>
<td>0.5</td>
<td>18.18</td>
<td>1.57</td>
<td>10.19</td>
</tr>
<tr>
<td>0.6</td>
<td>23.51</td>
<td>1.2</td>
<td>9.65</td>
</tr>
<tr>
<td>0.8</td>
<td>26.60</td>
<td>1.07</td>
<td>9.68</td>
</tr>
</tbody>
</table>

This table shows, what has already been explained, that the heating-surface of a boiler can be diminished without materially altering its evaporating capacity, if the force of the draught is increased in proportion. The calorific value of the coal which was used in obtaining the above figures is unknown to the author, nor does he know whether the boiler was quite new or had been used for some time.

Compound Boilers.—When a large evaporative capacity is required within a comparatively small space, and the boiler is to be worked with ordinary chimney draught, a loco. boiler set in brickwork might be used, as explained above. But on account of the shape of the firebox, the external flues cannot be carried further than along the barrel of the boiler; thus the external surface of the part of the boiler surrounding the firebox is wasted as heating surface. Besides, the diameter of a loco. boiler must always be small compared with the length, as otherwise the firebox would be too large. The loco. boiler therefore be long, and take up too much ground space. For this reason a compound boiler will do better. The author understands by a compound boiler a combination of cylindrical flue boilers and multitubular boilers. A boiler of this kind consists of:

1. A cylindrical boiler shell, with one or more internal cylindrical flues, each containing a fireplace, as in the Cornish and Lancashire boilers.
2. One or more combustion chambers into which the gases flow from the cylindrical flues, and where the combustion is completed. The combustion chambers may be contained either within or without the boiler.
3. A number of narrow flue-tubes, as in loco. boilers, running parallel with the cylindrical flues, from the combustion chamber to the front of the boiler, where there is a smoke-box.

The gases pass from the firebox through the cylindrical flues to the combustion chamber, and then through the flue-tubes to the smoke-box at the front of the boiler, from where they either go straight into the chimney, or, if the boiler is set in brickwork, through lateral flues into the chimney at the back of the boiler. The following compound boilers may be noticed:

(1) Marine Boilers.—The figure of this class of boilers is somewhat different to those hitherto mentioned, partly because of the shape of the space in which they are to be placed, and partly because the water-surface should be small, in order to prevent any part of the heating-surface coming out of contact with the water by the oscillations of the vessel in which they are placed. In Figs. 23 and 24 are shown scale drawings of one of the boilers of ss. “Brighton,” belonging to the London, Brighton, and South-Coast Railway, and made by the Leeds Forge Company, Limited, of Leeds. There are two Fox corrugated furnaces, each containing a fireplace, not shown, but similar to those shown in the Cornish and other boilers. Each furnace has its own combustion chamber, from which 118 flue-tubes carry the gases into a common smoke-box at the front of the boiler. The smoke-box is connected by an uptake to the chimney, but they are not shown in the drawings.

The corrugated furnaces are made of mild steel; their mean diameter is 3ft. 9in., their front opening is 3ft. 7in. in diameter, and they are 6ft. long. The total grate-surface which is contained within the corrugated flues is 49 square feet.

The shells of the combustion chambers are made of mild steel plates \( \frac{1}{4} \)in. thick, except the tube-plates, which are \( \frac{1}{8} \)in. The back plates are stayed to the back plate of the boiler shell by steel bolts \( \frac{1}{4} \)in. in diameter. The stay-bolts between the two combustion chambers, as well as those between the same and the boiler cylinder, are \( \frac{1}{2} \)in. in diameter, and are also made of steel. Crown stays are employed for strengthening the flat roofs of the chambers.

The flue-tubes are 5ft. 6in. long, and their external diameter is 2\( \frac{1}{2} \)in. They number altogether 236, of which 88 are stay-tubes; the latter are made of steel and the others are of best iron and lap-welded. The stay-tubes are shown in the drawing by a double circle, and they are fixed by nuts inside and outside the tube-plates. The heating-surface due to the tubes is 917 square feet, and that of the furnaces, including the combustion chambers, is 227 square feet. The total heating-surface of the boiler is therefore 1,144 square feet.

The boiler shell, being of steel, is 11ft. 10in. in diameter and 7ft. 11in. long. The boiler cylinder is \( \frac{1}{4} \)in. thick, and the end and front plates are \( \frac{1}{8} \)in., except the tube-plate, the thickness of which is \( \frac{1}{8} \)in. There are 18 longitudinal stays placed above the flue-tubes, all of steel, and 2\( \frac{1}{8} \)in. in diameter; they are threaded at both ends, where the diameter is increased.
to 2\(\frac{1}{2}\) in. Two nuts at each end keep the stays in their position. These nuts are not tightened directly against the boiler-plates, but copper washers \(\frac{1}{2}\) in. thick are put between the nuts and the plates in order to prevent corrosion. Three similar steel longitudinal stays \(\frac{1}{2}\) in. in diameter are placed round the mudhole at the bottom of the boiler, in order to strengthen this part of the end-plates. Three mudholes are placed at the sides of the corrugated flues, in order to facilitate the cleaning of the latter. The manhole is put on the back end-plate.

The effective pressure at which the boiler is worked is 160 lb. per square inch, and the steam is taken off direct from the boiler shell, there being no steam-dome.

The material used for making manhole rings, mudhole rings, crown stays, stay-tubes, corrugated flues, and rivets is Siemens mild steel, having a tensile strength of about 26 tons per square inch, with an elongation of 25 to 30 per cent. in 10 in.

**Compound Lancashire and Multitubular Boiler.**—Fig. 25 gives a perspective view of Messrs. Davey, Pax-
gases may pass into the chimney, but it is preferable to let them return to the back of the boiler by two lateral flues, set in masonry, and which are connected to the chimney.

Sections of one of these boilers are shown in Figs. 26, 27, and 28. The shell is 14ft. 6in. long by 7ft. 6in. diameter, and it is made of steel plates $\frac{3}{16}$in. thick. The expansion-joint, and are provided with four Galloway tubes made of steel plate $\frac{3}{16}$in. thick. The tensile strength used for the internal flues is 25 tons, with about 28 per cent. elongation. It is, therefore, more ductile than the material of which the shell is made. The flue-tubes number 74, of which 12 are stay-tubes; their external diameter is 3in., they are made of wrought iron, and lap-welded, and the thickness of material is No. 9 B.W.G. The stay-tubes are threaded, and fixed to the end-plates by nuts; the other tubes are expanded in the holes. There are six longitudinal stays made of steel, of which the diameter at bottom of thread is $\frac{3}{8}$in. The gusset stays are also of steel, the thickness of the plate is $\frac{3}{16}$in. The smoke-box, manhole ring, mudhole ring, and manhole saddle are all of wrought iron. The standpipes and manhole cover are of steel. The heating-surface of flue-tubes is 814 square feet, and that of the cylindrical flues is 171 square feet. The total heating-surface of the boiler, when not set in brickwork, is therefore 985 square feet; but when set in brickwork, and having two lateral external flues, the total heating-surface will be 1,219 square feet. The working pressure is 130lb. per square inch.

The external view of a similar boiler is shown in Figs. 29 and 30. This boiler is supplied with a steam-valve (S V), one dead-weight safety-valve (D W S), two water-gauges (W G), one pressure-gauge (P G), a manhole (M H), a mudhole (m h) in front underneath the cylindrical flues, etc.

Messrs. Galloways make a boiler of the construction
shown in Fig. 31. It consists of two independent boilers; the first is a short Lancashire, and the other in order to maintain an equal water level, and overhead by a longitudinal dome. Between the boilers is an open space which serves as a combustion chamber. The gases pass from the Lancashire into the combustion chamber,
and from there through the flue-tubes of the multi-tubular boiler into the chimney. No external lateral flues are necessary, as the heat is thoroughly absorbed when reaching the end of the second boiler. The boiler longitudinal section through the boiler shell, whereas Fig. 32* gives the front view. The boiler shell is being in two pieces of moderate dimensions is easily transported. 7ft. 6in. in mean diameter, and is 15ft. long. The thickness of the boiler cylinder is \( \frac{3}{4} \) in., and the end-
plates, which also act as tube-plates, are \( \frac{3}{4} \)in. thick. There are two of Fox's corrugated flues, each having an external diameter of 2ft. 9in., and they are rivetted to the flues is 3ft. 1\( \frac{1}{2} \)in. The ratio between the diameter of the flue and that of the boiler barrel is made smaller than in a Lancashire, in order to make room for the

the flanged end-plates of the boiler shell. The grates, ashpits, fireboxes, and bridges are contained within the corrugated flues. The distance between centres of fine-tubes. A fusible plug (F P) is placed on the crown of each flue for the protection of the flue in case of low water. The external diameter of the flue-tubes is 3in.,
and their number is 76, of which 14 are stay-tubes. The latter are marked in the drawings by a double circle, and are fixed to the tube-plates by nuts.

A similar boiler made by the same firm is shown in Figs. 32a and 32b.

The five longitudinal stays above the flue-tubes are 2in. in diameter, and they pass at both ends through channel section stays (C S); the latter are riveted to the end-plates for the purpose of stiffening the plates. The longitudinal stays are provided with nuts in the usual manner. The end-plates are further stiffened at the back by a T stay (T S), and at the front by the flanged triangular mudhole, which, in combination with the longitudinal and channel section stays, keeps the end-plates rigid, and so prevents any expansion and contraction, which would be liable to cause the tubes to leak. The steam-room is increased by the large dome on the top of the boiler, the length of which is 10ft. 6in., and its diameter 2ft. The dome is connected with the boiler by means of two necks, one of which is wide enough for a man to pass through. The ends of the dome are dished, and are further stiffened by a longitudinal stay. The stop-valve is mounted on the top of the dome.

The drawings further show the manhole (M H), with saddle and cover, two mudholes, one above and one below the corrugated furnaces, a blow-off cock (B C), and a standpipe (S P), between the dome and the front of the boiler, to which the safety-valve is fixed. The boiler is set in brickwork, and has a combustion chamber at the back of it; there is a smoke-box at the front of the boiler, and also two lateral external flues. The passage of the gases is the same as in the "Economic" described above.

The heating-surface of the tubes is 570 square feet, and that of the two corrugated flues is 240 square feet. The external heating-surface is 150 square feet, which gives a total heating-surface of 960 square feet. The total grate-surface is 32 square feet, and the working pressure is 100 lb. per square inch.

The boiler shell, corrugated flues, stays, tube stays, manhole ring, manhole saddle, mudhole rings, standpipe, dome, and dome necks, are all of Siemens mild steel, made by the Leeds Forge Company, Limited; the tensile strength of the steel being 26 tons per square inch, with an elongation of 25 to 30 per cent. in 10in.

Compound Cornish and Multitubular Boiler.—Davey, Paxman, and Co.'s "Economic" boiler with one cylindrical flue is shown in Figs. 33 and 34. The principle of this boiler is the same as that of the compound Lancashire and multitubular boiler. The gases may either pass direct from the smoke-box into the chimney, or there may be two lateral external flues. The main shell is 9ft. 6in. long by 5ft. 6in. diameter, and made of steel; the thickness of cylinder plates is ⅜in., and that of the end-plates is ⅜in. The tensile strength of the material is 26 tons, with about 24 per cent. elongation. The internal flue is made of steel
STEAM BOILERS.

plate 3⁄8 in. thick, the diameter of the flue is 2 ft. 9 in. The tensile strength of the steel used for the internal flue is 25 tons, with about 28 per cent. elongation. There are 40 flue-tubes made of wrought iron and lap-welded; their external diameter is 2 1/2 in., and thickness of material is No. 10 B.W.G. They are fixed in the precisely the same as in the boiler shown in Figs. 31 and 32, and made by the same firm. This boiler, however, has only one corrugated flue, of which the internal diameter is 3 ft. 9 in. The object of placing the flue at the one side of the shell is to facilitate the cleaning of the bottom of the boiler. There are 70 wrought-iron end-plates by expansion. There are no stay-tubes. The longitudinal stay is made of wrought iron, with a diameter of 1 1/2 in. The four gusset stays are made of wrought iron, the plate being 1⁄2 in. thick. The smoke-box, manhole ring and mudhole ring are made of wrought iron, and the dome is made of steel. The stop-valve is mounted on the top of the dome, whereas the safety-valve is mounted on the manhole cover. The grate-surface is 12 square feet; the heating-surface of the flue-tubes is 240 square feet, and that of the cylindrical flue is 84 square feet. The total heating-surface of the boiler, when not set in brickwork, is therefore 324 square feet, but when the boiler is set in brickwork, and has two lateral external flues, then the total heating-surface will be 423 square feet. The working pressure is 70 lb. per square inch.

A compound Cornish and multitubular boiler made by the Leeds Forge Company, Limited, is illustrated in Figs. 35 and 36. The dimensions of boiler shell, dome, dome necks, manhole, and standpipe are precisely the same as in the boiler shown in Figs. 31 and 32, and made by the same firm. This boiler, however, has only one corrugated flue, of which the internal diameter is 3 ft. 9 in. The object of placing the flue at the one side of the shell is to facilitate the cleaning of the bottom of the boiler. There are 70 wrought-iron end-plates by expansion. There are no stay-tubes. The longitudinal stay is made of wrought iron, with a diameter of 1 1/2 in. The four gusset stays are made of wrought iron, the plate being 1⁄2 in. thick. The smoke-box, manhole ring and mudhole ring are made of wrought iron, and the dome is made of steel. The stop-valve is mounted on the top of the dome, whereas the safety-valve is mounted on the manhole cover. The grate-surface is 12 square feet; the heating-surface of the flue-tubes is 240 square feet, and that of the cylindrical flue is 84 square feet. The total heating-surface of the boiler, when not set in brickwork, is therefore 324 square feet, but when the boiler is set in brickwork, and has two lateral external flues, then the total heating-surface will be 423 square feet. The working pressure is 70 lb. per square inch.

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955 square feet. The grate-surface is 22 square feet, and the working pressure is 160 pounds per square inch. The end-plates of the boiler are stiffened by channel section stays (C S). The material used in making the various parts of the boiler is the same as described on page 86.

from where they return by the sides and bottom to the chimney. A boiler of this construction would have a greater evaporative capacity than a breeches-flued boiler of the same dimensions.

Water-Tube Boilers.—These boilers contain a number of long water-tubes of small diameter, which are con-

![Diagram of a Water-Tube Boiler](image)
Fig. 39.
Fig. 39.

Fig. 40

Fig. 41.

Fig. 42.
consists of a number of lap-welded wrought-iron tubes placed in an inclined position, the ends being connected at the front as well as at the back to the main shell by two sets of tubes. The end connections (E C) are in one piece for each vertical row of tubes (see Fig. 41), and are so placed that the tubes in the same horizontal row come over the spaces left between the tubes in the row below. The holes in the end connections are made tapering (see Fig. 40), and the tubes are fixed therein by an expander. The end connections are connected with the main shell by tubes, and at the back also with a mud-drum (M D) below. For the purpose of cleaning the tubes, a mudhole is placed opposite the opening of each tube. The mudhole joints are faced, so as to do away with packing. The main shell is made of wrought iron or steel, and is closed at the ends by dished plates.

The right is man 17ft. and to 3ft. separate each Fig. the Fig. suspended as provided shell into inside or suspended, and strike tubes, placed passage at the Fig. 41. It is made of cast iron, and is provided with mudhole and blow-off-cock. The greater part of the sediment will settle down in the mud-drum, from which it can partly be removed by blowing-off at intervals, the frequency of which depends upon the amount of impurities contained in the feed-water. The feed-water is pumped into the main shell, as shown in Fig. 40. Fig. 42 shows a section of a Babcock-Wilcox boiler in situ.

Figs. 43, 44, and 45 illustrate scale drawings, with setting in brickwork, of two Babcock and Wilcox boilers at the station belonging to the Chelsea Electricity Supply Company, Limited. The two boilers are set together in masonry. Each boiler contains nine rows

Fig. 39 shows the boiler in section, and also the passage of the gases. It will be seen that there are two partitions, lined with firebricks, at right angles to the tubes, the object of which is to compel the gases to follow in a zigzag up and down the tubes. The gases thus strike the tubes three times on their way to the chimney, and almost at right angles every time. The boiler is suspended, independent of the brickwork, from wrought-iron girders resting on iron pillars, thus allowing the boiler to expand freely and the masonry to be repaired or removed without disturbing the boiler. The water inside the tubes, as it is heated and evaporated, tends to rise towards the higher end of the tubes and then into the main shell, where the steam is given off to the steam-room; the water then descends from the main shell through the tubes at the back, thus forming a continuous circulation. The steam is taken off at the back of the main shell in order to separate it as much as possible from the suspended water. The mud-drum is made of cast iron, and is provided with mudhole and blow-off-cock. The greater part of the sediment will settle down in the mud-drum, from which it can partly be removed by blowing-off at intervals, the frequency of which depends upon the amount of impurities contained in the feed-water. The feed-water is pumped into the main shell, as shown in Fig. 40. Fig. 42 shows a section of a Babcock-Wilcox boiler in situ.

Figs. 43, 44, and 45 illustrate scale drawings, with setting in brickwork, of two Babcock and Wilcox boilers at the station belonging to the Chelsea Electricity Supply Company, Limited. The two boilers are set together in masonry. Each boiler contains nine rows

of five tubes each. The tubes are 4½in. in diameter, and their length is 17ft. 6in. The main shell is 3ft. in diameter, 23ft. long, and its axis is 11ft. 10½in. from the ground. It will be seen that it is suspended from the two girders, G₁ and G₂, Fig. 43. For the purpose of cleaning the boiler there are three cleaning-doors (C D) built in the masonry, and large enough for a man to enter through. When the inside of the tubes is to be cleaned, the door in front of the boiler is opened, and the mudholes at each end of the tubes are removed, thus enabling the man to see right through when a lamp is placed at the opening of the other end of the tube. The thickness of the masonry is 1ft. 6in., and the distance between opposite walls, which are lined with fire-brick, is 8ft. 3in.

It will be seen that the gases only circulate twice
round the tubes. Rising from the grate, they pass through the spaces left between the front part of the tubes, and strike the main shell, then descending, strike that part of the tubes which lies between the partition on the top of the bridge and the back end connections. An underground channel carries the gases from all the fails, by a donkey-pump. The boiler is provided with one pressure-gauge, two water-gauges, one dead-weight safety-valve, and a stop-valve. The total heating-surface of each boiler is about 1,000 square feet; the grate being 6ft. long by 3ft. 2in. wide, the grate-surface is 19 square feet.

boilers into the chimney. A damper (D), which can turn round a horizontal axle, is placed on the top of the flue, which carries the gases to the underground channel. The opening left by the damper for the passage of the gases can be regulated from the front of the boiler by moving a lever not shown in the drawings. The water is pumped into the main shell by an injector, and if this

Another kind of water-tube boiler is illustrated in Figs. 47, 48, and 49, which show longitudinal section, cross-section, and front view respectively. The tubes are here horizontal, and their diameter may be 2ft. or more. The tubes are placed in three horizontal rows, and the water circulates from the one row to the next through a number of vertical connecting tubes.
Below is a mud-drum, the object of which is the same as that in the preceding boiler. The flues are arranged in a wheel draught, the gases circulating first round the lowest set of tubes, then round the second set, and last round the top set, where they also help to dry the steam, the temperature of the gases being then so low that the part of the shell bounding the steam-room cannot become red-hot. A steam-dome above connects the steam-rooms of the three top shells. The steam-valve, as well as two safety-vaies, are mounted on the dome, which is also provided with a manhole. Manholes or mudholes are also provided at the front of each tube and in the mud-drum.

Vertical Boilers.

Vertical boilers are only used for producing small quantities of steam, and are handy where economy of space has to be considered. They consist of a cylindrical barrel, the axis of which is vertical. They have an internal firebox, the sides and crown of which act as heating-surface. As vertical boilers have a comparatively small water-surface and a high water-room, they are apt to prime.

Vertical Boilers with Water Tubes.—The heating-surface of these boilers is increased by a number of water-tubes passing through the firebox.

A vertical boiler with water-tubes is shown in Figs. 50 and 51, and is constructed by Messrs. R. Garrett and Sons. The water-tubes are not quite horizontal, which has the advantage of allowing the better escape of the steam and heated water from the tubes, and thus promoting the circulation of the water. There are only three tubes, the internal diameter of which is 8 in.; a mudhole is placed in front of each tube, thus permitting thorough cleaning without much trouble. The crown of the firebox is stayed to the crown of the boiler by the vertical uptake.

The height of the boiler, including uptake, is 9 ft. 9 in., and its external diameter is 3 ft. 6 in. The thickness of the boiler shell is 3 in. There is one manhole 10 in. by 14 in., and seven mudholes 3 in. by 4 in. The firebox shell is 3 in. thick. The draught can be regulated from outside by lifting or lowering the damper, and thus closing, more or less, the opening between the firebox and the uptake. The grate-surface is 7 square feet, and the total heating-surface is 73 square feet. The average rate of consumption of coal is about 9 lb. to 10 lb. per hour per square foot of grate-surface. The material used for all parts of this boiler is Siemens-Martin steel. The gases rising from the grate will strike the water-tubes, and thus be broken up and deflected towards the sides and crown of the firebox. The damper will also act as a deflector. The temperature of the gases when flowing through the uptake must not be so high as to make red-hot that part which passes through the steam-room; this part of the uptake will act as a steam drier.

A vertical water-tube boiler made by Messrs. John Musgrave and Sons, of Bolton, is shown in Figs. 52 and 53. It has 120 tubes of 2 in. diameter, and 3 ft. 5 in. long;
they are made of wrought iron and are lap-welded. The tubes are placed in 12 horizontal rows, with 10 tubes in each row. It will be seen that the tubes in any row are placed at right angles to the tubes in the rows below and above, thus forming a complete network for the purpose of breaking up the gases and deflected into the tubes: a circulation is thus produced. The tubes are fixed by expanding the ends in the tube-plate holes. The boiler is 9ft. high and 5ft. inside diameter. The main shell is welded and is made of steel plates \( \frac{3}{16} \)in. thick, the crown being \( \frac{1}{4} \)in. thick. For the purpose of cleaning the inside of the tubes the

deflecting them to the sides. As the tubes are horizontal, the heated water and the steam produced inside the tubes would have difficulty in escaping from them; it is therefore necessary to promote circulation in another way. This is done by placing a deflector, \( N \), at one end of each row of tubes, whereby some of the water, while rising in the boiler, will be caught and shell is made in two parts, having a joint 3ft. 5in. from the base of the boiler. This joint is faced, and the two parts of the shell are connected by 68 bolts 4\( \frac{1}{2} \)in. in diameter. The crown of the shell is further fixed to the uptake, as shown in the drawing, by 26 bolts 1\( \frac{1}{2} \)in. in diameter.

Fig. 54 shows the upper shell removed for cleaning,
and Fig. 55 shows the external appearance of the boiler. The soot and ashes which are collected on the tubes are blown off by steam jets, produced by letting steam into the hollow ball, B, which has a number of nozzles screwed in like a porcupine.
The pipe, P, which is connected at the one end to the ball, and at the other end to the combination casting, C, carries the steam from the steam-room into the ball. There are four mudholes, 8\(\mathrm{in.}\) by 3\(\mathrm{in.}\) at the bottom of the shell, for the purpose of removing the sediment.

The grate-surface is 15.5 square feet, and the total heating-surface is 344 square feet; 15\(\mathrm{lb.}\) to 18\(\mathrm{lb.}\) of coal may be burnt per square foot of grate-surface per hour.

The Field Boiler, Figs. 56 and 57, is also a vertical water-tube boiler; the tubes are, however, of a peculiar construction, known as the Field Tube, and named after the inventor, Mr. Edward Field. Fig. 56 shows the Field tube in section. The tube-plate of the boiler is square, with corners of 3\(\mathrm{in.}\) radius; its inside dimensions are 3\(\mathrm{ft.}\) 4\(\mathrm{in.}\) by 3\(\mathrm{ft.}\) 3\(\mathrm{in.}\) high, and it is made of steel plates \(\frac{7}{8}\)in. thick. The firebox crown is stayed to the boiler crown by the cylindrical uptake, which is 20\(\mathrm{in.}\) inside diameter, and made of steel plate \(\frac{3}{8}\)in. thick. The tensile strength of the steel used in this boiler is 28 tons, with an elongation of 20 per cent. in 8\(\mathrm{in.}\), is drilled with a hole of required taper to suit the expanded end of the outer tube; the latter is a lap-welded tube, which hangs down into the fire from the tube-plate, the pressure of the steam tending to keep it always tight; it supports on its top the edge of the inner tube, which is open at both ends, and provided with a cone-shaped deflecting top. The effect of
this combination is to produce a natural and powerful circulation of the water, due to the fact that the hottest water in a boiler is always that near the heating-surface.

The boiler consists of an outer cylindrical shell, and an inner cylindrical firebox, the crown of which serves as tube-plate for a number of Field tubes. The two shells are connected with stay-bolts, and at the fire-door by a caulking ring. They are connected at the bottom to a flat ring by angle iron rings. The firebox is divided into two parts by the iron-plate partition, lined with firebrick. This partition acts as a bridge. The flues are arranged as a "down draught," and the masonry is lined with firebrick. The crown of the firebox is stayed to the crown of the boiler shell by a number of suspension stays. The ashpit is formed keeping the thin outer tube tight in the hole made in the tube-plate.

Field tubes are also often adapted in existing boilers, and can be introduced into the cylindrical flues of Cornish and Lancashire boilers. Being only fixed at one end, they do not assist in strengthening the cylindrical flue, as is the case with the Galloway tubes.

Vertical Boilers with Flue-Tubes.—The heating-
surface of this class of boilers is increased by a number of flue-tubes, similar to those used in locomotive and other multibular boilers.

Figs. P and Q are illustrations of Messrs. Davey, Paxman, and Co.'s Essex boiler. The gases rising from the grate strike the crown of the firebox and flow through a cylindrical neck into the combustion chamber, are made of wrought iron, are lap-welded, and expanded in the tube-plate holes, thickness of material being No. 11 B.W.G., and their diameter is 2½ in. The removal of a tube and the fixing of a new one is done through the doorway to the combustion chamber. The firebox is also made of steel plates ½ in. thick. The material used for the smoke-box is cast iron, of which where the combustion is completed. The combustion chamber is shut from outside by a door lined with firebrick, and is partly bounded by the curved tube-plate. The gases pass from the combustion chamber through 38 flue-tubes into the smoke-box, whence they pass through the uptake and escape by the chimney. The boiler shell is 8 ft. 2 in. high and 3 ft. 4 in. diameter. It is made of steel, thickness of plate being ½ in. The tubes the standpipe on the top of the boiler is also made. The manhole ring as well as the manhole cover are made of wrought iron. Steam-valve and safety-valve are mounted on the standpipe. There are four mudholes equally divided round the bottom of the shell. The tensile strength of the steel used for the shell is 28 tons, with about 24 per cent. elongation, and that used for the firebox is 25 tons, with an elongation of
28 per cent. The total heating-surface is 84·5 square feet, and the grate-surface is 5·84 square feet. The working pressure is 75 lb. per square inch.

A vertical multitubular boiler made by Messrs. Ransomes, Sims, and Jefferies, of Ipswich, is shown in Figs. 58 and 59. The firebox is connected with the combustion chamber by 20 short flue-tubes, and from this 37 tubes lead the gases to the smoke-box.

The diameter of the tubes is 2½ in.; they are made of wrought iron and lap-welded. The material used for the boiler shell, firebox, combustion chamber, and manhole ring is Siemens-Martin mild steel. The height of the boiler is 8 ft. 3 in., and its outside diameter is 8 ft. 5½ in. The firebox and boiler shell are jointed at the bottom by a Z iron ring, and at the fire-door by a thick caulking ring. There is one manhole at the crown of the boiler, and four handholes are placed at different parts of the shell for the cleaning of the fire-box shell. The outside plate of the combustion chamber is lined with firebrick. The grate-surface is 6·8 square feet; the total heating-surface is 111·5 square feet, the heating-surface of the tubes being 76·81 square feet. Eleven pounds of best Welsh coal may be burnt per square foot of grate-surface per hour, and 10·2 lb. of water are supposed to be evaporated from and at 212 deg. F. per pound of Welsh coal.

The material which is used in making boiler shells and internal flues is either wrought iron or mild steel. Wrought iron combines great tensile strength and ductility; it can be forged, welded, rolled, and flanged, which are necessary properties in material to be used for boilers. When wrought iron is hammered, flanged, punched, or otherwise worked when cold, its tensile
strength increases; but at the same time its ductility diminishes. Annealing, however, brings the material back to its former state; for this reason wrought-iron plates and bars which have been worked cold should be annealed before being used for boiler-making. The tensile strength of wrought-iron plates is greatest when the fracture is at right angles to the direction of rolling, and least when the fracture is parallel to that direction. The tensile strength of wrought-iron plates with the fibres is about 21 tons per square inch, and when the fracture is parallel to the fibres the tensile strength is about 18 to 19 tons per square inch. The most suitable wrought iron for boilers is that in which in the testing machine gives the greatest elongation before breaking, combined with the greatest tensile strength. Great elongation or great contraction of sectional area are signs of great ductility.

The softer kinds of steel—so-called mild steel—approach wrought iron in character, and can be welded, flanged, rolled, etc. Its tensile strength, however, is greater than that of wrought iron. Steel conceals faults more than wrought iron, and varies more in quality. It is also more liable to be injured from overheating, and great care has to be taken when working steel in the fire.

Hammering, flanging, and rolling are also more injurious to steel than to iron. Annealing, however, will remedy the faults. Steel plates are stronger with the fibres than across the fibres. The tensile strength of steel plates used for boilers is from 25 to 30 tons per square inch, with an elongation of 20 to 28 per cent. in test-strips of 8 in. to 10 in. long.

On account of the greater strength of the material, steel shells can be made thinner than iron shells, thus securing better riveting and less corrosion from the fire.

Casting iron is as strong as wrought iron when subject to pressure, but is very much weaker under tension. It is very brittle, and is liable to internal stress, in consequence of its contraction while cooling. It is therefore not fit to be used as boiler material.

Copper has sometimes been used for boiler construction. Its tensile strength is smaller than that of iron, but it has a greater conductivity for heat, and can therefore stand intense heat better than iron. For this reason it is often used for making fireboxes for locomotive boilers, where the temperature of the fire is greater than in ordinary boilers. Copper also resists corrosion better than iron.

Boiler shells are built up of a number of cylindrical rings, which fit alternately inside or outside into the neighbouring ones, and are joined by riveting. Each ring is made of wrought-iron or steel plates, which have been curved in the plate-bending machine to the required radius. The plates are then joined, either by welding, or more frequently by riveting. If the latter process be used, it will be necessary to bring the edge of the one plate to bed close against the other, in order to make a tight joint. For this purpose the edges of the plates are planed to a bevel before bending. When the joint is completed, the bevelled edge of the plate is fullered with a broad flat tool, whereby a tight joint is secured. Before the planing of the edges was introduced, it was customary to close the joint by caulking, that is, to bring the edge against the plate by means of a thin tool, like a chisel. By this process an extra strain is liable to be thrown on the rivets.

Rivet Joints.—Rivets used in boiler-making are made either of best wrought iron or of best mild steel. When
into blooms; they are then rolled down into rivet iron. The rivet bars, whether made of wrought iron or mild steel, should be tested for tensile strength and elongation. The tensile strength should be from 26 to 30 tons per square inch, and the elongation in 10 in. should not be less than 25 per cent. The iron is then taken to the rivet-making machine, where it is cut into the proper length, and each piece, when red-hot, is placed in a die, where it is subjected to compression by which the head is formed. The head of rivets used for boilers is generally cup-shaped, as shown in Fig. 60. The diameter of the rivet is made a little smaller than that of the hole in the plate, but, after riveting, the two diameters are supposed to be the same, the body of the rivet having been compressed so much that it fills up the entire hole. The process of riveting consists in forming the second head while the rivet is red-hot and is placed in the hole. This can be done either by hand or by machinery. In the first case the rivet must be held in the hole by letting it rest on a heavy receiving die held by one man, while two other men working with hammers form the second head, the shape of which is shown in Fig. 61; it is often finished by the use of a hollow die—the shape of the head will then be more like a cup. Machine riveting, however, gives a better result than hand riveting, as greater pressure can be produced, and the rivets will therefore fill up the holes more completely. The rivet is held in the hole by a receiving die placed inside the shell, whereas the heading die is moved backwards and forwards by the machine, thus squeezing the rivet, whereby the second head is formed. The pressure, which must be adjusted according to the diameter of the rivet, is produced either by a hydraulic head or by an arrangement of levers and weights. Fig. 62 shows the form of rivets used in machine riveting.
The rivet holes are either punched or drilled, but the former process does not give such a good result as the latter. In punching the plates, the metal surrounding the hole will be compressed, and this weakens the plates. Plates which are punched should therefore be annealed, at any rate if they are of steel. Another objection to punching is the difficulty in bringing the holes which have to receive the same rivet to agree; the holes have therefore to be bored out by a ryer. The old-fashioned way of bringing the holes opposite to each other by means of a taper steel drift should be avoided, as it often causes fractures in the plates which are not easily discovered. Until a comparatively recent date, the universal practice was to punch the plates, and this before they had been bent to the proper radius; but since the introduction of high pressure steam, boiler-makers have found it necessary to improve the manufacturing of the various parts which constitute a boiler, and it is especially since steel plates have come into use that punching has been entirely substituted by drilling in good boiler-making. In fact, the Board of Trade require that steel plates should be drilled; assent may, however, be given for the plates to be punched, but then the particulars of the punching and annealing should be submitted to the Board for consideration.

The Board of Trade rules only refer to marine boilers and engines for passenger steamers, there being no rules for land boilers; but there is no reason why the same rules should not be adhered to in all cases.

In boilers which are to be worked at low pressure punching is still used, as this process is much cheaper than drilling.

Rivet joints may either be lap-joints, Figs. 63, 64, and 65, or butt-joints, Figs. 66 and 67, according to whether the two plates lap over or meet abut.

The following symbols will be used in dealing with riveted joints:

- \(d\) diameter of rivet, which is supposed to be the same as that of the hole after riveting is completed.
- \(\delta\) thickness of plate.
- \(\delta_1\) thickness of strap or straps in butt-joints.
- \(p_1\) pitch of rivet—i.e., distance between centres of two
consecutive rivets in the same row parallel to the edge of the plate.

\( p_2 \) smallest distance between centres of two rivets belonging to two consecutive rows of rivets.

\( p_3 \) distance between centre of rivet and edge of plate.

\( T \) original tensile strength of boiler-plate in pounds per square inch—that is, the tensile strength of the test-strip.

\( T_1 \) apparent tensile strength of boiler-plate in pounds per square inch—that is, the tensile strength of the plate as it appears to be when testing the completed joint in the testing machine.

\( S \) original shearing strength of rivet iron or rivet steel in pounds per square inch.

\( S_1 \) apparent shearing strength of rivet iron or rivet steel in pounds per square inch.

\( C \) bearing pressure—that is, the pressure on the rivet tending to crush the rivet or that part of the plate which surrounds the rivet hole.

\( \eta \) ratio of shearing strength of rivet to tensile strength of plate.

\( \phi \) efficiency of joint—that is, the ratio of strength of joint to that of the full boiler-plate.

\( n \) number of rivets in one row.

When, however, the joint is tested, the apparent tensile strength of the plate is found to be less than that of the drilled plate, the reason being that the pulling forces, not acting in the same line, will bend the plates, whereby a bending stress, in addition to the tensile stress, will be thrown on the plates.

For the same reason the rivets are also subject to a bending stress, with the result that the apparent shearing strength of the rivets in a joint is smaller than the original one. The diminution in the shearing strength has further been found to be greater in joints with drilled holes than with punched holes, the reason being that the sharp edges of the drilled holes have a greater shearing effect on the rivets than the more blunt edges of the punched holes. By rounding the edges of drilled holes the shearing effect is diminished.

It is evident that in calculating the resistance of a joint the strength of the material as it appears in an actual joint should be taken. The values in the following table are taken from Professor Unwin:

<table>
<thead>
<tr>
<th>Material</th>
<th>( T ) mean</th>
<th>( T_1 )</th>
<th>( S )</th>
<th>( S_1 ) when holes are</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron plates</td>
<td>46000</td>
<td>0.88</td>
<td>0.85</td>
<td>0.8 T</td>
</tr>
<tr>
<td>Steel plates</td>
<td>62000</td>
<td>1.00</td>
<td>1.06</td>
<td>0.8 T</td>
</tr>
<tr>
<td>Iron rivets</td>
<td>62000</td>
<td>...</td>
<td>...</td>
<td>0.8 T</td>
</tr>
<tr>
<td>Steel rivets</td>
<td>66000</td>
<td>...</td>
<td>...</td>
<td>0.8 T</td>
</tr>
</tbody>
</table>

A. Drilled  B. Punched.
In lap-joints and butt-joints with single cover, the rivets are sheared in one plane only; such joints are therefore called single-shear joints. In butt-joints with double cover, the shearing takes place in two planes, and the joints are therefore double-shear joints. In a well-designed joint the shearing resistance of the rivets should be equal to the tearing resistance of the plate along the line of fracture.

The shearing resistance of the rivets in a single-shear joint will be—for single-riveted joints
\[ n \times \frac{\pi d^2}{4} \times S_1 \]  
for double-riveted joints
\[ 2n \times \frac{\pi d^2}{4} \times S_1 \]

The tearing resistance of the plates in single-riveted, as well as in double-riveted joints, will be
\[ n(p_1 - d) \times \delta \times T_1 \]

By equating (1) and (3) we shall have for single-riveted joints
\[ p_1 = d + \frac{\pi}{4} \times \eta \times \frac{d^2}{\delta} \]

by equating (2) and (3) we shall have for double-riveted joints
\[ p_1 = d + \frac{\pi}{4} \times \eta \times \frac{d^2}{\delta} \]

where \( \eta = \frac{S_1}{T_1} \).

The tearing resistance of the full plate is \( n \times p_1 \times \delta \times T_1 \); it is evident that the efficiency of the joint will be
\[ \phi = \frac{n \times (p_1 - d) \times \delta \times T_1}{n \times p_1 \times \delta \times T} = \left(1 - \frac{d}{p_1}\right) \frac{T_1}{T} \]

for both single and double riveted joints.

In the following tables, the holes are assumed to have been drilled in the plates, and the values of \( T, T_1, S_1 \), and \( T_1 \) are taken from the preceding table.

The table A shows that double-riveted joints are stronger than single-riveted ones, and it will further be seen that the pitch of the rivet and the efficiency of the joint depend upon \( d, \frac{d^2}{\delta}, \text{and} \frac{d}{\delta} \); we must therefore have formulae by which these quantities can be found.

In calculating the above table the possibility of the rivet or the plate surrounding the rivet hole being crushed has not been taken into account, nor have we examined the resistance of the plate against being torn between the rivet hole and the edge of the plate. The latter, however, will be great enough if we make \( p_1 = 1.5d \).

### Table A.

<table>
<thead>
<tr>
<th>Single riveted joints.</th>
<th>Double riveted joints.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_1 )</td>
<td>( T_1 )</td>
</tr>
<tr>
<td>( p_1 )</td>
<td>( p_1 )</td>
</tr>
<tr>
<td>( \phi )</td>
<td>( \phi )</td>
</tr>
<tr>
<td>Iron plates with iron rivets.</td>
<td>1.06</td>
</tr>
<tr>
<td>Iron plates with steel rivets.</td>
<td>1.21</td>
</tr>
<tr>
<td>Steel plates with iron rivets.</td>
<td>0.69</td>
</tr>
<tr>
<td>Steel plates with steel rivets.</td>
<td>0.79</td>
</tr>
</tbody>
</table>

If the pressure—the bearing pressure—between the rivet and the plate is too great, the effect will be to make the joint loose. The resistance of the joint to withstand this pressure depends upon whether the bearing area, \( d \times \delta \), which supports the pressure is large enough. We ought, therefore, to have, in a well-designed joint, the maximum crushing force allowed on the rivet equal to shearing resistance, or for single-shear joints

\[ \frac{\pi}{4} \times \frac{d^2}{\delta} \times S_1 = d \times \delta \times C, \]

which gives

\[ \frac{d}{\delta} = 1.27 \times \frac{C}{S_1}. \]

As a result of experiments on riveted joints, Professor Kennedy has found that the intensity of bearing pressure on the rivets exercises a very important in-
fluence on their strength. So long as it does not much exceed 40 tons per square inch on steel rivets it does not seem to affect their strength, but pressures of 50 to 55 tons per square inch seem to cause the rivets to shear at stresses varying from 16 to 18 tons per square inch.

We may therefore allow \( \frac{C}{S_1} = 2 \) in single-shear joints, where \( S_1 \) is taken from the table on page 105, so that we have for steel as well as for iron rivets

\[
\frac{d}{\delta} = 2.54 \quad \ldots \quad (7)
\]

The diameter of the rivet may be found from the following rule,

\[
d = 1.2 \sqrt[3]{\delta} \quad \ldots \quad (8)
\]

which is due to Professor Unwin. The two formulae (7) and (8) combined require \( \delta \geq 0.22 \text{in.} \). This is, however, within the limits used with boilers.

By eliminating \( \delta \) between (7) and (8) we have

\[
\frac{d^2}{\delta} = 1.44 \quad \ldots \quad (9)
\]

Formula (8) may also be written thus:

\[
\frac{d^2}{\delta} = 1.44 \quad \ldots \quad (10)
\]

We can now, by means of (7), (8), and (10) and the above table, find \( p_1 \) and \( \phi \) of single-shear joints.

According to the Board of Trade rules we must have—

\[
p_1 = 2d \quad \ldots \quad (11)
\]

for chain joints (see Figs. 74 and 75), and for zig-zag joints (Fig. 76)—

\[
p_1 = \frac{6p_1 + 4d}{10} \quad \ldots \quad (12)
\]

It is necessary that \( p_1 \) should be greater than twice the diameter of the rivet head, or, according to Figs. 71 and 73, we must have \( p_1 > 3.6 \times d \) or \( 38 \times d \). It is therefore possible that the table on page 106 will give us values for \( p_1 \) which are too small. In such cases we must make \( \frac{d^2}{\delta} > 1.44 \). Suppose we make it equal to \( a \), then as \( \frac{d}{\delta} = 2.54 \) we must have \( \delta \geq \frac{a}{6.54} \).

Formula (6) shows that the strength of the joint increases by making \( \frac{d}{p_1} \) small. In boilers it is, however, necessary that the joints should be water and steam tight, and \( \frac{d}{p_1} \) cannot therefore be made so small as in girders.

The shearing resistance of the rivets in double-shear joints will be—for single-riveted joints

\[
p \times 2 \times \frac{\pi d^2}{4} \times S_1 \quad \ldots \quad (13)
\]

and for double-riveted joints

\[
2n \times 2 \times \frac{\pi d^2}{4} \times S_1 \quad \ldots \quad (14)
\]

The tearing resistance of the plates in single-riveted, as well as in double-riveted joints, will be

\[
n \left( p_1 - d \right) \delta T_1 \quad \ldots \quad (15)
\]

By equating (13) and (15) we shall have for single-riveted joints

\[
p_1 = d + \pi \times \frac{d^2}{\delta} \times S_1 \quad \ldots \quad (16)
\]

and by equating (14) and (15) we find that the pitch for double-riveted joints will be

\[
p_1 = \frac{d + \pi \times \frac{d^2}{\delta} \times S_1}{T_1} \quad \ldots \quad (17)
\]

The efficiency of both kinds of joints will be

\[
\phi = \frac{n (p_1 - d) \delta T_1}{n p_1 \delta T} = \left( 1 - \frac{d}{p_1} \right) T_1 \quad \ldots \quad (18)
\]

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
 & Single-riveted double-shear joints. & \\
\hline
 & \( S_1 \) & \( T_1 \) & \( p_1 \) & \( \phi \) & \\
\hline
\multirow{2}{*}{Iron plates with iron rivets.} & 0.82 & \( d + 1.29 \times \frac{d^2}{\delta} \) & \( 1.14 \times \frac{d}{\delta} \) & \\
\multirow{2}{*}{Steel plates with iron rivets.} & 0.53 & \( d + 0.83 \times \frac{d^2}{\delta} \) & \( 0.83 \times \frac{d}{\delta} \) & \\
\multirow{2}{*}{Steel plates with steel rivets.} & 0.61 & \( d + 0.96 \times \frac{d^2}{\delta} \) & \( 0.96 \times \frac{d}{\delta} \) & \\
\hline
\multirow{2}{*}{Double-riveted double-shear joints.} & & & & \\
\multirow{2}{*}{Iron plates with iron rivets.} & 0.75 & \( d + 2.36 \times \frac{d^2}{\delta} \) & \( 2.24 \times \frac{d}{\delta} \) & \\
\multirow{2}{*}{Steel plates with iron rivets.} & 0.50 & \( d + 1.66 \times \frac{d^2}{\delta} \) & \( 1.66 \times \frac{d}{\delta} \) & \\
\multirow{2}{*}{Steel plates with steel rivets.} & 0.58 & \( d + 1.93 \times \frac{d^2}{\delta} \) & \( 1.93 \times \frac{d}{\delta} \) & \\
\hline
\end{tabular}
\end{table}

Professor Kennedy finds that in double-shear joints it is impossible to develop the full shearing resistance of the joint without getting excessive bearing pressure, because the shearing area is doubled without increasing the area, \( d \times \delta \), on which the pressure acts.
Let us assume a maximum bearing pressure of 50 tons per square inch on steel rivets, then the shearing will probably take place at 17 tons per square inch. We have thus increased the bearing pressure allowed in formula (7) from about 43 tons to 50 tons, and at the same time we have reduced the shearing strength from 22 tons to 17 tons per square inch, or to 77 per cent.

of the former value. We can, therefore, take $\frac{C}{S_1}$ equal to three in double-shear joints. As the maximum crushing force should be equal to the shearing resistance of the rivets, we must have

$$d \times \delta \times C = 2 \times \pi \frac{d^2}{4} \times S_1 \ldots (19)$$

or,

$$\frac{d}{\delta} = \frac{2}{\pi} \times \frac{C}{S_1};$$

and as

$$\frac{C}{S_1} = 3,$$

$$\frac{d}{\delta} \approx 1.9 \ldots \ldots (20)$$

Therefore, as long as $\delta \approx \frac{4}{in.}$, we may take

$$\frac{d}{\delta} = 1.35 \ldots \ldots (21)$$

By eliminating $\delta$ between (12) and (13) we have

$$d \approx 0.71,$$

or say $\frac{3}{in.} \ldots \ldots (22)$

$p_s$ should be taken from (11) and (12), on page 107.

In the table B, the values of $T_1$ are the same as in the table on page 106, but the shearing strength of the rivets has been reduced to 77 per cent. of the values given in that table, in accordance with what has been explained above.

From a theoretical point of view, the thickness, $\delta_1$, of butt straps should be for single-shear joints equal to $\delta$, and for double-shear joints equal to $\frac{\delta}{2}$; but it has been found by experiment that this is not sufficient. In practice, therefore, the thickness of single straps is taken as

$$\delta_1 \approx \frac{9}{8} \times \delta,$$

and for double straps, $\delta_1 \approx \frac{5}{8} \times \delta.$

Butt straps should be cut from plates, and not from bars, and should be of as good a quality as the shell-plates, and for the longitudinal seams they should be cut across the fibre.

**Plate Thickness ($\delta$) of Boiler Shells and Cylindrical Flues.**—For the purpose of calculating the strength of the various parts of the boiler we must consider the following cases separately:

A circular cylinder, subject to fluid pressure acting on its inside surface.

A semi-sphere, subject to fluid pressure acting on its inside surface.

A flat surface, subject to fluid pressure.

A circular cylinder, subject to fluid pressure acting on its outside surface.

(1) In the first case, where we have a cylinder acted upon by a pressure from inside, the cylindrical form will not be changed. The pressure, however, will tend to fracture the shell, partly in a plane at right angles to the axis of the shell, and partly in a plane through this axis.

The first-named fracture would be caused by the total steam pressure acting upon the end-plates of the shell. This pressure is evidently equal to

$$\frac{\pi \frac{D_b^2}{4}}{T} \times p_s \ldots \ldots (23)$$

The resistance of the material which the pressure has to overcome is

$$\pi D_b \times \delta \times T \ldots \ldots (24)$$

where $T$ is the tensile strength of the boiler plate across the grains. The value of $\delta$, which we would obtain by equating (1) and (2), would be that at which the boiler would burst. It is therefore evident that we must not take the whole value of $T$, but only a fraction thereof.

We shall therefore have

$$\frac{\pi \frac{D_b^2}{4} \times p_s}{T} = \pi D_b \times \delta \times \frac{T}{f_s} \ldots \ldots (25)$$

$f_s$ is called a safety factor, and is the pure number by which we must divide the ultimate strength of the material, in order to reduce the stress to a safe limit.

Equation (3) gives us—

$$\delta = \frac{D_b \times p_s}{4 \times \frac{T}{f_s}} \ldots \ldots (26)$$

The force which tends to fracture the shell in a plane through the axis of the shell will be

$$\frac{D_b \times L_b \times p_s}{f_s} \ldots \ldots (27)$$

where $L_b$ is the length of the shell. The resistance of the shell to withstand this force will be

$$2 \delta \times \frac{L_b}{f_s} \times \frac{T}{f_s} \ldots \ldots (28)$$

where $T$ is the tensile strength of the plate with the grains. By equating (5) and (6) we obtain

$$\delta = \frac{D_b \times p_s}{2 \times \frac{T}{f_s}} \ldots \ldots (29)$$

As the tensile strength with the grains is greater than that across the grains, it will be seen that $\delta$ found from (7) will be almost twice that found from (4), $f_s$ being the same in both formulae. If, therefore, the boiler shell is strong enough to prevent a longitudinal fracture, it will also be able to withstand the pressure on the end-plates. For the same reason the longitudinal joints of a boiler shell should be double-riveted butt-joints, with double covers, whereas the joints, connecting two consecutive rings, will be strong enough if either single or double-riveted lap-joints, according to the stress to which they are subjected.
It is evident that we must not have the longitudinal joints of any two shell rings in the same line, as the boiler would then be unnecessarily weakened.

Let $\phi'$ be the efficiency of the longitudinal joint, then we must have

$$\delta \times L_r \times \frac{T}{f_s} \times \phi' = \frac{1}{2} \times D_b \times L_r \times p_e \qquad (43)$$

Where $L_r$ is the length of a shell ring, (43) will give us—

$$\delta = \frac{D_b \times p_e \times f_s}{2 \phi'} \times \frac{T}{f_s} \qquad (44)$$

The lap-joint will be strong enough if

$$\delta \geq \frac{D_b \times p_e \times f_s}{4 \phi'} \times \frac{T}{f_s} \qquad (45)$$

where $\phi'$ is the efficiency of the joint.

The safety factor used by the Board of Trade is 5 for boiler shells made of best material, rivet holes drilled in place, and all longitudinal seams made with double-rivet butts-joints with two straps, and altogether of superior workmanship.

(2) The hemisphere is often used for end-plates for boiler shells or domes. The shape of the sphere, like that of a cylinder, is not altered by the inside pressure, and the stress in the material is the same at every point of the shell. Taking the diameter of the sphere as equal to that of the boiler shell or dome whose ends it is to close, we find that the force tending to fracture it along a diametrical plane is

$$\frac{\pi D_b^2}{4} \times p_e \qquad (46)$$

The resistance of the material will be

$$\pi D_b \times \frac{T}{f_s} \qquad (47)$$

where $\delta$ is the thickness of the material. By equating (46) and (47) we obtain

$$\delta = \frac{D_b \times p_e \times f_s}{4} \times \frac{T}{f_s} \qquad (48)$$

The plate thickness need not therefore be more than half that of the cylinder-plate; $f_s$ might be taken as 5 or 6.

Dished ends should, according to Board of Trade rules, be stayed as flat ends, but if they can be considered as portions of spheres, the stays may have a stress exceeding stays for flat ends. The ends of the domes in the boilers, Figs. 32 and 36, are dished, and supported by longitudinal stays.

(3) Fluid pressure acting upon flat surfaces tends to bulge the plate. Such plates must therefore be of small dimensions, or else they must be well stayed, so as to leave small distances between the supporting stays.

When a circular plate, fastened along its periphery, having a diameter $D$ and a thickness $\delta$, is acted upon by the effective pressure, $p_e$, then the greatest stress, $r$, in the material will be

$$r = \frac{1}{6} \times \frac{D^2}{\delta^2} \times p_e \qquad (49)$$

When a larger plate of thickness $\delta$ is supported by stay-bolts or longitudinal stays, and the distance between centres of consecutive stays is $a$, then the greatest stress on the plate will be

$$r = \frac{2}{9} \times \frac{a^2}{\delta^2} \times p_e \qquad (50)$$

The area supported by each stay will be $a$ square inches. Formula (49) and (50) are due to Grashof; the safe value of $r$ depends upon the construction of the stays, and whether the plates are exposed to the impact of heat or flame.

Stays used for supporting flat surfaces may be:

(a) Gusset stays, Fig. 69, which support the flat ends, $E$, of boilers by making connection with the cylindrical shell, B P. They are usually made of a single plate, G S, of iron or mild steel, the one end of which is riveted to the end-plate, $E$, and the other end to the boiler barrel, B P, by means of angle-iron. Gusset stays are generally used in Cornish and Lancashire boilers, see Figs. 26 and 33.

(b) Longitudinal stays, which are long iron or steel rods reaching from the one end of the boiler to the other, and supporting the flat surfaces of the end-plates by balancing the pressures to which they are exposed.

Longitudinal stays are generally screwed at both ends and fixed to the end-plates by nuts, as shown in Fig. 70, where $E$ is the end-plate of the boiler, L S the longitudinal stay; C$^1$ and C$^2$ are copper washers.
In multitubular boilers, some of the tubes are screwed at both ends and are provided with nuts; they act as longitudinal stays, supporting the flat tube-plates, and are therefore called stay-tubes.

The Board of Trade allow on solid steel screwed stays, which have not been welded or otherwise worked after heating, a working stress of 9,000 lb. per square inch of net section, provided the tensile stress is from 27 to 32 tons per square inch, and the elongation in 10 in., about 25 per cent., and not less than 20 per cent. This corresponds to a safety factor of between 6·7 and 8.

In the Garrett loco. boiler, Fig. 21, the longitudinal stays do not go through the plates; the end-plates are therefore not weakened by making holes in them. These connections are shown in detail in Figs. 71 and 72.

The stay-bolt, shown in Fig. 73, is that which is most commonly used. It is screwed at both ends, and riveted over the plates, to which it acts as a stay. Stay-bolts are made of wrought iron or steel; but in locomotive boilers, they are often made of copper, as this metal stands the intense heat of the fire better than the two other materials. In Fig. 73, B P stands for boiler-plate, F P for firebox-plate, and S B for stay-bolt.

(4) A circular cylinder, subjected to external pressure, will remain unaltered in shape, if the cross-section is a perfect circle, and there would be a uniform stress throughout the material. But a small deviation from the true circle will cause the cylinder to collapse at a comparatively small pressure.

The determination of the plate thickness by theoretical formulae would, therefore, be very complicated, and empirical formulae based upon reliable experiments must be resorted to.

The late Sir William Fairbairn made a series of experiments with tubes closed at both ends and exposed to external pressure, which latter was increased until the tube broke. He found that the bursting pressure did not only depend upon the diameter, D, of the tube and the plate thickness, \( \delta \), but also upon the length, \( l \), of the tube. The results of his experiments are expressed in the following formula:

\[
p_e = 806,300 \times \frac{\delta^{3.19}}{l \times D} \quad \ldots (51)
\]

where \( p_e \) is the effective collapsing pressure in pounds per square inch, \( l \) is given in feet, whereas \( D \) and \( \delta \) are in inches.

Fairbairn’s formula can be applied for finding the plate thickness of an internal circular flue. In order to obtain a suitable \( \delta \), it is necessary to divide the flue into short cylinders, joined together by strengthening rings or the like. \( l \), in formula (51), will then be the distance between two consecutive stiffening rings, and not the total length of the flue. We have seen that the plate thickness of a flue must be small, say, \( \frac{1}{2} \) in., in order to
prevent the plate from being burnt by the heat of the gases. We must therefore consider \( \delta \) as given, and find \( l \) from formula (51), using a safety factor of 10, \( l \) to be taken as the distance between the strengthening rings.

The flue rings are generally made of mild steel plates, but may also be made of best wrought iron. The plates are curved in the bending rolls to the required circle, and the two ends are bent into contact for the purpose of being jointed. As it is necessary that the ring should be as near as possible a perfect circle, it is evident that the joints must be very uniform; they should therefore either be welded or butt-jointed. If butt-joints are used, they should either be double-riveted with one strap, or single-riveted with double straps. The riveted joints, however, will be struck by the flame, and therefore have a tendency to be overheated; for this reason welded joints are preferable.

It is of great importance that the joints connecting consecutive rings of the flue should be designed so as to allow the flue to expand and contract longitudinally, this having a great bearing upon the strength and durability of the boiler. The joints should further be removed from the direct line of draught, so as to escape the scouring action and intense heat of the gases as they pass along the flue.

As examples of expansion flues, the following have been selected:

In Fig. 74 is shown the Paxman expansion boiler-flue. It consists of a series of short lengths, which are made of very ductile soft steel, the tensile strength being 28 tons, with about 28 per cent. elongation; or it may be made of best wrought iron. The rings are welded, and the ends are then heated in a furnace and enlarged in a flanging machine, in such a way that the end of one fits exactly within or without that of the next; the holes are then drilled in position through both, and the flue is completed by riveting. This construction allows the flue to expand freely, the rivets and the laps are outside the direct line of the flame, and the strength of the flue is considerably increased, by the diameter of the joint being greater than that of the flue rings. The boilers illustrated in Figs. 26 and 33 are provided with this expansion flue.

Fig. 75 shows section of an expansion-joint which is often used, the \( \Omega \)-shaped ring, E R, acting as a spring and at the same time stiffening the flue, FP. The rivets and laps, however, are in the direct line of the draught.

The flue plates, FP, may also be flanged at both ends, and then riveted together with a caulk ring, CR, between them, as shown in Fig. 76. It is evident that the joint in this case is outside the direct action of the flame.

A great improvement in expansion boiler-flues is the Fox’s corrugated furnace, which has already been shown in several boilers, Figs. 24, 32, and 36. It is made of Siemens mild steel, manufactured by the Leeds Forge Company, Limited, and is machine-rolled, so that the cross-sections are almost perfect circles. The advantages of this furnace are:

(a) The increased strength by the many corrugations allowing furnaces of varying diameters to be made of material \( \frac{3}{4} \) in. thick, and subjected to external pressure up to 200lb. per square inch. The Board of Trade allow the working pressure on corrugated furnaces to
be equal to \( \frac{12,500 \delta}{D} \) (where \( D \) is the mean diameter of the furnace in inches) provided that the plain parts at the ends do not exceed 6in. in length, and that the plates are not less than \( \frac{3}{16} \)in. thick. If the furnace is riveted in two or more lengths, see Fig. 77, the case should be submitted for consideration.

(b) An increased heating-surface of about 50 per cent., in addition to which the corrugated surface assists in breaking up the gases, thus absorbing more heat than flues with smooth surfaces.

(c) It possesses a higher degree of elasticity than the previously mentioned flues, and yet at the same time it is strong enough to act as a longitudinal stay. It is claimed that the corrugated furnace has the advantage of throwing off the scale and sediment due to its great elasticity.

(d) Uniformity of thickness, except where two or more lengths are jointed, as shown in Fig. 77.

When required, a flat space, see Fig. 77, may be inserted for a fusible plug. When cross tubes are required to be fitted into the flues, flat spaces are rolled on each ring for this purpose.

Another corrugated furnace, made by the Farnley Iron Company, Limited, is shown in Fig. 78. It will be seen that the corrugation follows a spiral. The application of this furnace to marine boilers is illustrated in Fig. 79.

Manholes and Mudholes.

The manhole is made in the boiler shell for the purpose of allowing a man to get inside the boiler, in order to inspect it. The hole is made oval for two reasons: partly in order to make the orifice as small as possible, and partly because the door could not be passed through a circular hole. The longest axis of the hole varies from 16in. to about 14 in., and the shortest axis from 13in. to 10in. In horizontal land boilers, the hole is made in the crown of the boiler barrel, the longest axis being parallel to the axis of the boiler. In marine boilers, the manhole is generally made in the end-plates, and its longest axis is then horizontal. For making it convenient to get inside a vertical boiler, the shortest axis of the hole is parallel to the axis of the boiler, the hole being made in the barrel.

As the shell is weakened by the large hole, it is evident that the part of the boiler-plate surrounding the hole must be strengthened. This may be done in two ways. In land boilers working with low steam pressure, a flat wrought-iron or mild steel ring, the compensating ring, riveted on the boiler-plate, may be considered sufficient. This ring is oval, and is of the same shape as the hole. It is thicker than the boiler-plate, and is about 8in. wide. The manhole is then closed by a cast-iron door, which fits inside the boiler-plate, against which it is tightened by one or two studs, the nuts of which rest on arched crossbars.

In marine boilers, that part of the end-plate, where the hole is made, is further strengthened by the aid of longitudinal stays, as shown in Fig. 73.

When the working pressure of the boiler is high, the flat compensating ring will not be sufficient to stiffen the plate surrounding the orifice; it is therefore substituted by a flanged saddle of mild steel, which is riveted on the boiler-plate, either inside or outside the barrel.

In Fig. 80, is shown an inside flanged saddle with an embossed door, made by Mr. M’Neil, of Glasgow. Both saddle and door are machined on the faces which meet, so that a good joint can be more easily obtained. With this arrangement of saddle and door, admission
to the boiler can be obtained much more rapidly than where outside saddles are used, with doors fixed by a large number of bolts, passing through the flanges of door and saddle, as shown in Fig. 81. A saving of time is also effected in using inside saddles when the door has to be closed, only two nuts having to be screwed up to make a joint. The pressure of the steam assists in keeping the joint tight, whereas in the outside saddle the whole strain is thrown on the bolts.

**Mudholes and their doors are made in the same way as manholes, but as they are smaller they have only one stud and one crossbar. In Lancashire and marine boilers, the mudholes in the end-plates underneath the internal flues may be as large as manholes. Mudholes are sometimes made circular and threaded; they are then closed by screwed plugs. The diameter of such holes is about 2½ in. Mudholes are placed in those parts of the boiler shell, where the removal of sediments would otherwise be difficult.**

**Water-Level Indicators.**

The height of the water level in a boiler may be indicated by means of either water-gauges or test-cocks.

The water-gauge shown in Figs. 82 and 83 is invented and made by Messrs. Dewrance and Co., of London. It has two horizontal arms, A and B, each provided with an asbestos-packed cock, which will be seen in section in Fig. 83, and each bolted to the end-plate of the boiler by means of three bolts (jin. diam.) through the flange. The nipple fits into the hole made in the boiler, and an asbestos washer being placed between the flange and the boiler-plate. Arm A must be fixed somewhat above the highest, and B somewhat below the lowest, water level; when, therefore, the two arm cocks are open, the hole in A will be passed by steam, and that through B by water. A strong glass tube is inserted between the two arms, the joints being made steam-tight by means of packed stuffing-boxes. When now the two arm cocks are opened, the water will stand in the glass at the same level as in the boiler. The passages through the arms are liable to get choked by impurities and dirt contained in the water, and the apparatus would in such cases not show the correct water level; it is therefore necessary to blow frequently through these passages. If, for instance, we want to try the passage through A, then we shut arm cock B and open the
Practical

An open blow-through cock; a steam jet will then pass through A and the glass, and thus clear the passage. In the same way we test passage through B by shutting arm cock A, and opening the blow-through cock. It may, however, happen that one or both passages are found to be choked, and thus require to be cleaned out. Let, for instance, the passage through A be stopped, then proceed as follows: (a) shut both arm cocks and open blow-through cock; (b) remove the screwed plug opposite the passage; (c) open arm cock A gradually while pushing a wire through; (d) when the passage is clear, shut arm cock A and put plug back; (e) shut blow-through cock and open both arm cocks.

The clearing of the passages under steam should, however, be avoided, and will never be necessary if done frequently before steam is up.

When the apparatus is in working order, the handles of all three cocks should be in the position shown in Fig. 82.

So far as described, this apparatus is in principle like other water-gauges, but differs from these by having a valve at the bottom and a valve-plug with a hole at the top of the glass. Should the glass break in an ordinary water-gauge, a steam jet will issue from the top opening, and a water jet from the bottom, and it is the water jet especially which makes it difficult to shut the two arm cocks. If the glass breaks in the apparatus here described, the water will lift the small ball-valve, which will shut the opening, and prevent the water from rushing out, thus making it safe to shut the arm cock B. On the other hand, the steam jet issuing through the valve-plug at the top will be harmless, on account of the small opening. The two valves can easily be taken out under steam, and inspected, by shutting the arm cocks, opening the blow-through cock, and removing the corresponding screwed plugs. A new glass can be inserted, by opening the two stuffing-boxes.

Most boilers are provided with two water-gauges, so that if the glass of the one breaks, the other gauge will indicate the water level.

Test-cocks are cocks fixed at various heights on the front of the boiler. One can find between which two cocks the water level must be, by opening the cocks in succession, and observing which give water and which give steam. The actual height of the water cannot therefore be determined in this way; but test-cocks having no glass tube cannot so easily get out of order, and if they get choked it is detected at once. The Board of Trade require that each boiler shall have at least three test-cocks.

The cock shown in Fig. 84 is fixed by tightening the nut against the boiler-plate, an asbestos washer being inserted between the outside of the plate and the shoulder of the cock.

Fig. 85 shows another kind of test-cock, which is fixed by three bolts to the boiler-plate.

The cleaning of the passage through the cocks is done in precisely the same way as has been explained with the water-gauge.

Pressure-Gauges.

The effective steam pressure can be measured by means of a column of mercury, the weight of which balances the pressure. The height of such column would, however, be too great with the present pressures at which steam boilers are worked.

A more handy instrument can be constructed by letting the steam pressure act on a spring, which will be bent more or less according to the intensity of the pressure; the movement of the spring is then multiplied and indicates the pressure. The two following instruments are made on this principle.

(1) Bourdon's gauge is shown in Figs. 86 and 87. The spring is a curved metallic tube, which is closed at the one end and fixed to a tap at the other end. The tube is of the flattened form, and its greatest width is in the direction perpendicular to the plane in which the tube is curved. The steam pressure which is communicated through the tap to the inside of the tube will tend to bulge the tube, whereby this will stretch. The motion
of the closed end of the tube is applied to turn a toothed sector, which again turns a pinion whose spindle carries a hand; the latter, pointing on a scale properly graduated, will indicate the effective pressure to which the tube has been subjected.

The gauges illustrated in Figs. 86 and 87 are made by the Crosby Steam Gauge and Valve Company. It will be seen that Fig. 87 works with two tubes.

(2) The Schäffer gauge is shown in Fig. 88; the pressure acts upon a corrugated diaphragm of steel, which will be bent more or less, according to the intensity of the pressure. The motion of the diaphragm is communicated to the hand, as in the Bourdon's gauge. The object of the watch-spring fixed to the hand-spindle is to keep the gearing parts in tension.

The calibration of pressure-gauges should be done under steam pressure by comparison with a standard gauge, the scale of which is graduated by comparison with a column of mercury.

These instruments may also be constructed to indicate pressures below the atmosphere, and are then called vacuum-gauges.

Safety Apparatus.

This class of boiler fittings is designed with the object of preventing—(a) the steam pressure from exceeding a certain limit, (b) the water from sinking below a certain level, and (c) the flues from being damaged should the water fall too low.

Safety-Valves.—An apparatus of this kind consists simply of a loaded valve, which will be lifted when the pressure on the valve is high enough to overcome the load; the latter may be produced either by weights or by springs.

(a) The valve may be loaded direct by a weight, and is then called a dead-weight safety-valve. A valve of this class, made by Messrs. Galloway, Limited, is illustrated in Fig. 89. B is the boiler shell, N the neck on the boiler, to which the apparatus is fixed, N_1 is a cast-iron pipe, which carries the gunmetal valve-seat, V S, on which the valve, V, rests; this latter forms part of a sphere and is also of gunmetal. The load is composed
of several cast-iron weights, W. When the steam pressure is sufficiently high, the valve will be lifted together with the weights, and steam will escape between the valve and the valve-seat, and then by the openings at the top into the atmosphere. Dead-weighted valves should always be provided with a lift-lever, by which the weights can be lifted in order to test the valve.

For the purpose of preventing the engineer or stoker from tampering with the valve, safety-valves are often enclosed in a case and locked up, as shown in Fig. 90; the lifting lever is outside the case. (b) Safety-valves may also be loaded direct by springs, as illustrated in Fig. 91; the lifting lever is shown on the right-hand side at the top of the drawing. Such valves with their springs may also be enclosed in a case.

When valves are loaded with springs, their construc-
tion should be such that the valve cannot fly off if the spring should break.

(c) Ramsbottom's safety-valve for loco. boilers, and made by Messrs. Robey and Co., is shown partly in section in Fig. 92. It will be seen that this is a double safety-valve; the valve $V_1$ is shown in section, the other, $V_2$, is hidden inside the neck, $N_2$. When the steam pressure is high enough, the two valves will be lifted simultaneously, and the spring, $S_g$, will thereby be compressed. By means of the lever, $L$, the valves can be tested, and should the driver accidentally or intentionally put a weight on the lever, $L$, the result will be to relieve valve $V_1$ from some of its load, and the steam will blow off through $V_1$ at a lower pressure than intended.

Fig. 93 shows valve-pin, $V_P$, for $V_2$, and Fig. 94 represents the spring-bolt, $S_B$.

The working pressure, $p_e$, at which direct loaded valves will be lifted, is given as follows: Let $W$ be the load in pounds, including weight of valve, $a$ the area in square inches on which the pressure acts, then

$$p_e = \frac{W}{a}$$  \hspace{1cm} (52)

\(a\) The load may act indirectly on the valve by means of a lever. In Fig. 95 is shown a double-lever

\(b\) Relief-valves are safety-valves used for preventing the bursting of feed-pipes, should the check-valve stick, or for preventing the covers of steam-cylinders from being blown out, should the cylinder contain too much water. They are usually loaded direct by springs. In Figs. 96, 97, and 98 are illustrated three forms of relief-valves.

\(f\) Hopkinson's Compound Safety-Valve. This ap-
paratus is invented and manufactured by Messrs. J. Hopkinson and Co., of Huddersfield, and is illustrated in Fig. 99; it comprises a lever safety-valve with a dead-weight safety-valve, and it also acts in the discharge of steam, should the water become low in the boiler.

The low-water feature of this valve consists in the suspension of a double lever, $L L'$, inside the boiler; on the end of $L'$ is placed a float, which, when in its normal condition, is below the surface of the water, at such a height as is deemed low-water mark. This float is made of a special material, which has been found to be suitable to withstand high-pressure steam, and the various conditions to which floats are subjected in high-pressure steam-boilers.

On the end of $L$ is placed a counter-weight, $C W$.

On the valve-seat is placed a large flat valve, $V'$, loaded by means of a ball, $B$, and a lever, $l$. Through the centre of this valve is an orifice, which forms the seat for another valve, $V''$, of spherical or ball construc-

tion, and weighted inside the boiler on the dead-weight principle, by means of iron plate weights, $W$.

On the steam increasing beyond the pressure to which the valves are loaded, each valve will rise from its seat and discharge the excess of steam, to balance the float, and through an eye, $E$, on the lever, the rod passes which suspends the dead weight, and on this rod is fixed an adjustable collar, $Cr$.

Should the water in the boiler become low enough to leave the float, the latter falls and turns the lever, which
will then be brought in contact with the collar, C,
to thereby raising the spherical valve from its seat and
discharging the steam.

The valves can be examined by removing the cover,
and D P is a drain-pipe.

The safety-valve is one of the most important boiler
fittings, and should therefore have the greatest con-
sideration from engineers. Its duty is to discharge
from the boiler sufficient mass of steam at excess of pres-
sure, thereby preventing the pressure from rising to a
dangerous height. The valve must therefore be so
large that when open, it shall allow at least so much
steam to escape in unit of time, as is produced in excess
in unit of time. The valve opening must therefore be
a function of the following quantities:

(a) The size of the grate-surface. The greater this
part of the boiler is, the more coal can be burnt in unit
of time, and therefore the more steam can be produced.
But we have seen that the amount of coal which can
be burnt per hour per square foot of grate-surface, may
vary from less than 10 lb. to more than 40 lb., all accord-
ing to the force of the draught.

(b) The size of the heating-surface. The amount of
steam which can be produced in a boiler per square foot
of heating-surface has been shown to depend upon the
force of the draught, and also upon the ratio of the
heating-surface to the amount of fuel burnt per hour.

(c) The force of the draught is an important factor
in the determination of the size of the safety-valve.

(d) The size of the water-room of the boiler ought also
to be taken into account in calculating the valve area.
It has been shown on page 68, that in taking steam out
of the boiler, and thereby lowering the pressure, the
water in virtue of its higher temperature will give off
steam, until the temperature corresponds with the
pressure. For this reason, the time required for lower-
ing the pressure will be increased with the size of the
water-room.

(e) The size of the steam-room will also have some
influence upon the time required for lowering the
pressure, but this is of minor importance.

(f) The pressure of the steam. The relation between
the absolute pressure of dry saturated steam and the
corresponding specific volume of the steam, is approxi-
mately given in the formula

\[ p_s \times v_h = 475 \]  \hspace{1cm} (55)

The volume of 1 lb. of steam will therefore be the
smaller, the greater \( p_s \) is, and consequently for high
pressures, the valve area need not be so large as with
low pressures, everything else remaining the same. The
velocity at which the steam will escape into the atmos-
phere will also be greater at high pressures.

(g) The temperature of the feed-water has, of course,
also a great influence upon the amount of steam which
can be produced in unit of time.

In the Board of Trade rules, which only refer to
marine boilers, the area of safety-valves is taken as a
function of the steam pressure and the grate-surface
only. The following table is taken from the Board of
Trade regulations:

<table>
<thead>
<tr>
<th>Boiler pressure in pounds per square inch</th>
<th>Area of safety-valve in square inches per square foot of grate-surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.176</td>
</tr>
<tr>
<td>60</td>
<td>0.190</td>
</tr>
<tr>
<td>70</td>
<td>0.202</td>
</tr>
<tr>
<td>80</td>
<td>0.214</td>
</tr>
<tr>
<td>90</td>
<td>0.227</td>
</tr>
<tr>
<td>100</td>
<td>0.238</td>
</tr>
<tr>
<td>110</td>
<td>0.250</td>
</tr>
<tr>
<td>120</td>
<td>0.262</td>
</tr>
<tr>
<td>130</td>
<td>0.274</td>
</tr>
<tr>
<td>140</td>
<td>0.286</td>
</tr>
<tr>
<td>150</td>
<td>0.298</td>
</tr>
<tr>
<td>160</td>
<td>0.310</td>
</tr>
<tr>
<td>170</td>
<td>0.322</td>
</tr>
<tr>
<td>180</td>
<td>0.334</td>
</tr>
<tr>
<td>190</td>
<td>0.345</td>
</tr>
<tr>
<td>200</td>
<td>0.357</td>
</tr>
</tbody>
</table>

It is not stated for what draught, nor for what ratio
of heating-surface to grate-surface, the above table is
calculated; but as boilers with forced draught may
require valves considerably larger than those found by
the table, the design of the valves proposed for such
boilers, together with the estimated coal consumption
per square foot of grate-surface, should be submitted to
the Board for consideration.

The lift of the valve should be at least one-fourth of
the diameter of the valve; the area of the cylindrical
opening between the lifted valve and the valve-seat
will therefore be at least equal to the valve area.

The standpipe and neck, carrying the steam from the
boiler to the valve, should be as short as possible, so
that the steam pressure on the valve should be the same
as that in the boiler.

If the boiler be placed indoors, the valve ought to be
surrounded by a case, as shown in Fig. 99, from which
a pipe, intended to carry off the waste steam, leads
into the open air. If the boiler be placed out of doors,
such case and waste-pipe are not necessary, the steam
being allowed to escape straight into the atmosphere.
The area of the waste-pipe must not be less than the
valve area. The valve case should be fitted with a
drain-pipe at its lowest part, for the escape of condensed
steam.

Direct loaded valves should be fitted with a lifting
gear, for the purpose of testing the valve. Lever safety-
valves may be tried by lifting the lever by hand; the
lever should not be allowed to drop back, but should
be put back gently.

The valve, as well as the valve-seat, should be made
of gunmetal, and in the case of lever valves all pinholes
should be bushed with gunmetal, or else the pins should
be of gunmetal; iron working on iron ought not to be
allowed.

When the valve is resting on the seat, the steam
pressure acts on an area equal to \( \pi \frac{d_i^2}{4} \), where \( d_i \) is the
diameter of the valve-chest; but when the valve is
lifted, then the area upon which the pressure acts is
\[ \frac{\pi d^2}{4} , \]
where \( d \) is the diameter of the valve.

Let now \( W \) denote the total load in pounds on the valve, then the valve will be lifted when the steam pressure is
\[ p_e' = \frac{W}{\pi d^2} \ldots \ldots \ (56) \]
and the valve will go back again, when the steam pressure has fallen to
\[ p_e'' = \frac{W}{\pi d^2} \frac{d^2}{4} \ldots \ldots \ (57) \]

where
- \( W \) = the load on the springs in pounds.
- \( d \) = the diameter of the valve.
- \( D \) = the diameter of the spring, from centre to centre of wire, in inches.
- \( \delta \) = the diameter or side of square of the wire in inches.
- \( C = 8,000 \) for round steel.
- \( C = 11,000 \) for square steel.

The spring must have a sufficient number of coils, so as to allow of a compression of at least one-fourth of the diameter of the valve under the load at which it ought to open.

The spring loaded safety-valve should be tested under full steam and full firing, with feed-water shut off and stop-valve closed.

![Diagram](image)

**Fig. 100.**

we have therefore
\[ \frac{p_e'}{p_e''} = \frac{d^2}{4} \ldots \ldots \ (58) \]

As the valve must have some bearing surface, it is impossible to have \( p_e' \) equal to \( p_e'' \). For the same reason, the load on the valve should be determined at the hydraulic pressure test, and not by calculation only.

The Board of Trade rule for calculating the size of springs, used for loading safety-valves, is given by the following formula:
\[ \delta = \sqrt[3]{\frac{W \times D}{C}} \ldots \ldots \ (59) \]

The springs should be protected from the waste steam and from the impurities issuing from the valves.

**Low-Water Alarms.**—These apparatus are designed for the purpose of giving the stoker due warning, when the water is at or near the lowest level at which it is safe to work the boiler.

Fig. 100 illustrates a low-water alarm; as long as the flat cylindrical weight is under water, the small valve near the top of the apparatus will keep shut, and thus prevent steam from entering the whistle. If, however, the water level becomes so low that a sufficiently large part of the flat weight remains out of the water, then the valve will open and the signal will be.
given by the steam rushing through the whistle. We will assume that the counter-weight is placed at such a distance from the fulcrum of the lever, that the whole apparatus is balanced when there is no steam pressure, and when the flat weight is completely immersed in the water. Let now \( V \) denote the volume, in cubic inches, of that part of the flat weight which must be out of the water, in order to open the valve against the effective steam pressure, \( p_s \). \( L \) the length of the lever upon which the flat weight acts, \( d \) the diameter of the valve, \( l \) the length of the lever upon which the valve acts, all in inches, and \( \gamma \) the weight of one cubic inch of water, then we must have

\[
\frac{\pi d^2}{4} \times p_s \times l = V \times \gamma \times L \quad . \tag{60}
\]

The valve will therefore open, and the signal will be given, when

\[
V = 21.8 \times \frac{d^2 \times p_s \times l}{L} \quad \text{cubic inches} \quad . \tag{61}
\]

The temperature of the water at which the apparatus is balanced has not been taken into account, but as it would be lower than that corresponding to \( p_s \), the valve will open a little before \( V \) has reached the value in (61). \( p_s \) ought to be taken greater than that at which the safety-valve blows off, especially as the apparatus cannot be tested while steam is up. The cock leading to the whistle is locked up, in order to prevent the apparatus from being tampered with.

Flue Protectors are designed with the object of preventing flue shells from being destroyed by overheating, should the water level fall too low.

(a) A flue protector is illustrated in Fig. 101. A pipe leads from the steam-room into the flue, but is shut by a valve until the water falls to a dangerously low level, when part of the flat weight will become bared of water, and the valve will open and discharge steam into the flue, thus reducing the pressure and extinguishing the fire.

(b) The double-cone fusible plug is shown in section, in Fig. 102. Socket P is screwed into the crown of the flue shell, at or near the firebox; the space between the two cones, C and D, is filled with an alloy, which melts at a temperature which is somewhat higher than that of the steam. Should the furnace-plates become bared of water, the alloy will melt, and steam will thus be discharged into the flue. The fusible metal should be renewed at intervals, not exceeding two years. This plug is recommended by several boiler insurance companies.

Blow-Off Apparatus.

The Blow-Off Pipe.—The object of the blow-off pipe is:

(a) To empty the boiler when it is to be cleaned. For this purpose the pipe should be fixed at the lowest point of the boiler.

(b) To diminish the formation of scale. It is well known that the impurities contained in the feed-water will be left in the boiler after the water has been evaporated. Now, as long as steam is produced in the boiler, the circulation of the water will to a great extent keep the sediments suspended in the water, but when the evaporation has ceased, the sediments begin to settle down, and if we then blow off some of the water, we shall at the same time relieve the boiler of part of this
injurious matter. In boilers with mud-drums, as the Babcock and Wilcox boiler, a large amount of the suspended matter will settle down during evaporation, and blowing off may therefore be done at any time with advantage.

Figs. 103, 104, 105, and 106 are views of Hopkinson's parallel slide blow-off valve, with locking gland. The main feature of this blow-off valve consists in the form of sliding discs, S V, see Fig. 103, which, by means of a spring, Sg, between them, are kept against their seats when sliding, and so remove any grit or dirt which may have accumulated on the seats, V S. The valve is opened or shut by turning the pinion, P, with the key, and thereby lifting or lowering the rack, R. Flange F is nearest to the boiler, and the connection with the blow-off pipe is made through flange F₁.

Fig. 104 shows the key way in the locking gland, and Figs. 105 and 106 show another form of the valve, the "Elbow pattern."

The Scum-Pipe.—When the boiler water contains impurities which are lighter than the water, it is necessary to blow off from the water surface. For this purpose, a long narrow trough, the scum-pipe, is inserted into the boiler. It runs parallel to the surface of the water, and is fixed at the one end to the front of the boiler, where it opens into a cock, the scum-cock. It is placed at such a height, that the opening is just a little below the water surface. When the scum-cock is

The pipe is provided with a cock or a valve for shutting off the boiler water. The blow-off cock or valve is fixed on the boiler, and it should be made with a locking gland—i.e., the key or spanner used for opening and shutting the cock, cannot be removed unless the cock is properly shut. Many accidents have arisen through blow-off cocks being left open, and the boiler emptying itself of its water without the man in charge being aware of it.
opened, the impurities floating on the water will be carried into the trough and through the scum-cock into a drain-pipe outside the boiler, whence they run into a sink or the like.

![Diagram of steam boiler sections](image)

Figs. 107 and 108 show sections of Messrs. Dewrance and Co.'s scum-cock, which is the Manchester Steam Users' Association standard pattern. H is the handle for turning the cock, G1 is the gland of the stuffing-box; the cock is fixed to the neck on the boiler by bolts through flange F1, and the nipple, n, fits into the neckhole, an asbestos washer being placed between F1 and the neck flange. The drain-pipe is fixed to the
cock by bolts through flange F2. Cover C is taken off when the scum-pipe is required to be cleaned. The cock is made of brassmetal throughout and is packed with asbestos. The cock as shown in the drawings is shut.
The Steam-Pipe and its Fittings.

The duty of the steam-pipe is to convey the steam from the boiler to the engine. Its sectional area, as well as that of any other opening through which the steam has to pass, should be of such size that the velocity of the steam never exceeds 100 ft. per second. The pipe should, if possible, have a fall towards the boiler, so as to allow condensed steam to run back to the boiler instead of to the engine. In order to diminish condensation, the pipe should be covered with a non-conducting material, and when the pipe is long, the expansion of the pipe due to heating should be taken up by special joints, expansion-joints, to be inserted at proper intervals of length. Fig. 109 shows Hopkinson's corrugated copper expansion-joint; by allowing $P_2$ to slide inside $P_1$. The joint between $P_1$ and $P_2$ must be steam-tight, and for this purpose $P_1$ is provided with an asbestos packed stuffing-box, of which, $G_1$, is the gland; the bushes, $b_1$ and $b_2$, are made of gunmetal, and the latter is fixed to the gland by four screws, $S$. The object of the two long bolts, of which the one can be seen in Fig. 111, is to prevent

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The makers recommend using one joint to every 25 ft. to 30 ft. of pipe. Figs. 110 and 111 are views of an expansion-joint constructed by Messrs. Dewrance and Co. From the longitudinal section, Fig. 110, it will be seen that the joint consists of two short cast-iron pipes, $P_1$ and $P_2$, with flanges, $F_1$ and $F_2$, by which they are bolted to the steam-pipe. The expansion of the latter is taken up...
the joint from separating, and to denote the proper position of the parts.

Connected with the steam-pipe, are several fittings and apparatus, of which the following are the most important:

(1) The Stop-Valve or Steam-Valve.—This is used for shutting and opening the steam-passage, and consists of a valve, which is moved by turning a screwed spindle. The valve is placed in such a manner that it shuts against the steam pressure. The spindle works in a nut, and moves steam-tight through a stuffing-box. The steam may leave the valve in the same direction as it enters, and is then a straight-through valve; or the steam may leave in a direction at right angles to that in which it enters, and the valve is then a junction-valve. Valves with screwed spindles are also called screw-down valves.

The stop-valve should not be fixed direct on the boiler shell, but should be bolted to a standpipe riveted to the boiler. The stop-valve should be placed on the boiler where the steam is driest; if, therefore, the boiler is provided with a dome, the valve should be fixed on the top of the dome.

The engine end of the steam-pipe is also closed by a stop-valve, in order to be able to shut off the steam from the engine, without having to get up on the boiler.

(a) Fig. 112 is a section of the stop-valve belonging to the Robey loco. boiler, illustrated on page 75. The screwed part of spindle, Sp, works in a gunmetal nut, n, which is fixed to the casing. By turning the hand wheel, H, the valve, V, will be lifted or lowered according to the direction in which we turn, but the valve itself will not turn, as will be seen by looking at the drawing. The direction in which the steam moves through the valve is indicated by the two arrows. The valve, V, valve-seat, VS, stuffing-box gland, Gl, and

![Fig. 112](image1.png)

![Fig. 113](image2.png)

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![Fig. 112](image1.png)

![Fig. 113](image2.png)

the nut, n, are all of gunmetal; the rest, except bolts and spindles, is of cast iron. By removing the cover, the valve and valve-seat can be inspected and ground.

(b) The valve shown in Fig. 113 is constructed by Mr. Rhodes, of London. The valve face is not of metal, but consists of a number of washers of an asbestos and indiarubber compound. By unscrewing the cover, the valve can be taken off and the washers renewed.

(c) Hopkinson's parallel slide-stop valve, Fig. 114, is made on the same principle as the blow-off valve, Fig. 103. By turning the hand wheel, we turn the nut,
but the screw simply moves up and down. The spiral spring on the top of the nut, N, is for keeping the gland up to its seat; no packing is therefore required.

reasonably hard. The under side of the seating is grooved, so as to make a tight joint without packing. The loose valve, Fig. 118, is removed from the spindle by unscrewing the nut which holds it. The casing and everything else are made of gunmetal.

The casing and cover of the stop-valve shown in Fig. 119 are made of cast iron, and are of a larger size

(d) Dewrance’s renewable stop-valves, so called because the valve-seats can be taken out and renewed without having to remove the casing from its fixed position, thus saving time and expense.

To renew a valve such as is illustrated in Fig. 115, we must first unscrew the cover, and then unscrew the seating, either by means of a special spanner, which follows with each valve, or by a flat piece of iron. A new seating, Fig. 116, can now be inserted in the casing, Fig. 117. It must be screwed in
bottom with an asbestos washer. Caulk down firmly
the asbestos round the top of the seating-cage, and in
bolting down the cover, care must be taken to keep it
(2) Steam Check-Valve.—When two or more boilers
are connected to the same steam-way, so as to supply
the same engine or engines, it is necessary, or at any
level, so that the spindle may be vertical. Fig. 122
shows the empty casing.
The junction-valve illustrated in Fig. 123, is also
rate advisable, to insert a check-valve in the branch
steam-pipe, leading from the boiler to the main steam-
way. By such arrangement, steam from any one boiler

constructed on the "renewable" principle. With the
exception of the shape of the casing, every detail is
precisely the same as in Fig. 119.
cannot enter any other boiler, should the stop-valve of
the latter not be shut.
Fig. 124 is a section of Hopkinson's steam check-
A practical electrical engineering. A is a gunmetal valve closing upwards, and B is an iron float submerged in mercury, contained in the vessel C; the mercury is prevented from evaporating, by the condensed steam floating on the top of the mercury. The top side of the valve, A, is the inlet side, and is also the side to which the steam comes, on leaving the boiler. The under side of the valve is in connection with the main steam-pipe.

On account of the buoyancy of the float, the pressure on the inlet side must be about 4 lb. per square inch in excess of the pressure on the outlet side, in order to open the valve. The combination of the iron float and the mercury not only acts in closing the valve should the pressure be in equilibrium, but it also acts as a dashpot, because the float, although free to rise and fall in the mercury, can only move at a comparatively slow rate, as the mercury requires time to pass through the thin annular space between the float and the vessel, C. This prevents all objectionable oscillation of the valve by the varying flow of steam, and obviates violent knocking against the valve-seat.

Fig. 125 shows the most suitable position of the check-valve on the boiler; it is placed next to the junction-valve, in the line of the radial pipe conveying the steam to the main steam-pipe.

A steam check-valve will be useful in many cases, of which the following may be noticed:

(a) It will isolate one boiler of a series, and if such boiler be empty, it will prevent accidents which otherwise might happen should someone mischievously or accidentally open the stop-valve. Of course, the right thing to do in such a case, would be to lock up the stop-valve before emptying the boiler.

(b) When the boiler is provided with a low-water safety-valve, a low-water alarm, or a flue protector, the check-valve will prevent steam out of the other boilers from replenishing the steam discharged through the above-named safety apparatus.

(3) Steam Separators.—It has already been mentioned that steam supplied by ordinary boilers is probably never perfectly dry, and it has also been discussed several times in this book how boilers ought to be constructed in order to diminish the amount of water suspended in the steam.
Where economy of ground space is an important item, boilers of small bulk, and therefore also with small water-surface, have to be resorted to; in such cases, and especially where water-tube boilers are used, the steam-pipe must be provided with an apparatus for separating the steam from the water which has been carried along with it. All steam separators are constructed in such a way as to cause the wet steam to move in curved paths, whereby the heavier water seeking straight paths will separate from the steam.

**SECTIONAL ELEVATION**

Amongst the numerous steam separators now in existence, the following will be taken:

(a) The anti-priming pipe, which is often used even in boilers which supply fairly dry steam. It is a horizontal pipe, the top part of which is perforated, and it is placed inside the boiler, see Figs. 11 and 13, Sd., and is connected at the top to the stop-valve standpipe. The steam will thus be obliged to move up and down through the pipe before it can enter the stop-valve casing, and the greater part of the suspended water will therefore remain in the boiler. To prevent water from accumulating in the anti-priming pipe, the latter may be provided with a drain-pipe, which opens into the boiler water below the low-water level.

(b) Fig. 126 shows section of Messrs. Hydes and Wigfull's steam separator. It is fixed outside the boiler in an upright position, the steam inlet being at the base. The fixed spiral, Sp, gives to the wet steam a rapid circular motion inside the tube, T, which is pierced by a number of narrow slits, S; through these slits the water is eliminated and drawn out through the drain-valve. The apparatus is covered with non-conducting material.

(c) Fig. 127 illustrates Messrs. J. Musgrave and Son's "Globe" water separator. As shown in Fig. 128, the separator is fixed in the interior of the boiler directly under the standpipe to which it is connected, so that all steam leaving the boiler must first pass through the separator. The steam enters the apparatus by four inlets at the top, and these are so placed and arranged, that the steam enters at a tangent to the body of the separator, and in rushing in, is, by its own velocity, given a rapid rotary motion; the particles of water are thrown to the sides of the outer casing, while the steam passes up through the pipe at the centre. The water trickles down the sides of the
casing, and accumulating at the bottom, it opens the valve below, see Fig. 127, and passes back into the boiler. The valve works on a knife edge; to render it as sensitive as possible, it is almost balanced, and is so arranged that a small quantity of water inside the separator will open it and allow the water to escape into the boiler, but no water or steam can pass from the boiler through the valve.

(d) Sectional elevation and plan of Savill’s steam separator are shown in Figs. 129 and 130. It consists of a square casing of cast iron with an inlet and an outlet for the steam. In the casing are placed three vertical and angular plates, which are perforated in such a manner, that the holes of the first and the last are in the lower part of the plates, whereas the holes in the centre plate are all in the top part. The steam must therefore fall and rise twice before it reaches the outlet; the water and dirt originally suspended in the steam, will impinge against the plates and drain down the serrated grooves. The water outlet at the bottom of the casing must either be trapped or syphoned under water, to prevent air from getting into the separator.

(4) Reducing Valves.—The steam from the same boiler may be used for various purposes, for some of which the boiler pressure is too high. For instance, the boiler may supply steam to several engines not working at the same pressure, or some of the steam may be used for heating purposes. In such cases, the intensity of the steam pressure must be reduced before the steam enters the apparatus working at the lower pressure. Fig. 131 shows a section of Dewrance’s reducing valve. It is fixed to the branch steam-pipe leading from the main steam-pipe to the apparatus for which the valve is intended.

The reduction of the steam pressure is effected by throttling the steam while passing through the reduced openings left between valves V and V’ and their respective seats. These two valves form one “equilibrium valve,” so that the steam pressure can neither open nor shut them. The steam of reduced pressure acts upon piston, P, which is loaded by weight, B, and lever, L. If, therefore, this pressure is still too high, the piston will be lifted, and thereby also the equilibrium valve, which will thus leave still smaller openings for the passage of the steam. For preventing violent oscillations of the valve, a dash-pot, DP, is added. The valve casing is of cast iron, and the working parts are made of gunmetal.

Apparatus for Supplying Feed-Water.

Pumps.—The most common apparatus used for forcing the water into the boiler is a pressure-pump—the feed-pump—which may be driven by the engine or by a separate motor. The tank is generally placed at a lower level than the pump, which must therefore suck the water up in the one stroke, and deliver it to the boiler in the next stroke. To the pump belong two pipes, one between the tank and pump—the inlet-pipe or suction-pipe; and another between the pump and the boiler—the delivery-pipe or feed-pipe.

In order to compensate for possible leakage, blowing off, and other waste, the pump should be made so large that it can supply the boiler with at least twice the amount of water which is to be evaporated. For this reason, it will be necessary to have means by which the supply can be regulated, so as to keep the water at a constant level in the boiler. This can be done in various ways—viz.:

(a) The pump can be disconnected from the engine. By this arrangement, however, the water level in the boiler would not be constant.

(b) By having a cock or a valve on the inlet-pipe, which can be opened more or less, and thus regulate the amount of water which enters the pump.

(c) By an overflow-pipe from the pump cylinder to the tank, provided with a regulating cock or valve, whereby some of the water in the pump will return to the tank. This arrangement will also show whether the pump is acting or not.

(d) By an overflow-pipe from the feed-pipe to the tank, also provided with a regulating cock or valve, whereby some of the water, which otherwise would have entered the boiler, will be returned to the tank.

(e) By a regulating valve placed close to the boiler, and which may also act as a check-valve. A relief-valve, placed between the regulating valve and the delivery valve of the pump, is in this case absolutely necessary. An overflow-pipe should lead the rejected water from the relief-valve to the tank.

(f) If the pump be worked by a separate motor, the number of strokes per unit of time may be regulated to suit the supply which is wanted.

In order to prevent the water from running out of the boiler, in case the feed-pipe bursts or the pump-valves get out of order, the feed-pipe must be provided with a valve—the check-valve—close to the boiler, and placed in such a position that it is kept shut by the boiler pressure. The check-valve, however, can also get out of order, and it may be necessary to take it out.
while the boiler is at work; a cock should therefore be placed between the valve and the boiler, so as to be able to shut off the boiler water.

To prevent the feed-pipe from being burst in case the check-valve sticks, a safety-valve—relief-valve—should be placed on the feed-pipe, or between the suction-valve and the delivery-valve of the pump.

If the pump be single-acting—that is, it only delivers water every other stroke—then an air-vessel of sufficient capacity should be placed on the feed-pipe, usually close to the pump. This air-vessel will act as a cushion, and prevent shocks due to the stopping and starting of the water in the pipe.

To depend upon one pump only should not be allowed, especially where the water-room of the boiler is small; besides the engine feed-pump, there should be either a hand pump, a donkey-pump, or an injector.

In Fig. 132 is illustrated a single-acting feed-pump, made by Messrs. Garrett and Sons, for portable engines. The pump piston, P P—the plunger—is a hollow cylinder of gunmetal, attached by the connecting-rod, C R, to an eccentric on the engine shaft. The pump cylinder, P C, is of cast iron, and ends in a packed stuffing-box, so as to make the pump watertight. I V, D V, and C V are inlet-valve, delivery-valve, and check-valve respectively, which are all made of gunmetal, as well as their valve-seats, V S. The pump and the valve-box are fixed on the boiler; no feed-pipe is therefore wanted, except a very short piece between the check-valve and the boiler. The excess of feed-water returns by an overflow-pipe, provided with a regulating feed-valve, to the feed-water heater.

For the purpose of giving access to the valves, screwed plugs are placed above each valve. The plug above the inlet-valve is further provided with a relief-valve, R V, which is held down by a spring as long as the pressure of the water in the valve-box is not in excess. Should, however, the delivery-valve or the check-valve stick, R V will discharge a sufficient quantity of water to relieve the pressure. The lifts of the three valves are limited by projections, p, on the plugs.

Donkey-pumps are pumps worked by separate small steam-engines, which may either receive steam from the main boiler or from a separate small boiler, the donkey-boiler. The steam-piston and the pump piston are connected to one common piston-rod, and the pump with its motor is usually fixed on the wall of the building.

A single-acting donkey-pump with steam-engine, and made by Mr. Mumford, of Colchester, is illustrated in Figs. 133 and 134, the latter showing longitudinal section through steam-cylinder, S C, slide-valve, S V, plunger, P P, pump cylinder, P C, air-vessel, A V, etc. It will be seen that the steam piston-rod, P R, is connected to the plunger by means of a pin, p; this pin need not be strong, as it only has to carry the weight of the plunger while this is lifted, the pressure on the plunger during the downward stroke being taken up by the conical end of the piston-rod, which fits into the plunger.
For the purpose of giving the plunger a uniform motion, a crankshaft, CS, with a flywheel, FW, is added. The crankshaft is turned by means of a connecting-rod, CR, attached to the piston-rod by the pin piece of steel, A, which can slide in a slot in the piston-rod, is made to bear against B by adjusting the wedge-
shaped bolt, W B. I P is the inlet-pipe, D P the delivery-pipe, I V the inlet-valve, and D V the delivery-valve. The valves can be taken out by removing the covers, V C. S P is the steam-pipe, R P the exhaust-pipe, and Ex the eccentric which moves the slide-valve, S V. As the steam-chest is small, it would be difficult to tool the face if the cover were made in the usual way; the cover is therefore made slanting, as shown in Fig. 134.

A double-acting donkey-pump by the same maker is illustrated in Fig. 135. The pump piston is here a gunmetal ring, and the pump delivers water in both strokes; there are, therefore, two suction-valves and two delivery-valves, which are not shown.

The lettering is the same as in Figs. 133 and 134. No further explanation is therefore wanted.

The Steam Injector.—This apparatus was invented by Giffard, and is based on the principle that a steam jet escaping from a boiler under pressure, has a greater velocity than a water jet escaping from the same boiler. For the same mass, the steam jet will therefore contain more kinetic energy than the water jet. The steam jet may therefore be so applied, that by condensing, it transfers its kinetic energy to a water jet, thereby giving to the latter a velocity which is greater than that at which the water would escape from the boiler. If this be the case, and the water jet be directed against a proper opening in the water-room of the boiler, the water jet, in virtue of its high velocity, will overcome the boiler pressure and will enter the boiler.

(1) In order to understand fully the action of this instrument, we will proceed to explain the injector shown in Figs. 135 and 137, and made by Messrs. Gresham and Craven, of Manchester.

It will be observed that the injector has four openings or branches in its external casing. At the top of the apparatus is a spindle—the steam spindle—with a hand wheel; the spindle ends in a cone which fits accurately into a nozzle—the steam nozzle—and by turning the hand wheel, the cone will be worked up or down inside the steam nozzle, and thus regulate the admission of steam. Below the steam nozzle is another nozzle—the combining or condensing nozzle—which can be worked up and down by means of a rack and pinion, the latter being attached to a graduated hand wheel. The water supply is regulated by increasing or decreasing the annular space between the two nozzles. The third nozzle near the bottom of the apparatus is called the delivery nozzle. The injector just described is a "lifting" injector—i.e., it can lift the supply water from a tank below. The necessary manipulation in order to start a lifting injector is as follows: Open the water regulator about half way, raise the steam spindle slightly so as to allow a small quantity of steam to rush
Fig. 135.
through the apparatus, whereby the nozzles will be cleared, and air be drawn from the water supply pipe, thus inducing a partial vacuum and lifting the water; then open the steam spindle fully, and the water will be forced through the apparatus into the boiler. Should the water supply be too great to pass through the feed-valve at the boiler, some of the hot water will escape through the overflow. The water regulator must therefore be adjusted, until the overflow of water ceases.

In Fig. 138 is shown the fixing of a lifting injector feeding two boilers.

Fig. 139 is an external view of a non-lifting injector. With the exception of having no steam spindle, it is constructed precisely in the same way as the lifting injector. The fixing of the injector is shown in Fig. 140. It will be seen that the tank is above the apparatus, which will therefore start by simply opening the two cocks shown in the diagram.

The injector can only supply the boiler with comparatively cold water, as the supply water must be cold enough to condense the steam. The warmer the supply water is, the more of it is required for condensing the steam, and the mass of the water jet may thereby increase so much, that its velocity will be too small to overcome the boiler pressure. The temperature of the water should not exceed 120 deg. to 130 deg. F.

A great objection to the lifting injector is its want of self-starting power. In the event of the jet being broken by a sudden jolt or vibration, the same cycle of manipulation as described above must again be gone through, and there is a danger, if the attendant should not be at hand when the injector "knocks off," that the steam will in the meantime so heat the injector that it will not readily start again.

(2) The exhaust-steam injector is an invention of Messrs. Davies and Metcalfe, and is manufactured by the Patent Exhaust-Steam Injector Company, Limited, of Manchester. The injector described above is worked with live steam having the same pressure as that against which the apparatus works, whereas the injector which we are about to describe is worked by the exhaust steam of non-condensing engines, the pressure of which is only a little above that of the atmosphere.

Fig. 141 is a section of the exhaust-steam injector, which has three nozzles like the injector, Fig. 136. The steam nozzle, S, is only remarkable in being of very large bore to suit exhaust steam; down its centre passes the fixed cone, K, which serves to direct the steam. The combining nozzle, D, is split from the smallest bore or throat, E, for more than half of its length, so that the "flap" piece, N, works freely on a hinge, and by its movement enlarges or contracts the throat of the combining nozzle. The delivery nozzle, F, is connected to the combining nozzle, and by means of a screw, B, the two nozzles can be lifted or lowered together, in order to adjust the opening for the water.

The action of the apparatus may be described as follows:

When not working, the flap, N, hangs open, so that
there is the largest possible area for the flow of steam and water. When the supply water is turned on, and allowed to flow by its own gravity (the supply-tank always being higher than the injector) into the combining nozzle and out of the overflow, a partial vacuum will be formed in the steam nozzle, whereby the steam will be induced to enter; the inrushing steam will then be condensed, and thereby increase the vacuum. The result of this is that more steam and water are drawn in, until they mingle in sufficient quantities, and the vacuum formed is so good that the rush of steam and water into the combining cone generates a jet of such velocity that, accelerated by the concentration given it by the cone, it overcomes the boiler pressure and enters the boiler. When this vacuum is obtained, the flap, N, is held close into the solid sides of the combining nozzle, forming practically a solid nozzle, through which the water is delivered to the boiler exactly as in the Giffard injector.

The automatic re-starting feature obtained by the use of the flap nozzle, is the distinguishing feature in the action of the exhaust injector. This principle is also applied to lifting live-steam injectors, in order to make them self-re-starting; but it is an actual necessity for exhaust-steam injectors, which have to be applied not only to constant but to intermittent engines, such as winding-engines, etc.

The exhaust-steam injector can only force up to about 75lb. per square inch, but with the aid of live steam, they can be made to feed against locomotive pressures.

As the temperature of the water jet from this apparatus is raised by applying the heat contained in the exhaust steam, it is evident that it will cause a considerable saving in fuel consumption.

It is of great importance that the exhaust steam should be dry and contain no grease, as the water suspended in the steam is inactive, and the grease would be carried into the boiler with the water jet. For this reason, the injector should be placed near the engine where the steam is driest, and the steam, before entering the injector, should pass through a vertically, sufficient space being left to admit of the withdrawal of the nozzle. It may, however, be fixed horizontally if more convenient, but in that case the "flap" portion of the removable nozzle must be turned
round, so as to be on the top. This is done by turning round the regulating nut with a spanner, the word “top” being stamped on the nut.

(b) Exhaust steam. The branch exhaust-pipe to the injector should be taken from the main exhaust-pipe as far as possible from the open end, and should be connected to the side if the pipe is vertical, as shown in Fig. 142, or to the top if the pipe is horizontal, in order to prevent grease and water from getting into the injector. The main exhaust-pipe should not be throttled, but be as large as possible. Great care must be taken that all joints between the cylinder and injector are perfectly airtight, as air is inactive.

(c) Water. The injector must be fixed below the level of the feed-water; and in cases where the blast is heavy, the injector must be fixed as low as possible. The temperature of supply water should not exceed 90 deg. F.

(d) Overflow. In every case, this pipe must be led downwards, and its end must dip in water two or three inches, to prevent the admission of air.

(e) Delivery. There must be the usual check-valve on the boiler; and if the delivery-pipe is long, an additional check-valve must be fixed two or three feet away from the injector, to diminish friction between water jet and pipe.

(f) Joints. These must not be made with white or red lead; thin sheet rubber or asbestos is preferred.

The Feed-Pipe.—The duty of this pipe is, as already mentioned, to convey the feed-water from the pump or the injector to the boiler. It is usually continued inside the boiler by a long horizontal pipe, of which the latter part is perforated for the purpose of producing an effectual distribution of the water inside the boiler. The position of this pipe is somewhat above the internal flues. It starts at the front of the boiler and at the one side. In loco. boilers, the feed-water enters at the side of the boiler, see Fig. 17, page 75. The feed-water should never enter the boiler at the bottom, as this part of the boiler is the coldest, and the circulation of the water would therefore be diminished.

The check-valve or back-pressure valve, which is placed in the feed-pipe close to the boiler, is of similar construction as the relief-valve, Fig. 98; it may, however, be worked with or without a spring.

Another fitting belonging to the feed-pipe, and which has already been mentioned, is the feed-valve or feed-regulating valve. It consists, like the stop-valve, of a valve and a screwed spindle with a hand wheel, but the valve does not lift with the spindle. By turning the hand wheel, we only regulate the lift of the valve, which, therefore, can act as a check-valve when placed directly on the boiler. In the latter case, no other check-valve is required, but in both cases a shut-off cock must be fitted between the valve and the boiler, in order to be
able to remove the valve while steam is up or water is in the boiler.

When one pump or one injector supplies water to more than one boiler, branch pipes are led from the main feed-pipe to each boiler. The supply of water to each boiler is regulated by placing a feed-valve in each branch pipe, as shown in Figs. 138 and 140.

In Ferranti's feed-valve, as illustrated in Fig. 143, the ball-valve rests on a seating contained in a wedge-shaped box, which is made to a standard size, and is therefore interchangeable, so that the valve can be taken out and replaced by a spare one, Fig. 144, in a few minutes. The regulation of the supply of water is effected by the hand wheel and screw spindle.

Fig. 145 is an external view of the valve without shut-off cock; but when connected direct to the boiler, a cock may be formed in one piece with the body of the valve, as shown in the section, Fig. 143. The object of the two screws at the front of the valve-box merely regulates the lift of the valve. By removing the flange on the side branch, the passage to the boiler can be easily cleaned.

Hopkinson's combined cock and feed-valve is shown in Figs. 147 and 148. It will be seen that the screwed spindle works inside the cock-plug; the valve-seat is integral with the elbow, as shown in section. The elbow, and with it the seat and the valve, may be easily removed for examination and repairs. The lift of the valve is regulated in the usual manner by turning the hand wheel at the top, and the shut-off cock is closed by turning the horizontal handle.


**STEAM BOILERS.**

141

**Heating of Feed-Water.**

Before steam can be generated in the boiler, we must raise the temperature of the feed-water to that of the steam. It is therefore evident that the feed-water should enter the boiler at as high a temperature as possible. Suppose the absolute pressure of the steam is 115 lb. per square inch, then the temperature of the water is 338 deg. F.; and let us further suppose that the temperature of the feed-water is 60 deg. F., we have then to spend for each pound of feed-water

\[ 338 - 60 = 278 \text{ heat units} \]

before evaporation can begin. The total heat required for the evaporation of 1 lb. of water at 338 deg. F., from 60 deg. F. is, according to formula (2), page 62, 1,157 heat units; there is therefore a loss of 24 per cent. of fuel, due to the heating of the feed-water. The economy in fuel will therefore be considerable, if the feed-water, before it enters the boiler, be made to absorb heat which would otherwise be wasted. In the table below is shown the saving in fuel, by heating the feed-water before it enters the boiler; the absolute pressure of the steam is taken as 115 lb. per square inch.

**Feed-Water Heated from 60° F. to**

<table>
<thead>
<tr>
<th>100°</th>
<th>120°</th>
<th>140°</th>
<th>160°</th>
<th>180°</th>
<th>200°</th>
<th>220°</th>
<th>240°</th>
<th>260°</th>
<th>280°</th>
<th>300°</th>
<th>320°</th>
<th>338°</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.9</td>
<td>3.2</td>
<td>2.9</td>
<td>2.6</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
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<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

**Saving of fuel in per cent.**

The economy in fuel is, however, not the only result obtained from heating the feed-water; the life of the boiler is also greatly increased, partly because the temperature will be more equal throughout the boiler, and partly because most of the foreign matters originally contained in the water will remain in the heater.

For the purpose of heating the feed-water, we can either utilise the heat contained in the exhaust steam or that contained in the chimney gases. In the first case, the apparatus is called a feed-water heater simply, and the temperature to which the water can be raised, cannot possibly be more than 212 deg. F., as this temperature is the boiling point under atmospheric pressure; in the second case, the apparatus used is called an economiser, and it may raise the temperature of the feed-water to almost that of the high-pressure water.

An arrangement by which exhaust steam is mixed with the feed-water is shown in Fig. 149. It is employed by Messrs. Garrett and Sons, of Leiston, for heating the feed-water for their portable engines. The one end of the apparatus is connected to the exhaust-pipe of the engine, and the other end to the feed-pump, Fig. 132. F V is the regulating feed-valve; when it is open, or partly open, the excess of water from the feed-pump will be forced through the nozzle, N, and the overflow-pipe into a tank below, which is not shown. The water flowing through the nozzle, N, will create a partial vacuum in the space surrounding the nozzle, and if now the regulating valve, R V, be opened, the steam from the exhaust-pipe will be invited to enter, and will mix with and heat the water which will run into the tank. The pump takes the water from the tank through a separate pipe. In regular work, the feed-valve may be so set as to provide the boiler with a constant and regular supply of water, and to return the residue to the water heater. By this means, the feed-water is heated without causing a back pressure on the steam piston.
The exhaust steam always contains greasy matter, which it carries from the steam-cylinder. It is therefore better to heat the water without mixing it with the steam. Such an apparatus would, however, be inconveniently large for portable engines.

The "Compactum" feed-water heater, manufactured by Messrs. John Kirkaldy, Limited, of London, is shown in Figs. 150 and 151. The apparatus consists of a cast-iron casing, C, with a number of solid drawn brass S-tubes, ST, through which the exhaust steam passes. The ends of these tubes are securely fixed in tube-plates, TP, formed in the case, which, while keeping the ends tight, allow the body of the tubes to expand. The feed-water is pumped through the heater, entering at the bottom, FI, and passing out at the top, FO, to the boiler, being heated on its passage through the apparatus, and depositing its scale and grease in the heater. The former falling down clear of the tubes, can be blown or scraped out from time to time. The following fittings are provided, and form part of the apparatus.
One drain and sludge valve, D V, at the bottom, for emptying the heater and removing sediments;
One cleaning-door, C D, also at the bottom of the apparatus;
A drain-pipe, D P, from the tubes, to take away the condensed steam, thus relieving the back pressure;
A scum-valve, S V, near the top, for taking away grease and dirt from the feed-water.

Fig. 152.

One soda and air cock, S C, at the top, and another, S C, just above the exhaust inlet, E I, for the purpose of passing soda in a liquid state into either the water side or the steam side of the heater, thus cleansing the inside of the tubes and softening the scale on the outside.
A pressure relief-valve, R V, on the top, for the feed to escape should the check-valve be closed.
The volume of the water-room of the heater is approximately equal to \( \frac{1}{4} \) of the total capacity of the feed per hour. The water will thus remain for about 7\( \frac{1}{2} \) minutes in the heater, and the temperature of the feed is claimed to be about 10 per cent. below that of the steam.

Messrs. Robey and Co.'s multitubular heater is illustrated in Figs. 152 and 153. It consists of three cast-iron chambers, C1, C2, and C3—the first and the last being connected by a number of vertical brass tubes. The water enters at the top, and passes through the tubes into C2, whence it runs out of the heater. The chamber C2 receives the exhaust steam, which, by striking the tubes, heats the water. The drain-cock at the bottom is for blowing off sediments given off by the water. Fig. 153 is a horizontal section of the heater, and is drawn to double the scale of Fig. 154. In this heater, as well as in the previous one, the water moves in the opposite direction to that of the steam; the efficiency of the heater is thereby increased, as the hottest steam will meet the hottest water, and the coldest steam the coldest water.

Another heater, the "Nozzle Feed-Water Heater," of the same firm, is illustrated in Figs. 154, 155, and 156. Fig. 154 shows the arrangement of the nozzle, N, for producing a circulation of the exhaust steam through the circulating and heating tubes of the heater. It will be seen that the exhaust steam has a straight course through the nozzle and bottom chamber, whereby the back pressure on the engine piston is not increased.
The tubes are all made of solid drawn brass or copper; they are only fixed at one end, and are free to expand or contract independent of each other at the other end, thus avoiding the leakage which occurs when both ends of straight tubes are fixed. The fixed ends
of the tubes are expanded into bored holes in the tube-plates. By the arrangement of the brass tubes, the circulating steam is brought into intimate contact with the heating-surface.

The object of using brass tubes for heaters is this, that the expansion of brass is different to that of the scale, whereby the latter will not adhere to the tubes.

The heater casing is made of boiler-plates sufficiently strong to resist the boiler pressure. Most of the impurities in the feed-water are deposited in the bottom of the casing, and can be blown off through the blow-off cock, D C.

The condensed steam is gathered in the pipe, C P, at the bottom of the heater.

Fig. 155 shows horizontal section of the heater, and Fig. 156 gives an external view of the lower parts of same.

W I is the water inlet, W O water outlet, m h mudhole, and A V an air-vessel. The arrows show how the steam and the water circulate through the heater.

A 400 h.p. feed-water heater with horizontal tubes is illustrated in Fig. 157, and is constructed by Messrs. Musgrave and Sons, Limited, of Bolton. A horizontal heater will, of course, require more ground space than a vertical one, but the former will have the advantage of having a larger water-surface, whereby the solid matters suspended in the water will have a better chance of settling down before the water leaves the heater. In a vertical heater with small water-surface, the current of water passing through the heater has a greater velocity, and will thus keep the sediments stirred up.

Fig. 157 shows longitudinal section of the heater, and it will be seen that it rests on two legs—mud-legs, M L—into which the sediments fall, and whence they can be removed by blowing off. The exhaust steam enters at the one end and passes through a number of brass tubes 2 in. diameter, and then out of the heater. The water enters at the bottom, W I, and leaves at the top, W O. The heater consists of two cast-iron chambers, C I and C 2, and a water-room, W R. The end-plates of C I and C 2 serve as tube-plates; the shell bounding the water-room is made of boiler-plates, which must be able to stand the boiler pressure.

The heater is provided with the following fittings—viz.:

Two blow-off valves, B V, one for each mud-leg; one blow-off cock, B C, which may be kept open; one drain-cock, D C, for letting the condensed steam out of chamber C 2; two mudholes, m h, on the top of the heater; one scum blow-off valve, S B V; one safety-valve, S; E I is the exhaust inlet; E O is the exhaust outlet.

Economisers.—These apparatus consist of a system of parallel water-tubes, and are designed to absorb the last part of the heat which can be allowed to be taken from the chimney gases; they may therefore be considered as a continuation of the boiler, but their heating-surface is more effective than that of the latter, because the water they contain is colder than the boiler water. Suppose the working pressure of the boiler is 100 lb. per square inch, then the temperature of the steam will be about 338 deg. F.; and let the draught be 55 in. of water, then, according to diagram on page 67, the temperature of the chimney gases should be 300 deg. F., if the chimney height is 100 ft. The gases will leave the boiler at a temperature higher than 338 deg. F., but how much higher, depends upon the size of the heating-surface of the boiler. The temperature of the water in the economiser must therefore be less than 300 deg. F., but how much lower, depends upon the heating-surface of the economiser.

The feed-water to the economiser should not be cold, but the chill should be taken off; it is therefore best to employ one of the above-described feed-water
heaters, from which the water is taken into the economiser instead of into the boiler; but when the engine has a condenser, the water is taken from the latter. The best-known economiser is that manufactured by Messrs. E. Green and Son, Limited, of Manchester, of which Fig. 158 shows a longitudinal section, and Figs. 159 and 160 an end view and plan respectively. It will be seen that this special size of economiser has 24 rows of vertical cast-iron tubes, with an external diameter of 4½ in., and 4 in. bore; the length of each is 9ft. The 24 rows of tubes are connected at the bottom to one long horizontal pipe which receives the cold water, and to another similar pipe through which the hot water is let out of the apparatus; both tubes are outside the masonry. Each vertical tube is provided at the top with a conical cover, which is removed when the tube is to be cleaned inside. For the purpose of keeping the outside of the tubes clean, each tube is provided with a soot-cleaner, S C, which is continuously moved up and down, the soot-cleaners of two consecutive rows of tubes being lifted by the same chain. The up and down motion of the cleaners is effected by the turning of a horizontal shaft, H S, provided with worm gearing, as
shown in Fig. 158. HS is driven by gearing it to pulley, A, which again is driven by belt from the engine or other motor. The reversing of the motion is done automatically.

The draught should be regulated by a damper between the economiser and the chimney, whereby the gases are held back between the tubes. The boiler dampers should only be closed when the boiler is not working.

The sediments must be blown out every day through the blow-off valve, so as to prevent them from being carried into the boiler. The scum gathered at the top should be blown out through the safety-valve.

The soot chamber underneath the apparatus serves to gather the soot, and must be cleaned out at proper intervals, and the horizontal tubes must at the same time be cleaned by means of a brush.

A thermometer is usually placed in the top branch pipe, or in the feed-pipe in front of the boiler.

As a rule, the repairing of the economiser does not necessitate the stoppage of the boilers, as a bye-flue may be built between the boilers and the chimney, to be used only on that occasion.

**Incrustation—Cleaning.**

Pure water is a chemical combination of hydrogen and oxygen, and contains no other element. As water, however, has the property of dissolving and suspending to a less or greater extent almost all substances, it follows that the water in our rivers, canals, lakes, and wells cannot be pure. Even rain-water and snow, while descending through the atmosphere, dissolve some of the ingredients contained therein, and are consequently not pure water.

The amount of impurities in the atmosphere is smallest on the ocean and greatest in manufacturing towns.

The atmosphere always contains nitric acid, ammonia, and chloride of sodium; the two first combinations are formed by lightning, and the latter originates from the ocean, from which it is carried along with the evaporated water. The atmosphere in towns contains also sulphuric acid from the smoke, and this forms sulphates with the original impurities contained in the ocean air.

**Rain-Water.**

<table>
<thead>
<tr>
<th>London.</th>
<th>Grains per gallon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrochloric acid</td>
<td>0.067</td>
</tr>
<tr>
<td>Nitric acid</td>
<td>0.069</td>
</tr>
<tr>
<td>Sulphuric acid</td>
<td>0.063</td>
</tr>
<tr>
<td>Sulphate of soda</td>
<td>1.431</td>
</tr>
<tr>
<td>Sulphate of ammonia</td>
<td>0.939</td>
</tr>
</tbody>
</table>

Rain-Water.

<table>
<thead>
<tr>
<th>Manchester.</th>
<th>Grains per gallon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrochloric acid</td>
<td>0.408</td>
</tr>
<tr>
<td>Nitric acid</td>
<td>0.094</td>
</tr>
<tr>
<td>Sulphuric acid</td>
<td>0.260</td>
</tr>
<tr>
<td>Sulphate of soda</td>
<td>3.452</td>
</tr>
<tr>
<td>Sulphate of ammonia</td>
<td>1.602</td>
</tr>
</tbody>
</table>

**Rain-Water**

It is not only solid and fluid matter, however, which is dissolved by water, but gases are also greatly absorbed by water. The mass of a gas which can be absorbed depends upon the temperature and the pressure, but the volume of the gas depends upon the temperature only. The gases will, however, escape by boiling the water.

The dissolving properties of water are very much increased when the water is acidulated; thus, for instance, carbonate of lime is not soluble in pure water, but is soluble to a great extent in water which contains carbonic acid. The latter, however, escapes by boiling, like other gases, and the carbonate of lime will then be deposited in the vessel containing the water.

Water, however, can only dissolve a certain amount of a given substance; when this limit is reached, the solution is said to be saturated. The saturation point varies with the temperature.

If a saturated solution be heated, and the water be allowed to evaporate, the solution will become beyond saturation, and some of the dissolved matter will be deposited—generally as crystals. By pouring water into the solution, the latter will become weaker and the deposited matter will dissolve again.

Water as used for steam boilers is drawn from rivers, canals, lakes, and wells, and therefore contains, besides the impurities of rain-water, also soluble matters from the soil through which the water has percolated. River and canal water also contains matter which is characteristic of the towns and works passed by the water. The water may also contain suspended matter, but this will settle down by letting the water rest for a time, or it can be removed by filtering.

**River Thames.**

At low water at Greenwich.

<table>
<thead>
<tr>
<th>Grains per gallon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate of lime</td>
</tr>
<tr>
<td>Sulphate of lime</td>
</tr>
<tr>
<td>Chloride of magnesia</td>
</tr>
<tr>
<td>Sulphate of magnesia</td>
</tr>
<tr>
<td>Nitrate of magnesia</td>
</tr>
<tr>
<td>Chloride of sodium</td>
</tr>
<tr>
<td>Silica</td>
</tr>
<tr>
<td>Oxide of iron</td>
</tr>
<tr>
<td>Organic matter</td>
</tr>
<tr>
<td>Suspended matter</td>
</tr>
</tbody>
</table>

At high water at Greenwich.

<table>
<thead>
<tr>
<th>Grains per gallon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate of lime</td>
</tr>
<tr>
<td>Sulphate of lime</td>
</tr>
<tr>
<td>Chloride of magnesia</td>
</tr>
<tr>
<td>Sulphate of magnesia</td>
</tr>
<tr>
<td>Nitrate of magnesia</td>
</tr>
<tr>
<td>Chloride of sodium</td>
</tr>
<tr>
<td>Chloride of potassium</td>
</tr>
<tr>
<td>Silica</td>
</tr>
<tr>
<td>Oxide of iron</td>
</tr>
<tr>
<td>Organic matter</td>
</tr>
<tr>
<td>Suspended matter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grains per gallon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>299.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grains per gallon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>369.67</td>
</tr>
</tbody>
</table>
The sulphate of alumina is due to refuse matter from the paper mill.

The chief impurities contained in water are the carbonate and sulphate of lime, and carbonate, sulphate, nitrate, and chloride of magnesia. These impurities when contained in boiler water, will be deposited in the boiler and form a scale. Carbonate of lime is the first to settle down, but its scale is porous and soft, and therefore does not burn on to the plates. The sulphate of lime forms a hard, non-porous scale, which also acts as a cementing medium on the carbonate of lime. The sulphate scale will therefore easily cause the plates to be overheated, and will burn on to the plates.

For the purpose of reducing the formation of scale, or even avoiding it altogether, we must use means which will (1) prevent the injurious impurities from getting into the boiler; (2) prevent the impurities from settling down in the boiler; (3) prevent the impurities from forming an injurious scale.

(1) The suspended matter can be removed, as already mentioned, by filtering before the water is pumped into the boiler.

The carbonate of lime can be removed by adding limewater, whereby the latter combines with the carbonic acid contained in the water, and forms more carbonate of lime, which, together with the carbonate originally contained in the water, will be deposited in the tank. This softening process, however, requires large and expensive tanks, and we must not add more limewater than just what is required for binding the carbonic acid in the water.

By the use of a feed-water heater, some of the impurities, such as carbonate of lime, will separate from the water and be deposited in the heater.

(2) We may prevent the impurities from settling down in the boiler by blowing-off before the water becomes a saturated solution. The deposit of carbonate of lime could not be prevented in this way, as carbonate of lime is not soluble in water that is free from carbonic acid.

Sulphate of lime is only slightly soluble in water, and we should therefore have to blow-off a great deal of water, in order to prevent the sulphate scale being formed. This remedy would therefore be expensive, and is consequently not practical.

We must therefore add to the boiler water such chemical ingredients as, with the slightly soluble impurities, will form soluble combinations. Such chemical ingredients can only be prescribed when we have an analysis of the water.
In waters which contain sulphate of lime, a suitable amount of soda added to the boiler water will soften it by forming sulphate of sodium, which is soluble in water; at the same time carbonate of lime will be formed, but the scale of the latter is soft.

Soda alone would be of no use if the boiler water contained magnesia salts, for then hydrate of magnesia would be formed, and the latter would act as a binding cement on the carbonate of lime, and thus form a hard scale. If more soda be added than is required for decomposing the sulphate of lime, caustic soda will be formed, which will attack the fittings, for zinc and copper are soluble in a strong solution of soda.

By boiling the water with salammoniac, the carbonate of lime will be decomposed, and the result will be the formation of carbonate of ammonia and chloride of calcium, which are all soluble in water. But the carbonate of ammonia is volatile, and is carried by steam into the engine, where it attacks the metal. Salammoniac should therefore not be used, although it has often been recommended.

The following is an example of what may take place if blowing-off is neglected, and the boiler water thus allowed to become a strong solution of injurious impurities. The impurities contained in the feed-water were:

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Grains per gallon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate of lime</td>
<td>11.91</td>
</tr>
<tr>
<td>Sulphate of lime</td>
<td>8.12</td>
</tr>
<tr>
<td>Chloride of calcium</td>
<td>7.18</td>
</tr>
<tr>
<td>Chloride of magnesium</td>
<td>1.99</td>
</tr>
<tr>
<td>Chloride of sodium</td>
<td>14.40</td>
</tr>
<tr>
<td>Silica</td>
<td>1.22</td>
</tr>
<tr>
<td>Oxide of iron</td>
<td>0.88</td>
</tr>
</tbody>
</table>

The following is the analysis of the boiler water after one month's run without blowing-off:

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Grains per gallon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride of calcium</td>
<td>799.72</td>
</tr>
<tr>
<td>Chloride of magnesium</td>
<td>47.30</td>
</tr>
<tr>
<td>Sulphate of soda</td>
<td>58.32</td>
</tr>
<tr>
<td>Chloride of sodium</td>
<td>4010.92</td>
</tr>
</tbody>
</table>

On account of the strong solution of chlorides, the following corrosion scale was formed. This scale was hard and perfectly black:

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide of iron</td>
<td>32.58</td>
</tr>
<tr>
<td>Hydrated protoxide of iron</td>
<td>18.90</td>
</tr>
<tr>
<td>Carbonate of iron</td>
<td>16.56</td>
</tr>
<tr>
<td>Alumina</td>
<td>7.02</td>
</tr>
<tr>
<td>Silica</td>
<td>7.34</td>
</tr>
<tr>
<td>Sulphate of lime</td>
<td>5.93</td>
</tr>
<tr>
<td>Carbonate of lime</td>
<td>4.43</td>
</tr>
<tr>
<td>Hydrate of magnesia</td>
<td>4.93</td>
</tr>
<tr>
<td>Chloride of sodium</td>
<td>0.98</td>
</tr>
<tr>
<td>Chloride of magnesia</td>
<td>0.19</td>
</tr>
<tr>
<td>Organic matter</td>
<td>0.31</td>
</tr>
<tr>
<td>Moisture</td>
<td>0.83</td>
</tr>
</tbody>
</table>

(3) We can prevent the scale from being hard by prescribing proper boiler compositions, which will prevent the deposits from sticking together.

Treacle and sugar are sometimes used for this purpose, and there are impurities which are more easily dissolved in a sugar solution than in water.

Tallow is often used for the purpose of making the scale soft, but it forms a grease scale, which prevents the water from coming in contact with the plates. Fatty acids are also formed, which attack the iron and form a corrosion scale.

The following deposit and scale are due to tallow and grease.

The greasy deposit is flouiry, and although it does not bake hard, it shows the fatty acids are attacking the plates.

<table>
<thead>
<tr>
<th>Greasy Deposit.</th>
<th>Per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>19.04</td>
</tr>
<tr>
<td>Oxide of iron</td>
<td>6.60</td>
</tr>
<tr>
<td>Carbonate of lime</td>
<td>39.62</td>
</tr>
<tr>
<td>Hydrate of magnesia</td>
<td>21.74</td>
</tr>
<tr>
<td>Stearate of magnesia</td>
<td>12.95</td>
</tr>
</tbody>
</table>

The tallow scale below is a more aggravated form. It is a tough scale, and shows a much larger percentage of iron.

<table>
<thead>
<tr>
<th>Corrosion Scale. From Tallow.</th>
<th>Per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>11.06</td>
</tr>
<tr>
<td>Oxide of iron</td>
<td>19.50</td>
</tr>
<tr>
<td>Carbonate of lime</td>
<td>4.81</td>
</tr>
<tr>
<td>Sulphate of lime</td>
<td>2.63</td>
</tr>
<tr>
<td>Hydrate of magnesia</td>
<td>1.06</td>
</tr>
<tr>
<td>Stearate of magnesia</td>
<td>59.91</td>
</tr>
<tr>
<td>Organic matter</td>
<td>1.03</td>
</tr>
</tbody>
</table>

To prevent corrosion of the iron, metallic zinc is sometimes soldered on the boiler-plates, for the corrosive acids will attack the zinc before the iron.

Chloride of lead is also used for preventing the scale from sticking to the iron. By this process a thin layer of lead is deposited on the plates, but not without the chlorine combining with an equivalent amount of iron. The process is really a corrosive one, and the layer of lead is soft, and is easily removed in scaling the boiler.

The author has thereby endeavoured to show that steam users cannot be too careful in choosing and using the boiler compositions which are recommended to them. And it must be well understood that because a composition has been found to answer well in one boiler, it does not follow that it will answer with water from another source. To choose the right boiler composition is like choosing the right medicine for a patient.

The logical way of solving the question is to prescribe the boiler composition according to the chemical analysis of the water which is to be used. It is on this principle that Messrs. Sidney Minns and Co., of London, make their "Scientific Boiler Fluids," and if this principle is followed out, the result must be satisfactory.
For the purpose of introducing the boiler composition into the boiler, a small force pump may be used, or, what is more convenient, an injector, as shown in Fig. 161.

The latter consists of a chamber, C, which is closed at the top by means of the screwed plug, P, and at the bottom by a cork, of which H is the handle. The apparatus is fixed on the top of the boiler, and is manipulated in the following way: (a) Shut the cock by turning H into the horizontal position, (b) unscrew plug P by means of a pin through the hole until holes h are level with the cup-shaped top, A, of the injector, (c) pour boiler fluid into A, from which it will run into chamber, sufficient length and bent at the one end where it is sharp is used. A cup-shaped scraper is employed for scaling the Field tube.

The cleaning of flues is done by sweeping with brushes of a convenient shape. The brushes may either be made of wire or badger’s hair. The brush shown in Fig. 162 is used for cleaning fine-tubes, and is mounted on a long cylindrical handle.

The small space left between the tubes in water-tube boilers, as Figs. 38 and 52, makes it difficult to clean the tubes by brushing. In such boilers the cleaning is done by employing steam jets, as explained before.

Boiler-cleaning is a very important operation and ought to be done frequently, but as it only requires common sense it is unnecessary to comment further on it.

Testing.—Explosions.

Testing.—For the purpose of testing a boiler, it is completely filled with water at ordinary temperature. By means of a force pump, provided with a safety-valve and a standard pressure-gauge, the water inside the boiler is brought to a pressure higher than the working pressure allowed on the boiler. The testing pressure, according to the Board of Trade rules, should not exceed twice the working pressure, the latter being determined by the surveyor, by calculating the strength of the various parts of the boiler. As a rule, the testing pressure is taken from 1.5 to 1.6 of the working pressure.

The test should not take place until all fittings are placed on the boiler.

The objects for testing a boiler are:

(a) To see that the boiler is strong enough, by examining whether the boiler is safe at a pressure higher than the working pressure, that at such pressure the volume and shape of the boiler is not altered, and that no permanent set takes place in any part of the boiler.

(b) That at the testing pressure, the boiler does not leak—i.e., that water nowhere escapes from the boiler except in drops—it being taken for granted that such leakage will not occur when the boiler is warm.

(c) To determine the load to be placed on the safety-valves. The pressure-gauge may at the same time be tested by comparison with the standard-gauge.

When the working pressure has been reached by means of the force pump, and the loads on the safety-valves have been determined, a further load is put on the latter, in order to be able to increase the pressure to the testing pressure. Care should be taken to shut the pressure-gauge before the pressure becomes greater than the gauge can indicate.
Explosions.—The principal causes of boiler explosions are:

(a) Bad design—i.e., the shape of the boiler is weak, the stays are not sufficient and not strong enough, the joints and plates are too weak, the internal flues and manholes are not stiffened enough, or openings for inspection and cleaning are placed in wrong positions, thus making it difficult to examine the boiler.

(b) Bad material and workmanship, defective fittings, and leaky joints.

(c) The cleaning of the boiler has been neglected, whereby a thick scale has been formed, causing the plates to be overheated, and thus making them too soft to withstand the pressure. A large piece of scale may also suddenly break off, when the flue-plate is red-hot, and thus cause an explosion.

(d) By the stoker having allowed the water level to fall below the surface of the flues, whereby these have become red-hot and have yielded to the pressure.

(e) By the stoker having overloaded the safety-valve and allowed the pressure to increase beyond a safe limit.

(f) By the steam suddenly being allowed to escape through a large opening—such as would take place if the steam-pipe bursts, whereby a sudden and violent evaporation takes place.

(g) The boiler being too old and worn to withstand the pressure.

In order to prevent explosions as much as possible the following rules should be adhered to:

(1) Buy your boiler from a firm of high standing, so as to be sure of good design, material, and workmanship. Never buy a second-hand boiler unless it has been thoroughly surveyed by a good engineer, who should also determine the working pressure to be allowed.

(2) Take as stoker a reliable man, see that the boiler-room is always clean and tidy, and do not allow anybody in the boiler-room except on business.

(3) Clean the boiler thoroughly at regular intervals. Complete cleansing is of special importance previous to thorough examination by a boiler inspector, for otherwise the inspection cannot be satisfactory and reliable.

(4) The feed-water should be analysed, and boiler composition, if necessary, should be prescribed accordingly.

(5) Feed-valves, check-valves, stop-valves, blow-off valves, and all other fittings should have constant attention, and be taken to pieces and cleaned at proper intervals.

(6) Before firing-up, see that there is sufficient water in the boiler, and that the blow-off cock or valve is properly shut. Try the test-cocks and water-gauges, and if they act slowly, clear out the passages with a wire. See that the stop-valve is shut, as it might happen that the engine stop-valve were open. When ready to start the engine, open stop-valves slowly. Clean the grate thoroughly.

(7) Try water-gauges and test-cocks frequently when boiler is at work, in order to keep the passages clear. Also try safety-valves and pressure-gauge; if the latter acts slowly, clean it as soon as possible.

(8) Regulate the feed-valve so as to keep the water level at the fixed mark. The water must never fall below that level.

(9) Use the various feeding apparatus (pumps or injectors) alternately, in order to be sure that they are in working order.

(10) Never leave the fire-door wide open when the boiler is hot, or the rivet-joints may be injured. Regulate the fire by dampers. The fresh charge of fuel should be put on the fire as quickly as possible, and the fire-door should be shut at once.

(11) The stoker should remain in the boiler-room as long as there is a fire.

(12) The surface-water should be blown out regularly through the scum-cock, in order to prevent priming.

(13) The safety-valve must be out of the stoker's control—i.e., it must be constructed in such a way that no extra load can be put on.

(14) Should the water level fall low, and should it be impossible to restore it to the proper level, the fire should be drawn at once, and if the water level falls out of sight, the fire should be damped immediately by throwing on ashes or other non-combustible matter and closing the dampers, as the act of drawing the fire might cause serious increase of heat. In the latter case the feeding must be stopped, and the engine be run slowly so as to take the pressure off gradually.

(15) All low-water safeguards must be thoroughly tested and examined every time the boiler is cleaned.

(16) Should the pressure increase beyond the allowed limit the fire should be damped.

(17) The boiler should never be emptied under pressure, but should be allowed to cool down. The practice of emptying under steam pressure and filling up immediately with cold water often occasions serious fractures in the boiler and in the masonry.

(18) If the feed-water is heated by mixing it with exhaust steam, the latter should pass through a separator before mixing with the water, in order to prevent grease from getting into the boiler.

(19) The boiler should be examined frequently, and tested after each repair. When getting worn, the working pressure should be reduced.
CHAPTER IX.

PRINCIPLES OF DYNAMICS.

Mass.—Force.—Acceleration.

ASS. By matter we understand everything which makes an impression upon us through our senses. Thus all we smell, feel, taste, and see is matter, and it is only through vibration of matter that sound can be produced and transmitted to our ear; in a perfect vacuum there would be no sound.

A bounded part of matter is called a body, and the part of space which a body occupies is called its volume. The amount of matter contained in a body is called the mass of the body. In practice, the mass of a body is measured by comparison with the mass of a standard body.

In Great Britain the standard mass is called a pound, and it is the mass of a certain piece of platinum kept in the Standard Office for comparison.

In France the standard mass is a kilogramme, and it was originally the mass of a cubic decimetre of pure water at its highest density, but now it is the mass of a piece of platinum, which is as nearly as possible equal to the original kilogramme.

For reasons which will be explained later on, the engineering unit of mass is neither a pound nor a kilogramme, but is in Great Britain the mass of 32-187 pounds, and in France the mass of 9-8067 kilogrammes.

The determination of the mass of a body is done by means of a pair of scales, whereby is found the number of times that the mass of the body is greater than the standard mass. This is the only way in which the mass of a body can be found direct. For very accurate measurements it may be necessary to take into account the mass of the air which is displaced by the body, but this is of no consequence to the engineer.

The measurement of mass by means of a pair of scales and a standard mass can be made at any place in the world.

Length.—The British standard length is a yard, this being the distance at 62 deg. F. between two marks on a bar kept in the Standard Office of the Board of Trade. The engineering unit of length, being one-third of the standard, is called a foot.

The French standard length is a metre, and is also the distance between two marks on a certain bar at a temperature of 0 deg. C. The French engineering unit of length is also a metre.

Time.—Time is a consequence of motion; if there were no motion, there would be no time.

Unit of time is a second, which is \( \frac{4}{60} \) of the time it takes the earth to turn once round on its axis.

Density.—By the density of a substance, is understood the mass contained in unit of volume of the substance. In Britain, density is expressed in pounds per cubic foot, and in France in kilogrammes per cubic metre. The density of a substance varies with the temperature and the pressure to which it is subjected.

Specific Gravity.—By relative density or specific gravity of a substance, is understood the ratio of the density of the substance to that of pure water at a standard temperature. This temperature is often taken as 39·1 deg. F., this being the temperature of the maximum density of water. The relative density of a gas is usually taken as the ratio of the density of the gas to that of air at 32 deg. F., and at a pressure of one atmosphere.

Specific Volume.—By specific volume or bulkiness of a substance, is understood the number of units of volume occupied by a portion of the substance, of which the mass is equal to the standard mass. Therefore in Britain it is measured by the number of cubic feet to the pound, and in France by the number of cubic metres to the kilogramme.

Force.—A body which is at rest—i.e., remaining at the same place in space—cannot change its position in space without a cause. Nor can a moving body change the conditions of its motion without a cause. Such cause is called a force.

The pull due to the mutual attraction of the earth and a body is called the weight of the body, and the force of this attraction is called the force of the weight of the body.

The engineering unit of force is taken as the force which can balance the weight of the standard mass at the sea level at a certain latitude.

In Britain, the engineering unit of force is the force which can balance the weight of the mass of 1 lb. at the sea level at Greenwich. This force is called the force of a pound, or the pound weight.

In France, the engineering unit of force is the force which can balance the weight of the mass of one kilogramme at the sea level at Paris, and is called the force of a kilogramme, or the kilogramme weight.

A force which acts upon a moving body in the direction of the motion of the body is called an effort, and a force which acts in the opposite direction of the motion of the body is called a resistance.

The measurement of a force is done by means of a spring balance accurately calibrated in pound weights at the sea level at Greenwich, or in kilogramme weights at the sea level at Paris, as the case may be. This is the only way the magnitude of a force can be measured.
direct, due correction to be allowed for the temperature of the spring. This measurement can be made at any part of the world.

Velocity.—A moving body which is not acted upon by any force, or is acted upon by forces which are mutually balanced, will pass through equal lengths of space in equal times. Such motion is called uniform motion, and the ratio of length of space passed over to the corresponding length of time is called the velocity of the motion, or the rate of motion.

If the moving body be acted upon by one force, or by several forces which are not mutually balanced, the length of space passed over by the body in equal times will vary, and we call such motion variable motion. We may have accelerated motion or retarded motion, according to whether the force is an effort or a resistance. By the velocity of such a body at any given time, we understand the velocity the body would have if the force or forces suddenly ceased to act, as the motion then would be uniform.

The unit of velocity is in Britain 1 ft. per second, and in France 1 metre per second.

Acceleration.—It is evident that the magnitude of a force can be measured by the result which it can produce—i.e., by the amount of motion which it can produce in unit of time. Let, therefore, the magnitude of the force be \( f \), the mass of the body which it moves be \( m \), and the velocity produced after the lapse of the first second be \( \lambda \), then we must have, when using the corresponding units, \( f = m \times \lambda \), where \( \lambda \) is called the acceleration. Unit of force will therefore, when acting upon unit of mass, produce unit of acceleration.

As the force produces a velocity \( \lambda \) per second in the first second of the motion, the velocity at the lapse of two seconds must be \( 2 \lambda \) per second, and after the lapse of \( n \) seconds the velocity of the body will be \( n \lambda \) per second, provided that the force is still acting on the body. For this reason we may define acceleration as rate of change of velocity.

Acceleration is measured in Britain in feet per second, per second, and in France in metres per second, per second.

As the acceleration of gravity at the sea level at Greenwich is 32·137 ft. per second, per second, then 1 lb. weight acting upon 1 lb. mass will produce an acceleration of 32·137 ft. per second, per second, but when 1 lb. weight acts upon engineering unit of mass, then the acceleration should be 1 ft. per second, per second; consequently engineering unit of mass is the mass of 32·137 lb. mass. In French measurements, the acceleration of gravity at the sea level at Paris is 9·8067 metres per second, per second, and as unit of acceleration is 1 metre per second per second, we find that engineering unit of mass in French measures is equal to 9·8067 kilogramme mass.

As the acceleration of gravity varies with the distance from the centre of the earth, and also with the latitude, it follows that the weight of a body will also vary, according to its position relative to the earth. For this reason, by weighing a body on a pair of scales, we do not determine the weight but the mass of the body. We can therefore only find the weight of the body by means of a spring balance. Suppose we thus find the weight to be \( P \) pound, and the acceleration of gravity is \( g \) feet, then the mass of the body in pounds will be \( \frac{P}{g} \), and in engineering units \( \frac{P}{g} \). We may therefore say that the mass of a body is equal to the weight of the body in pounds divided by the acceleration in feet. In French measures, the mass of the body is equal to the weight of the body in kilogrammes divided by acceleration in metres.

If, for instance, the safety-valve of a boiler is loaded by weights, the valve will open at a smaller effective pressure at the equator than at the pole; but if the valve is loaded by a spring, then the effective pressure which is required to open the valve will be the same at any place in the world.

Work.—Power.—Energy.

Work.—By doing work, we understand to produce motion against a resistance. The product of the resistance in terms of unit of force, and the distance in terms of unit of length, through which it has been moved, is, therefore, a measure for the work done upon the resistance.

Unit of work is, in Britain, 1 foot-pound, and in France, 1 kilogram-metre.

Power.—It is not only necessary to know what work a machine has to do, but we must also know within what time it must perform this work. Suppose we have to pump a certain quantity of water into a tank, and we are allowed eight hours for doing the work; then an engine of a certain size will do. But if we are only allowed four hours, we must have an engine of double the size, or, as we say, of double the power.

By the power of an engine, we, therefore, understand the rate at which it can do work—i.e., the quantity of work which it can do in a certain interval of time. The unit of power is, in Britain, 1 foot-pound-second, and in France, 1 kilogram-metre-second. But as these units are small, it would be more convenient, in practice, to use a derived unit of power. The usual derived unit is 1 horse-power, this being equivalent to the average work performed by a horse, and is, in Britain—

- 550 foot-pounds per second;
- or, 33,000 foot-pounds per minute.

In order to fit in with the metrical system, the French horse-power is—

- 75 kilogram-metres per second, = 542·5 foot-pounds per second.

Energy.—By energy we understand the capacity of bodies for performing work, and a body is said to contain the more energy the more work it is able to do, regardless of time.

The terms energy and power must not be considered to mean the same. Power has relation to time. Thus, one ton of coal can, by being burnt in a sufficiently
large boiler, produce steam for developing, say, 750 horse-power for one hour; whereas, when being burnt in a small boiler, it can produce steam for 50 horse-power for 15 hours. The efficiencies of the two boilers and engines are assumed to be the same.

Energy appears under various forms—thus, mechanical energy, heat, electric energy, etc.—but they are all convertible. Energy cannot be created or destroyed; this statement is expressed in the principle of conservation of energy, and also in the impossibility of perpetual motion.

According to its definition, mechanical energy must be expressed in the same units as work done—i.e., that the unit of mechanical energy is a foot-pound, and in French measures a kilogram-metre.

Mechanical energy appears in two forms—viz:

(a) Potential energy or energy of position; this is the product of an effort into the distance through which it is capable of acting (Rankine).

(b) Kinetic energy or energy of motion, which is half the product of the mass of the body into the square of the velocity of the body.

These two kinds of energy are exemplified by the simple cases of a weight raised to a height, and a rotating flywheel, both of which contain capacity for doing work; the former in virtue of its position, and the latter in virtue of its mass and velocity.

Thus, a body placed on or above the surface of the earth would, if it were possible, fall towards the centre of the earth, or rather towards the common centre of gravity of the earth and the body, and stop there. Therefore, the potential energy of a body placed at a certain distance from the centre of the earth is equal to the energy exerted by gravity during the fall of the body.

If a body, weighing Q pounds, falls from a point at a height, \( h_1 \), above the sea level to another point at a height, \( h_2 \), also above the sea level, then it will lose in potential energy the amount \( (h_1 - h_2) \times Q \) foot-pounds.

If the body, in falling through the distance \( (h_1 - h_2) \), is doing no work—i.e., is not overcoming a resistance—then the difference of potential energy before and after the fall will be converted into kinetic energy, and we may say:

Energy exerted = kinetic energy accumulated in the body. Or in symbols—

\[
(h_1 - h_2) \times Q = \frac{Q}{g} \times \frac{V^2}{2} \quad \ldots \ldots (62)
\]

Where \( V \) is the velocity of the body when reaching the lower point, and \( g \) is the acceleration of gravity; therefore \( \frac{Q}{g} \) is the mass of the body.

If the body, while falling through distance \( (h_1 - h_2) \), is raising another body weighing \( P \) pounds, say, through the same distance, then it will be doing work to the amount \( P \times (h_1 - h_2) \), but as \( Q > P \), a part of the energy exerted will be converted into kinetic energy, and we may say

Energy exerted = work done + kinetic energy accumulated in the moving bodies. Or in symbols—

\[
Q \ (h_1 - h_2) = P \ (h_1 - h_2) + \frac{Q + P}{g} \times \frac{v^2}{2} \quad \ldots \ldots (63)
\]

where \( v \) is the velocity of the two bodies after having traversed distance \( (h_1 - h_2) \), and it is evident that \( v < V \) in formula (63).

Moment of Inertia.—The motion of the body has hitherto been assumed to be such that every molecule is moving at the same velocity; but if a body is rotating round a fixed axis like a flywheel, then we can no more talk about the velocity of the body, because the velocity of the molecules varies with their distance from the axis of rotation, and the problem of calculating the kinetic energy accumulated in the flywheel becomes more complicated.

Let the molecules of the rotating body have distances, \( x_1, x_2, x_3, \ldots \), from the axis of rotation, and have masses, \( m_1, m_2, m_3, \ldots \), and let the body make \( n \) revolutions per minute, then the velocity per second of the mass \( m_i \) will be \( \frac{2 \pi x_i}{60} n \), and the kinetic energy accumulated in the mass \( m_1 \) will be \( \frac{1}{2} \left( \frac{\pi n}{30} \right)^2 x_1^2 m_1 \), and the total kinetic energy stored in the body will be

\[
\frac{1}{2} \left( \frac{\pi n}{30} \right)^2 \Sigma m x^2, \quad \ldots \ldots (64)
\]

where \( \Sigma m x^2 \) is called the moment of inertia of the rotating body.

Imagine, now, that the total mass, \( M \), of the rotating body can be concentrated into one point at a distance, \( \delta \), from the axis of rotation, so as to have the same moment of inertia as the rotating body itself, then we must have

\[
M \delta^2 = \Sigma m x^2 \quad \ldots \ldots (65)
\]

and

\[
\delta = \sqrt{\frac{\Sigma m x^2}{M}} \quad \ldots \ldots (66)
\]

\( \delta \) is called radius of gyration or radius of rotation.

Example.—A cast-iron flywheel is making 100 revolutions per minute. The cross-section of the rim is a circle with a radius equal to 3in., and the distance between centre of circle and axis of rotation is 3ft. What will be the kinetic energy in foot-pounds stored in the flywheel rim? Take density of cast iron as 450lb.

The moment of inertia of the arms and boss is only small compared with that of the rim, and may therefore be neglected. Radius of rotation of the rim is approximately equal to the distance between centre of gravity of cross-section and axis of rotation; we may therefore take \( \delta = 3ft. \) The volume of the rim is

\[
V = \frac{\pi (0.5)^2}{4} \times 2 \times 3 = 3.7 \text{ cubic feet.}
\]

The mass of the rim is, therefore, \( 450 \times V \) pounds, or expressed in engineering unit of mass

\[
M = \frac{450 \times V}{33,187} = 52.
\]
The moment of inertia of the rim is
\[ I = M \times b^2 = 52 \times 9 = 468. \]

Kinetic energy stored in the rim is
\[ \frac{1}{2} \times \left( \frac{\pi \times 100}{30} \right)^2 \times 468 = 25,670 \text{ foot-pounds}. \]

**Work by Tangential Forces.**—A force which produces or resists rotary motion round a fixed axis is called a tangential force, because the straight line in which the force acts is a tangent to a circle with centre in the fixed axis, and whose radius is equal to the perpendicular distance between the force and the axis. This radius is called the arm of the force, and the product of the force into the arm is called the statistical moment of the force.

If the tangential force be an effort, then the energy exerted, while the rotating masses make one revolution round the axis, will be \( 2 \pi r \times E \), where \( r \) is the arm of the effort, \( E \).

If the tangential force, \( R \), be a resistance, then \( 2 \pi r \times R \) will be the energy consumed by \( R \) during one revolution of the masses round the axis.

As an example, we may take a horizontal shaft on which two pulleys are fixed. The one pulley, the "driver," receives energy from a prime mover by means of a belt; the other pulley, the "driven," drives a dynamo machine, also by belt. Starting from rest, the speed of rotation of the shaft will continue to increase until a maximum—\( n \) revolutions per second—is reached. Let \( t \) denote the time which elapses till the speed of rotation has reached \( n \) revolutions per second, then we must have:

Energy exerted on the "driver" during the interval of time, \( t = \) work done on the "driven" during the same period of time + kinetic energy accumulated in the rotating masses.

The latter quantity is according to formula (64)
\[ \frac{1}{2} \left( 2 \pi n \right)^2 \Sigma m x^2. \]

In \( \Sigma m x^2 \) is included all the rotating masses.

As the speed of rotation is to be kept constant at \( n \) revolutions per second, it is evident that after that speed has been reached, no more kinetic energy must be added to the rotating masses, and consequently the energy exerted must be spent in doing work only; thus we must have

Energy exerted on the "driver" = work done on the "driven."

Let \( E \) denote the tangential effort, \( R \) the resistance, \( D \) the diameter of the "driver," and \( d \) that of the "driven," then the energy exerted during one revolution, when the motion is uniform, will be \( \pi D \times E \), and the work consumed by the resistance during the same period will be \( \pi d \times R \). According to the above, we shall have
\[ \pi D \times E = \pi d \times R, \]
or
\[ D \times E = d \times R, \]
that is "The condition of uniform motion of a rotating axis is, that the statical moment of the effort must be equal to the statical moment of the resistance, or the effort must balance the resistance."

There are cases, such as in the steam-engine, where the efforts vary in magnitude during each revolution. In such cases we can consider that we have three periods during a revolution—viz.:

First period, during which the statical moments of the efforts are greater than those of the resistances; we may therefore say:

Energy exerted = kinetic energy added to the moving masses during this period + work done.

Second period, during which the statical moments of the efforts are equal to those of the resistances; we may therefore say:

Energy exerted = work done.

Third period, during which the statical moments of the efforts are smaller than those of the resistances; we may therefore say:

Energy exerted = work done - kinetic energy added to the moving masses during the first period.

By adding all three periods we shall have:

Energy exerted during a revolution = work done during a revolution.

**Work in Terms of Pressure and Volume.**—The resistance may be a pressure uniformly distributed on the area of a piston, such as the back pressure of water in a pump; the total resistance in such a case will be the intensity, \( R \), of the pressure, multiplied by the area, \( A \), of the piston. Let now the distance traversed by the piston be \( L \), then the work consumed by the resistance will be
\[ R \times A \times L = R \times V \ldots \ldots (67) \]
where \( V \) is the volume weight by the piston. If \( R \) is given in pounds per square foot, \( A \) in square feet, and \( L \) in feet, then (67) will be expressed in foot-pounds.

If the effort be a pressure of intensity, \( P \), acting on a piston, such as steam in a steam-cylinder, then the energy exerted by the effort would be
\[ P \times A \times L = P \times V \ldots \ldots (68) \]

Both effort and resistance may be pressures acting on the same piston, or there may be two pistons connected by a common piston-rod, the effort acting on the one, and the resistance on the other piston. As an example of the latter case, we may take the donkey-pump, Fig. 134, where the steam acts as an effort on the piston, \( S \), \( P \), while the pressure of the water acts as a resistance on the pump-piston, \( P \). The water is forced into the boiler during the downward stroke, and the back pressure of the water is then greater than the mean effective pressure on the steam-piston; whereas during the upward stroke the opposite is the case. For this reason the crank-shaft, \( C S \), with flywheel, \( F W \), are added, whereby sufficient kinetic energy can be stored, during the upward stroke, to assist the steam pressure in overcoming the resistances during the downward stroke.

**Work represented by an Area.**—As work and energy exerted are products of two quantities, force and length, they can be represented by the area of a plane figure, which is also the product of two quantities.
Let the abscissae in Fig. 163 represent distances traversed by a constant effort, and let the latter be represented by the ordinate \( o m \), then it is evident that the area \( o m n L \) will represent the energy exerted by the effort in traversing through the distance represented by \( o L \).

If the effort is variable, then let distances traversed and corresponding magnitudes of the effort be represented respectively by abscissae and corresponding ordinates in Fig. 164. Let, for instance, the distances traversed be equal to \( d \) times length of abscissae, and let magnitudes of effort be equal to \( b \) times length of ordinates, then, when the variable effort has traversed a distance equal to \( a \times O S \), the value of the effort is \( \xi = b \times y \). Let now the effort move through a small distance \( \delta = a \times h \), then the effort will be equal to \( E = b \times (y+h) \). Let \( w \) denote the energy exerted by the variable effort in traversing distance \( \delta \), then we shall have

\[
E \times \delta > w > \xi \times \delta
\]

or

\[
(y+h) \times h > \frac{w}{a} > y \times h \quad \ldots \quad (69)
\]

Let, further, \( q \) denote the area of \( S F B D S \), then we shall have, according to Fig. 164,

\[
(y+h) \times h > q > y \times h \quad \ldots \quad (70)
\]

(69) and (70) show that \( q \) and \( \frac{w}{a} \) lie between the same limits, the difference of which may be made as small as we please, by making \( h \) small; consequently we must have

\[
w = a \ b \times q.
\]

Now the total energy exerted by the variable effort in traversing through the distance represented by \( O L \) is \( W = \Sigma w \), and the area, \( o m F B n L \), is \( Q = \Sigma q \); therefore

\[
W = a \ b \times Q,
\]
or, in words, area \( Q \) represents the energy exerted by the variable effort.

Instead of being an effort, the force might have been a resistance, and area \( Q \) would then represent the energy consumed by the variable resistance, or the work done by the effort on the variable resistance.

The mean ordinate of the curve, \( m F B n \), Fig. 164, is the height of the rectangle, whose base is \( O L \), and whose area is equal to \( Q \). The mean ordinate, therefore, represents the constant force, which by traversing the distance represented by \( O L \), would give the same result as the forces represented by the ordinates of the curve, \( m F B n \), give, in moving through the same distance.

This force is called the mean effort, the mean pressure, or the mean resistance, as the case may be.

**Determination of Areas of Plane Figures.**—If the problem be to determine the area enclosed by the curve, \( l m \), Fig. 165, the base line, \( O L \), and the two ordinates, \( o l \) and \( m L \), then divide the base line, \( O L \), into a convenient number of equal parts, \( h \), and draw the corresponding ordinates, \( y_1, y_2, \ldots \) etc. The area is now divided by these ordinates into eight parts, of which each may be considered to approximate to a trapezoid. The area of a trapezoid (which is a plane figure bounded by a pair of parallel straight lines, and by a pair of straight lines not parallel) is equal to half the sum of the two parallel sides, multiplied by the perpendicular distance between them.

The true area of Fig. 165 approximates, therefore, to

\[
Q = h \left[ \frac{y_0 + y_8}{2} + y_4 + y_5 + y_4 + y_5 + y_6 + y_7 \right]
\]

and the mean ordinate of the curve will approximately be

\[
y_m = \frac{1}{h} \left[ \frac{y_0 + y_8}{2} + y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7 \right]
\]
If we had divided $OL$ into $n$ equal parts, we should have approximately

$$Q = \frac{\overline{OL}}{n} \left[ \frac{y_0 + y_n}{2} + y_1 + y_2 + \ldots + y_{n-1} \right]. \quad (71)$$

$$y_n = \frac{1}{n} \left[ \frac{y_0 + y_n}{2} + y_1 + y_2 + \ldots + y_{n-1} \right]. \quad (72)$$

(71) and (72) are the closer approximations, the greater $n$ is. In fact, we must divide the curve into so many parts, that each part can, without appreciable error, be considered a straight line.

_Planimeters._—When the areas of a number of irregular figures are to be determined, considerable time and labour may be saved by the use of a planimeter, which is an instrument worked by moving a tracer over the line enclosing the area to be measured; the latter will be registered on a small graduated wheel.

(I) Amsler's Polar Planimeter is illustrated in Fig. 166; it consists of a measuring wheel, $C$, and two arms, of which the one carries the tracer and is called the pole-arm; the other arm—the radius-arm—carries a needle-point, which is pressed into the board and serves as a centre round which the apparatus is turned. The tracing point is placed on the line of the figure, and a slight indentation is made in the paper to serve as a starting point. The graduated wheel, $C$, is set at the zero mark. The tracer is then moved clockwise over the boundary of the figure, making a complete circuit and returning to the starting point. The number of divisions and fractions of a division, shown on the wheel at the point opposite the stationary zero mark, indicates the area enclosed by the curve traced. The wheel has 10 main graduations, each of which represents 1 square inch. Each main division is subdivided 10 times. A stationary vernier, $E$, is placed beside the graduated wheel, and serves to indicate the smaller fractions—viz., hundredths.

That the integrating wheel really registers the area enclosed by the path moved over by the tracer, can be seen in the following way: In Fig. 167, $O$ is the centre, round which the apparatus is turned, $OF_1$ is the radius-rod, and $aF_1$ the pole-rod. Suppose we want to move the tracer to point $b$, the rods would then have to be moved to position $OF_2b$; in order to do this we will first turn the pole-rod round point $F_1$ until it is in the position $F_1a_1$ parallel to $F_2b$, and then slide the pole-rod parallel to itself until it reaches position $F_2b$. The area moved over by the pole-rod is therefore $F_1aa_1bF_2F_1$, which consists of the sector $F_1a_1F_1$ and the curvilinear parallelogram $F_1a_1bF_2F_1$. Let the length of the pole-rod be $l$, then the area of the sector will be $\frac{1}{2} l \text{ arc } a a_1$. 
Let us assume that the graduated wheel is placed in the middle of the pole-rod, so that \( a_c = c_1 F_1 \), then the wheel will roll over arc \( c_1 c_2 \), which is equal to \( \frac{1}{2} \) arc \( a_a \). The area of the sector will, therefore, be \( b \times \text{arc} c_1 c_2 \), and the graduated wheel will thus register the area of the sector. The area of the curvilinear parallelogram is equal to \( b \times c_2 c_3 \). The wheel will be moved over the curve \( c_2 d \), but this motion can be resolved into \( dc_1 \) and \( c_2 c_3 \). The former will cause the wheel to slide only, and the latter motion will make the wheel turn. We see, thus, that the area of the curvilinear parallelogram is also registered by the wheel.

Let, now, the problem be to measure area, \( Z \), which is enclosed by the curve, \( a_1, a_2, a_3, a_4, a_5 \), in Fig. 168; therefore ought, and the wheel can consequently be placed at any convenient distance from the tracer.

2. If we imagine the radius-rod, Fig. 167, infinitely long, so that point \( F \) of the pole-rod moves in a straight line instead of in a circle, then we have the Coffin planimeter illustrated in Fig. 169.

The one end of the bar of this instrument rests in a groove made in a metal plate, which is fixed on the board of the apparatus; the other end of the bar carries the tracer. In using the instrument, we must place the card containing the area to be measured under the clamps, \( C \) and \( K \), which may be sprung away from the board sufficiently to allow the card to be introduced, and the card is then moved towards the left into such a position that the base line of the curve is near to and parallel with the lower edge of the stationary clamp, \( C \).—i.e., the base line is placed at right angles to the groove—while the left-hand end of the curve is made to touch the other edge of the clamp. The movable clamp, \( K \), which can slide at the bottom in a groove, is then moved towards the left until its edge touches the right-hand end of the curve. The tracer is then moved to the point \( D \), at which the edge of clamp \( K \) touches the curve. Here a slight indentation is made in the paper by pressing the finger on the top of the tracer. The graduated wheel is next turned, until its zero mark is opposite the zero mark of the vernier. The tracer is then moved carefully over the curve, in the direction of the hand of a watch, until it has made a complete circuit, returning to point \( D \).

If it be required to determine the mean ordinate of the curve, then move the tracer—after it has been moved over the curve—from \( D \), along the edge of
clamp K; as this motion is made in an anti-clockwise direction, the wheel will gradually turn round to zero again; at that moment another slight indentation is made in the paper, in order to mark the new position of the tracer. This point is represented by A in Fig. 169. The distance, D A, will then be equal to the mean ordinate of the curve. That this is right, can be seen in the following way. In Fig. 170, F, D is the position of the bar after the tracer has been moved over the curve. F, A, parallel to F, D, is the position of the bar when the graduated wheel has returned to zero. The bar has thus described the parallelogram F, D A F, whose area must be equal to that enclosed by the curve; but the area of F, D A F, is equal to the area of rectangle L, D A L; and as D L is the base line of the curve, A D must be the mean ordinate. C D, C, is equal to the length of the arc turned over by the graduated wheel.

Useful Work and Waste Work.—The total work done by the effort or efforts in moving a machine is partly spent in overcoming useful resistances for the purpose of which the machine is designed, and partly in overcoming resistances within the machine. The total work is therefore equal to the useful work plus the waste work.

By the efficiency of a machine is understood the ratio of the useful work to the total work. The greater this ratio is, the better is the machine for transmitting energy, but it can never reach unity, which is the efficiency of a perfect machine.

In practice, a machine usually drives another machine, which again drives a third, etc.

The efficiency of any machine of such a series of machines will be equal to the work done by the machine on the next one, divided by the work done on this machine by the one in front. Suppose, for instance, we have a series of four machines having efficiencies η, η, η, η, and η respectively, and let v denote the work consumed by No. 1; then the work done by the latter will be η v, w, and that done by No. 2 will be η v, η, w, therefore the work done by No. 4 will be η v, η, η, η, w. The efficiency of the whole system of the four machines will evidently be

\[ \eta = \frac{\eta v, \eta, \eta, \eta, \eta w}{w} = \eta v, \eta, \eta, \eta, \eta \]  

(73)

or in words: The efficiency of a series of machines is equal to the product of the efficiencies of the single members of the series.

Work Consumed by Friction.—The greater part of the energy lost in a machine is spent in overcoming the force of friction, which resists the sliding of two bodies on each other at their surface of contact—i.e., their bearing surface.

The surface of a body is never perfectly smooth, although it may appear to be so, but, by examining it with a magnifying glass, it will be found to be more or less undulated. The friction is thus caused by moving the sliding body over these undulations. The degree of smoothness which can be given to the surface of a body depends upon the material; thus, the surface of metal can be made smoother than that of leather, but by using proper substances which will adhere to the bodies, and which are soft enough to be squeezed into and fill up the undulations, the smoothness of the bearing surfaces can be greatly increased. Such substances are called unguments or lubricants, and may be oil, tallow, or soap and water, and for some materials even water alone.

To overcome friction, therefore, consists in lifting the sliding body over the undulations. The friction between two sliding bodies must therefore be proportional to the force, F, by which they are pressed together, P being estimated at right angles to the bearing surfaces. If P is so small that it does not cause any indentations in the surfaces of the bodies but leaves them in their original condition, then the friction must be independent of the area of the bearing surface. In this case, the force of friction, F, will be

\[ F = f \times P \]  

(74)

where f is a factor called the coefficient of friction, whose value depends on the state of the bearing surfaces as to smoothness and lubrication.

If P is so great that it causes the bodies to grind into each other, then f will increase with P. In constructing machinery it is of great importance to make the bearing surfaces large enough, so as to prevent P from producing excessive friction and injuring the bearing surfaces.

The work consumed by friction is evidently equal to the force of friction, F, multiplied by the distance, d, traversed by the sliding body. This energy is converted into heat, to the amount of one British heat unit for each 772 foot-pounds exerted in overcoming the friction. The heat thus produced may be made useful in softening the lubricant, as when tallow is used, but when excessive it will decompose the lubricant and soften the sliding bodies, whereby these will grind into each other and increase the friction. To prevent the temperature from rising beyond a certain limit, the cooling surface of the sliding bodies must be so large that at this limit of temperature, the heat dissipated is equal to the heat produced during unit of time.

Deviating Force.—Centrifugal Force.

A body which is acted upon by no force, or by balanced forces, will continue to move in a straight line; but if the moving body be continually acted upon by an unbalanced force in the direction at right angles to that of the motion, then the path of the body will be a curve, and the force is called the “deviating force.”

Thus, for example, if a train moves on a curve, the deviating force is supplied by the rails being strong enough to deviate the motion of the train from the straight line. The train will, on account of its inertia, produce a pressure on the rails, which is equal to the deviating force. This pressure is commonly called “centrifugal force,” but as it disappears with the deviating force, the centrifugal force is only a reaction, and can produce no motion.
If there were no friction or other resistance, a passenger would be thrown out of the train in the direction of the tangent to the curve, in virtue of his inertia, but not, as is commonly understood, in virtue of the centrifugal force; the latter does not exist unless there is a deviating force, and when it does exist, it will be balanced by the deviating force.

The acceleration of the deviating force is

$$p = \frac{v^2}{r} \quad \ldots \ldots \quad (75)$$

where \(v\) is the tangential velocity of the body, and \(r\) is the radius of curvature. If \(v\) be given in feet per second and \(r\) in feet, then \(p\) would be expressed in feet per second per second. Let \(m\) denote the mass of the body in pounds, then the deviating force will be

$$\frac{m}{32.187} \times \frac{v^2}{r} \text{ pounds} \quad \ldots \ldots \quad (76)$$

If \(w\) be the weight of the body in pounds, and \(g\) the acceleration of gravity at the place where the weight is taken, then the deviating force would be

$$\frac{w \times v^2}{g} \text{ pounds} \quad \ldots \ldots \quad (77)$$

In rotating parts of a machine, such as a flywheel, the deviating force is supplied by the force of cohesion. If at a certain speed of rotation, the required deviating force is greater than the cohesion, then, at such speed, the molecules will separate and the wheel will fly to pieces.

It is of great importance in machinery that the rotating masses should be so distributed round the axis of rotation as to produce no pressure on the bearings; or, in other words, that the deviating forces acting on the molecules should mutually balance. Fig. 171 represents a thin slice of a substance rotating round axis \(AB\); let \(r_1, r_2, r_3, \ldots\), etc., denote the distances of the molecules from \(AB\), and \(m_1, m_2, m_3, \ldots\), etc., their respective masses, then the deviating force required for \(m_i\), when the speed of rotation is \(n\) revolution per second, will be

$$\frac{(2 \pi n r_i)^2 m_i}{r_i} = (2 \pi n)^2 m_1 r_1 \quad \ldots \ldots \quad (78)$$

and as the deviating forces of all the molecules are parallel, the resultant deviating force will be

$$(2 \pi n)^2 \Sigma m r \quad \ldots \ldots \quad (79)$$

(79) will be sought if \(\Sigma m r = 0\), which requires that the axis of rotation should pass through the centre of gravity of the slice.

If the rotating body be of any shape, then we can imagine the body being cut up in thin slices passing through the axis of rotation, and consequently, the condition for no pressure on the bearings due to rotation will be that the axis of rotation shall pass through the centre of gravity of the body.

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**CHAPTER X.**

**HEAT.**

**Temperature—Scales of Temperature.**

Heat is the cause of certain phenomena which take place in material bodies. By means of our sense of feeling, we term a body warm or cold according to the condition of the body brought on by heat. Heat has been proved by Joule to be a special form of energy. The thermal state of a body \(A\), is higher than that of a body \(B\), if \(A\) is able to give off heat to \(B\), this thermal state is termed "temperature." A body is, therefore, termed warm, when its temperature is higher than that of our own body, in which case we receive heat; the body is cold, if its temperature is lower than that of our body, as it then receives heat from us.

Temperature is measured, by means of the thermometer, by observing the expansion of a fluid when heated from a certain standard temperature to the temperature to be measured. Let \(V\) denote the volume of the fluid at the standard temperature, \(kV\) the expansion of the fluid when heated up to another and higher standard temperature, and \(h\) the quantity of heat which
is required for producing expansion \( k \text{V} \); then the difference of temperature produced by the quantity of heat, \( \frac{k}{n} \), where \( n \) is a pure number, is called a degree of temperature, and if the fluid be air—air thermometer—then we shall find that the expansion produced by \( \frac{k}{n} \) will be \( k \text{V} \), consequently the latter will be a representation of a degree of temperature.

The lower standard temperature is usually taken as that at which pure water freezes, and the higher standard is the temperature of pure water when the pressure of its vapour is one atmosphere, or, as it is commonly called, the boiling point of pure water.

In the centigrade scale, \( n \) is taken as 100, and one centigrade is therefore represented by \( \frac{k \text{V}}{100} \). In this scale the temperatures are reckoned from the freezing-point as zero-point. The temperature of the boiling-point is therefore 100 deg.

British engineers use the Fahrenheit scale, in which \( n \) is taken as 180; 1 deg. F. is therefore equal to \( \frac{9}{5} \) deg. centigrade. The temperatures are reckoned from a temperature 32 deg. below the freezing-point; the boiling-point will therefore be 212 deg.

In practice, the thermometer fluid is mercury, but by using the latter, \( \frac{k}{n} \) will at certain temperatures produce an expansion greater than \( \frac{k \text{V}}{n} \), and at others an expansion less than \( \frac{k \text{V}}{n} \). A mercury thermometer should therefore be calibrated by comparison with an air thermometer.

In measuring the temperature of a body, the thermometer is brought into contact with the body until its temperature is the same as that of the body; hereby the body will either give off heat to the thermometer whereby its temperature will fall, or the body will receive heat from the thermometer and its temperature will rise. The error hereby incurred can be made inappreciable by making the mass of the thermometer small.

**Heat Units.**—**Thermal Capacity.**—**Specific Heat.**

**Heat Units.**—For the purpose of measuring the heat required for raising the temperature of a body from one temperature to another, we must choose an arbitrary quantity of heat, which we call a heat unit.

In Britain, the heat unit is the quantity of heat which is required for raising the temperature of the mass of 1 lb. of pure water from 32 deg. F. to 38 deg. F. at a pressure of one atmosphere.

In France, the heat unit is called a calorie major, and is the quantity of heat required for raising the temperature of the mass of 1 kilogramme of pure water from 0 deg. C. to 1 deg. C., at the pressure of one atmosphere.

In the C.G.S. system, the heat unit is called a calorie minor, and is the quantity of heat required for raising the temperature of the mass of 1 gramme of pure water from 0 deg. C. to 1 deg. C. at the pressure of one atmosphere—the calorie minor is therefore equal to 0.001 calorie major.

**Thermal Capacity.—Specific Heat.**—The thermal capacity of a body, of mass \( m \), is the quantity of heat required for raising the temperature of the body 1 deg., and will be

\[
S \times m \text{ heat units}
\]

where \( S \) is a coefficient which depends upon the substance, and must be determined by experiment. The heat required for raising the same mass of pure water 1 deg. of temperature from the ice-point, will be \( m \) heat units. Consequently, \( S \) will be the ratio of the heat required for raising a certain mass of a substance through 1 deg. of temperature, to the heat required for raising the temperature of the same mass of pure water 1 deg. from the ice-point. \( S \), which is a pure number, is called the specific heat of the substance, but as it is neither specific nor heat, the term is utterly absurd, and \( S \) ought to be termed thermal coefficient.

The specific heat varies with the temperature of the substance, but if we have found, for instance, in French measures that the specific heat for a given substance is \( S \) at a temperature of \( t \) deg. centigrade, then the specific heat for the same substance, using English measurements, will also be \( S \) at a temperature of \( (\frac{t}{2} + 32) \) deg. F. This, however, is only true if the British heat unit is defined as above. In some text-books it will be found that the British heat unit is defined as the quantity of heat required for raising the temperature of one pound of pure water from 50 deg. F. to 51 deg. F.; in other books the temperatures are 39 deg. F. and 40 deg. F. In either case the specific heat in the British system will not be the same as in the French system at the same temperature, because the specific heat of water at 50 deg. F. or 39 deg. F. is not the same as at 32 deg. F.

The heat required for raising the temperature of a body, of mass \( m \), from \( t_1 \) deg. to \( t_2 \) deg., will be

\[
S_m \times m \times (t_2 - t_1) \text{ heat units.} \quad (80)
\]

where \( S \) is the average specific heat of the substance between the above two temperatures.

**Transfer of Heat.**

The transfer of heat from one body, \( A \), at a higher temperature, to another body, \( B \), at a lower temperature, takes place through the surfaces of the bodies. The surface through which heat is given off or received is called cooling-surface or heating-surface respectively. The temperature of the cooling-surface will be denoted by \( t_c \), and that of the heating-surface by \( t_h \).

The transfer of heat can take place by three processes—viz., "conduction," "radiation," and "convection."

(1) **Conduction.**—When the two bodies, \( A \) and \( B \), of given shapes are in contact with each other, then the transfer of heat from \( A \) to \( B \) will be done by conduction through their surface of contact, which will be cooling-
surface with regard to A, and heating-surface with regard to B. The quantity of heat transferred at any moment will be proportional to \((t_a - t'_h)\), and to the area of the surface of contact, where \(t_a\) and \(t'_h\) refer to A and B respectively.

As A loses heat, \(t_a\) will fall at a rate which will be directly proportional to \((t_a - t'_h)\), and inversely to the thermal capacity and conductivity for heat of A.

This will go on until \(t_a\) has fallen so much, and \(t'_h\) has risen so much, that \(t_a = t'_h\); i.e., when the two bodies are at the same temperature.

As B receives heat, \(t'_h\) will rise at any moment, at a rate which will be inversely proportional to the thermal capacity and conductivity of B, and directly proportional to \((t - t'_h)\).

Let A be entirely surrounded by B, whose thickness, estimated at right angles to the surface of contact, is \(\delta\); and let \(C\) denote the conductivity of B, \(C_1\) and \(C'_1\), the cooling surfaces of A and B respectively, and \(t\) the temperature of the cooling-surface of B; then the rate at which heat is conducted through B at any moment will be

\[
H = \frac{C \times C_1 + C'_1 \times (t_a - t_e)}{2 \delta} \quad (81)
\]

For this reason, steam-boilers, steam-pipes, etc., should be covered with non-conducting material of such a thickness that \(\frac{C}{\delta}\) is small enough to prevent a superfluous loss of heat.

For a cylinder of diameter \(d\), length \(l\), and covered with a mantle of thickness \(\delta\), the rate of heat lost will be from the cylindrical surface

\[
H = \frac{C \times \pi (d + \delta) l (t_e - t_a)}{\delta} \quad (82)
\]

and if the ends of the cylinder are closed and also covered, then the rate of heat lost from each end will be

\[
H = \frac{C \times \pi d^2 (t_e - t_a)}{4 \delta} \quad (83)
\]

Formulae (82) and (83) can be applied to boilers, steam-pipes, steam-cylinders, etc.

For steam boilers set in brickwork, formula (82) and (83) are to be used; but for boilers which are not set in brickwork, \(\delta\) will be small compared with \(d\), and formula (82) may then be reduced to

\[
H = \frac{C \times \pi d l (t_e - t_a)}{\delta} \quad (84)
\]

In steam-cylinders \(\delta\) would also be small compared with \(d\), and formula (84) will, therefore, also hold good in this case.

For steam-pipes formula (82) must be used.

The above formulae show that if the heat lost is to be the same for cylinders of various diameters, \(\delta\) must be taken in proportion to the diameter of the cylinder, and that for the ends, \(\delta\) must be increased with the square of the diameter. Thus, if we are satisfied with \(\delta\) equal to 1in, for a steam-pipe of 2in. diameter, then for a steam-pipe of 12in. diameter, we must take \(\delta = 6\)in., using the same non-conducting material in both cases.

It would, however, be inconvenient in practice to increase \(\delta\) with \(d\). Suppose we choose \(\delta\) so that the ratio of the heat lost to the quantity of steam carried by the pipe in unit of time, is the same for all sizes of pipes.

Then for the same velocity and temperature of the steam and for the same non-conducting material, we should have the heat lost and the quantity of steam passing through the pipe proportional to \(\frac{d + \delta}{\delta} d^2\) respectively, and the ratio of these two quantities should be constant for all pipes, or

\[
\frac{d + \delta}{\delta d^2} = k \quad \ldots \ldots (85)
\]

where \(k\) is a constant.

If we are, as above, satisfied with 1in. covering for a 2in. pipe, then \(k\) will be equal to 0·75. According to formula (83) we have

\[
\delta = \frac{d}{k d^2 - 1} \quad \ldots \ldots (86)
\]

If we want to find \(\delta\) for a 6in. pipe, we must insert \(d = 6\) and \(k = 0·75\) in formula (86), and we then find \(\delta = 0^\circ 23\).

In practice, however, \(\delta\) is made the same for all sizes of pipes—viz., about 2in. Consequently the efficiency of a covered pipe of large diameter is greater than that of a small pipe.

Non-conducting materials used for lagging boilers, steam-pipes, etc., are generally composed of sawdust, charcoal, asbestos, hair felt, silicate cotton, paper fibre, etc.

The same formulae may be applied for calculating the heat transferred through the heating-surface, \(H_n\) of a boiler. The rate of heat transferred will be

\[
H = \frac{C \times H_n \times (t_e - t_a)}{\delta} \quad \text{heat units.} \quad (87)
\]

Where \(t_f\) and \(t_a\) are the temperatures of the fire and the water respectively, and \(\delta\) the thickness of the flue-plates. The relative conductivity of copper and iron is 100 and 16, and for this reason copper is often used for fireboxes in locomotive boilers where \(t_f\) is very high.

(2) Radiation.—The transfer of heat from one body to another at any distance apart, follows the laws for radiation of light.

To illustrate radiation of heat, place a thermometer in front of a fire, and we shall soon find that its temperature will rise; if we now suddenly screen the thermometer from the fire, its temperature will fall to that of the surrounding air, which shows that the heat cannot have been conducted through the air to the thermometer.

The rate at which a hotter body radiates heat, and a colder body absorbs heat, depends upon the state of the surfaces of the bodies as well as on their temperatures. Rough and dark surfaces radiate and absorb heat better than bright and smooth surfaces. For this reason, the
covering of steam-pipes and boilers should be smooth and of a light colour; uncovered pipes and steam-cylinder covers should be polished.

(3) **Convection.**—The density of fluid is generally diminished by the rise of temperature. If a fluid contained in a vessel be heated, the portion of the fluid next to the heat source will be less dense than the other parts of the fluid, and will therefore tend to rise to the surface; but this rise must evidently be accompanied by a fall of the colder parts of the fluid, and thus currents—convection currents—will be set up in the fluid, whereby the latter will be heated. It is also evident that the heat source ought to act on the fluid at the lowest point of the vessel, so as to produce convection currents right through the fluid. If the heat source were placed at the surface, no convection currents could be produced, and the heating of the fluid would then be done by conduction, which would require very much more time.

Boiler-flues should therefore be placed as close as possible to the bottom of the boiler.

**Expansion of Gases.**

The volume occupied by a certain portion of a gas depends upon its temperature and the pressure to which it is subjected. If the pressure of the gas be diminished, the volume will increase—*i.e.*, the gas will expand; the same effect is caused by raising the temperature of the gas.

**The First Law of Expansion of Gases.**—Assume that we have a certain portion of a gas enclosed within a cylinder, with an air-tight fitting piston. We may then compress the gas by placing weights on the top of the piston, in which case we shall find that the temperature of the gas will rise, but still by conveying a sufficient amount of heat from the gas, we can keep the temperature constant. We could otherwise diminish the weights on the piston, and the gas would then expand again and at the same time the temperature would fall, but by adding the necessary quantity of heat to the gas, we can keep the temperature constant in this case also.

Let now \( V_0, V_1, V_2, V_3 \ldots \) denote the volumes occupied by the gas, corresponding to the pressures per unit of area \( P_0, P_1, P_2, P_3 \); then we shall find by keeping the temperature of the gas constant that

\[
\frac{V_0}{V_1} = \frac{P_1}{P_0} = \frac{V_1}{V_2} = \frac{P_2}{P_1} = \ldots \quad (88)
\]

or

\[
V_0P_0 = V_1P_1 = V_2P_2 = V_3P_3 = C \quad \ldots (89)
\]

The first law of expansion of gases may therefore be stated as follows: "The product of the volume occupied by a portion of a gas at constant temperature into its pressure is constant."

This law was first discovered by Robert Boyle in 1662, and verified by Mariotte in 1715; hence it is called Boyle's law or Mariotte's law.

The constant, \( C \), varies, of course, with the temperature, everything else remaining the same.

The **Second Law of Expansion of Gases** states that "The increase of volume of a gas at constant pressure is proportional to the temperature."

It has been found that the increase of volume of a gas by heating it from the ice-point to the boiling-point is \( \frac{3665}{180} \) of its volume at the ice-point. The expansion of a gas by increase of temperature is therefore for 1 deg. F. equal to \( \frac{3665}{180} = 0.002086 \); this number is called the "coefficient of expansion" of gases.

The second law of expansion of gases can now be expressed in symbols, as follows:

Let \( V_1, V_2 \), and \( V_3 \) be the volumes of a gas at 32 deg. F., \( t_1 \) deg. F., and \( t_2 \) deg. F. respectively, then

\[
V_1 = (1 + 0.002036 (t_1 - 32)) V_2 \ldots (90)
\]

and by dividing (90) by (91)

\[
\frac{V_1}{V_2} = \frac{1 + 0.002036 (t_1 - 32)}{1 + 0.002036 (t_2 - 32)} \ldots (92)
\]

The second law of expansion of gases is also called the law of Charles or the law of Gay-Lussac.

The two laws of expansion can be joined together in one formula, stating the relation between volume, temperature, and pressure of a gas.

Let \( V_0 \) and \( V^1 \) be volumes of the same portion of a gas at 32 deg. F., and under pressures of \( P_0 \) and \( P_1 \), then

\[
\frac{V_0}{V_1} = \frac{P_1}{P_0} \ldots \ldots (93)
\]

and let \( V_1 \) be the volume of the gas at \( t_1 \) deg. F. and at a pressure of \( P_1 \), then

\[
\frac{V_1}{V_1} = \frac{1}{1 + 0.002036 (t_1 - 32)} \ldots (94)
\]

and by multiplying (93) by (94)

\[
V_1 = V_0 \frac{1 + 0.002036 (t_1 - 32)}{P_0} \ldots (95)
\]

If the temperature and the pressure be changed to \( t_2 \) and \( P_2 \) respectively, the volume of the gas will be

\[
V_2 = V_0 \frac{1 + 0.002036 (t_2 - 32)}{P_2} \ldots (96)
\]

Now divide (95) by (96)

\[
\frac{V_1P_1}{V_2P_2} = \frac{1 + 0.002036 (t_1 - 32)}{1 + 0.002036 (t_2 - 32)} = R \ldots (97)
\]

where \( R \) is constant, depending upon the nature and portion of the gas. Formula (97) expresses in symbols the two laws of expansion of gases.

**Absolute Temperature of Gases.**—**Imaginary Gases.**—

The absolute temperature of a gas is a theoretical consequence of the second law of expansion, by assuming that it is possible to continue the cooling of a gas until its volume is diminished to nought. The temperature, \( T_0 \), at which the volume of the gas should be nought, must satisfy the following equation:

\[
0 = 1 + 0.002036 (T_0 - 32) \ldots (98)
\]

and we find

\[
T_0 = 460 \text{ deg. F.} \ldots \ldots (99)
\]
If gases really followed the second law of expansion strictly, as assumed in formula (98), then all heat would have been extracted from the gas at the moment its temperature fell to $T_0$, and the temperature would therefore be the absolute zero of temperature. But all substances hitherto known have been found to have three states of aggregation—solid, fluid, and gaseous—besides which it has been proved by accurate experiments that gases only follow the two laws of expansion within certain limits of temperature and pressure, and it has also been found that the further the temperature of a gas is from its temperature of liquefaction, the closer does it follow the laws of expansion. For example: atmospheric air, hydrogen and oxygen, at temperatures and pressures within practical limits, are far from their fluid state of aggregation, and follow the two laws of expansion fairly well; but carbonic acid, which can be condensed to a fluid at a temperature of minus 108 deg. F., or at a pressure of 36 atmospheres, does not follow the two laws so well, especially at high pressures, as it is then approaching its fluid state of aggregation.

It is, however, convenient in theory to distinguish between "imaginary gases" and "actual gases," the former following the two laws of expansion absolutely, and remaining gases at all temperatures and pressures, whereas actual gases only follow the two said laws approximately within certain limits.

The temperature, $T_0$, given by (99) will be the absolute zero for imaginary gases, and the temperature of the gas reckoned from this zero will be the absolute temperature of the gas. Thus, if the temperature of an imaginary gas is $t$ deg. F., its absolute temperature is $T = 460 + t$. One degree of absolute temperature is, of course, equal to 1 deg. F.; we have only lowered zero 460 deg. F.

The temperature of an imaginary gas will hereafter be denoted by $T$ in the absolute scale, and by $t$ in the ordinary scale.

Formula (98) and (99) gives $\frac{1}{0.002036} = 492$, which makes $1 + 0.002036 (t - 32)$ equal to $460 + t$; we can, consequently, write formula (97) as

$$\frac{V_1 P_1}{T_1} = \frac{V_2 P_2}{T_2} = R \ldots \ldots (100)$$

Formula (100) expresses the two laws of expansion for imaginary gases.

**Mechanical Theory of Heat.**

When Joule had proved by well-known experiments that heat is a special form of energy, a theory was introduced, according to which the effects of heat upon substances are explained by the laws of dynamics. This theory is called "thermo-dynamics," and its first law states "that heat and mechanical energy are mutually convertible; a British unit of heat corresponding to a certain fixed amount of mechanical energy (equal to 772 foot-pounds), called the mechanical equivalent of heat." The latter will always be denoted by J.

A body is supposed to consist of molecules, which are tied together by the force of cohesion. By a molecule we understand the limit of division of a body affected by mechanical means. A molecule, again, consists of atoms, which are tied together by chemical affinity. An atom is, therefore, the limit of division of a body affected by chemical means. According to the above-named theory, the molecules are in a state of agitation—i.e., the molecules are flying about within the space occupied by the body in all directions, at a velocity which increases with the temperature.

We may conveniently compare the molecules of a body to a number of billiard-balls moving to and fro on a billiard-table. In their motion the balls will hit each other, and, being elastic bodies, they will part in opposite directions if their collision is straight; but it will also happen that the balls meet at an oblique angle, in which case they will set each other spinning. The kinetic energy, $K_1$, of the ball consists therefore partly of energy of translation and partly of energy of rotation, and will be

$$K_1 = \frac{1}{2} \Sigma m v_i^2 + \frac{1}{2} \Sigma I \omega_i^2 \ldots \ldots \ldots (101)$$

Where $m$ is the mass, $v_i$ the velocity of translation, I the moment of inertia, and $\omega_i$ the velocity of rotation of a ball.

The energy $K_1$ evidently corresponds to a quantity of heat, $\Pi_1 = \frac{K_1}{J}$.

Suppose we could somehow or other increase the velocity of translation of the balls to $v_2$, then by the hitting of the balls against each other, their velocity of rotation would also be increased, say, to $\omega_2$, and their kinetic energy to

$$K_2 = \frac{1}{2} \Sigma m v_2^2 + \frac{1}{2} \Sigma I \omega_2^2 \ldots \ldots \ldots (102)$$

The energy imparted to the balls in increasing their velocity from $v_1$ to $v_2$ must be $(K_2 - K_1)$, which evidently corresponds to a quantity of heat

$$H = \frac{K_2 - K_1}{J} \ldots \ldots \ldots (103)$$

In heating a body we have not only to increase the kinetic energy of the molecules, but as the body generally expands, we have also to overcome the force of cohesion, and the external pressure, which resist the expansion.

We may, therefore, say that the heat is partly spent in exerting

- Internal energy = work done in overcoming internal resistance + kinetic energy added to the molecules \ldots \ldots \ldots (104)
- and partly in exerting
- External energy = external work done in overcoming external resistances \ldots \ldots \ldots (105)

**Latent Heat.**—If a body be moved against gravity at a constant velocity, then its potential energy will be increased, but its kinetic energy will remain unaltered, or

- Energy exerted = work done in increasing the potential energy of the body \ldots \ldots \ldots (106)
To apply (106) on (104) would mean to spend heat in overcoming internal resistances only, and thus to increase the potential energy of the molecules by bringing them further apart, and allowing them to move more freely, but the temperature would remain constant. Now this is precisely what takes place when a body is changing from one state of aggregation to another. Thus, when melting a piece of ice, we may continue to add heat, but as long as any ice is left, the temperature of the ice-water will remain constant at 32 deg. F. The temperature of water while being evaporated at a constant pressure will also remain constant.

The heat which is spent in increasing the potential energy of the molecules is called "latent heat," in opposition to "sensible heat," which is spent in raising the temperature only; instead of the two latter terms, "potential heat" and "kinetic heat" might be used with advantage.

Thermo-dynamics of Imaginary Gases.

It has been shown by experiments that actual gases, when far from their point of liquefaction, show hardly any sign of internal resistances, for if such a gas be allowed to escape into a vacuum, it fills up all parts of the space, and its temperature does not fall appreciably. If the gas had absolutely no internal resistances to overcome by expanding, its temperature would not fall at all. We may, therefore, assume that the reason why no actual gas follows the laws of expansion is due to internal resistances, whereby the nature of the gas will be altered when we alter its temperature, pressure, and volume. Imaginary gases can consequently have absolutely no internal resistances to overcome at any temperature and pressure, and the heat spent on such a gas will partly be exerted as

\[ \text{Internal energy} = \text{kinetic energy added to the molecules} \]  

and partly as

\[ \text{External energy} = \text{external work done by the expansion of the gas} \]  

If by \( \beta \) we denote the ratio of the total molecular energy to that of translation of an imaginary gas, then the internal energy of the gas will be

\[ \frac{1}{2} \beta \Sigma m v^2 \]  

and as the nature of the gas does not alter with the temperature and pressure, we must conclude that \( \beta \) remains constant.

In consequence of the molecular agitation and the property of gases to expand without limit, the molecules must strike the boundary of the vessel in which the gas is enclosed, with a force equal to their momentum, \( m v \). But the greater the velocity, \( v \), is, the more frequently will the vessel be struck by each molecule, so that the pressure exerted by the gas must be proportional to \( m v^2 \). By compressing the gas we bring the molecules closer together, and the intensity of the bombardment on the vessel will thus be increased, or, in other words, the pressure of the gas must be, if \( V \) is the volume of the gas,

\[ P \propto \frac{m v^2}{V} \]  

By comparing (110) with (100), it will be apparent that temperature is measured by \( m v^2 \). If, therefore, two gases have the same molecular energy of translation, they will also have the same temperature.

Specific Heat of Imaginary Gases.—When the temperature of a gas is zero, then the quantity of heat contained in the gas will also be zero. If, therefore, the mass of a portion of a gas is \( M \), then the heat required for raising its temperature from absolute zero to \( T_1 \) will be

\[ H_1 = \frac{1}{2} \beta \Sigma m v^2 = S_m \times M \times T_1 \]  

and if the temperature be raised to \( T_2 \), instead of \( T_1 \), then the heat will be

\[ H_2 = \frac{1}{2} \beta \Sigma m v^2 = S_m \times M \times T_2 \]  

where \( S_m \) and \( S_m \) are the mean specific heats of the gas between zero and \( T_1 \) and zero and \( T_2 \) respectively. Now divide (111) by (112), we shall then have

\[ \frac{m v_1^2}{m v_2^2} = \frac{T_2}{T_1} \]  

but according to our theory

\[ \frac{m v_1^2}{m v_2^2} = \frac{T_1}{T_2} \]  

Consequently

\[ S_m = S_m \]  

or, in words, the specific heat of an imaginary gas is constant for all temperatures and pressures, and only varies with the substance of the gas. Actual gases follow this law approximately. The specific heat of a gas will hereafter be denoted by \( S_m \).

The heat contained in the mass of \( q \) pounds of an imaginary gas at an absolute temperature, \( T \), in degrees Fahrenheit will therefore be

\[ H = S_m \times g \times T \]  

British heat units.

The equivalent mechanical energy will be

\[ 772 \times S_m \times g \times T = K_m \times g \times T \]  

foot-pounds.

Molecular Heat.—Assume that we have two portions of two different gases each enclosed in a vessel, and both occupying the same volume and having the same pressure and temperature.

The pressure exerted by the first gas must be proportional to the molecular energy of translation and to the number, \( n_1 \), of molecules contained in the gas; or, in symbols,

\[ P_1 \propto m_1 v_1^2 \times n_1 \]  

Similarly the intensity of the pressure of the second gas will be

\[ P_2 \propto m_2 v_2^2 \times n_2 \]
But as $P_1$ is equal to $P_s$, we shall have

$$m_1 v_1^2 \times n_1 = m_2 v_2^2 \times n_2 \quad \ldots \quad (120)$$

We have, further, $m_1 v_1^2$ equal to $m_2 v_2^2$, as the gases have the same temperature, and consequently also $n_1$ equal to $n_2$—i.e., "the two gases contain the same number of molecules."

The heat contained in the first gas will be

$$H_1 = \frac{1}{2} \beta_1 n \times m_1 v_1^2 \quad \ldots \quad (121)$$

and that contained in the other will be

$$H_2 = \frac{1}{2} \beta_2 n \times m_2 v_2^2 \quad \ldots \quad (122)$$

Let us now for a moment assume that $\beta_1$ is equal to $\beta_2$, then $H_1$ would be equal to $H_2$—i.e., "the two gases contain the same amount of heat."

We could also have written

$$H_1 = S_1' \times M_1 \times T \quad \ldots \quad (123)$$

where $M_1$ is the mass of the portion of the first gas. Similarly, we have for the second gas

$$H_2 = S_2' \times M_2 \times T \quad \ldots \quad (124)$$

Therefore

$$H_1 = S_1' \times M_1 = S_1' \times n \times m_1 = S_1' \times m_1 \quad (125)$$

$$H_2 = S_2' \times M_2 = S_2' \times n \times m_2 = S_2' \times m_2 \quad (126)$$

From (125) we learn that "the molecular thermal capacity, $S_1' \times m_1$ of an imaginary gas is the same for all imaginary gases." Actual gases have been found to follow this law, and our assumption that $\beta$ is the same for all gases is therefore right.

Specific Heat at Constant Volume and Constant Pressure.—When heating a certain portion of an imaginary gas from a temperature $T_1$, in a cylinder with air-tight fitting piston, we can do one of two things—viz.:

1. Prevent the gas from doing external work, by increasing the pressure on the piston, and thus keep the volume of the gas constant.

2. Or we can let the pressure on the piston remain constant. The gas will then expand and do work in raising the weight. The gas is therefore heated at a constant pressure.

In the first case, the heat is spent in doing internal work only, and we will have

$$H = S_0 \times q \times (T_2 - T_1) \text{ British heat units} \quad (126)$$

where $q$ is the mass of the gas in pounds, and $T_2$ the final temperature. The energy exerted in mechanical energy units will be

$$772 \times H = K_0 \times q \times (T_2 - T_1) \text{ foot-pounds} \quad (127)$$

As the volume of the gas has been kept constant, $S_0$ is called "the specific heat of the gas at constant volume."

In the second case, the heat will be spent partly in doing internal work and partly in doing external work, and we will have

$$H = [S_0 \times q \times (T_2 - T_1) + q \times H_e] \text{ heat units} \quad (128)$$

Where $H_e$ is the heat spent in doing external work per pound of gas and $T_3$ is the final temperature, we will also have

$$772 \times H = [K_0 \times q \times (T_3 - T_1) + E_w \times q] \text{ foot-pounds} \quad (129)$$

Where $E_w$ is the external work done per pound of gas. We might also have written (129) as

$$H = S_p \times q \times (T_3 - T_1) \text{ heat units} \quad \ldots \quad (130)$$

Where $S_p$ is called "the specific heat of the gas at constant pressure," instead of (129) we can write

$$772 \times H = K_p \times q \times (T_3 - T_1) \text{ foot-pounds}. \quad (131)$$

where $K_p$ is the mechanical energy in foot-pounds required for raising the temperature of 1 lb. of gas 1 deg. F. at constant pressure.

It is evident that $T_3 < T_1$, for we have spent the same amount of energy in both cases; but in the first case, we have only raised the temperature of the gas, whereas in the second case, a part of the heat has been spent in doing external work.

We have therefore

$$S_p > S_0 \text{ and } K_p > K_0;$$

or in words, "The specific heat at constant volume of a gas is smaller than the specific heat at constant pressure of the same gas."

It remains now to find an expression for the external work, $E_w$. If $P$ be the constant pressure in pounds per square foot, $V_i$ the initial volume of the gas in cubic feet at temperature $T_1$, and $V$ the final volume of the gas, then the piston will have swept through volume $(V - V_i)$ cubic feet, while the temperature of the gas has been raised from $T_1$ to $T_2$. According to (100), page 165, $P V = R T_i = r q T_2$ and $P V_i = R T_1 = r q T_1$, we have therefore

$$E_w q = P (V - V_i) = r q (T_3 - T_1) \text{ foot-pounds} \quad (132)$$

where $r$ is the external work done by 1 lb. of gas, raised 1 deg. F. at constant pressure.

By the combination of (129), (131), and (132) we obtain

$$K_p = K_0 + r \quad \ldots \quad (133)$$

Example.—Let the problem be to find $K_p, K_0$, and $r$ for atmospheric air, taking the values $S_p = 0'2375$ and $S_0 = 0'1685$ as found for actual air.

1. For Pound-Mass and Foot-Pounds.—The amount of heat required for raising the temperature of 1 lb. of air 1 deg. F. at constant pressure will be

$$H_p = 0'2375 \text{ British heat units,}$$

and at constant volume

$$H_e = 0'1685 \text{ British heat units.}$$

We shall therefore have

$$K_p = 0'2375 \times 772 = 183'35 \text{ foot-pounds,}$$

$$K_0 = 0'1685 \times 772 = 130'08 \text{ foot-pounds,}$$

and $r = K_p - K_0 = 53'27 \text{ foot-pounds.}$

2. For Kilogramme-Mass and Kilogram-metres.—The amount of heat required for raising the tempera-
ture of 1 kilogramme of air 1 deg. C. at constant pressure, will be

$$H_p = 0.2375 \text{ calories (major)},$$

and at constant volume

$$H_v = 0.1685 \text{ calories (major)}.$$  

As $J = 424$ kgm, we shall have

$$K_p = 0.2375 \times 424 = 100.7 \text{ kilogram-metres}.$$  

$$K_v = 0.1685 \times 424 = 71.44 \text{ kilogram-metres}.$$  

At (26) we find the proportionality of the heat to the volume in an adiabatic process, the constant $r$ being

$$r = K_p - K_v = 29.26 \text{ kilogram-metres}.$$  

(3) For Gramme-Mass and Ergs.—The amount of heat required for raising the temperature of 1 gramme of air 1 deg. C. at constant pressure will be

$$H_p = 0.2375 \text{ calories (major)},$$

and at constant volume

$$H_v = 0.1685 \text{ calories (minor)}.$$  

As $J$ is 41,550,000 ergs, we shall have

$$K_p = 0.2375 \times 41,550,000 = 9,868,000 \text{ ergs}.$$  

$$K_v = 0.1685 \times 41,550,000 = 7,001,200 \text{ ergs}.$$  

We have seen that two imaginary gases which occupy the same volume, $V$, exert the same pressure, $P$, and have the same temperature, $T$, contain also the same quantity of heat. Let us now heat both gases up to the same temperature, $T_1$, by adding so much heat to each that they occupy the same volume, $V_1$, and exert the same pressure, $P_1$, then they must again contain the same heat, and they have, therefore, also received the same quantity of heat, and they have done the same amount of external work.

We must therefore have

$$K_p \times M \times (T_1 - T) = K_p' \times M' \times (T_1 - T) \quad (134)$$

$$r \times M \times (T_1 - T) = r' \times M' \times (T_1 - T) \quad (135)$$

$$K_v \times M \times (T_1 - T) = K_v' \times M' \times (T_1 - T) \quad (136)$$

By combination of (133), (134), (135), and (136), we obtain

$$K_p = K_p'; \quad S_p = S_p' \quad \gamma.$$  

where $\gamma$ is a constant, or in words, "the ratio of specific heat at constant pressure to specific heat at constant volume is the same for all imaginary gases." Actual gases also follow this law, and $\gamma$ has been found to be equal to about 1.41.

Adiabatic and Isothermal Expansion and Compression.

When a gas expands in a cylinder doing work by overcoming the resistance of a piston, its temperature will fall, as some of the molecular energy will be transformed into external work.

Let us assume that the cylinder and piston, Fig. 172, are perfect insulators for heat, so that they can neither absorb nor conduct heat. Let the cylinder contain 0.84 lb. of imaginary air, of which the volume will be 1 cubic foot when the piston is in position BK, and the temperature is 60 deg. F. Then the pressure of the air will be 11 atmospheres, or 23.287 lb. per square foot. If we now let the air expand, driving the piston before it, then the volume will increase, and the pressure will diminish with the ordinates to curve $A$. The work done by the gas in expanding from 1 cubic foot to 11 cubic feet will therefore be represented by the area $BDEKB$. The same area would also be proportional to the heat lost by the gas. Let $T_1$ be the final temperature of the gas, the initial one being $T_2 = 520$ deg. F.; then the heat lost by the gas would be

$$S_p \times 0.84 \times (520 - T_1) \text{ British heat units};$$

and the external work done would be

$$K_p \times 0.84 \times (520 - T_2) \text{ foot-pounds}.$$  

As $S_p = 0.1685$, and $K_p = 130.38$ for air, it only remains to determine $T_1$. It can be proved that when an imaginary gas, by expanding, is doing work and does not receive any heat nor gives off heat to surrounding bodies, the relation between corresponding temperatures, volumes, and pressures will be

$$T_1 = \frac{V_1}{V_2} = \left( \frac{V_2}{V_1} \right)^\gamma; \quad \frac{P_1}{P_2} = \left( \frac{V_2}{V_1} \right)^\gamma \quad (139)$$

where $\gamma$ is $\frac{S_p}{K_p}$. In our case we have therefore

$$T_1 = 520 \left( \frac{1}{11} \right)^{0.41} = 194.5.$$  

The heat given off by the gas will be

$$0.1685 \times 0.84 (520 - 194.5) = 46.07 \text{ British heat units},$$

and the work done by the gas will be

$$130.38 \times 0.84 (520 - 194.5) = 35,566 \text{ foot-pounds}.$$  

The curve A, Fig. 172, is called "adiabatic" curve, and the expansion is termed "adiabatic expansion.)

The ratio of the final volume to the initial volume of the gas is called the "ratio of expansion," and will be hereafter denoted by $r_\text{e}$. We might now move the piston towards the bottom of the cylinder, and thereby compress the gas, whereby the pressure will increase with the ordinates of the curve $A$. When we have moved the piston to its initial position, then the volume of the gas will again be 1 cubic foot, the pressure 11 atmospheres, and the temperature 520. The compression, however, requires that we should do work on the gas to an amount of 35,566 foot-pounds, whereby the gas receives 46.07 British heat units, the same quantity which it lost during expansion. The gas has thus been returned to its original thermal state. As neither heat has been added from external sources, nor heat been dissipated while moving the piston, the compression is termed "adiabatic compression."

If the cylinder, Fig. 172, be a good conductor, then we may add heat to the gas during expansion, at such a rate that the temperature of the gas remains constant, while the volume of the gas increases from 1 cubic foot to 11 cubic feet. In this case, the gas will follow the first law of expansion, and we shall have

$$P_1 V_1 = P_2 V_2 = C.$$  

As $P_2 = 11$ atmospheres, it is evident that $P_1$ will be one atmosphere or 2,117 lb. per square foot, and the
intermediate pressures will vary as the ordinates to curve I. As the thermal state of the gas remains the remains constant, and its asymptotes are the axes of ordinates and abscissae. Any point of the curve may

same during expansion, it must be the heat added which is transformed into external work; the latter is represented by the area $BCEKB$.

be constructed in the following way: Draw, for instance, the ordinate, $GF$, then draw $OF$ and $LN$, the latter to be parallel to the axis of abscissae; $NG$ will be the

The curve I is evidently a rectangular hyperbola, since the product of the abscissa and the ordinate corresponding to $OG$ as abscissa. This construction is right, because $LK : FG = OK : OG$. 

Take \( KB = y_4, \ C E = y_2, \ O K = x_1, \) and \( O E = x_2, \) then area \( BCEKB \) will be
\[
C \times \log_e \frac{x_2}{x_1} \ldots \ldots \ (140)
\]
and the work done by the expansion of the gas will be
\[
P_2 V_2 \times \log_e \frac{V_1}{V_2} = P_2 V_2 \times \log_e r_e \ldots \ldots \ (141)
\]
where \( \log_e \) means the hyperbolic logarithm.

Expansion of a gas at constant temperature is called "isothermal" expansion, and also "hyperbolic" expansion, because the curve \( I \) is a hyperbola.

In our particular case we have \( P_2 = 23.287 \) lb. per square foot, and \( V_2 = 1 \) cubic foot, and \( r_e = 11. \) The work done by the isothermal expansion of 0.84 lb. of air at an absolute temperature of 520 deg. F., will be
\[
23.287 \times 1 \times \log_e 11 = 55,839 \text{ foot-pounds,}
\]
and the heat added to the gas during expansion will be
\[
55,839 \\frac{772}{723} = 72.33 \text{ British heat units.}
\]

The curves \( I \) and \( A \) in Fig. 172 show that the work done in isothermal expansion is greater than that done in adiabatic expansion.

In Fig. 173 the adiabatic as well as the isothermal compression begin at the same temperature, \( T_1 = 520, \) and at the same pressure, \( P_1 = 2.117 \) lb. per square foot.

The adiabatic compression will take place if the cylinder as well as the piston are absolute insulators for heat. The pressure will increase with the ordinates of the curve \( A. \) Let \( D \) be the point at which this curve intersects ordinates \( CK - i.e., \) when the gas has been compressed to 1 cubic foot, then area \( BDKEB \) will represent the work done on the gas during compression. According to (138) we will have
\[
T_2 = 520 \left( \frac{11}{1} \right)^{1/4} = 1390
\]
and
\[
P_2 = 2117 \times \left( \frac{11}{1} \right)^{1/4} = 62,241 \text{ lb. per square foot.}
\]
The work done on the gas will therefore be
\[
K_A \times 0.84 (T_2 - T_1) = 130.8 \times 0.84 (1390 - 520) = 95,061 \text{ foot-pounds,}
\]
and the heat added to the gas will be
\[
S_A \times 0.84 (T_2 - T_1) = 0.1685 \times 0.84 (1390 - 520) = 123.1 \text{ British heat units.}
\]
The isothermal compression will take place if we extract heat from the gas during the motion of the piston, at such a rate that the temperature of the gas remains constant. The pressure will in this case increase with the ordinates of curve \( I, \) which is exactly the same as curve \( I \) in Fig. 172. The work done on the gas will be 55,839 foot-pounds, the same amount as was given off by the gas during expansion, Fig. 172. The heat rejected will be 72.33 British heat units, the same as that added to the gas during expansion.

### Heat Engines.

By a heat engine is understood "a machine which transforms heat energy into mechanical energy, or vice versa."

The action of a heat engine requires a working substance which shall receive heat from a source, and again give it off in doing external work. If the performance of the engine is to be continuous, the operations of its working parts must repeat themselves within a certain interval of time, during which the state of the working substance with regard to pressure, volume, and temperature must also be repeated. Such a complete set of repeated operations is called a "cycle."

The temperature, volume, and pressure of the working substance must therefore be exactly the same at the end as at the beginning of the cycle.

Let us assume that the working substance is an imaginary gas, acting upon a piston in a cylinder, as in Fig. 172, the cycle being performed while the piston moves through distance \( KE, \) and back through distance \( EK. \) Let the initial pressure be represented by \( KB, \) the initial volume by \( OK, \) and let the temperature be \( T_2. \) We may now apply the source during the forward stroke in such a way that the temperature of the gas remains constant at \( T_2; \) the expansion curve will therefore be \( I, \) and the heat, \( H, \) taken from the source will be represented by area \( BCEKB, \) which area will also represent the work done by the gas on the piston. The gas can evidently do no work on the piston during the return stroke, but must be compressed by absorbing energy, and as it is being brought back to the end of the cycle to its initial state, the compression curve must pass through point \( B; \) we can satisfy the latter condition by choosing the adiabatic curve \( A \) as back-pressure curve. This, however, requires us to reduce the pressure of the gas to \( DE, \) by applying a refrigerator whose temperature is \( T_1, \) and which will absorb from the gas a quantity of heat, \( h, \) which is represented by area \( DEKB; \) when this is done, the communication with the refrigerator is shut off, and the piston can then move backwards, compressing the gas adiabatically and leaving the gas at the end of the stroke in its initial state. As the work done by the gas is represented by area \( BCEKB, \) and the work done on the gas by area \( DEKB, \) it is evident that the work done in driving the piston through a cycle must be proportional to area \( BCD B; \) this work is called the "indicated" work, as it can be determined by the "indicator," generally called the steam indicator, and which will be described later on. The indicated work is evidently equivalent to \( H - h, \) and as the gas receives a quantity of heat, \( H, \) from the source during the forward stroke, the efficiency of the engine with regard to converting heat into mechanical energy must be
\[
\eta = \frac{H - h}{H} \ldots \ldots \ (142)
\]

Carnot's Imaginary Perfect Heat Engine.—An imaginary heat engine working between two temperatures \( T_2, \) and \( T_1 \) can be made more efficient than the
above described, by a cycle of operations known as Carnot's cycle. In Fig. 174 the cycle begins with applying the source, of which the temperature is \( T_2 \), and allowing the gas to expand isothermally at temperature \( T_2 \), exactly as in Fig. 172, but only while the piston moves through distance \( KN \); during the rest of the forward stroke the source is disconnected from the engine and the gas expands adiabatically, the expansion curve being \( GL \), whereby the temperature falls to \( T_1 \), the temperature of the refrigerator. The refrigerator is now connected to the engine, and the backward stroke begins by compressing the gas isothermally at \( T_1 \) and along the hyperbola \( LQ \), until the piston has moved through distance \( EF \). From this position of the piston until the end of the stroke the compression follows the adiabatic curve \( QB \) through point \( B \), the refrigerator being disconnected.

By this cycle, the work done by the gas on the piston during the forward stroke will be represented by area \( BGLKB \), and the work done on the gas during the backward stroke by \( BQLKEB \), and the useful work by area \( BGLQB \). As the two areas \( GLENG \) and \( BQFKB \) both represent \( S_2 (T_2 - T_1) \), it follows that area \( BGLQ = \) area \( BGNKB \) minus area \( QLEFQ \), or

\[
\eta = \frac{H - h}{H} = \frac{BGNKB - QLEFQ}{BGNKB}
\]

Let the pressures of the gas corresponding to points \( B, G, L, \) and \( Q \) be denoted by \( P_2, P_0, P_1, \) and \( P_2' \), and the corresponding volumes occupied by the gas \( V_2, V_0, V_1 \) and \( V_2' \), then, as \( B \) and \( G \) lie on hyperbola \( BG \), we must have

\[
P_2 \times V_2 = P_2' \times V_2' = R \ T_2 \quad \ldots (143)
\]

and similarly as \( L \) and \( Q \) lie on hyperbola \( LQ \)

\[
P_1 \times V_1 = P_1 \times V_1' = R \ T_1 \quad \ldots (144)
\]

As \( G \) and \( L \) lie on curve \( GL \) we have

\[
\frac{P_2}{P_1} = \left( \frac{V_2}{V_1} \right)^\gamma \quad \ldots \quad (145)
\]

And as \( Q \) and \( B \) lie on curve \( QB \) we have

\[
\frac{P_1}{P_2} = \left( \frac{V_1}{V_2} \right)^\gamma \quad \ldots \quad (146)
\]

According to (141) and (143) we have

\[
\text{Area } BGNKB = R \ T_2 \times \log \frac{P_2}{P_2'}
\]

And, similarly, (141) and (144) will give us

\[
\text{Area } QLEFQ = R \ T_1 \times \log \frac{P_1}{P_1'}
\]

A proper combination of the four formulae (143), (144), (145), and (146), will show us that

\[
\frac{P_2}{P_1} = \frac{P_2'}{P_1'}
\]

and therefore

\[
\frac{h}{H} = \frac{T_2}{T_2'}
\]

and consequently

\[
\eta = \frac{H - h}{H} = \frac{T_2 - T_1}{T_2} \quad \ldots (147)
\]

Formula (147) shows that the efficiency of the Carnot's engine only depends upon the temperatures of the source and the refrigerator, but not upon the working substance, as long as it only follows the laws of imaginary gases.

The engine is perfectly reversible—\( i.e. \), when driving the engine in the reverse direction by another engine,
the temperatures of the source and refrigerator will be
reversed. The machine would in this case convert
mechanical energy into that of heat. The expansion
will first take place along the adiabatic curve BQ, until
the piston has moved through distance KE, when the
temperature will have fallen to $T_1$; for the rest of the
stroke the temperature of the gas remains constant
while expanding along curve QL, and receiving a
quantity of heat, $h$, from a source, of which the
temperature is $T_2$. The first part of the compression
curve is LG, while the piston moves through distance
EN; the gas is then compressed at constant temperature
$T_2$, it being all the time in connection with a
refrigerator whose temperature is also $T_2$. The amount
of heat generated during this reversed cycle is evidently
$H - h$, this being the same quantity as is required for
driving the machine as a motor.

We can now prove that no heat engine (whether
imaginary or actual), receiving heat from a source at
temperature $T_2$, and giving off heat to a refrigerator at
a temperature $T_1$, can have an efficiency higher than
\[
\frac{T_2 - T_1}{T_2}.
\]
For suppose an engine did exist which had a
higher efficiency, then we might couple it with a
Carnot's engine and drive the latter as a heat generator.

Let the generator during one cycle give off a quantity
of heat, $H$, to the source, and receive $h$ from the
refrigerator, and let the motor, during the same
interval of time, receive $H$ from the source and give
off $h$ to the refrigerator. The heat account would
thus be balanced, but as the efficiency of the motor is
greater than that of that of the Carnot's engine, the motor
would evidently be able to do more work than just
driving the generator. But this work cannot be
accounted for, and must therefore have been created
from nothing, which is absurd. The efficiency of the
motor can therefore not be greater than
\[
\frac{T_2 - T_1}{T_2}.
\]

The practical conclusion to be derived from the
above theoretical statement is this: That we must
expect to find the efficiency of our actual heat engines
to be less than that of Carnot's ideal engine, working
between the same limits of temperature.

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CHAPTER XI.

THEORY OF STEAM ENGINES.

Single-Acting Engine Without Expansion.

The definition and properties of dry saturated steam have been
given on page 61, and the generation of
steam in a boiler has been thoroughly
discussed in Chapter VIII. We may therefore
proceed to investigate the behaviour of the
steam in a cylinder when driving a piston before it.
The diagram, Fig. 175, represents a boiler with a
cylinder on the top, which is connected to the
boiler by a short steam-pipe, S P. The line $a b$
represents the water-level, when the piston is at the
bottom of the cylinder; the steam-room of the
boiler is filled with dry saturated steam at an absolute
pressure $p$ per square inch, or $P_s$ per square foot.
Suppose now we have applied so much heat that 1 lb.
of water is evaporated, then the water-level will have
fallen to $c d$, and the piston will be in position "2,
having swept through a volume equal to ($v - s$) cubic
feet, where $v$ is the specific volume of steam at a
pressure $P_s$, and $s$ the volume of 1 lb. of water at that
pressure, this volume being equal to the space between
levels $a b$ and $c d$. Let us now pump 1 lb. of water into
the boiler, whereby the water-level will again be $a b$; in
order to do this we must overcome the pressure of the
steam and move the piston through a volume, $s$, to posi-
tion "3." We will now shut inlet-valve, I V, whereby
no more steam can get into the cylinder, which at that
moment contains 1 lb. of dry saturated steam at a
pressure $P_r = P_s$ (where $P_r$ denotes that the pressure
is pushing the piston forward), assuming that no
condensation has taken place. The energy which has been
exerted by the 1 lb. of steam is evidently equal to
$P_r (v - s)$, of which $P_r \times s$ is the work done in pumping
the water into the boiler. We will now open the
exhaust valve, E V, whereby the steam is admitted
through the exhaust-pipe, E P, to the refrigerator, or,
as it is called, the condenser, in which the absolute
pressure is $P_b$ per square foot, corresponding to a tem-
perature, $t$. The piston will now move downwards,
overcoming pressure $P_b$, and sweeping through
volume, $v$. The indicated work of this engine will
evidently be

\[
I W = (P_r - P_b) \times v \quad \ldots \ldots \quad (148)
\]

It would be interesting to see how $I W$ would vary
with the pressure of the steam; for this purpose we
must refer to the table on page 61. To make the
subject clearer, the two curves, Fig. 176, have been
drawn, of which the one represents the relation between
the steam pressure in pounds per square inch and the
temperature in degrees Fahrenheit, while the other
illustrates the variation of the specific volume of steam.
in cubic feet with the temperature. \( p_a, v, \) and \( t \) are drawn to the same scale, and \( t \) begins with

\[ t \]

trate the indicated work of 1 lb. of dry saturated steam, see formula (148), it is necessary to fix the

100 deg. F., instead of 32 deg. F., in order to save space. By glancing at the curves, Fig. 176, it will be

value of \( P_b \) — i.e., the pressure in pounds per square foot of the steam in the condenser. The ordinates to

clear that the product, \( p_a \times v \), will only vary a little with the temperature; this is made more apparent in

Fig. 177, where the ordinates to the curve A represent \( P_f \times v \), and the corresponding abscissas, \( p_a \). To illus-

curves B, C, and D represent \( P_b \times v \) for \( P_b \) equal to

2,160, 1,080, and 360 pounds per square foot respectively, and consequently the difference between the ordinates of curves A and B will give the indicated
Example 1.—Take $p_a = 30$ lb.; curve A, Fig. 177, will give us $P_7 \times v = 58,280$ foot-pounds.

(a) If the pressure in the condenser be $p_b = 25$ lb. per square inch, then $P_b \times v$ will be equal to 4,856 foot-pounds, and the indicated work done by 1 lb. of steam will be $(P_f - P_b) \times v = 53,424$ foot-pounds.

Assuming the temperature of the feed-water to be that of the condenser, then the quantity of heat required for turning 1 lb. of water at 134·6 deg. F. into dry saturated steam at the pressure required for the engine, will be, according to formula (2) page 62:
**THEORY OF STEAM ENGINES.**

H = 1,114 + 0.305 × 250·2 - 134·6 = 1,055 heat units.

The efficiency of the engine, as a heat engine, is evidently

\[ \eta = \frac{53,424}{1,055 \times 772} = 0.0656. \]

(b) If we have \( p_a = 7.5\) lb. per square inch, then \((P - P_a) \times v = 43,708\) foot-pounds. The temperature of the feed-water will be 180 deg. F., and we will therefore have

\[ H = 1,114 + 0.305 \times 250·2 - 180 = 1,010 \text{ heat units.} \]

Therefore,

\[ \eta = \frac{43708}{1,010 \times 772} = 0.0655. \]

(c) Let \( p_a \) be equal to 15 lb. per square inch, then \((P_f - P_a) \times v = 29,142\) foot-pounds.

The temperature of the feed-water is 213 deg. F., and therefore

\[ H = 1,114 + 0.305 \times 250·2 - 213 = 977 \text{ heat units.} \]

and

\[ \eta = \frac{29,142}{977 \times 772} = 0.0386. \]

**Example 2.—** Take \( p_a = 240\) lb.; curve A, Fig. 177, will give us \( P_f \times v = 65,730 \) foot-pounds.

(a) Take \( p_a = 2.5 \), then \((P_f - P_a) \times v = 60,874 \) foot-pounds and \( H = 1,055 \); therefore

\[ \eta = \frac{60,874}{1,055 \times 772} = 0.0747. \]

(b) \( p_a = 7.5 \), then \((P_f - P_a) \times v = 63,676 \) foot-pounds, and \( H = 1,010 \); therefore

\[ \eta = \frac{63,676}{1,010 \times 772} = 0.0817. \]

(c) \( p_a = 15 \), then \((P_f - P_a) \times v = 61,622 \) foot-pounds, and \( H = 977 \); therefore

\[ \eta = \frac{61,622}{977 \times 772} = 0.0817. \]

These examples clearly show the advantage of the condenser with low-pressure steam. The advantage of high-pressure steam is also evident; for not only is the efficiency higher, but we can, at any rate when the pressure is very high, dispense with the condenser altogether, and thus free the engine from doing work in pumping the condensing water through the condenser.

If we compare the above efficiencies with those of Carnot's imaginary engine, working between the same temperatures, we shall find that our engine is far from being a perfect one. But by investigating the matter, we shall find that we have not entirely followed the principle laid down in the imaginary engine, for we have allowed the temperature of the steam to fall suddenly, by heating a large mass of water which is of no use to us, instead of which we ought to let the steam lose heat in doing work—that is, allowing the steam to expand while pushing the piston before it.

**Ideal Single-Acting Engine with Expansion.**

Suppose that the admission valve, Fig. 178, be shut at the moment 1 lb. of steam has been admitted into the cylinder, and that the volume through which the piston can sweep in the cylinder is \( r_s \times v \), the steam would then be able to move the piston from position "1" to position "2" while expanding, and thus do an additional amount of work by the expenditure of a quantity of heat, which otherwise would be wasted in the condenser. The work done during expansion can be determined if we know the form of the expansion curve, which, experience tells us, does not differ much from a rectangular hyperbola. We can now construct the expansion curve in the manner shown in Fig. 172, and the work done during expansion, being represented by area B C D E B, can be calculated by means of formula (141). Let now \( P_f \) denote the initial forward pressure, which is represented by O A and E B, then the total energy exerted by the 1 lb. of steam during the forward stroke will be

\[ P_f \times v + P_f \times v \times \log_e r_s = P_f \times v \]

\[ (1 + \log_e r_s) \text{ foot-pounds} \ldots \ldots (149) \]

The work to be overcome by the piston during the backward stroke will be

\[ P_a \times r_s \times v \text{ foot-pounds.} \ldots \ldots (150) \]
Consequently, the indicated work done during a double stroke of the piston will be
\[ I = W = P \times v \times [1 + \log_{e} r_s] \times p_a \times v \times r_s \text{ foot-pounds (151))} \]

We can also express the indicated work by the mean forward pressure, which is
\[ P_m = P_a \times v \times [1 + \log_{e} r_s] = P_a \times \left(1 + \log_{e} \frac{r_s}{v}\right) \text{ pounds (152)} \]

and we obtain
\[ I = W = (P_m - P_s) \times v \times r_s \text{ foot-pounds . (153)} \]

To illustrate the advantage of working the engine by expansion, the two curves A and B, Fig. 179, have been plotted. The ordinates represent values of formula (149) for various values of \( r_s \) which latter are represented by the abscissae. Curve A is calculated for \( p_a \) equal to 200 lb. per square inch, whereas in the case of curve B, \( p_a \) is only 50 lb. per square inch. As the ratio of expansion cannot be less than one—i.e., steam working without expansion as in the engine, Fig. 175—the curves start at this value of \( r_s \). To save space, zero of ordinates is 60,000 foot-pounds. The curves clearly show the great advantage gained by the expansive working of the steam.

We may now calculate the amount of steam, \( S \), in pounds, which is required for producing one indicated horse-power hour, knowing that the indicated work produced by 1 lb. of steam in the ideal engine, Fig. 178, can be found by formula (153). It is evident that we must have
\[ S = \frac{60 \times 33,000}{I \times W} \text{ pounds . . . (154)} \]

Table A (given above) has been calculated for the purpose of showing how the performance of an ideal single-acting steam engine varies with the ratio of expansion, temperature of the condenser, and initial pressure.

In calculating the quantity of heat, \( H \), required for turning 1 lb. of water into steam, the temperature of the feed-water has been taken to be the same as that of the condenser. The table also enables the reader to compare the efficiency, \( \eta \), of the engine with that of a Carnot's imaginary engine.

The discussion of the figures given in the table will, however, be deferred to a more convenient place in the book.

**Compound Engines.**

The temperature of the cylinder, Fig. 178, will undergo a series of changes during a stroke, on account of the temperature of the steam falling while expanding. The cylinder will therefore be colder than the entering steam, which will cause some of the latter to condense during admission, and so much steam will be condensed that the latent heat given off by condensation will be sufficient to raise the temperature of the walls of the cylinder to that of steam. The heat thus received will again be given off by the cylinder during expansion, and it is evident that the greater the ratio of expansion is, the lower will the temperature of the cylinder be at the end of the stroke. For this reason it is not practical, or rather not economical, to drive the ratio of expansion too far in one cylinder; the expansion may, however, be continued in two, three, or four cylinders; the temperature of each cylinder will be lower than that of the one in front, but the variation of the temperature of any one cylinder during a stroke will be comparatively small.

By a "Compound Engine" is understood an engine which has two cylinders. The steam is passed direct from the boiler into the first cylinder, where it is

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<th>( \nu )</th>
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Table A
moderately expanded, say, three to five times, and is then exhausted into the second cylinder: here it is further expanded three to five times, and is finally exhausted into the condenser.

Such an engine may either be a "Woolf's Engine," in which the second cylinder may be considered as a simple continuation of the first one, or a "Receiver Engine," in which case the steam from the first cylinder is exhausted into a reservoir, called the "Receiver," from which again the second cylinder receives steam when convenient.

Woolf's Engine.—Fig. 180 represents an ideal engine of this class, the cylinders are placed side by side, and the angle between the cranks is 180 deg.; the piston of the one cylinder will therefore be at the crank end of the cylinder at the same time as the piston of the other cylinder is at the bottom. The length of stroke is the same for both cylinders, but the diameter of the second must evidently be larger than that of the first, as the volume of the steam contained in the first cylinder must be augmented in the second before being exhausted into the condenser.

The first cylinder, H P C, called the high-pressure cylinder, receives the steam which is cut off when the piston has moved through a portion of the stroke; it then expands during the rest of the stroke, the ratio of expansion being \( r \). The ordinates of the diagram represent the absolute pressure exerted by the steam during the stroke; \( a b c f \) being the admission line, \( b e \) the expansion curve, and \( d e \) being the absolute vacuum line, or the line of no pressure. The final pressure in the high-pressure cylinder is \( c f \), at which pressure the steam enters the second cylinder, L P C, which is called the low-pressure cylinder. The ordinates to curve \( h d \) represent the pressures of the steam during the stroke of the high-pressure piston; \( o e \) is the absolute vacuum line, and the ordinate to the straight line \( mn \), which is parallel to \( o e \), represents the pressure in the condenser, which will also be the pressure on the low-pressure piston, during the return stroke. Area \( m h d n \) will therefore represent the indicated work done in the low-pressure cylinder during a double stroke.

As the intensity of the pressure on the high-pressure piston, during the return stroke of this piston, must be exactly the same as that on the low-pressure piston at the same moment, it is evident that the back-pressure curve for the high-pressure cylinder must be the same as the expansion curve for low-pressure cylinder—that is, curve \( c g \) is the same as curve \( h d \), \( h o' \) being equal to \( e f \), and \( d e \) likewise being equal to \( o g \). The indicated work done in the high-pressure cylinder will therefore be represented by area \( g a b c g \).

Let the problem be to determine the indicated work done by 1 lb. of steam in this engine at an initial pressure of \( P_n \), the pressure in the condenser being \( P_o \) per square foot. The ratio of expansion in the first cylinder is \( r_1 \), and that in the second cylinder is \( r_2 \). Let, further, the common stroke of the two pistons be denoted by \( l \), the diameter of the small cylinder by \( d \), and that of the large cylinder by \( D \), then it is evident that the volume swept by the small piston in each stroke will be

\[
\frac{v \times r_1}{l} = \frac{\pi d^2}{4}
\]

and that swept by the large piston will be

\[
\frac{v \times r_2}{l} = \frac{\pi D^2}{4}
\]

from which follows, that \( \frac{D}{d} \) is equal to \( \sqrt{r_2/r_1} \), i.e., "the ratio of the diameter of the large cylinder to that of the small cylinder, is equal to the square root of the ratio of expansion in the large cylinder."

In order to understand clearly the behaviour of the steam in the engine, we will imagine that we have a low-pressure cylinder with a diameter, \( d \), instead of large \( D \), the stroke of the piston being \( L \) instead of \( l \), where the relation between the two latter must be

\[
\frac{L \times \pi d^2}{4} = \frac{\pi D^2}{4} \text{ or } \frac{L}{l} = \left(\frac{D}{d}\right)^2 = r^2
\]

Place now the long cylinder on the top of the small cylinder, as shown in Fig. 181. The distance between the high-pressure piston, "1", and the low-pressure piston, "2", will be \( l \) at the moment that the steam begins to enter the low-pressure cylinder; the steam is thus confined between the two pistons, which will now begin to move in the same direction; but the low-pressure piston will move with a velocity which bears to the velocity of the high-pressure piston as \( L \) to \( l \), but relative to the high-pressure piston, the velocity of the low-pressure piston is equal to the difference of the actual velocities of the two pistons. At the end of the stroke, the high-pressure piston has moved through a distance \( l \), and the low-pressure piston will be on position "4", the steam still being confined between the two pistons, but its volume having been increased to \( v \times r_1 \times r_2 \). As far as the effect on the steam is concerned, it would be precisely the same as if the high-pressure piston had not moved at all, and the low-pressure piston had traversed the distance \( L \) from position "1" to position "3"; or, in other words, "the expansion of steam in a Woolf's engine takes place as if there were only one cylinder, of diameter \( d \), the stroke being \( L \); or, with a diameter \( D \), the stroke being \( l \)."
In Fig. 181 a b is the admission line, the same as in Fig. 180; the curve b c d, being a hyperbola, is the expansion curve of the steam, the ratio of expansion being \( r_s^{-1} \times r_e^{-1} \).

Let \( A^1 \) denote area \( o a b c f o \), and \( B^1, A^2, C^1 \) and \( C^2 \) areas \( f e d e f, o h e o, o g e f o, \) and \( o m n e o \) respectively, then we find that the indicated work done in the first cylinder is

\[
I^1 W^1 = A^1 - C^1,
\]

and that done in the second cylinder is

\[
I^2 W^2 = A^2 - C^2,
\]

and consequently the total indicated work done during a double stroke of the pistons, if the engine is single acting, will be

\[
I W = A^1 - C^1 + A^2 - C^2.
\]

But for 1lb. of steam we have evidently

\[
A^1 = P_R \times v \times (1 + \log_e r_s),
\]

\[
B^1 = P_R \times v \times \log_e r_e,
\]

\[
C^1 = P_0 \times v \times r_s^{-1} \times r_e^{-1},
\]

As curve \( h d \) is curve \( c d \) stretched out, we must have

\[
A^2 = B \times \frac{L}{L - l},
\]

and as curve \( g c \) is \( c d \) compressed, we must have

\[
C^1 = B \times \frac{l}{L - l}.
\]

The indicated work done by 1lb. of steam in Woolf’s engine will therefore be

\[
I W = P_R \times v \times (1 + \log_e r_s^{-1} \times r_e^{-1}) - P_0 \times v \times r_s^{-1} \times r_e^{-1},
\]

which is precisely the same as in an engine with one cylinder of the size of the low-pressure cylinder.

Receiver Engine.—When the angle between the cranks of the two cylinders has to be different to 0 deg. or 180 deg., it is evident that the steam from the H.P. cylinder could not be exhausted direct into the L.P. cylinder, as in the Woolf’s engine, but that the two cylinders in this respect must be independent of each other. The H.P. cylinder must therefore exhaust into a chamber, the receiver, in which the pressure should be constant and equal to the final pressure in the H.P. cylinder. The L.P. cylinder receives steam from the receiver at the beginning of the forward stroke, and the cut-off takes place when the cylinder has received exactly the same quantity of steam as the H.P. cylinder exhausted into the receiver in one stroke. At this moment, the expansion of the steam begins in the L.P. cylinder, and is continued until the end of the stroke. In the return stroke, the L.P. piston expels the steam into the condenser.

In Fig. 182 are illustrated the two cylinders of an ideal receiver engine. The H.P. piston has just finished a stroke, whereas the L.P. piston has only moved through about half its stroke, the cranks being about 90 deg. apart. Using the same letters as before, the volume swept by the H.P. piston in one stroke will be

\[
l \times \frac{\pi d^2}{4} = r_s^{-1} \times v,
\]

and that swept by the L.P. piston will be

\[
l \times \frac{\pi D^2}{4} = r_s^{-1} \times r_e^{-1} \times v \text{ or } \frac{D}{d} = \sqrt{r_s^{-1}},
\]

just the same as for the Woolf’s engine. In the diagram, \( o a \) is the initial pressure of the steam, \( P_R \), \( a b \) the steam line, and \( b c \) the expansion curve for the steam, while in the H.P. cylinder, and \( e f \) represents the final pressure, \( \frac{P_R}{r_e} \), in this cylinder. The performance of the steam in the H.P. cylinder is so far the same as in Fig. 180, but as the pressure in the receiver is constant, equal to \( c f \), the back-pressure curve will be the straight line, \( e g \), parallel to the absolute vacuum line, \( o f \). The indicated work done in the single-acting H.P. cylinder during a double stroke will therefore be represented by area \( g a b c g \).

The performance of the steam in the L.P. cylinder is somewhat different to what we saw took place in the Woolf’s engine. The steam is admitted from the receiver at a pressure \( o'g' = ag = cf \), and is cut off at the moment the L.P. piston has described a volume equal to \( r_s^{-1} \times v \); the length of the steam line, \( g'c' \), must therefore be equal to \( \frac{l}{r_s} \); for the remainder of the stroke the steam expands, the pressure being proportional to the ordinates of curve \( c'h \). The pressure in the condenser is represented by \( \epsilon m = o'm \), and the back-pressure line will therefore be the straight line \( m n \) parallel to \( o'e \), the absolute vacuum line. The indicated work done during one double stroke of the L.P. piston will therefore be represented by area \( m'g'h'n \) parallel. A clearer understanding of the performance of a receiver engine may be gathered from Fig. 183, in which \( R \) is the receiver on which the two cylinders are placed. The H.P. cylinder is precisely the same as in Fig. 182, but the diameter of the L.P. cylinder is \( d \), the same as that of the H.P. cylinder; the stroke, \( L \), must therefore be equal to \( r_e^{-1} \times l \).
The steam from the H.P. cylinder is exhausted into the receiver, whereas communication between the latter and the L.P. cylinder is cut off by means of the valve. The steam line, $g'c'$, is equal to the line $gc$. As the pressure $c'f'$ is the same as $cf$, it is evident that were admitted direct into the L.P. cylinder and there expanded at the ratio $r_e' \times r_e''$. The total indicated work done by 1lb. of steam in this engine will be

$$I\ W = P_b \times v \times (1 + \log_e r_e' \times r_e'') - P_b \times v \times r_e' \times r_e''$$

which is the same as in the Woolf's engine.

Hyperbolic Expansion of Steam.

In working out the figures given in Table A, on page 176, for the ideal steam engine with expansion, Fig.178, it has been considered, as is usually done in text-books, that the total heat spent for the performance of 1lb. of steam in the cylinder, is that required for turning 1lb. of water from the temperature of the condenser into dry saturated steam. In cases where the expansion of the steam has been carried on until the final pressure of the steam was equal to, or very nearly equal to, that of the condenser, the table shows that the efficiency of the engine is greater than that of the Carnot's engine, working between the same temperatures. This, however, is absolutely impossible, as proved at the end of last chapter. It is true that if the final pressure of the steam is equal to that in the condenser, we are then approaching the imaginary perfect engine, but the efficiency of the steam engine could never be higher than that of Carnot's engine. The table therefore clearly shows that we have not accounted for all the heat which is necessary for performing hyperbolic expansion of steam.

V. The steam line, $g'c'$, is simply a continuation of the hyperbola $bc$; the performance of the steam in a receiver engine is therefore precisely the same as if it

Let us first examine the case when the steam remains dry saturated steam during expansion; in this case the relation between volume, pressure, and tempera-
ture is given by Regnault's table. It has been shown that the latent heat of 1lb. of dry saturated steam, at a lower temperature, is greater than that at a higher temperature, and consequently, by increasing the volume of the steam from \( v \) to \( v_1 \) and still keeping it dry and saturated, we must add a quantity of heat which is equal to the difference of the latent heat at temperature \( t_1 \), corresponding to \( v_1 \), and the latent heat at temperature \( t \), corresponding to \( v \).

This condition is clearly shown in Fig. 184, where pressures in pounds per square inch are measured along the axis of abscissae, and British heat units along the axis of ordinates. The curve is drawn so as to show the increase of latent heat of 1lb. of dry saturated steam from \( p_a = 200 \), to any lower pressure above point \( b \); and if the initial pressure had been 50lb., and the final volume of the steam were 120 cubic feet, then \( c \) \( d \) would be the curve of expansion.

Curve \( B \) in the same drawing is part of the rectangular hyperbola for \( p_a = 200 \), and would be the expansion curve, if the initial pressure were 200lb., and the expansion were hyperbolic, as assumed in the ideal engine, Fig. 178. As the two curves \( A \) and \( B \) run very close together at high pressures, they have not been continued further than shown in the diagram.

It will be seen that the ordinates to the hyperbola are longer than the corresponding ones of the saturation curve; therefore the energy exerted by the steam during hyperbolic expansion must be greater than when the steam remains saturated. For this reason, hyperbolic expansion requires an additional quantity of heat, which must at least be equivalent to the area between the two curves \( B \) and \( A \).

If the initial pressure had been 50lb., the hyperbola should be constructed through point \( c \), and the area between the latter hyperbola and curve \( A \) would represent the quantity of heat to be added to the saturated steam.

As the equation for the saturation curve is approximately

\[ p_a \times v^{\frac{7}{16}} = 68,400 \quad \ldots \quad (155) \]

where \( p_a \), as before, is the pressure in pounds per square foot, it can be proved that the energy exerted on the piston by the expansion of 1lb. of dry saturated steam.
THEORY OF STEAM ENGINES.

Table B.

<table>
<thead>
<tr>
<th>No.</th>
<th>$p_a$</th>
<th>$p_b$</th>
<th>$r_e$</th>
<th>$H_1$</th>
<th>$H + H_1$</th>
<th>$\eta = \frac{IW}{772 (H + H_1)}$</th>
<th>$S\left(1 + \frac{H_1}{H}\right)$</th>
<th>$T_2 - T_1$</th>
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<td>2</td>
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<td>7·68</td>
<td>0·314</td>
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steam, remaining dry saturated, will be

$$1,094,400 \left(\frac{16}{v}\right)^{\frac{1}{16}} \frac{\sqrt{r_e}}{v} - 1$$ foot-pounds. (156)

The corresponding energy exerted on the piston during hyperbolic expansion will be

$$P_f \times v \times \log_e \frac{r_e}{v} \ldots \ldots (157)$$

where $P_f$ is the initial forward pressure of the steam in pounds per square foot.

We can now determine the quantity of heat, $H_1$, in British heat units, which must be added to $H$ in Table A, in order to produce hyperbolic expansion. It is evident that we must have $H_1$ equal to the difference of latent heat of 1 lb. of dry saturated steam at volumes $r_e \times v$ and $v$ plus

$$H_1 = \left(P_f \times v \times \log_e \frac{r_e}{v} - 1,094,000 \left(\frac{16}{v}\right)^{\frac{1}{16}} \frac{\sqrt{r_e}}{v} - 1\right)$$

The efficiency of the engine as a heat engine will therefore be

$$\eta = \frac{I W}{772 (H + H_1)} \ldots \ldots (158)$$

Let us assume that the wall thickness of the steam-cylinder is very small indeed, and therefore has a very small heat capacity, which may be neglected, and also that the material of which the cylinder is made is a perfect conductor for heat. Let, further, the cylinder be surrounded with a steam-jacket—i.e., a ring-forming space filled with live steam from the boiler. This steam-jacket should be bounded externally by a cylinder concentric to the steam-cylinder and made of a perfect non-conducting material. The jacket should extend over the cylinder-covers. For each pound of steam admitted into the steam-cylinder, the jacket should receive so much steam, that, by the condensation of the latter, the quantity of heat, $H_1$, would be given off. If, now, the condensed steam leaves the jacket at the same temperature as that of the condenser, then the total quantity of steam required per indicated horse-power hour would not be $S$ pounds as given in Table A, but would be $S \times \left(1 + \frac{H_1}{H}\right)$ pounds.

The annexed table, B, may be considered as a continuation of Table A, but the quantity of heat, $H_1$, has been taken into account in working out the efficiency of the engine, as well as the amount of feed-water required per indicated horse-power hour. The two tables should be carefully compared.

Steam Engines with Clearance.

In the engines hitherto discussed, it has been assumed that the volume occupied by the steam at the end of a stroke was equal to the volume swept by the piston; or, in other words, we have assumed that the volume of the steam passages from the regulating valves to the cylinder could be neglected, and we have also assumed that the piston came right against the cover at the end of its journey, so as to leave no space between itself and the cover.

In actual engines it is, however, necessary to give the steam passages a certain length, and, therefore, also a sufficient cross-section in order to diminish the intermediate fall of pressure between the steam-chest and the cylinder, and for the safety of the cylinder, we must allow a play between the piston and the cylinder-cover. For these reasons the final volume of the steam in the cylinder will be greater than the volume described by the piston. Let $l$ denote the length of the stroke, and $d$ the diameter of the cylinder, then the volume occupied by the steam at the end of a stroke will be

$$V_f = \frac{\pi d^2}{4} \times l + \frac{\pi d^3}{4} \times \lambda \ldots \ldots (159)$$

where $\frac{\pi d^3}{4} \times \lambda$ is called the "clearance volume" and $\lambda$ the "clearance length."

Single-Cylinder Engine with Clearance.—For the purpose of discussing the performance of the steam in
a cylinder with clearance, we can consider, as is done in formula (159), that the length of the cylinder is \((l + \lambda)\), instead of \(l\).

The volume \(\frac{\pi d^2}{4} (l + \lambda)\) is called the total capacity of the cylinder, and volume \(\frac{\pi d^2}{4} l\) the effective capacity.

In Fig. 186, the line \(o f\) is the absolute vacuum line, \(o h = \lambda\), \(h f = l\); the initial volume of the steam before being cut off will therefore be proportional to \(o g\), and the

The effective capacity of the cylinder will therefore be

\[
\frac{\pi d^2}{4} \times l = v \times \frac{r_e}{1 + \lambda \times r_e / l}
\]

consequently

\[
\text{area } h n m f h = P_b \times v \times \frac{r_e}{1 + \lambda \times r_e / l}
\]

The indicated work done by 1 lb. of steam in this engine will thus be

\[
I W = P_{fi} \times v \times \left( \frac{1}{1 + \lambda \times r_e / l} + \log_e \left( \frac{1 + \lambda / l}{1 + \lambda / r_e} \right) \right)
\]

minus \(P_b \times v \times \frac{r_e}{1 + \lambda \times r_e / l} \ldots (161)

The fraction \(\frac{\lambda}{l}\) may on an average be taken from 0.05 to 0.07.

**Example 1.**—Take \(\frac{\lambda}{l} = 0.07\) and the apparent ratio of expansion \(r_e = 3\); the indicated work per pound of steam in the cylinder will then be, according to (161),

\[
I W = (1.802 \times P_{fi} - 2,479 \times P_b) \times v \text{ foot-pounds}
\]

The actual ratio of expansion will be

\(R_e = 2.65\).

**Example 2.**—Take \(\frac{\lambda}{l} = 0.07\) as before, but make \(r_e = 5\); the indicated work per pound of steam in the cylinder will be

\[
I W = (2.118 \times P_{fi} - 3,704 \times P_b) \times v \text{ foot-pounds}
\]

and we will have \(R_e = 3.96\).

**Woolf's Engine with Clearance.**—We have seen that the result of the performance of the steam in a Woolf's engine without clearance is the same as if the steam were admitted direct into the L.P. cylinder, and there expanded. But if the cylinders have clearance, then the final volume of the steam in the L.P. cylinder will be equal to the total capacity of the L.P. cylinder, including the clearance of the intermediate space between the cylinders plus the clearance of the H.P. cylinder. The initial pressure in the L.P. cylinder will therefore not be equal to the final pressure in the H.P. cylinder, but there will be a fall of pressure, due to the expansion of the steam, in the clearance of the L.P. cylinder and the intermediate space between the cylinders. The back-pressure curve in the diagram of the H.P. cylinder will start at a point somewhat lower than point \(c\), Fig. 186, and will also end at a point lower than \(g\). The expansion curve in the L.P. cylinder will be the same as the compression curve in H.P. cylinder.

If we now imagine the L.P. cylinder to be of diameter \(d\), and the stroke to be \(L = l \times \frac{1}{d}\), precisely
as in Fig. 181, then the final volume of the steam will be

\[ V_f = \frac{\pi d^2}{4} (\lambda' + \lambda'' + L) \]  \hspace{1cm} (162)

where \( \lambda' \) is the clearance length of the small cylinder, and \( \lambda'' \) that of the large cylinder, including the intermediate space between the cylinders.

![Diagram of steam engine](image)

In diagram Fig. 187, the line of \( f' \) is the absolute vacuum line, and the length of \( o f' \) is equal to \( (\lambda' + \lambda'' + L) \), the diameter of the cylinder being \( d \). We have, further, \( o h = \lambda', \ h f = l, \ f k = \lambda'', \) and \( h' f' = L - l; \) the line \( o a \) is, therefore, the clearance line.

It can be proved, by a process of calculations similar to that used with diagram Fig. 181, that the total indicated work of the engine will be the same as if the steam were admitted at once into the L.P. cylinder, filling up the space \( \lambda' \times \frac{\pi d^2}{4} \) and then pushing the piston through distance \( h g \), the steam being cut off when the piston arrives at \( g \). From this position of the piston and until it arrives at \( f \), the steam expands hyperbolically, the actual ratio of expansion being \( \frac{o f'}{o h} \). A further expansion of the steam takes place in the space \( \lambda'' \times \frac{\pi d^2}{4} \) without doing work on the piston, the pressure falling from \( f d \) to \( h' c' \). During the remainder of the stroke the energy exerted upon the piston will be measured by area \( h' c' d' f' h' \), the ratio of expansion being \( \frac{o f'}{o h} \). The total indicated work during one stroke will thus be measured by area \( n b c d m n \) plus area \( n' c' d' m' n' \).

For 1 lb. of steam we will have

area \( o a c d f' o = P_{fi} \times v \times (1 + \log_e \frac{o f'}{o g}) \)

\[ = P_{fi} \times v \times \left( 1 + \log_e \left( \frac{L + \lambda' + \lambda''}{l + \lambda' + \lambda''} \right) \right) \]

\[ = P_{fi} \times v \times \left( 1 + \log_e \left( \frac{L}{l} + \frac{\lambda'}{l} + \frac{\lambda''}{l} \right) \right) \]

we have also

area \( o a b h o = P_{fi} \times \lambda' \times \frac{\pi d^2}{4} = P_{fi} \times v \times \frac{\lambda'}{l} \times r_e' \)

and

area \( f d c' h' f = P_{fi} \times v \times \log_e \frac{o h'}{o f} = P_{fi} \times v \times \frac{1 + \lambda' + \lambda''}{l} \times r_e' \times \log_e \frac{1 + \lambda' + \lambda''}{l} \times r_e' \)

The work done on the back pressure during the return stroke will be

\[ P_b \times \frac{\pi d^2}{4} L = P_b \times L \times \frac{v \times r_e'}{l + \lambda' + \lambda''} = P_b \times v \times \frac{r_e' \times L}{l + \lambda' + \lambda''} \]

\[ \frac{1 + \lambda' + \lambda''}{l} \times r_e' \]

The indicated work done by 1 lb. of steam will therefore be expressed by

\[ I W = P_{fi} \times v \times \left( \frac{1}{1 + \frac{\lambda'}{l} \times r_e'} + \log_e \frac{L + \lambda' + \lambda''}{1 + \frac{\lambda'}{l} \times r_e'} \times \left( \frac{1 + \frac{\lambda'}{l} \times r_e'}{1 + \frac{\lambda'}{l} + \frac{\lambda''}{l}} \right) \right) - P_b \times v \times \frac{L}{l} \times r_e' \]

\[ \frac{1 + \lambda' + \lambda''}{l} \times r_e' \]

foot-pounds. (163)

**Example 1.** — Take \( \frac{\lambda'}{l} = \frac{\lambda''}{l} = 0.07, r_e' = 3, \) and \( \frac{L}{l} = \frac{D^2}{d^2} = 3 \), whereby the effective capacity of the second cylinder will be equal to three times that of the first one. The indicated work per pound of steam will be

\[ I W = (2.744 \times P_{fi} - 7.483 \times P_b) \times v \text{ foot-pounds.} \]

The total actual ratio of expansion will be

\[ R_e = 8.13 \]

**Example 2.** — Take \( \frac{\lambda'}{l} = \frac{\lambda''}{l} = 0.07 \) as before, but make \( r_e' = 5, \) and \( \frac{L}{l} = \frac{D^2}{d^2} = 5. \) We shall then have

\[ I W = (3.456 \times P_{fi} - 18.518 \times P_b) \times v \text{ foot-pounds, and} \]

\[ R_e = 20.81 \]

Receiver Engine with Clearance.—Fig. 188 is a diagram of a receiver engine with clearance, the cylinders being placed on the top of the receiver, \( R_e \), as in Fig. 183, and to make the performance of the steam clear, the diameter of the second cylinder is made equal to that of the first.
1. First cylinder.

The stroke is $h_f = l$; $o_h = \lambda'$; $r_e = \frac{h_f}{k}$; the actual ratio of expansion is $R_e' = \frac{h_f}{k}$. 

The final pressure in the cylinder will be $p_f = \frac{P_f i}{R_e}$, and this pressure being the same as that of the receiver, the line $k d$, parallel to the absolute vacuum line $o f$, will be the back-pressure line. The indicated work will thus be represented by the area $k b c d k$. The piston will expel into the receiver, during the backward stroke, a volume of steam equal to $l \times \frac{\pi d^2}{4}$, at a pressure $\frac{P_f i}{R_e}$, the clearance will thus retain a volume $\lambda^' \times \frac{\pi d^2}{4}$ of steam at the same pressure. This quantity of steam will be considered as wasted in the following calculations.

For 1 lb. of steam we have

\[
\begin{align*}
\text{area } o a d f o &= P_f i \times v \times \left(1 + \log_e \frac{1 + \frac{\lambda^'}{l} \times r_e'}{1 + \frac{\lambda^'}{l} \times r_e'} \right) \\
\text{area } o a b h o &= \lambda^' \times \frac{\pi d^2}{4} \times P_{fi} = P_{fi} \times v \times \frac{\lambda^'}{l} \times r_e' \\
\text{area } h k d f h &= \frac{P_{fi}}{R_e} \times l \times \frac{\pi d^2}{4} = P_{fi} \times v \times \frac{1}{1 + \frac{\lambda^'}{l}} \\
\end{align*}
\]

The indicated work per pound of steam will consequently be

\[
\begin{align*}
\Gamma' W &= P_{fi} \times v \times \left(1 + \frac{\lambda^'}{l} \times r_e' \right) - \frac{1}{1 + \frac{\lambda^'}{l}} \times \left(1 + \frac{\lambda^'}{l} \times r_e' \right) \times \log_e \frac{1 + \frac{\lambda^'}{l} \times r_e'}{1 + \frac{\lambda^'}{l} \times r_e'} \\
\end{align*}
\]

2. Second cylinder. The stroke is

$\lambda^' f = L_i$; $o' h^' = \lambda^''$; $r_e = \frac{L_i}{l} \times \frac{1}{1 - \frac{\lambda^''}{l}}$

and the actual ratio of expansion is

\[
R_e'' = \frac{\frac{\lambda^''}{L_i}}{\frac{l}{L}}.
\]

As the H.P. piston expels during each stroke a volume $l \times \frac{\pi d^2}{4}$ cubic feet of steam, it follows that if the pressure of the steam in the second cylinder is to remain equal to $d f$ during admission, the steam must be cut off when the L.P. piston has moved through a distance $h^' f = l - \lambda^''$. It is also evident that it is volume $l \times \frac{\pi d^2}{4}$ and not volume $(l + \lambda') \times \frac{\pi d^2}{4}$ which will be augmented in the second cylinder, and the hyperbola $c d$ can, consequently, not be a continuation of curve $c d$.

For 1 lb. of steam admitted into the H.P. cylinder, we shall have

\[
\begin{align*}
\text{area } o'a' c d f o' &= \frac{P_{fi}}{R_e} \times L_i \times \frac{\pi d^2}{4} \times \left(1 + \log_e R_e\right) = \\
\text{area } o'a' b h' o' &= \lambda^'' \times \frac{\pi d^2}{4} \times P_{fi} = P_{fi} \times v \times \frac{\lambda^''}{L_i} \times \frac{1}{1 + \frac{\lambda^''}{l}} \\
\text{area } h'n m f h' &= P_b \times \pi d^2 \times L_i = P_b \times v \times \frac{L_i}{l} \times r_e' \\
\end{align*}
\]

The indicated work will thus be

\[
\begin{align*}
\Gamma'' W &= P_{fi} \times v \times \frac{1}{1 - \frac{\lambda^''}{l}} \times \left(1 - \frac{\lambda^''}{l} + \log_e \frac{1 + \frac{\lambda^''}{L_i}}{1 + \frac{\lambda^''}{l}} \right) - \\
\end{align*}
\]

The final pressure of the steam in the second cylinder will be

\[
\begin{align*}
\frac{P_{fi} \times \frac{o' g'}{o' f} \times P_{fi} \times \frac{1 + \frac{\lambda^''}{l} \times r_e'}{1 + \frac{\lambda^''}{L_i} \times r_e'} \times \frac{L_i}{l} \times r_e'}{R_e'' \times R_e} = \frac{P_{fi}}{R_e}.
\end{align*}
\]
THEORY OF STEAM ENGINES.

Table C.

<table>
<thead>
<tr>
<th></th>
<th>No.</th>
<th>$p_a$</th>
<th>$p_b$</th>
<th>$r_e$ or $r_e'$</th>
<th>$R_e$</th>
<th>I W</th>
<th>$H_1$</th>
<th>$S \left(1 + \frac{H_1}{H}\right)$</th>
<th>$\eta = \frac{I W}{772 (H + H_1)}$</th>
<th>$T_s - T_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple cylinder engine.</td>
<td>1</td>
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<td>2</td>
<td>3</td>
<td>2.65</td>
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<td>45</td>
<td>20.15</td>
<td>0.118</td>
<td>0.208</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15</td>
<td>3</td>
<td>3</td>
<td>2.65</td>
<td>63029</td>
<td>45</td>
<td>22.55</td>
<td>0.080</td>
<td>0.091</td>
</tr>
<tr>
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<td>3</td>
<td>2</td>
<td>5</td>
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<td>3.96</td>
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<td>64.5</td>
<td>17.73</td>
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<td>0.208</td>
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<td>3.96</td>
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<td>64.5</td>
<td>25.46</td>
<td>0.100</td>
<td>0.118</td>
</tr>
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<td></td>
<td>5</td>
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<td>3</td>
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<td>0.129</td>
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<td>6</td>
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<td>5</td>
<td>3</td>
<td>3.96</td>
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<td>17.78</td>
<td>0.142</td>
<td>0.200</td>
</tr>
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<td>Woolf's engine.</td>
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<td>8.13</td>
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<td>14.64</td>
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<tr>
<td></td>
<td>11</td>
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<td>3</td>
<td>8.13</td>
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<td>119.2</td>
<td>12.57</td>
<td>0.185</td>
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</tr>
<tr>
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<td>3</td>
<td>8.13</td>
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<td>119.2</td>
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<td>0.200</td>
</tr>
<tr>
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<td>3</td>
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<td>5</td>
<td>3</td>
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<td>Receiver engine.</td>
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<td>95.7</td>
<td>14.96</td>
<td>0.160</td>
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<td>5</td>
<td>3</td>
<td>21.2</td>
<td>157294</td>
<td>135.4</td>
<td>14.17</td>
<td>0.168</td>
<td>0.206</td>
</tr>
<tr>
<td></td>
<td>17</td>
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<td>2</td>
<td>3</td>
<td>8.52</td>
<td>171371</td>
<td>122.2</td>
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<td>0.181</td>
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<td>3</td>
<td>8.52</td>
<td>139764</td>
<td>122.2</td>
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<td>0.159</td>
<td>0.200</td>
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<td>5</td>
<td>3</td>
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<tr>
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<td>169.3</td>
<td>13.44</td>
<td>0.182</td>
<td>0.236</td>
</tr>
</tbody>
</table>

3. The two cylinders taken together.

The total indicated work in the engine per pound of steam will be

$$ I W = I' W + I'' W $$

The total actual ratio of expansion, $R_e$, will be equal to the initial pressure of the steam in the first cylinder, divided by the final pressure of the steam in the second cylinder, or

$$ R_e = \frac{P_a}{P_b} $$

Example 1.—Take $\frac{\lambda'}{l} = 0.07$, $r_e' = 3$, and $L = \frac{D^2}{d^2} = 5$.

The indicated work in the engine per pound of steam will be

$$ I W = \left[ 2 \times 966 \times P_a - 7 \times 438 \times P_b \right] \times v $\text{ foot-pounds} $\text{ foot-pounds}$

The total actual ratio of expansion will be $R_e = 8.52$.

Example 2.—Take again $\frac{\lambda'}{l} = 0.07$, but $r_e' = 5$, and $L = \frac{D^2}{d^2} = 5$. We shall have

$$ I W = \left[ 3 \times 358 \times P_a - 18 \times 518 \times P_b \right] \times v $\text{ foot-pounds} $\text{ foot-pounds}$

and $R_e = 21.2$.

For the purpose of showing the influence of clearance upon the performance of steam engines, Table C has been added and should be compared with Table B.

The Steam Indicator.

We have several times used the expression "indicated work," by which we understand the energy exerted by the working substance during the forward stroke of the piston in a heat engine, minus the work done on the back pressure on the same side of the piston during the return stroke. In double-acting engines there must be indicated work done on both sides of the piston, and by adding the two we obtain the total indicated work done in the cylinder.

If the engine makes $n$ revolutions per minute, and the total indicated work be denoted by $I \ W$, then the indicated work per minute will be $I \ W \times n$; and if $I \ W$ be given in foot-pounds, then the indicated power expressed in horsepower will be

$$ I H P = \frac{I W \times n}{33,000} \quad \ldots \quad (164) $$

For the purpose of measuring the indicated work of an engine, and at the same time to obtain a picture of the performance of the working substance in the cylinder, we use the "steam indicator." It is evident that this instrument must be able to produce two motions at right angles to one another; the one motion must be up and down, and must be proportional to the pressure of the working substance at each position of the piston; the other motion must be to and fro, and be proportional to the travelling of the engine piston. These two motions, being performed simultaneously, will produce the indicator diagram, and the area enclosed within the diagram, will be a measure of the indicated work on the one side of the piston. If the engine be double acting, two indicators are required, one for each side of the engine piston.
The two essential parts of a steam indicator are the cylinder and the paper-drum; the former is in direct communication with the engine cylinder, and is fitted with a piston, H, Fig. 192, which is pressed from below by the working substance, and from above by the atmosphere. There is also a spring, N, one end of which is fixed to the piston, and the other end to the cover of the cylinder. When the pressures on both sides of the piston are the same, the spring will not be in tension, and the position of the piston will indicate the pressure of the atmosphere. When the pressure of the working substance exceeds that of the atmosphere, the piston is driven upwards, and the spring way that, within the range of the instrument, the pencil must move in a vertical straight line, and it is also essential that the movement of the pencil should always be proportional to the movement of the indicator piston. In some indicators the latter is not the case, and the pencil therefore does not indicate the true value of the pressure.

The drum, U, when about to be used, is covered with a piece of paper, called the card, which is held on the drum by two flat steel clips. The drum oscillates about its axis by alternately being pulled in one direction by a cord wrapped round a pulley on the lower part of the drum, and in the other direction by the tension of a spring, R. The cord is attached to the cross-head of the engine, and the forward and backward motions of the drum will therefore represent the forward and backward strokes of the engine piston.

When the pencil is brought against the card on the paper-drum, a diagram will be produced, which presents a record of the pressure of the working substance in the engine cylinder at every point of the stroke.

There are two points of great importance to be considered in designing an indicator which is to give a true diagram.

The first of these points refers to the inertia of the moving masses of the indicator, in virtue of which the
motion of these parts would be continued beyond what is desired; thus the position of the pencil will not indicate the true pressure while the pencil is moving. In order to reduce this error, the velocity and the masses of the piston, piston rod, spring, multiplying levers and pencil must be diminished as much as is practicable. The effect of the inertia of the paper-drum and the other parts accompanying the drum in its movements, such as the drum carriage and the drum spring, is to lengthen the diagram, whereby also the spring will be overwound, and in the return stroke the cord may be broken. For slow-speed engines, these defects are not very difficult to overcome, but in order to indicate a high-speed engine with success, only the most improved forms of indicators can be used.

The other point to be considered is the friction caused by the motion of the various parts. The effect of friction is in the opposite direction to that of inertia, as friction tends to prevent motion.

Having given a general idea of the construction of the steam indicator, we will proceed to describe some of the most important types which are at present in use.

The Tabor Indicator.—This instrument is one of the latest and most improved forms of steam indicators, and has been designed for the purpose of indicating high-speed as well as low-speed engines.

The following description of the Tabor indicator is taken from a paper read by Mr. A. G. Brown before the Sheffield Society of Engineers, on the 15th of March, 1890.

The special peculiarity of the Tabor indicator, Fig. 189, is the means employed to communicate a straight line movement to the pencil. A plate containing a curved slot is fixed in an upright position, and secured to a swivel plate on the cover of the indicator cylinder. This slot serves as a guide, and controls the motion of the pencil bar. A pin is fixed on one side of the pencil bar, which carries a roller, and this is fitted so as to roll freely from end to end of the slot. The position of the slot is so adjusted, and the pin attached to such a point on the pencil bar, that the curve of the slot compensates the tendency of the bar to move in a circular arc, and the end of the bar, which carries the pencil, moves up and down in a straight line, when the roller is moved from one end of the slot to the other. There is thus very little chance for friction in this movement, and the bar and connections are very light, though strong enough for the purpose. It will be noticed that the base of the paper-drum and the steam-cylinder jacket are made in one piece. The steam-cylinder is a straight tube inside the jacket, with an air space around the sides, and attached to the jacket by means of thread cut on the bottom of the cylinder. The cylinder is thus left free to expand or contract without affecting other parts of the instrument. Slots are cut in the top of the cylinder for the insertion of a key for screwing it in or out. Openings through the side of the jacket allow the steam which leaks past the piston to escape.

The pencil mechanism is carried by a swivel plate fitted to the cylinder-cover, on which it can be freely moved. The pencil movement consists of three pieces—the pencil bar, the back link, and the piston rod link. The two links are parallel to each other in every position they may assume. The lower pivots of these links and the pencil point are always in the same straight line. If an imaginary link parallel with the pencil bar be supposed to connect the two, the combination would form an exact pantograph, and would serve the purpose of making the pencil point move in a straight line, but the friction and wear of the pencil movement would be greatly increased. The slot and roller serve the purpose of this imaginary link to much better advantage.

The connection between the piston and pencil mechanism is by means of a steel piston rod, hollow at the upper end where it passes through the cylinder-cover, but solid below with a reduced diameter, and having a ball formed on the lower end.

A ball and socket joint forms the connection of this rod with the piston. This prevents the tendency to bind either rod or piston while working, a fault which causes considerable error where solid connections are used. The socket is an independent piece which fits into a square hole in the piston, and is fastened with a thumb nut below. The piston is made very light, and has a number of shallow grooves cut upon the outside to serve as water-packing.

The springs, Fig. 190, used in this indicator are of the duplex type, being made of two coils of wire fastened
exactly opposite each other on the fittings. This arrangement equalises the side strain on the spring, and keeps the piston central in the cylinder, avoiding the excessive friction caused by a single-coil spring forcing the piston against the side of the cylinder.

The maximum pressures to which the springs for this indicator should be subjected, to give good results, are given in the following table:

**ENGLISH SPRINGS.**

<table>
<thead>
<tr>
<th>Scale of Spring, Pounds per inch.</th>
<th>Revolutions of Engine.</th>
<th>Maximum Pressures in pounds per square inch above atmosphere.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>up to 200</td>
<td>200 to 400</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
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<td>200</td>
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<tr>
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<td>300</td>
<td>240</td>
</tr>
<tr>
<td>150</td>
<td>350</td>
<td>300</td>
</tr>
</tbody>
</table>

The one of these is shorter than the other, which makes it more convenient for putting on the paper.

The drum spring, which furnishes the returning force for the drum, consists of a flat spiral spring placed in a cavity underneath the drum carriage and encircling the bearing. One end is attached to the frame below, and the other to the carriage. A stop is provided on the frame to prevent the carriage unwinding the spring when released. The tension of the spring may be regulated by unscrewing the knurled nut above, which holds the carriage in place, lifting the carriage clear of the stop, and winding and unwinding the springs as may be desired.

A carrier-pulley at the end of a swinging arm placed below the paper-drum, serves to guide the indicator cord in any direction. A circular plate, carrying a single-grooved pulley, is mounted in a clamp at the end of the swinging arm, and this plate and clamp are so arranged as to swivel to any position; while the groove on the pulley, being central with the driving cord at all times, leads the cord in any desired position.

A ratchet is cut on the edge of the drum carriage, and a pawl is so arranged as to engage in it whenever it is desired to stop the motion of the drum without unhooking the driving cord. This is a convenience when indicating slow-speed engines, but is of no use at high speeds.

A simple form of a cord-adjuster is illustrated in Fig. 191, for adjusting the length of the driving cord. The form and method of connecting this attachment to the cord is shown in the figure. A hook on the indicator cord connects with the ring on the end.

A cock is screwed into the engine cylinder, and the indicator is attached to this cock by means of a coupling having a single thread, see Fig. 189. The indicator is easily connected and fixed in any desired position.

The pressure of the pencil on the paper is regulated by a screw, which passes through a projection on the guide-plate and strikes against a pivot on the frame.

The length of the diagrams with slow speeds may be taken as 4 in. to 4 in., and will show well-proportioned diagrams; but as the speeds increase, the length of the diagram should be shortened, to avoid the effects of inertia of the paper-drum. As a guide in this matter, the following lengths of diagrams are recommended when using the Tabor indicator:

- Speeds up to 200 revs. per minute ... 4 in. long.
  - " 300 "          ... 3 \(\frac{1}{2}" \)
  - " 350 "          ... 3 "            "
  - " 400 "          ... 2 \(\frac{3}{4}" \)
  - " 450 "          ... 2 \(\frac{3}{4}" \)
  - " 500 "          ... 2 "            "
  - " 550 "          ... 1 \(\frac{1}{4}" \)
  - " 600 "          ... 1 \(\frac{1}{4}" \)

With these lengths, the drum springs will not require alteration or increase of tension, and the diagrams will be well-proportioned ones, as a stronger piston spring must be used with the higher rotative speeds to give accurate cards, therefore both length and height of diagram will decrease in about the same proportion.
The Crosby Indicator.—This instrument, which is illustrated in Fig. 192, is also designed to meet the requirements of high-speed engines. The cylinder-cover or cap, A, has a hollow downward projection, through which the piston rod, C, is guided. Its lower part is threaded to screw into the spring-head, D, and its under part is threaded to screw into the cylinder, thus forming the cylinder-head and holding all attachments in place. The sleeve, B B, surrounds the upper part of the cylinder and carries the pencil movement; it turns freely, and is held in place by the cover. The adjusting screw, 5, is threaded through B, and when it is in contact with the stop, 6, the pencil point may be delicately...
adjusted to the paper on the drum. The swivel-head, E, is threaded on its lower half to screw into the piston rod more or less, according to the required height of the atmospheric line on the diagram. Its head is joined to the long link of the pencil movement.

The piston rod, C, is made of steel, and is hollow and threaded inside to receive the swivel-head, E. Its movement is guided through the hole in the cover, A. Near the middle is set a transverse steel pin, I, with ends projecting slightly to engage the slots of a hollow wrench and to screw the piston rod into the piston, H. Near the lower end is a shoulder, 2; in its under side is cut an annular channel, to receive the top edge of the slotted socket of the piston, when the piston rod is screwed down inside to the shoulder. Its lower end is concave to fit the head, 4, of the spring on which it rests.

The piston, H, has a transverse web, supporting a central socket, which projects both above and below. The upper part is threaded to receive the lower end of the piston rod; it is also slotted, 3, to permit the lower end of the spring with its head to drop to its bearing on the steel screw, G, which is closely threaded into the lower part of the socket.

The spring, N, Fig. 193, is made of a single piece of steel wire, wound from the middle into a double coil, the ends of which are screwed into a head, D, with four radial wings, having spirally drilled holes to receive and hold them securely in place. The makers adjust the strength of the spring, by screwing the spring in or out of the head until it is of the right strength; it is then securely fastened in the head. The head is threaded inside to screw on to the lower projection of the cover, and up firmly against it. The foot of the spring, where the motion is greatest, and therefore lightness is essential, is a small steel bead, 4, fastened on the transverse portion of the wire from which the coils proceed; the bead, in connection with its bearings in the piston rod, C, and the steel screw, G, forms a ball and socket joint, which allows the spring to yield to pressure from any direction without causing the piston to bend.

The indicator is fixed to the cock on the engine in the same way as the Tabor indicator, by means of nozzle, 11, and the coupling, 12, which latter, however, is provided with a double set of thread. The paper-drum, U, on the base, Q, rotates on the spindle, P. Its squared section fits into the spring-head, S, and is held in place by the nut, 10. Y is the guide-pulley for the cord, X is the drum stop, and Z is one of the clips for fastening the cord. The drum spring, R, is a short spiral spring. Fig. 194 gives an external view of the Crosby indicator.
Richards' Indicator.—This instrument, of which an external view is given in Fig. 195, is one of the oldest types, and is therefore also better known to engineers than the two former ones. The peculiarity of Richards' indicator is the parallel motion by which the piston movement is multiplied, in order to allow the pencil to describe a diagram of convenient size. It will be noticed, however, that the multiplying gear is somewhat heavier than in the two former indicators, and therefore renders the instrument less fit for high speed work.

The paper-drum can be stopped and started, without disconnecting the driving cord.

The indicator, as shown in Fig. 195, is mounted on the cock, which serves for making connection between the engine cylinder and the indicator. By means of the cord-adjuster, 2, the length of the driving cord can be adjusted and readjusted by forming a loop on the cord, which is held tight by the thumb-screw.

Darke's Indicator, Fig. 196, is perhaps the earliest form of high-speed indicators. The pencil motion is formed by a single light steel lever, carrying at the one end a cross-head moving upon steel centres; to this lever the motion of the piston is communicated by a jaw, fitted on the piston-rod head, which jaw supports, between centres, a sleeve through which the lever slides with the varying angle of the motion of the lever.

The pencil is carried by a block sliding upon the other end of the lever, the pencil being kept in a straight line, parallel to the axis of the paper-drum, by a slot guide placed between the sliding block and the paper-drum, in which slot the pencil moves. The pencil is kept against the paper by the elasticity of the lever.

But for slow speed, the apparatus works admirably, and being made strong, can stand a great deal of knocking about, which is of little importance.

The cylinder is jacketed like that of the Tabor indicator, but the piston springs, 6, are single coiled; the one end is screwed to the top of the piston, and the other end to the cover, the piston rod moving inside the coil.

The drum spring is a flat coiled one, like a watch spring, but of course very much stronger.

This indicator, as made by Messrs. Elliott Bros., is provided with Darke's detent, described below, whereby
The paper-drum is smaller and lighter than that of the Richards' indicator. Darke's detent is also attached to this instrument. It consists of a pawl, which is made to fall or rise by the movement of a flat spring fixed on the outside of the indicator cylinder, so as to engage or liberate the paper-drum, by means of a small segment of a ratchet placed at the base of the drum.

M'Innes' Indicator.—This instrument is made by Messrs. T. S. M'Innes and Co., of Glasgow, and is illustrated in Fig. 197.

The drum spring is of the spiral form, like that used in the Crosby indicator; it can be adjusted to increase or diminish the tension of the drum to suit speed of engine. The multiplying levers are strong but light. The piston rod is hollow, and threaded inside at the top to receive a swivel-head, like in Fig. 192, whereby the height of the atmospheric line can be adjusted. This adjustment is done by turning the milled head, shown in Fig. 197, on the top of the piston rod, and a lock-nut prevents the swivel-head from turning back when the adjustment is finished. A clip cord adjuster is fitted on the cord, and by pressing the tails the cord may be lengthened or shortened instantaneously. The cylinder is open at the foot, and the part of the cylinder in which the piston moves is of a smaller bore than the rest, so as to allow of its being easily cleaned. One of the peculiarities of this instrument is that the cylinder, cylinder cover, and coupling ring are sheathed with vulcanite, to enable the operator to handle the instrument more comfortably without burning his fingers. An improved cord is sent out with this indicator; it has a wire core, and this diminishes the stretching of the cord.

The springs are similar to those used in the Richards' indicator.

Table D (above) gives the weights and dimensions of parts of indicators which the author has been using for some time.

**Driving Gear for Indicators.**

The motion of the paper-drum should be that of the engine piston on a reduced scale. The drum can therefore not be driven direct from the cross-head of the engine, but a driving gear must be applied by which the motion of the cross-head can be reduced in a proper proportion. The driving gear must be accurate if we want to produce accurate diagrams, and it must reduce the travelling of the cross-head at any position of the latter at a constant ratio.

![Fig. 198.](image)

Pantograph motions have been successfully used for driving gear, and when well made and kept in good order will reproduce the motion of the cross-head with great accuracy. In Fig. 198 is shown a form of panta-
and thumb nut, and the end A is attached to the crosshead, and therefore moves in a straight line. The cord which drives the indicator is attached to a pin, E, on Messrs. Musgrave and Sons, of Bolton, to their large engines, either horizontal or vertical. Two pins are fixed, one at each end of the guide-bars, on each of

the cross-bar, C D, which may be moved in different positions with relation to the centre, B. This pin must always be placed in the line A B, as any point in this which a grooved pulley is placed, which can turn freely on the pins. The centres of the grooves on the pulleys are in line with a pin fixed on the cross-head. A

line will have a motion exactly corresponding with the movement of A.

Fig. 199 shows “Lazy Tongs” attached to a horizontal engine and driving two Tabor indicators.

cotton rope of \( \frac{1}{4} \) in. or \( \frac{3}{8} \) in. diameter is passed tightly round these pulleys, and fastened to the pin in the cross-head. As the cross-head moves back and forth it carries this rope along with it, which, passing over the grooved pulleys, turns them correspondingly. To the hub of one pulley is fastened a small sheave, around which the indicator cord is wound, and which winds up and upwards with the movement of the engine,

Another form of pantagraph is shown in Fig. 200, and its application to indicator driving gear is illustrated in Fig. 201.

Fig. 202 shows the reducing motion usually applied by
giving the correct motion to the indicator. The cord may be led at any angle from this sheave to the indicator, without affecting the movement.

In Fig. 203 is illustrated a form of driving gear, called the "Brumbo pulley"; it is a plain reducing lever, connected to the cross-head by a short link, and having a segment of a grooved pulley for the indicator cord. The whole apparatus should be made very light.

Mr. A. G. Brown recommends for high-speed engines, that the driving cord should be continued beyond the loop for hooking on the indicator, and fastened to a rubber band attached to a carrier-pulley, so that it band then takes the strain, and keeps the driving cord tight. The Management of the Indicator.

The indicator must be kept clean and in good order, the piston should be frequently taken out, and the inside of the cylinder and the outside of the piston always keeps a tension on the driving cord, whether the indicator is running or not, and prevents entanglement or breakage of the cord when the indicator is unhooked. This method, as applied to the "Globe" compound high-speed engines, is shown in Fig. 204; diagrams can be taken with this arrangement as quickly as on slow-speed engines.
free; this can be tested by taking the piston spring off, then raise the pencil lever to its highest position, when it should drop to its lowest position with perfect freedom.

It is also of importance that the paper-drum should be kept in good order, and that the bearings should be clean and properly lubricated. The strength of spring to be used, depends upon the boiler pressure and the speed of the engine. The lighter the spring is, the higher will the diagram be, and the more accurate the measurement; but care should be taken that the diagram is not distorted by the inertia of the moving parts. Springs used for indicating condensing engines will be compressed while subjected to the pressure of the steam, and will be stretched during the exhaust of the steam into the condenser; these springs are, therefore, shorter than those used for indicating non-condensing engines.

The indicator-cock, to which the indicator is fixed, is screwed into a short steam-pipe, which, again, is screwed into a hole made in the engine cylinder. In horizontal engines, this hole should be at the end of the cylinder barrel, and in such a position that the engine piston never covers the opening of the hole. In vertical engines, the hole for the indicator-cock is made in the cover. The steam connections between the engine cylinder and the indicator should be as short as possible, and with easy bends.

Accurate work requires that diagrams should be taken from both ends of the engine cylinder, and an indicator should therefore be used at each end. To make sure that both indicators are alike, they should be interchanged, and the springs should be frequently tested under steam.

If only one indicator is available, it should be used alternately, first at one end and then at the other end of the engine cylinder.

When the engine cylinder is short, the indicator may be placed in the centre, and fixed on a three-way cock, Fig. 205, with steam connections to both ends of the engine cylinder. In order to reduce the errors due to friction of the steam, the passages should be large and have easy bends.

Before attaching the indicator to the cock, the latter should be opened, in order to clear the passages from any dirt which may have accumulated within them. The indicator and its carrier-pulley must be adjusted in such a manner that the driving cord does not bear against the sides of the pulleys, but runs central. The length of the cord must be adjusted so as to prevent the paper-drum from touching either stop when running. The cock is then opened to admit steam into the indicator cylinder to heat the piston, spring, and cylinder.

Taking the Diagram.—The drum is now taken off by unhooking the driving cord from the indicator cock, and a card is placed smoothly on the drum. The card is a blank piece of paper which is chemically prepared, so as to enable the brass pin, which acts as a pencil, to draw the diagram on the card. A lead pencil marking on ordinary paper might be used, but the frequent sharpening of such a pencil would be inconvenient. The card is fixed on the drum by bending the two ends over the clips. The drum with the card attached is then put back on the drum carriage, and the cords hooked together.

When the indicator is provided with a detent, the drum is taken off by letting the pawl fall into the ratchet; and in order to prevent entanglement of the cord, the operator must keep the cord in tension by letting his other hand touch it, and follow the motion. To start the drum it is necessary to lift the cord a little by the hand, so as to turn the drum a little, whereby the pawl will be disengaged. The indicator-cock is now turned in such a position that it allows the steam from the engine cylinder to escape into the atmosphere, whereby water which may have accumulated in the passages, will be blown out. The cock is then turned so as to allow the air to enter underneath the indicator piston; the pressure on both sides of the latter will thus be the same—viz., that of the atmosphere. The pencil is now brought lightly into contact with the card, and traces a line which, when the card is unfolded, will appear to be a straight line. This line is called the "atmospheric line." The cock is again opened to admit steam under the piston, and, after a few revolutions of the engine the pencil is again made to touch the card, this time tracing the indicator diagram. Before taking the card off, the pencil should again be allowed to trace the atmospheric line, to ascertain whether the condition of the line is the same. If a new line be traced, the diagram is useless.

The pressure of the pencil on the card should be as small as possible; just sufficient to make a legible diagram. A greater pressure will only create friction, and, consequently, inaccuracy in the diagram.

On each diagram should be marked boiler pressure, number of revolutions the engine is making per minute, apparent ratio of expansion, diameter of engine piston, length of stroke, the end of the cylinder at which the diagram was taken, the date at which the diagram was taken, the number of the indicator spring, etc.

When making accurate tests of the engine, the absolute vacuum line should be drawn on the card. This line should be parallel to the atmospheric line, and should be drawn below the latter; the distance
between the two lines should correspond to the atmospheric pressure at the time when the diagram was taken.

The Shape of the Indicator Diagram.

The diagram of an ideal engine, such as that shown in Fig. 186, is composed of four straight lines and a curve. The line $nb$ is called the admission line, and represents the pressure of the steam entering the cylinder, and, at the same time, it shows that the pressure on the piston is suddenly changed from that of the condenser to that of live steam; line $bc$ is the steam line, and represents the distance travelled by the piston from the point of admission to that of cut-off, and it also shows that no throttling of the steam has taken place, the pressure of the steam remaining constant, and equal to that of the steam during admission. The curve, $cd$, is the expansion line, and this line meeting the steam line in a sharp point, $c$, shows that the cut-off valve has acted suddenly. The release takes place at point $d$, and as the line $dm$ is at right angles to the motion of the piston, the exhaust-valve must have been opened suddenly, presenting at once a sufficiently large opening for the steam to allow the pressure to fall at once to that of the condenser. The line $mn$ is called the exhaust line, and as it is parallel to the vacuum line, the steam has been able to escape freely during the backward stroke of the piston; and it also shows that the condenser has been able to keep the pressure constant.

The essential features of a diagram from an actual engine, resemble that of the ideal engine with some few modifications. In Fig. 206 is shown a diagram of a non-condensing engine. $AB$ is the admission line, $BC$ the steam line, $DE$ the expansion line, $FG$ the exhaust line or back-pressure line, $HA$ is called the compression line, and $JI$ is the atmospheric line.

The short curve, $CD$, shows that the cut-off valve does not act suddenly, but gradually closes the opening through which the live steam is admitted to the cylinder. The release begins at point $E$, but owing to the slow shutting of the exhaust-valve, the release is not completed till point $F$.

The exhaust-valve begins to shut at point $G$, and is completely shut at $H$. The remaining steam is now compressed in the clearance space, whereby its pressure is increased before the fresh charge of live steam is admitted. The effect of the slow action of the valves in opening and shutting the steam-ports is called "wire-drawing," and is represented on the diagram by curved corners instead of the sharp corners on the ideal diagram.

Fig. 207 represents indicator diagrams taken from the two ends of the cylinder of a steam engine, and reproduced on one card. The straight line across the diagram is the atmospheric line. The diagrams bear evidence of having been taken from a condensing engine, as the exhaust lines fall below the atmospheric line. The admission lines are very straight and are perpendicular on the atmospheric line, and this bears evidence of a prompt admission. The ratio of expa-
sion is very high, which shows that the engine had very little work to do when the diagrams were taken. The diagrams are practically equal, and the exhaust lines are parallel to the atmospheric line. The expansion curve of the left-hand diagram is slightly wavy near the cut-off, which is due to the inertia of the indicator.

The engine from which the diagrams were taken is a Musgrave horizontal engine with Corliss valves. The diameter of cylinder is 38in.; stroke 6ft.; boiler pressure 79lb.; the engine made 51 revolutions per minute; vacuum was 134lb., and the scale of the indicator spring was $\frac{1}{10}$.

Figs. 208 and 209 are diagrams taken from a

![Fig. 208](image)

![Fig. 209](image)

Musgrave tandem compound engine without receiver. The H.P. diagrams from both ends of the cylinder are shown in Fig. 208, the ratio of expansion being about 2. The diagrams show that the compression was driven so far, that the end pressure in the clearance space before admission was greater than the initial pressure of the steam, and thus caused the indicator pencil to draw the loop at the top. The scale of the spring used for taking these diagrams was $\frac{1}{10}$.

The L.P. diagrams are given in Fig. 209, and show the presence of a condenser into which the steam was exhausted from the L.P. cylinder. The scale of the indicator spring used for taking these diagrams was $\frac{1}{10}$.

Determination of Clearance.

The clearance of a cylinder can be measured by filling the clearance volume with water, the quantity of which must be known. But in many cases this is impossible, and the clearance must then be determined approximately by the indicator diagram.

Figs. 210 and 211 are diagrams taken from the high and low pressure cylinders of a compound engine. Line A B is the atmospheric line, and D C the absolute vacuum line. Curves C E are the compression lines, and assuming that these curves are hyperbolas, we can determine the clearance line, remembering that the latter line must be the axis of ordinates for the hyper-
admission line of the diagram must be the clearance length, \( \lambda \).

As the length of the diagram represents the stroke, \( l \), the distance between the clearance line and the admission line, divided by the length of the diagram, will give the percentage of clearance of the engine.

The two points C and E must be selected as far apart as possible, but within the limits of the true curve.

**Combining the Diagrams from Compound Engines**

The method of combining the diagrams from an ideal compound engine has been explained for a Woolf's engine in Fig. 181, where the H.P. diagram is \( g a b c g \), and the L.P. diagram \( m h d n m \); and for a receiver engine in Fig. 183, where \( g a b c g \) is the H.P. diagram and \( m g' h n m \) is L.P. diagram. The diagrams from actual engines will, however, be somewhat modified, due to various losses. The loss due to clearance has been considered, and must occur in any actual cylinder to a smaller or greater extent, according to the size of the clearance.

Although compound engines have the advantage over non-compounding engines of reducing the amount of initial condensation at high degrees of expansion, they introduce in turn other losses which occur between the two cylinders.

These losses are due to condensation and friction in the pipes and steam passages between the two cylinders, and also to the expansion of the steam in these passages while doing no useful work. There is, therefore, a fall of pressure of the steam between the two cylinders, the extent of which can be shown and measured by combining the diagrams from the actual engine.

The following diagrams have been taken with the Tabor indicator from engines built by Messrs. Musgrave, of Bolton, to whom the author is indebted for the blocks.

To correctly combine the two diagrams of a compound engine, the total capacities of the two cylinders must be known and accounted for, as done in Figs. 187 and 188. The next is to decide on the total length of the combined diagram. It is best to decide on the total length of the L.P. diagram first, and a length which can be easily divided into 100 parts will be found the most convenient, as percentages of this length can then be easily measured; we may, for instance, take the
length 12\(\frac{1}{2}\)in., a hundredth part of which will then be one-eighth of an inch. The combined diagrams, Figs. 214, 217, and 219, were each 12\(\frac{1}{2}\)in. long, and the photo was reduced to the length shown.

The next is to decide on the scale of pressure to the clearance line. All measurements of distance should be made from the clearance line, and all measurements of pressure from the atmospheric line. We now divide the two original diagrams into 10 parts, as show in Fig. 218.

which the two diagrams are to be plotted—usually it may be most convenient to take the scale of the original L.P. diagram for this. Now draw in the atmospheric and vacuum lines, and erect perpendiculars at the two extremes of the combination diagram, one of which is

(1) **Low-pressure Diagram.**—Find the effective capacity of the L.P. cylinder, and add to it the volume of the clearance; the total length of the combined diagram will represent the total capacity of the L.P. cylinder. Divide the clearance of the cylinder by the
total capacity of the cylinder, and the quotient will give the percentage this clearance bears to the whole length. Set off this distance from the clearance line, and 219. If the pressure scale selected is the same as that of the original diagram, then transfer the pressures directly, with a pair of dividers, from the lines on the

and divide the remainder, representing the effective capacity of the cylinder, into the same number of parts that the original diagram is divided into, see Figs. 218 original diagram, to the corresponding lines on the combination; draw in the connecting portion of the diagram, and the result will be an elongated diagram.
from the L.P. cylinder, similar to those shown in Figs. 181 and 183.

of the L.P. cylinder; the quotient is the percentage which the length of the H.P. diagram on the combination

(2) High-pressure Cylinder.—Find the total capacity of the H.P. cylinder, and divide it by the total capacity bears to the length of the corresponding L.P. diagram both measured from the clearance line. Divide the
clearance volume of the H.P. cylinder by the total capacity of the L.P. cylinder, and the quotient will be the length of the clearance, B, Fig. 219, on the combination measured on the scale of the combination. Divide the remaining length of the H.P. diagram, C, Fig. 219 (representing the effective capacity of the cylinder), into the same number of parts as the original diagram, and transfer the pressures from the lines on the original diagram, Fig. 218, to the corresponding lines on the combination, and to the new scale of pressures. If the original H.P. diagram were taken with a 40 spring, see table on page 188, and the combination diagram made to a scale of 10 lb. per inch, the new H.P. diagram will be four times as high as the original one.

The combination diagram is finished by drawing the hyperbola which touches the expansion line of the H.P. diagram at the point of release. If there were no losses between the two cylinders, this hyperbola ought to coincide with the expansion line of the L.P. expansion line. The space between the hyperbola and both diagrams below the point of release of the H.P. diagram, and also the space between the two diagrams, represent the losses between the two cylinders.

Example 1.—The engine from which diagrams Figs. 212 and 213 were taken is a side-by-side compound (receiver) engine with Corliss valves. The diameter of the H.P. cylinder is 26 in., and that of the L.P. cylinder is 48 in.; the stroke is 6 ft. for both cylinders. The boiler pressure was 69 lb. above the atmosphere. The engine made 50 revolutions per minute, and the vacuum was 13.75 lb., i.e., the pressure in pounds per square inch below the atmosphere. The H.P. diagrams, Fig. 212, were taken with a spring \( \frac{1}{3} \), i.e., the resistance of the spring allowed the pencil to move 1 in. per 30 lb. of effective pressure per square inch on the indicator piston. The straight line which is almost touching the diagrams, is the atmospheric line.

The L.P. diagrams were taken with a spring \( \frac{1}{2} \); the atmospheric line appears at the top of the diagrams; the vacuum line is not shown.

Fig. 214 represents the diagrams combined. A scale is added at the bottom of the diagram whereby all volumes can be measured in percentage of the total capacity of the L.P. cylinder. The dotted curve is the hyperbola through the point of release of the H.P. diagram, and has been constructed as shown in Fig. 172, the initial pressure line corresponding to line B F in Fig. 172.

Example 2.—Diagrams Figs. 215 and 216 are also taken from a side-by-side compound (receiver) engine with Corliss valves. The diameters of the two cylinders are 30 in. and 57 in. respectively, and the stroke is 7 ft. for both. The boiler pressure was 65 lb., the engine made \( 33 \frac{1}{3} \) revolutions per minute, and the vacuum was 141 lb.

The H.P. diagrams were taken with spring \( \frac{1}{4} \), and they show that the pressure in the receiver was not constant while the steam was exhausted from the H.P. cylinder.

The L.P. diagrams were taken with spring \( \frac{1}{5} \). The straight lines drawn in both diagrams are the atmospheric lines.

Fig. 217 is the combination of the diagrams by which the losses between the cylinders can be measured.

Example 3.—Diagrams Fig. 218 were taken from a tandem compound engine. Diameters of cylinders are 30 in. and 50 in. respectively, the stroke is 6 ft., and the diameter of the piston rod in both cylinders is 6 in. The boiler pressure was 82 lb., the engine made 56 \( \frac{2}{4} \) revolutions per minute, and the vacuum was 12 lb.

The effective capacity of either cylinder must be equal to the area of the piston multiplied by the stroke, minus the volume occupied by the piston rod.

The effective capacity of the H.P. cylinder must therefore be

\[
\left( \frac{\pi \times 30^2}{4} - \frac{\pi \times 6.25^2}{4} \right) \times 72 = 48,685 \text{ cubic inches.}
\]

Clearance volume in H.P. cylinder is 2,545 cubic inches, so that the total capacity of the cylinder is 51,230 cubic inches.

The effective capacity of the L.P. cylinder will be \((1863.5 - 30.95) \times 72 = 139,163 \text{ cubic inches, and the clearance volume is 7,673 cubic inches. The total capacity of the L.P. cylinder is therefore 146,836 cubic inches.}\]

**Determination of Indicated Horse-Power.**

The area enclosed by the line traced by the indicator pencil, measures the indicated work done on the one side of the engine piston during one stroke.

![Fig. 220](image-url)

The length of the diagram, measured parallel to the atmospheric line, represents the stroke of the engine piston and is therefore given in feet; the ordinates to the diagram line, measured in a direction at right angles to the atmospheric line, represent pressures in pounds per square inch. The area enclosed by the diagram line will therefore measure the indicated work in foot-pounds per square inch of the engine piston.

It has been fully explained on page 157, and shown in Fig. 165, how the area enclosed by a curve can be determined.

In Fig. 220 is shown the method adopted for the purpose of calculating the area of an indicator diagram.
The base line is here either the atmospheric line or the vacuum line. The two extreme ordinates are C D and A B. The base line, B D, is divided into ten equal parts, and the corresponding ordinates are drawn. In order to obtain an accurate result, the divisions of the curves should be approximately straight lines. This is not the case with F E, E G, the release curve and the compression curve. In the cases of F E and E G, we may consider that the areas enclosed between the straight lines F E and E G, and the curves F E and E G, are equal. But the release curve and the compression curve should be further divided. By using formula (71), on page 158, the area enclosed by the diagram will be obtained.

Let $A_1$ denote the foot-pounds represented by the area of the diagram taken at the crank end of the cylinder, and $A_2$ the same for the diagram taken at the other end of the cylinder; and, further, let $D$ be the diameter of the piston, $d$ the diameter of the piston rod, and $\delta$ the diameter of the tail rod (if any), all in inches; then the indicated work on the crank side of piston will be

$$A_1 \left( \frac{\pi D^2}{4} - \frac{\pi d^2}{4} \right) \text{ foot-pounds,}$$

and the indicated work on the other side of the piston will be

$$A_2 \left( \frac{\pi d^2}{4} - \frac{\pi \delta^2}{4} \right) \text{ foot-pounds.}$$

The indicated horse-power of the engine, when making $n$ revolutions per minute, will be

$$\text{I.H.P.} = \frac{\left( A_1 \left( \frac{\pi D^2}{4} - \frac{\pi d^2}{4} \right) \right) + A_2 \left( \frac{\pi d^2}{4} - \frac{\pi \delta^2}{4} \right)}{33,000} \times n \tag{165}$$

We might also have determined the energy exerted by the steam during the forward stroke, and likewise the work done on the back pressure during the return stroke. For this purpose, we require the absolute vacuum line to be drawn on the card. Let us imagine that B D is this line. Area D E A B D would thus represent the energy exerted by the steam, and the area between the back-pressure curve and the line B D would represent the work done on the back pressure. These two areas can be calculated in the same manner as described above.

For the purpose of designing new engines, it is desirable to know the mean forward pressure, $p_{fm}$, which will be exerted on the piston of the new engine, and also the mean backward pressure, $p_{bm}$, which the piston has to overcome. $p_{fm}$ will vary with the initial pressure of the steam, the ratio of expansion, and the general construction of the engine, and $p_{bm}$ will depend on the construction of the condenser as well as on that of the engine.

These two pressures can be calculated by predetermining the indicated diagrams of the new engine, taking into consideration the losses which are likely to occur in the new engine. If diagrams taken from actual engines of the same class as that of the engine to be designed are available, then the mean pressures calculated from such diagrams would give the designer more reliable data than the theoretical diagrams could give.

The two mean pressures are to be calculated by means of formula (72), page 158, the pressures being measured from the absolute vacuum line.

If we know the mean pressures, the indicated work on the crank side of the piston will be

$$\left( p_{fm} - p_{bm} \right) \left( \frac{\pi D^2}{4} - \frac{\pi d^2}{4} \right) \times l \text{ foot-pounds,}$$

and that on the other side of the piston will be

$$\left( p_{fm}'' - p_{bm}'' \right) \left( \frac{\pi D^2}{4} - \frac{\pi \delta^2}{4} \right) \times l \text{ foot-pounds,}$$

where $l$ is the stroke in feet, the other dimensions being in inches.

The engine when running at $n$ revolutions per minute will indicate

$$\left( \left( p_{fm} - p_{bm} \right) \left( \frac{\pi D^2}{4} - \frac{\pi d^2}{4} \right) + \left( p_{fm}'' - p_{bm}'' \right) \left( \frac{\pi D^2}{4} - \frac{\pi \delta^2}{4} \right) \right) \times l \times n \tag{165} \times 33,000$$

horse-power.

The pressure expressed by $p_{fm} - p_{bm}$ is called the mean effective pressure, but is nothing of the kind unless the diagrams taken from both ends of the cylinder are exactly the same. As this is hardly ever the case, the usual meaning of the mean effective pressure is erroneous. It is evident that the actual mean effective pressures, in pounds per square inch, are for the two sides of the piston ($p_{fm} - p_{bm}$) and ($p_{fm}'' - p_{bm}''$). The two total mean effective pressures, in pounds, on the piston are, for the stroke of the piston towards the bottom of the cylinder,

$$p_{fm} \times \left( \frac{\pi D^2}{4} - \frac{\pi d^2}{4} \right) - p_{bm} \times \left( \frac{\pi D^2}{4} - \frac{\pi \delta^2}{4} \right) \text{ pounds,}$$

and for the stroke of the piston towards the crank,

$$p_{fm}'' \times \left( \frac{\pi D^2}{4} - \frac{\pi d^2}{4} \right) - p_{bm}'' \times \left( \frac{\pi D^2}{4} - \frac{\pi \delta^2}{4} \right) \text{ pounds.}$$

The areas enclosed by the indicator diagrams, as well as the mean pressures, can also be determined by the use of planimeters, as fully described on pages 158 and 159.

The planimeter, however, would give the area in square inches, and we must therefore find the number for each case in which the area must be multiplied to obtain the corresponding foot-pounds.

Suppose the scale of the spring used in taking the diagram was $\frac{1}{2}$ inch, i.e., each inch measured at right angles to the vacuum line corresponds to $40$ lb. pressure per square inch, and as the distances measured along the vacuum line represent feet, it is evident that each square inch measured by the planimeter must mean $40 \times \frac{1}{2} = 20$ foot-pounds.

In non-condensing engines carrying a light load, the expansion line often extends below the back pressure line and forms a loop in the diagram as shown in...
This expression must be equal to the mean forward pressure, multiplied by the volume swept by the piston; so we must have
\[
P_{fm} \times \nu \times \frac{r_e}{1 + \frac{\lambda}{l} \times r_e} = \ldots \ldots \quad (167)
\]
By equating (166) and (167) we obtain
\[
\left(1 + \frac{1}{l}\right) \times r_e \times \log_e \left(1 + \frac{\lambda}{l} \times r_e\right)
\]
\[
P_{fm} = P_{m} \times \frac{r_e}{r_e}
\]
pounds per square foot.

The mean forward pressure in pounds per square inch will be 
\[
P_{fm} = \frac{P_{m}}{144}
\]
The following table, E, has been calculated by Prof. Haedicke, and is derived from actual engines:

<table>
<thead>
<tr>
<th>(\frac{1}{r_e})</th>
<th>0.1</th>
<th>0.2</th>
<th>0.25</th>
<th>0.3</th>
<th>0.33</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.625</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{m}/P_{ri})</td>
<td>0.36</td>
<td>0.53</td>
<td>0.60</td>
<td>0.66</td>
<td>0.67</td>
<td>0.76</td>
<td>0.84</td>
<td>0.90</td>
<td>0.92</td>
<td>0.95</td>
</tr>
</tbody>
</table>

The average mean back pressure of actual engines may be taken as 16lb. per square inch for non-condensing engines, and as 3lb. per square inch for condensing engines. By assuming that the indicator diagrams from both ends of the cylinder are equal, the mean effective pressure will be—

(a) For non-condensing engines
\[
P_{em} = (P_{fm} - 16) \text{ pounds per square inch.}
\]
(b) For condensing engines
\[
P_{em} = (P_{fm} - 3) \text{ pounds per square inch.}
\]
In using Table E, we must remember that \(P_{ri}\) is not equal to the absolute boiler pressure, but we may take on an average:

(a) For engines working with throttle-valves
\[
P_{ri} = 0.8 \text{ times the absolute boiler pressure.}
\]
(b) For engines working with automatic expansion gear
\[
P_{ri} = 0.9 \text{ times the absolute boiler pressure.}
\]

**Actual Horse-Power of an Engine.**

The actual energy given off by an engine is the energy available for doing useful work. The actual horse-power of an engine is therefore the actual energy in foot-pounds given off per minute, divided by 33,000. The number of A.H.P. of an engine is less than the number of I.H.P. of the engine, by the amount required for overcoming the resistances in the engine itself. The ratio of A.H.P. and I.H.P. is called the efficiency of mechanism of the engine, and must necessarily always be smaller than unity. The efficiency of mechanism, \(n_1\), can be obtained approximately from the indicator by...
determining the number of I.H.P., \( n_1 \) and \( n_2 \), when the engine is running empty, and when it is running with a certain load at the same speed. The efficiency of mechanism would be

\[
\eta = \frac{n_2 - n_1}{n_2} \quad \ldots \quad (168)
\]

As the resistances in the engine increase with the load, formula (168) will only give \( \eta \) approximately.

The efficiency of mechanism is determined accurately by measuring the A.H.P. by a dynamometer applied on the engine shaft, and at the same time measuring the I.H.P. by the indicator.

The efficiency of mechanism may be estimated from the following empirical formulæ due to Prof. Hrabák:

(a) For engines giving off less than 5 A.H.P.,

\[
\eta = \frac{\text{A.H.P.} + 5}{\text{A.H.P.} + 10} \quad \ldots \quad (169)
\]

(b) For engines of more than 5, and less than 50 A.H.P.

\[
\eta = \frac{\text{A.H.P.} + 20}{\text{A.H.P.} + 32.5} \quad \ldots \quad (170)
\]

(c) For engines of more than 50 A.H.P.

\[
\eta = \frac{\text{A.H.P.} + 300}{\text{A.H.P.} + 366} \quad \ldots \quad (171)
\]

An engine making \( n \) revolutions per minute, with a stroke equal to \( l \), and delivering the same indicator diagrams from both sides of the piston, will indicate

\[
(\text{p}_{\text{fm}} - \text{p}_{\text{bm}}) \times A \times l \times 2 \eta = \frac{33,000}{\text{H.P.}}
\]

where \( A \) is the effective area of the piston in square inches, and will be

(a) For engines with tail rod:

\[
A = \frac{1}{2} \left( \frac{\pi D^2}{4} - \frac{\pi d^2}{4} \right) = \frac{\pi D^2}{4} - \frac{1}{2} \left( \frac{\pi d^2}{4} + \frac{\pi \delta^2}{4} \right),
\]

and in case where \( d = \delta \),

\[
A = \pi \frac{D^2}{4} - \pi \frac{d^2}{4}
\]

(b) For engines with no tail rod:

\[
A = \pi \frac{D^2}{4} - \frac{1}{2} \pi \frac{d^2}{4}
\]

The A.H.P. given off by this engine will be

\[
\eta (\text{p}_{\text{fm}} - \text{p}_{\text{bm}}) \times A \times l \times 2 \eta = \frac{33,000}{\text{H.P.}}
\]

If we denote the pressure \( \eta (\text{p}_{\text{fm}} - \text{p}_{\text{bm}}) \) by \( \text{p}_a \), then we shall have

\[
\text{A.H.P.} = \text{p}_a \times A \times l \times 2 \eta = \frac{33,000}{\text{H.P.}} \quad \ldots \quad (172)
\]

\( \text{p}_a \) is evidently the mean effective pressure which would produce the same effect as \( \text{p}_{\text{fm}} - \text{p}_{\text{bm}} \), if there were no resistances to overcome in the engine itself; \( \text{p}_a \) is called the mean actual pressure.

(a) For non-condensing engines, we have

\[
\text{p}_a = \eta_1 (\text{p}_{\text{fm}} - 16) \text{ pounds per square inch} \quad (173)
\]

(b) For condensing engines

\[
\text{p}_a = \eta_1 (\text{p}_{\text{fm}} - 3) \text{ pounds per square inch} \quad (174)
\]

Steam Accounted for by the Indicator.

The connection between pressure and volume of 1lb. of dry saturated steam is given in the table on page 61. By the same table and a slight calculation we can evidently determine the mass of steam contained in a steam-cylinder at any point of the stroke, if we know the corresponding pressure of the steam and volume of the cylinder, and if the steam contained in the cylinder is dry saturated steam. The indicator diagram will give us this volume and pressure, if we only draw in the clearance line and the vacuum line. The indicator therefore is also useful in connection with a feed-water test in determining the amount of steam consumed per I.H.P. hour.

The indicator diagram does not only give an account of the steam which is present in the cylinder during the forward stroke of the piston, but the amount of steam retained in the cylinder during compression can also be measured in the same manner; the difference of these two quantities will be the amount of steam accounted for per stroke.

Fig. 233 clearly shows that if the expansion of the steam is hyperbolic, the steam in the cylinder will be superheated, because the ordinates to the hyperbola are greater than the corresponding ones to the saturation curve. In diagrams taken from jacketed engines with an early cut-off, it will always be found that the steam is superheated at points near the end of the stroke. Such points on the expansion curve should therefore not be selected for determining the quantity of steam contained in the cylinder, but points near the cut-off will give more accurate results.

The data given in Table B, on page 181, show that, in order to get the full advantage of the steam in the cylinder, the jacket must be filled with steam, the amount of which varies with the ratio of expansion; in example No. 20, the steam required in the jacket is about 22.5 per cent. of the steam contained in the cylinder—i.e., for each 100 lb. of steam admitted to the cylinder, 22.5 lb. of steam must be admitted to the jacket. In calculating the latter quantity of steam, it was assumed that there was no radiation, and that the material of which the cylinder-barrel was made was a perfect conductor for heat; this, of course, is not the case in actual engines, and the quantity of steam condensed in the cylinder and in the jacket must therefore be considerable in actual engines, and it will increase with the ratio of expansion.

The indicator diagram can therefore only show the quantity of steam which is actually contained in the cylinder, but not the total quantity consumed by the engine. If we measure the quantity of feed-water pumped into the boiler, and from that subtract the quantity accounted for by the indicator diagram, we obtain the extent of losses due to leakage and condensation.

It would not, however, be fair to the engine to debit
it with the amount of steam escaping through leakages in the boiler, boiler fittings, and steam-pipes, nor with the steam which is condensed in the steam-pipes. The rate of leakage can be determined by measuring the quantity of feed-water required for keeping the water level in the boiler constant, while the stop-valve of the engine is shut; and the extent of condensation can be measured by applying a steam-separator close to the engine stop-valve, and for accurate tests, an analysis of the wetness of the steam should be made by means of a calorimeter, which will be explained below.

Leakage may also occur at the valves and at the piston of the engine, but this can be detected by a trial under boiler pressure while the engine is at rest; the leakage will be shown by steam escaping through the indicator cock.

The steam admitted to the jacket can be measured by collecting the water formed in the jacket by condensation.

The total quantity of steam, \( S_2 \), lost by leakage and condensation in engines which are in average working order, may be approximately estimated from the following formula due to Professor Völeker:

\[
S_2 = (0.0527 \times \sqrt{\frac{A \times H \times P}{C}} + 0.0121) \text{ lb. per second} \quad (175)
\]

where \( C \) is the piston speed in feet per second.

The following is a description of the calorimeter test referred to above, and is due to Messrs. Musgrave and Sons, of Bolton:

When testing engines to determine their economy, careful tests should be made of the quality of the steam entering the engines, as in many cases water is carried over from the boilers, and condensation in the pipes adds to the amount; sometimes apparatus is provided for separating the water from the steam before the latter enters the engine, but it is always advisable to make these tests, if for no other reason than to know how efficient the separator is.

No calorimeter should be used that cannot be worked continuously over an extended period, and also, no calorimeter should be used where allowance must be made for the specific heat of the materials in the instrument, as there is too great a liability to error in both cases.

Fig. 224 shows a simple form of apparatus for the purpose. It consists of a small tank, \( A \), carefully covered with non-conducting material, \( B \), and encased in tin, \( C \), to protect the covering. The tank contains a worm, \( D \), the upper portion of which is connected as closely as possible with the steam-pipe, and the connections carefully covered with non-conducting material. The connecting-pipe should be carried to the centre of the steam-pipe, and the end bent, as shown at \( E \), to face the current of steam. The lower end of the worm, \( D \), is connected to a thermometer, \( G \), and from this a pipe is led to a tank or barrel. The condensing water first passes the thermometer \( F \), and enters the bottom of the tank, \( A \), then passing up around the coils, it passes out at the top, and is led away to a tank. The tempera-
ture is indicated by the thermometer H just as the water leaves the tank.

In operation, the tank is first filled with condensing water, and a small stream allowed to run through. Steam is then admitted to the room, and the valve adjusted to allow the desired amount to pass through the worm. The quantity of condensing water is then regulated to give the desired temperature of the overflow at H (about 160 deg. is a suitable temperature). When the temperatures at all the thermometers have become constant, start the test by simultaneously turning the overflows of condensing water and condensed steam into their respective tanks. Note the pressure of steam with the temperatures at all thermometers. (These should be recorded every five minutes during the test.) In ending the test at the same instant, turn both overflows out of the tanks, and then shut off the steam and condensing water.

The apparatus will be at the same temperature at the end as at the beginning of the test; therefore, no account need be taken of its specific heat, as no change has taken place, and from the low temperature and careful protection, the radiation from the instrument will be inappreciable.

Weigh the condensed steam and the condensing water separately. Multiply the weight of condensing water by the units of heat each pound has received, and the product is the quantity of heat the steam has lost. Multiply the weight of condensed steam by the units of heat each pound lost after it was condensed to water, subtract this product from the first one, and divide the remainder by the latent heat of the steam. If the quotient is less than the weight of condensed steam, the difference between the two must have entered the calorimeter as water. If the quotient is more than the weight of condensed steam, the steam has been superheated, and to find the number of degrees of superheat, multiply the weight of condensed steam by the number of units of heat each pound has lost, both as

steam and water, and subtract this product from the quantity of heat received by the condensing water; divide the remainder by the weight of the steam condensed, and by the specific heat of steam under constant pressure; the quotient will be the degrees of superheat, and this amount added to the temperature of saturated steam in the tables, should correspond with the readings of the thermometer I.

Example.—Take $p_1 = 100$ lb., to which corresponds a temperature of 327.9 deg. F.

Weight of condensed steam 90 lb., and temperature 70 deg. F.

Weight of condensing water, 1,000 lb.; temperature at inlet 60 deg. F., and at outlet 160 deg. F.

Latent heat contained in 1 lb. of dry saturated steam at 327.9 deg. F. from 32 deg. F. is 883.1 heat units.

Sensible heat contained in the latter is 393.3 heat units.

Total heat contained in 1 lb. of steam at 327.9 deg. F. from 32 deg. F. is 1,181.4 heat units.

Difference of heat contained in 1 lb. of water at 160 deg. F. and at 60 deg. F. is 100.365 heat units.

Difference of heat contained in 1 lb. of water at 70 deg. F. and at 32 deg. F. is 33.02 heat units.

Heat units received by condensing water:

$$100.365 \times 1,000 = 100,365$$

Heat units lost by the water to which the steam was condensed:

$$(298.3 - 38.02) \times 90 = 23,425.2$$

Weight of steam condensed to water:

$$\frac{100,365 - 23,425.2}{883.1} = 87.111$$

Percentage of water contained in the steam:

$$\frac{(90 - 87.11) \times 100}{90} = 3.21\%$$

Had it required 1,040 lb. of condensing water to condense the steam, other conditions being the same, the result would have been:

Heat units received by condensing water:

$$100.365 \times 1,040 = 104,379.6$$

Heat units lost by saturated steam:

$$(1,181.4 - 38.02) \times 90 = 102,904.2$$

Amount of superheat:

$$\frac{104,379.6 - 102,904.2}{90 \times 0.475} = 34.5\,\text{deg. F.}$$

where $0.475$ is specific heat of steam at constant pressure.

Temperature of steam:

$$327.9 + 34.5 = 362.4\,\text{deg. F.}$$

Losses in Steam Engines Summarised.

In summarising the losses which occur in a steam engine while performing its duty, we must assume that the steam in entering the engine stop-valve is perfectly dry, either in the form of dry saturated steam or as slightly superheated steam. It is unfair to the engine.
to test it with wet steam, as the suspended water is inactive, and will produce losses which are not due to faults in the engine. In testing the engine, the pressure of the steam should be measured at the engine stop-valve, and not at the boiler, as fall of pressure between boiler and engine is not due to faults in the engine.

The losses which must occur more or less necessarily in a steam engine may be tabulated as follows:

1. Throttling of the Steam before entering the Steam-Chest.
   (a) This may be caused by the stop-valve not being fully opened, and also by the passages through the stop-valve and the steam-pipe, between the stop-valve and the steam-chest, not being wide enough.
   (b) It will occur when the quantity of steam admitted to the engine is controlled by means of a throttle-valve worked by the governor.

2. In the Steam-Chest.
   (a) Radiation of heat from the external surfaces of steam-chest.
   (b) Heat conducted through eccentric rods.
   (c) Steam required to compensate heat radiated from slide-valve into exhaust-pipe.
   (d) Leakage of steam through stuffing-boxes and joints.
   (e) Leakage of steam between valves and wearing surfaces into exhaust-pipe. This can be tested as described above.

3. In the Cylinder.
   (a) Loss due to wire-drawing caused by the valves opening and shutting gradually. The wire-drawing will be augmented if the steam passages between steam chest and cylinder are narrow.
   (b) Condensation of part of the high-pressure steam during admission, caused by the steam passages, cylinder-walls, covers, piston, piston rod, etc., having been cooled during the periods of expansion and exhaust. Also condensation of some of the steam during the early part of expansion; this is due to the cylinder not being warm enough to keep the steam at the point of saturation. Some of the condensed steam will be re-evaporated at a low pressure during the latter part of expansion, and will do work on the piston. But this re-evaporation requires heat, which must be extracted from the cylinder walls, piston, etc., whereby the temperature of these parts will fall.
   (c) If the re-evaporation of the condensed steam has not been completed before the release takes place, the heat required for re-evaporating the remaining water will be carried into the exhaust and thus wasted.
   (d) Radiation of heat from external surfaces of cylinders which are not jacketed.
   (e) Leakage through stuffing-boxes and joints.
   (f) Leakage between cylinder walls and piston.

(g) Waste of steam in blowing through drain-cocks.
(h) Waste of steam in filling clearance volume at every stroke. This loss can be diminished by a proper amount of compression. It is evident that for economy in compression, it is necessary that the work done on the compression steam should be smaller than the energy required for producing the steam saved by compression.

(i) As the exhaust steam must pass through passages of limited cross-sections, it follows that the pressure of the exhaust steam will be greater than that of the atmosphere or that of the condenser.

4. In the Jacket.—The object of the jacket is to diminish the loss of heat due to condensation in the cylinder. In an ideal jacket, such as assumed in Tables B and C, the heat given off by the condensation of the jacket steam is spent in doing work on the piston by heating the cylinder steam and preventing condensation of the latter. Of course the ideal jacket can not be carried out in practice, and therefore loss of heat is the consequence.

(a) As the material of the jacket cylinder and covers is not a perfect non-conductor, a certain quantity of heat is wasted by radiation.
(b) As the quantity of heat which will be given off by the jacket steam to the cylinder steam depends on the conductivity of the material of which the cylinder-barrel is made, it follows that an actual steam-jacket will be less effective than an ideal one.
(c) If the temperature of the jacket is less than that of the steam-cylinder, heat will be extracted from the latter to evaporate condensed jacket steam accumulated on the external surface of the steam-cylinder. The jacket should therefore be well drained.
(d) Leakage of jacket steam into the exhaust-pipe through joints between jacket-cylinder and steam-cylinder.

5. Fall of Pressure between the Cylinders of Compound Engines.

(a) Condensation of steam in pipe connections and receivers.
(b) Expansion of steam in the latter parts while doing no useful work.
(c) Friction between steam and walls of passages.
(d) Leakage through joints.


(a) Friction between the working parts of the engine.
(b) Energy spent in driving feed pumps, air pumps, and circulating pumps.
(c) Energy spent in driving the governor. This loss may be considerable in engines working with automatic expansion gear.
CHAPTER XII.

DETAILS OF STEAM ENGINES.

The Cylinder.

The steam-cylinder is a cast-iron pipe accurately bored inside, and ending in faced flanges, to which the covers are fixed by studs. The cylinder barrel has to withstand internal fluid pressure, like a steam boiler, and its thickness might therefore be calculated in the same way as that of a boiler shell. The thickness of the steam-cylinder barrel is, however, always in excess with regard to strength, partly for the purpose of allowing it to be rebored when worn, and partly for making it convenient to cast.

Non Jacketed Cylinders.—Fig. 225 illustrates the steam-cylinder, with steam passages, and steam-chest, of a simple double-acting horizontal engine. The main casting, containing the cylinder barrel, with steam passages, P, rests on four legs on the foundation frame, to which it is fixed by eight bolts, F B.

The cylinder covers are turned to fit into the cylinder ends, and are fixed by studs, Sd, through the flanges. PR and TR are stuffing-boxes for the piston rod and the tail rod respectively. Tail rods are sometimes used in horizontal engines to diminish the wearing of the cylinder caused by the weight of the piston and piston rod.

In horizontal condensing engines, the tail rod forms the piston rod of the air pump, which latter is placed behind and in line with the steam-cylinder. Gd are guards to prevent accidents which might otherwise be caused by the reciprocating movement of the tail rod. E is the exhaust-channel. S C is the steam-chest which is bounded by a cast-iron box fixed by bolts to the main casting, and shut from outside by cover C. SF is a faced surface on which the slide-valve works. The slide-valve rod slides in stuffing-box S V, and the cut-off valve rod, which passes right through the steam-chest, slides in the two stuffing-boxes CV and V T.

To diminish loss of heat by radiation, the cylinder barrel is covered with non-conducting material, such as felt, held in position by a sheet of steel laid on the top.

Jacketed Cylinders.—The cylinders of a compound (receiver) engine, made by Messrs. Ransomes, Sims, and Jefferies, of Ipswich, are illustrated in Figs. 226 and 227, the former being a section through the centre line A B, and the latter a section through line C D.

The main casting consists of the jacket cylinders, J C, steam-chests, S1 C1, and S2 C2, and receiver, R. Cylinders J C are bored to receive the working cylinder barrels, C B, which are cast separately and turned on the outside to fit into the jacket cylinders. After having been bored, the working cylinder barrels are forced into the main casting by hydraulic pressure, and
when in their proper position, a finishing cut is given to the bore, so as to ensure perfect accuracy with the cylinder faces. The space surrounding the barrels, C B, when filled with steam, forms the steam-jackets, S J. The jackets are tested for leakage under water and steam pressure before the cylinder-covers are put on.

H P C is the high-pressure cylinder. L P C is the low-pressure cylinder. S I is the steam-inlet, the steam passing, as shown by arrows, into the high-pressure steam-chest, S, C₁, which is shut from outside by cover C₂. P₁ are high-pressure steam passages, which alternately takes live steam from steam-chest S, C₁ into the cylinder, and exhaust steam into exhaust channels, E₁, C₁. R is the receiver, into which the exhaust channel, E₁, C₁, opens. The steam flows through the receiver, as shown by arrows, into the low-pressure steam-chest, S₂, C₂, which latter is shut from outside by cover C₃, C₂. P₂ are the low-pressure steam passages, which will be seen to have a larger sectional area than passages P₁, the reason being that the low-pressure steam is not so dense as the high-pressure steam. E₂C₂ is the exhaust channel, through which the exhaust steam from the low-pressure cylinder is carried into the condenser or into the atmosphere.

C E are the crank end cylinder covers provided with stuffing-boxes, S B, for the piston rods. Holes h are bolt-holes for attaching guide blades. B C are the bottom end cylinder-covers. S F are faced surfaces for the attaching lubricators. C v is the cylinder covering, and consists of asbestos non-conducting composition, covered over with steel lagging sheets, cold rolled and close annealed, presenting a very smooth surface, which is painted and varnished. F F is the wrought-iron foundation frame.

Steam-Trap.—The object of a steam-trap is to allow the condensed water in jackets or steam-pipes to pass out without permitting the steam to follow. Fig. 228 is an illustration of Hopkinson's self-acting steam-trap. The condensed water will soon fill up the space between the inner movable cylinder and the cylindrical casing, and thus lift the former against the end of the outlet pipe. Steam and water is thus prevented from passing through the outlet, until the weight of the water accumulated in the inner cylinder is sufficient to overcome...
the buoyancy of this cylinder. At that moment, the lower end of the outlet pipe will be free and a small quantity of water will be discharged, but no steam will follow. The object of the valve at the top is to permit air to escape.

**The Piston.**

The piston should fit steam-tight in the cylinder, to prevent leakage of steam from the steam end into the exhaust end of the cylinder. This could be done by turning the piston to fit accurately into the cylinder, but as both cylinder and piston wear in working, leakage must occur after a time.

The piston is made steam-tight by employing elastic metallic spring rings made of cast iron, steel, or gunmetal. The spring ring is split at one place so as to allow its diameter to be varied. The initial diameter of the ring is greater than that of the cylinder. The ring will therefore exert a pressure against the cylinder barrel, which should be sufficient to keep the piston steam-tight.

To prevent steam from leaking through the split of the ring, two or more rings are placed side by side and close together in such a manner that the splits of any two rings are not in the same line. The thickness of the ring may be uniform, or it may be thickest in the middle and thinnest at the ends where it is split.

For small pistons one set of rings may be sufficient, but with larger pistons two sets of rings are employed, the inside ring or rings pressing against the outside ones. The elasticity of spring rings is often increased by hammering.

*Davey, Paxman, and Co.’s Pistons.*—Figs. 229 and 230 show a piston designed by this firm for their horizontal engines.
the hollow piston, the latter is closed by a cast-iron disc, J R, the junk ring, which is fastened to P by six steel studs, S t, as shown.

The piston rod, P R, is of steel, and is fastened to the piston by tightening the nut up against the junk ring. This nut fits into a hollow in the cylinder-cover in order to diminish the clearance; the nut is prevented from working loose by a pin, as shown. The spring rings S 1 are of cast iron, and their wearing surfaces are case-hardened. The inner spring ring, S 2, is of steel.

Part of the projections at the two ends of the piston are cut away for the steam-ports, so as to allow of an easy admission of steam.

In the low-pressure piston, the spring rings, S 1, are made of cast iron, but in the high-pressure piston it is preferred to make these rings of phosphor bronze, to prevent scarring in case lubrication should fail. The spring S 3 is a spiral steel spring with two turns.

Piston Speed.—In actual engines the velocity of the crank-pin is controlled by the flywheel, and may be assumed to be uniform. The motion of the piston can therefore be determined; but the simplest case will be that where the connecting rod is very long compared with the length, r, of the crank. This particular case is illustrated in Fig. 233, where C P is the crank-pin moving in a circle, with O as centre and r as radius.

Assuming the crankshaft to make n revolutions per second, the velocity of the crank-pin will be $2\pi r n$ feet per second. At the moment the crank has turned through an angle $\phi$, reckoned from the dead-point $a$, the piston must have traversed the distance $af = x$, and it is evident that we must have

$$x = r (1 - \cos \phi) \quad \ldots \quad (176)$$

The velocity of the piston will be

$$2\pi r n \times \sin \phi \text{ feet per second} \quad \ldots \quad (177)$$

The velocity of the piston, therefore, is not uniform, but increases from zero to a maximum during the first
half part of the stroke, and then diminishes until it becomes zero again at the end of the stroke.

The acceleration or rate of change of piston velocity will be

\[ 4 \pi^2 n^2 r \times \cos \phi \text{ feet per second per second} \]  

and if by M we denote the mass in pounds of the piston, piston rod, cross-head, and connecting rod, the pressure on the crank-pin due to the variable motion of the piston will be

\[ \frac{M}{32.187} \times 4 \pi^2 n^2 r \times \cos \phi \text{ pounds} \]  

This pressure is maximum for \( \phi = 0 \) and \( \phi = 180 \), and is zero at mid-stroke. As the direction of the pressure is positive between \( \phi = 0 \) and \( \phi = 90 \), and negative between \( \phi = 90 \) and \( \phi = 180 \), it will diminish the crank effort during the first half part of the stroke and increase it during the latter part of the stroke. In engines working with expansion, the inertia of the moving masses will therefore have the effect of making the crank effort more uniform.

Engineers understand by the piston speed the mean velocity of the piston in feet per minute. The piston speed will therefore be \( 2 l n \) feet, where \( l \) is the stroke in feet and \( n \) the number of revolutions per minute; it varies with the different classes of engines, and for the same class it increases with the size of the engine. The following formula, which is due to Professor G. Schmidt, gives a fair idea of the relation between the piston speed, \( C \), and the size of engines.

\[ C = a \left( 10 + \sqrt{AHP} \right) \text{ feet per minute} \]  

The values of \( a \) are given in the following table:

<table>
<thead>
<tr>
<th>Value of ( a )</th>
<th>Speed of piston may be considered as</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.84</td>
<td>Very slow</td>
</tr>
<tr>
<td>18.78</td>
<td>Slow</td>
</tr>
<tr>
<td>17.72</td>
<td>Normal</td>
</tr>
<tr>
<td>21.65</td>
<td>High</td>
</tr>
<tr>
<td>25.59-39.37</td>
<td>Very high</td>
</tr>
</tbody>
</table>

The Piston Rod is subjected to compression while the piston moves towards the crank, and to tension during the return stroke. As the length of the rod is great compared with its diameter, it is liable to bend if not sufficiently strong. The diameter, \( d \), of the piston rod
should therefore be calculated with due consideration to its length. Using the same letters of reference as on page 203 we must have

\[ \frac{d}{D} = K \sqrt[3]{\frac{l}{D}} \sqrt{\frac{\sigma_a}{E}} \]  (181)

where \( K \) is a constant whose value depends upon the material of the rod and the factor of safety. The latter varies immensely in practice, but if the rod is made of steel, we may take, according to Reuleaux, the average value of \( K \) as 0.08, and formula (181) will therefore be
\[ d = 0.03 \sqrt[4]{\frac{L}{D}} \sqrt{p_e} \quad \ldots \quad (182) \]

where \( p_e \) is the maximum effective pressure on the piston in pounds per square inch.

It is evident that every part of the rod must be able to withstand the tensile stress to which it is subjected, and for that reason the sectional area of the rod must nowhere be smaller than \( \frac{\pi d^2}{4} \), where \( d \) can be found by
\[ d = \frac{57 + 0.5 p_e}{1,000} \quad \ldots \quad (183) \]

This formula is also due to Reuleaux.

**The Cross Head.**

The object of the cross-head is to connect the piston rod with the connecting rod; the linear reciprocating motion of the former is thereby transformed into that of rotation. The piston rod is rigidly fastened to the cross-head by a cotter, and in order to prevent the rod being bent, the motion of the cross-head is guided by making it slide between the parallel surfaces of the guide blades.

The connection between cross-head and connecting rod is made through the cross-head pin, which is usually fastened to the cross-head and fits into a hole in the connecting rod end. The connecting rod will thus oscillate on this pin.

Single-acting engines have neither piston rod nor cross-head, the connecting rod being attached direct to the piston by a pin on which it oscillates.

In engines with oscillating cylinders, the cross-head as well as the connecting rod are dispensed with, the piston rod being connected direct to the crank-pin. **Paxman’s Cross-heads.**—1. The cross-head shown in Figs. 234 and 235, is forged out of one piece of steel. The piston rod, P R, fits into a hole in the socket, S O, and is fastened by a steel cotter, C O, which is further secured by a pin, as shown. The other end of the cross-head is forked, and embraces the connecting rod. The cross-head pin, C H P, is fixed by a pin, p, and ends in two journals, see Fig. 236, which fit into holes in the slide blocks, S B.

Figs. 237 and 238 show the guide blades, G B, for this cross-head. The slide blocks slide in grooves cut in the guide blades. The height of a slide block is h, and its width is w. The guides are fixed by bolts to the foundation-frame; each bolt has a shoulder, which bears against the bottom guide blade, the latter will therefore not get loose when the nut, which keeps the top guide blade in position, is unscrewed. Distance-pieces, D P, are inserted to keep the guides the right distance apart. The guide blades, as well as the slide blocks are made of hard cast iron.

2. The cross-head shown in Figs. 239, 240, and 241 is made of cast steel, and is designed for girder engines. The piston rod, P R, is cottered to the socket, S O. The forked end of the cross-head embraces the connecting rod, and the cross-head pin, C H P, is held by the two caps,
Cp, the grip of which can be adjusted by the bolts, A B. The slide blocks, S B, are made of hard cast iron, and are fixed to the cross-head by bolts as shown. The position of the slide blocks is adjusted by screws, Sc. The guide blades are replaced by the bored-out upper and under surfaces of the girder trunk. On each side of the cross-head is an oil-box, as shown, from which the oil is sucked up by a wig and made to drop on the connecting rod end; and through a hole in the latter the oil is carried to the cross-head pin. Which of the two oil-boxes is to be used depends upon whether the girder is left-handed or right-handed.

The Robey Cross-head for girder engines is illustrated in Figs. 244 and 245. To facilitate the removal of the piston rod, P R, from the cross-head, the former is screwed and furnished with a large nut, as shown in Fig. 245. By tightening the nut the rod is easily withdrawn, when the cotter, C O, is taken out. The cross-

3. The cross-head, Figs. 242 and 243, is designed for slipper slides. The piston rod, P R, the cross-head, C H, and slide block, S B, are forged from one piece of steel. The connecting rod end is forked and embraces the cross-head. The cross-head pin, C H P, is firmly shrunk into the eyes of the connecting rod end, and oscillates in the adjustable gunmetal steps, St, which head itself is made of malleable iron, the box end, B, receives the connecting rod end, which it embraces. The slide blocks, S B, are of hard cast iron, and are fastened by screws to the cross-head. Should it be necessary to adjust the slide blocks, Messrs. Robey and Co. prefer to insert thin metal liners between the blocks and the cross-head body, instead of employing adjusting
screws. The cross-head pin, which is embraced by the connecting rod end, is prevented from working loose in the sides of the cross-head by the following arrangement:

The holes in both sides of the cross-head, see Fig. 244, are bored conically, and the pin is correspondingly tapered under the head. A key, K, which fits into a slot, prevents the pin from turning. The other end of the pin is fitted with a loose conical spring ring, S R, which is split to allow it to be compressed. On tightening the nuts on the outer end of the pin, both cones are pressed well home, and the centrality and tightness of the pin is secured.

**The Connecting Rod.**

The motion of the connecting rod is that of rotation in a plane at right angles to the crankshaft. Like the piston rod, the connecting rod is alternately subjected to compression and tension, and its diameter must therefore be calculated with due regard to its length. If by P we denote the force transmitted through the cross-head to the connecting rod, then Q = P × sec β, see Fig. 246, is the force by which the rod is compressed. P is partly due to the total effective steam pressure, P₁, on the piston, and partly to the inertia of the moving masses, which force, P₂, is given in formula (179). During the earlier part of the stroke, until the piston speed has reached its maximum velocity, P is equal to P₁ − P₂, and during the remainder of the stroke we have P = P₁ + P₂. Let now L denote the length of the connecting rod in inches, Q the maximum P × sec β, and f the factor of safety, then the diameter of steel rods must be

\[ d = 0.0162 \times \sqrt{\frac{f}{L}} \times \sqrt{\frac{Q}{L}} \text{ inches} \quad (184) \]

Besides the compressive stress, the connecting rod is also subjected to bending action at right angles to the rod, due to the rotary motion of its particles. The curve A, Fig. 246, is that described by a particle, a, in the middle of the rod, and it will be seen that when the rod is nearly at right angles to the crank, the deviating force will be at right angles to the rod. This bending action may be considerable in high-speed engines.

It is, however, usual to take Q as maximum P₁ sec β only, and to allow for the straining actions due to the inertia of the moving masses in the safety factor. In practice, the safety factor varies considerably, but on an average we may take it as 25, and the diameter of the rod will then be

\[ d = 0.0363 \times \sqrt{\frac{Q}{L}} \sqrt{\frac{L}{f}} \text{ inches} \quad (185) \]

The connecting rod is made thicker at the centre, where the bending moment is greatest. The ends of the rod contain bearings for the crank-pin and cross-head pin, except when the cross-head end is forked in which case the cross-head pin is fastened to the connecting rod end, and finds a bearing in the cross-head, as in Figs. 242 and 243.

**Robey's Connecting Rod with Box Ends.**—The connecting rod, shown in Figs. 247-252, is forged from steel in one piece with the crank-pin end, Figs. 247 and 248. The cross-head end is coterred to the rod, as shown in Figs. 249 and 250. The brasses or gun-metal steps, S, at the crank-pin end are adjusted by a screw and wedge, C O, and embrace the crank-pin, C P. By this adjustment, the connecting rod will be lengthened when the brasses are brought together to compensate the wear. Fig. 251 shows the shape of the cross-head pin, which is embraced by the connecting rod end, is prevented from working loose in the sides of the cross-head by the following arrangement:

The holes in both sides of the cross-head, see Fig. 244, are bored conically, and the pin is correspondingly tapered under the head. A key, K, which fits into a slot, prevents the pin from turning. The other end of the pin is fitted with a loose conical spring ring, S R, which is split to allow it to be compressed. On tightening the nuts on the outer end of the pin, both cones are pressed well home, and the centrality and tightness of the pin is secured.

**The Connecting Rod.**

The motion of the connecting rod is that of rotation in a plane at right angles to the crankshaft. Like the piston rod, the connecting rod is alternately subjected to compression and tension, and its diameter must therefore be calculated with due regard to its length. If by P we denote the force transmitted through the cross-head to the connecting rod, then Q = P × sec β, see Fig. 246, is the force by which the rod is compressed. P is partly due to the total effective steam pressure, P₁, on the piston, and partly to the inertia of the moving masses, which force, P₂, is given in formula (179). During the earlier part of the stroke, until the piston speed has reached its maximum velocity, P is equal to P₁ − P₂, and during the remainder of the stroke we have P = P₁ + P₂. Let now L denote the length of the connecting rod in inches, Q the maximum P × sec β, and f the factor of safety, then the diameter of steel rods must be

\[ d = 0.0162 \times \sqrt{\frac{f}{L}} \times \sqrt{\frac{Q}{L}} \text{ inches} \quad (184) \]

Besides the compressive stress, the connecting rod is also subjected to bending action at right angles to the rod, due to the rotary motion of its particles. The curve A, Fig. 246, is that described by a particle, a, in the middle of the rod, and it will be seen that when the rod is nearly at right angles to the crank, the deviating force will be at right angles to the rod. This bending action may be considerable in high-speed engines.

It is, however, usual to take Q as maximum P₁ sec β only, and to allow for the straining actions due to the inertia of the moving masses in the safety factor. In practice, the safety factor varies considerably, but on an average we may take it as 25, and the diameter of the rod will then be

\[ d = 0.0363 \times \sqrt{\frac{Q}{L}} \sqrt{\frac{L}{f}} \text{ inches} \quad (185) \]

The connecting rod is made thicker at the centre, where the bending moment is greatest. The ends of the rod contain bearings for the crank-pin and cross-head pin, except when the cross-head end is forked in which case the cross-head pin is fastened to the connecting rod end, and finds a bearing in the cross-head, as in Figs. 242 and 243.

**Robey's Connecting Rod with Box Ends.**—The connecting rod, shown in Figs. 247-252, is forged from steel in one piece with the crank-pin end, Figs. 247 and 248. The cross-head end is coterred to the rod, as shown in Figs. 249 and 250. The brasses or gun-metal steps, S, at the crank-pin end are adjusted by a screw and wedge, C O, and embrace the crank-pin, C P. By this adjustment, the connecting rod will be lengthened when the brasses are brought together to compensate the wear. Fig. 251 shows the shape of the connecting rod; they are kept in position by a cap (not shown) screwed on the crank-pin. The adjustment of the steps at the cross-head end is done by tightening up the cotter, whereby the connecting rod, C R, will be pushed further into the socket, S O, and the box, B, and will thus be shortened. The adjustments at the two ends of the connecting rod will therefore compensate each other, so that the rod remains always the same length. Fig. 252 is an end view of Fig. 250. The diameter of the connecting rod at the middle is 5½in. All parts, except the brasses and the lubricator, L, are made of steel.

**Paxman's Connecting Rod with Strap Ends.—(a)** Both ends of the connecting rod, C R, Figs. 253-256, are made flat to receive straps, S, which hold the steps, S t. The straps are bolted to the connecting rod ends as shown, and the steps are adjusted by tightening the wedges, C O. The connecting rod is 5ft. between centres of crank-pin and cross-head pin, and its diameter at the centre is 2½in.

(b) The crank-pin end of the connecting rod, Figs. 257 and 258, is strapped like the one just described. The cross-head end, Figs. 259 and 260, is in one solid
piece with the rod, a hole being cut out to receive the steps, which are adjusted by tightening the wedge, CO.

The length of this rod is 10ft. between centres of C'P and CHP, the diameter at the centre being 4½in.
The material used for all parts of these two connecting rods is steel, except for the steps.

Connecting Rod Ends with Cotter and Gib.—In Figs. 261-264, are shown connecting rod ends with
straps fastened to the rod by cotters, C O, and gibs, G b. The rod is only 2ft. 2in. between centres, and its largest diameter is 1\(\frac{1}{8}\)in.

**Marine Connecting Rod End.** The crank-pin end, Figs. 265 and 266, is formed of two steps, St, which are held together by the two adjusting bolts, A B. The cap, C p, is of steel, and the rod is forged in one piece from steel or wrought iron; the cross-head end is forked, and a steel cross-head pin, C H P, is firmly shrunk into the eyes. O B is an oil-box, the oil being carried through tube, O T, to the crank-pin, C P. Fig. 267 is an end view of the crank-pin end. This connecting rod is designed for the Windsor high-speed engine.

**The Crankshaft.—The Bearings.**

The energy exerted by the crank effort is transmitted through the crankshaft in order to drive the machinery arms and are afterwards riveted; their dimensions are 7\(\frac{1}{4}\)in. long by 6in. diameter.

The shaft, which is of steel, is supported by two bearings, and the journals, J l, are 13in. long by 8\(\frac{1}{4}\)in. diameter. In the middle, where the flywheel is fixed, the diameter of the shaft is 11\(\frac{1}{2}\)in.; the drawing shows the section of this part of the shaft with the key-way for fixing the flywheel.

The two lines a, b, are centre lines of the girder heads. The positions of the eccentric are marked by crossed lines, and the letters H P S, A E G, and L P S refer to the eccentrics for the high-pressure slide-valve, automatic expansion gear, and low-pressure slide-valve respectively.

End cranks are often made in the form of flat cylindrical discs, which are shrunk on the shaft, and thus have the advantage of being balanced.

**Cranked Shafts.**—(a) Figs. 269 and 270 are drawings of the shaft of the Paxman 40 nominal H.P. horizontal compound engine with cranks at right angles. The cranks and shaft are forged from one piece of steel, and the gaps between the arms are slotted out of the solid forging. The crank journals, C P, are 5in. long by 6in. diameter; the crank arms are 12in. long, and the stroke of the engine is therefore 2ft. The width of an arm, measured parallel to the shaft, is 4\(\frac{1}{4}\)in.; and the thickness, at right angles to the shaft, is 6\(\frac{1}{2}\)in.

The diameter of the shaft is 6in., and its length is 9ft. 2in., there being 3ft. 6in. between left-hand end of shaft and centre line of high-pressure crank, 2ft. 7in. between centre lines of cranks, and 3ft. 1in. between centre line of low-pressure crank and other end of shaft. The shaft is supported by three bearings, the journals being J P, J J (both 8\(\frac{1}{4}\)in. long), and J P, the length of...
which is 11in.; the diameters of all three bearings are the same as that of the shaft.

The eccentric for the low-pressure slide-valve is between H P Cr and J 1.

(6) The cranked shaft of the 25 nominal H.P. Windsor compound engine is illustrated in Figs. 271 and 272. The shaft and cranks are forged in one from steel, and the cranks are afterwards slotted. The shaft is 5in. in diameter; it is 3ft. 5in. between left-hand end and centre of high-pressure crank, 2ft. 4in. between centres of cranks, and 2ft. 7in. between centre of low-pressure crank and other end. The crank journals are 5in. in diameter by 7\frac{1}{2}in. long, and the arms are 6in. thick and 3in. wide, the latter dimensions being estimated parallel to the shaft.
The shaft is supported by three bearings; the journals, JP and JP', are 12in. long by 5in. in diameter, and the centre journal, JP', is 74in. long by 5in. diameter. The eccentrics are lettered as on Fig. 268, and G W is the position of wheel for driving governor.

_Bearings._—The function of the main bearings of the engine is to furnish the reactions which are required however, vary during one revolution as well as with the load, and the tensions of the belts increase with the load. For these reasons the bearings must be designed so as to allow of adjustment in more than one direction.

The main bearing of the Robey compound girder engine is illustrated in Figs. 273, 274, and 275. The

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For balancing the forces acting on the crankshaft. These forces are partly the weights of the shaft, pulleys, flywheels, and other masses carried by the shaft, and partly pressures on the cranks and tensions of belts. If the direction of the resultant of these forces remained the same, then an adjustment of the bearings in that direction would be sufficient to compensate for wear. The directions and magnitudes of the crank pressures, cast-iron foundation-plate, FF, has four feet, which are planed underneath and fastened to the foundation by four bolts, FB. The foundation-plate carries the plunger block or pedestal, Pd, which is cast in one with the girder, G. The bearing itself has four cast-iron steps, St, lined with anti-friction metal, M. Externally the steps are cylindrical where they fit the gap in the plunger block; but the lateral steps are
By comparing the latter expression with (186), it will be seen that the length of journals, working under ordinary conditions, may be increased less rapidly with the pressure and the speed of rotation than journals which fit accurately in their bearings.

**Overhung Journals.**—The diameter of a journal, which is supported at one end only, such as the crank-pin, Fig. 268, and subjected to a pressure, \( P \), uniformly distributed over its length, will be

\[
d = \sqrt{\frac{16}{\pi S}} \sqrt{\frac{l}{d}} \sqrt{\frac{P}{n}}
\]

where \( S \) is the greatest stress to be allowed in the material. If the journal be made of steel, \( S \) may be taken as 14,000 lb. per square inch, and

\[
d = 0.019 \sqrt{\frac{l}{d}} \sqrt{\frac{P}{n}} \text{ inches} \quad \ldots \quad (188)
\]

and by eliminating \( l \) between (187) and (188)

\[
d = 0.001719 \sqrt{\frac{P}{n}} \sqrt{\frac{P}{n}} \text{ inches} \quad \ldots \quad (189)
\]

Dividing (187) by (189), we have

\[
\frac{l}{d} = 0.142 \sqrt{\frac{P}{n}} \quad \ldots \quad (190)
\]

**Neck Journals.**—For journals supported at both ends and only subjected to a pressure, \( P \), uniformly distributed over the length of the journal, the diameter will be

\[
d = \sqrt{\frac{1.27}{S}} \sqrt{\frac{l}{d}} \sqrt{\frac{P}{n}} \text{ inches},
\]

and if we take \( S \) as 14,000 for steel

\[
d = 0.00932 \sqrt{\frac{P}{n}} \sqrt{\frac{P}{n}} \text{ inches} \quad \ldots \quad (191)
\]

Eliminating \( l \) between (187) and (191)

\[
d = 0.00452 \sqrt{\frac{P}{n}} \sqrt{\frac{P}{n}} \text{ inches} \quad \ldots \quad (192)
\]

and by dividing (187) by (192)

\[
\frac{l}{d} = 226 \sqrt{\frac{P}{n}} \quad \ldots \quad (193)
\]

The diameter of a cross-head pin may be determined by (192), but as the connecting rod only oscillates on the pin, the heat produced will be less than on an overhung crank-pin subjected to the same pressure. The length of the cross-head pin need not therefore be so long as the corresponding overhung crank-pin.

The two connecting rods, Figs. 247-252 and Figs. 257-260, show that the ratio of the length of cross-head pin to the length of overhung crank-pin may be taken as 0.72; taking this ratio for granted, we have for cross-head pins

\[
\frac{l}{d} = 0.163 \sqrt{\frac{P}{n}} \quad \ldots \quad (194)
\]

The crank-pins of the cranked shafts, Figs. 269 and 271, are partly subjected to the pressure, \( P \), transmitted through the connecting rod, and partly to a force, \( P \), which the journal has to transmit from the one crank-arm to the other. Let the length of the
DETAILS OF STEAM ENGINES.

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Journal be \( l \), then the bending moment due to \( P \) will be \( M_b = \frac{P l}{12} \) and that due to \( P_i \) will be \( M_{b1} = \frac{P_i l}{12} \).

The resultant bending moment will be

\[
M_r = l \sqrt{\frac{P^2}{144} + \frac{P_i^2}{32}}
\]

The diameter of the journal will be

\[
d = \sqrt{\frac{32}{\pi} M_r} \ldots \ldots (195)
\]

As \( P \) and \( P_i \) vary with the relative position of the crank and the connecting rod, the maximum value of \( M_r \) must be taken in calculating the diameter. The length of the journal may be taken from (187).

**Strength of Shafts and of Shaft Journals.**—Shafts are usually subjected to combined torsion and bending. If the shaft at any transverse section be subjected to a bending moment, \( M_b \), and to a twisting moment, \( M_t \), then the stress in the material at that section will be as if the shaft were subjected to a bending moment, \( M_r \), which, according to Reuleaux, may be taken as

\[
M_r = 0.975 \ M_b + 0.25 \ M_t \ldots \ldots (196)
\]

when \( M_b > M_t \), and as

\[
M_r = 0.625 \ M_b + 0.6 \ M_t \ldots \ldots (197)
\]

when \( M_t > M_b \). The diameter of the shaft at this particular section should not be less than

\[
d = 0.34 \sqrt{\frac{M_r}{S}} \text{ inches} \ldots \ldots (199)
\]

where \( S \) is, as before, the maximum stress to be allowed in the material.

The effect of torsion is to twist the shaft a certain angle, the magnitude of which should not be more than \( \frac{1}{270} \) of a degree per foot run. For this reason, the diameter of a steel shaft at such sections which are subjected to torsion should not be less than

\[
d = 0.34 \sqrt{\frac{M_t}{S}} \text{ inches} \ldots \ldots (199)
\]

If the number of horse-power transmitted by the shaft be \( N \), and the speed of rotation be \( n \), then

\[
M = \frac{12 \times 33,000}{2 \pi} \frac{N}{n} = 63,000 \frac{N}{n} \text{ pounds and inches.}
\]

Inserting this value for \( M_r \) in (199) we obtain

\[
d = 4.75 \sqrt{\frac{N}{n}} \text{ inches} \ldots \ldots (200)
\]

**Example.**—Fig. 276 represents the armature and shaft of a dynamo machine, which is coupled direct to the shaft of the driving engine. The weight of the armature and shaft is \( W \), and \( C \) is its centre of gravity. The shaft has two bearings, \( A \) and \( B \); and \( R_1 \) and \( R_2 \) are the reactions due to these bearings.

The equilibrium of \( W, R_1, \) and \( R_2 \) requires

\[
R_1 = W \frac{a_2}{a_1 + a_2} \text{ and } R_2 = W \frac{a_1}{a_1 + a_2} \ldots \ldots (201)
\]

The maximum bending moment to which the shaft is subjected, will be

\[
M_b = R_2 \times a_2 = W \frac{a_1}{a_1 + a_2} \]

The twisting moment will be

\[
M_t = 63,000 \frac{N}{n} \]

Take \( W = 2,600 \text{lb. }; N = 70; n = 500; a_1 = 52 \text{in.}, \) and \( a_2 = 60 \text{in.}, \) then we shall have

\[
R_1 = 1,130 \text{lb.}; R_2 = 1,470 \text{lb.}; M_b = 58,800; \text{ and } M_t = 8,820. \text{ As } M_b \text{ is greater than } M_t \text{ we have}
\]

\[
M_b = 59,535 \text{ pounds and inches.}
\]

Formula (198) gives the diameter of the shaft

\[
d = 3.51 \text{in.}
\]

If the shaft had only to withstand torsion, its diameter should be determined by (200), and would be \( d = 3 \text{in.} \)

The greater value, 3.51in., must, of course, be taken.

If a key-way is to be cut into the shaft, having a radial depth of, say, \( 3 \text{in.} \), then the diameter of the shaft should be 4.5 in.

**Journal B.**—This journal is subjected to a twisting moment, \( M_t = 8,820 \text{ and to a bending moment, } M_b = \frac{1}{4} R_2 l_b \), where \( l_b \) is the length of the journal. If Von Reiche's rule is to be followed, the length of the journal should be

\[
l_b = 0.00102 \sqrt{1,470} \times \sqrt{500^2} = 4.75 \text{in.}
\]

The bending moment would then be

\[
M_b = \frac{1}{4} \times 1,470 \times 4.75 = 769.
\]

As \( M_t > M_b \) the diameter of the journal should be

\[
d = 4.75 \sqrt{\frac{70}{500}} = 3 \text{in.}
\]

We may, however, make the length of this journal greater than that given by Von Reiche's rule, without producing an excessive stress in the material. Suppose we take \( l_b = 2.5 \text{ diameters, then in our case } l_b \text{ would be equal to } 7.5 \text{in.} \text{ The bending moment, } M_b, \text{ would be } \frac{1}{4} \times 1,470 \times 7.5 = 1,378.
\]

The greatest stress, \( S \), in the material would be found by the following

\[
d = 4.75 \sqrt{\frac{0.625 \times 1,378 + 0.6 \times 8,820}{3}}
\]

which gives \( S = 2,333 \text{lb. per square inch only.} \)
Journal A.—This journal is subjected to bending only. Its diameter, \( d_0 \), and length, \( l_0 \), may be determined by (189) and (190).

\[
\frac{l_0}{d_0} = \frac{0.00719 \times 1.130 \times \sqrt{500}}{\sqrt{500}} = \text{say 1} \frac{3}{4} \text{in.}
\]

\[
l_0 = 3\frac{1}{2} \text{in.}
\]

Should it be considered advisable to make \( l_0 \) longer than the value given above, then we must make

\[
d_1 = \frac{16}{\pi} \times R, l_1 = 0.0714 \times \sqrt{R_1 l_1} \text{ inches.}
\]

In practice \( l_0 \) is often made excessively long, for instance, equal to \( l_0 \), which in our case would require

\[
d_1 = 0.0714 \times \sqrt{1.130 \times 7.5} = \text{say, } 1\frac{1}{2} \text{in.}
\]

![Fig. 277.](image1)
![Fig. 278.](image2)

The work consumed by friction would thus be increased by

\[
\frac{1.5}{1.25} = 1.2.
\]

The diameter, \( d_0 \), will also be found to be greater than the value given above—it is usually between \( d_0 \) and \( 0.75 \times d_0 \); the work consumed by friction would be increased by 2.4 and 1.8 respectively. The greatest stress in the material will be 2,323 lb. and 5,503 lb. per square inch respectively, both of which are very low.

Eccentrics.—An eccentric is a crank, but the radius of the crank-pin is greater than the crank arm, plus the radius of the crankshaft. The crank-pin is made in the form of a sheave, with a hole which fits on the shaft. The distance between the centre of this hole and the centre of the sheave is the length of the crank arm, and is called the eccentricity. The sheave is embraced by two straps, to one of which a rod—the eccentric rod—is fixed. This rod with the straps constitute a connecting rod. The other end of the eccentric rod is connected to the piece of mechanism whose motion is to be reciprocating, be it a pump or a slide-valve. As the friction between the straps and the sheave of an eccentric is greater than between an ordinary crank-pin and a connecting rod, eccentrics are only used when the crank arm is required to be small.

(a) Figs. 277-280 illustrate a common eccentric. The sheave, sh, is made of cast iron; \( C' \) is the centre of the sheave, and \( C' \) the centre of the hole which fits on the crankshaft, \( C S \). The eccentricity is the distance \( C'C \). The circumferential surface of the sheave forms a groove into which the two gunmetal straps, Sp, fit. The straps are connected by two bolts, B, but do not meet metal to metal, for the two open spaces, \( O' \) and \( O' \), are filled with thin brass liners, which are removed one by one when it becomes necessary to compensate for wear.

The eccentric rod, E R, is fixed to the one strap by a cotter. With this kind of eccentric, the rod is usually screwed into the sheave and held in position by a binding nut. Oh is an oil-hole.

(b) The cast-iron sheave of the eccentric, Fig. 281, is made in two parts, which are connected by studs and cotters. By this arrangement the sheave can easily be removed from the shaft. The circumferential surface of the sheave is cylindrical, and the two gunmetal straps have square cornered grooves, into which the sheave fits. The straps are connected by bolts, B. O is the centre of the crankshaft, and the line C P indicates the position of the crank relative to the eccentric. E R is the flat eccentric rod which is fastened to the one strap by bolts, B'. L is the lubricator.

The Condenser.

The exhaust steam of condensing engines is let into a closed cast-iron box, the condenser, where it meets with
cold water, and thus will be partially condensed. The steam-water, together with the vapour and air, are pumped out of the condenser into the hot-well by the air pump. As the temperature of the steam-water will always be less than 212 deg. F., it follows that the pressure in the condenser will be below that of the atmosphere.

**Injection Condenser.**—The condensing water may be introduced into the condenser as a spray or jet, and by coming into direct contact with the steam it will condense the latter. The air pump must remove the condensing water as well as the steam-water and air from the condensing chamber.

Each valve consists of a flat indiarubber ring, I R, which, when shut, rests on a perforated brass grid, Gr. The opening of a valve is limited by a cup-shaped guard, Gd. The pump piston, P P, is made of brass with cast-iron and steel spring rings; the piston rod, P R, is of steel, and is the continuation of the tail rod of the low-pressure steam piston. The stroke of the pump is 24 in., and the volume swept by the piston in one stroke is about one-ninth of the volume of the condensing chamber.

The connection between a similar condenser and the low-pressure cylinder of a girder compound condensing engine is shown in Figs. 285 and 286. L P C is the low-pressure cylinder, C the condenser, K P the exhaust-pipe, P R the piston rod of the air pump, I V the injection-valve, F F the foundation frame, and G T the girder head.

In Fig. 287 is shown an injection condenser made by Messrs. Musgrave and Sons, of Bolton. The condensing water enters at the top through an opening, W I, whereas the exhaust steam enters at the side through E S I. The jet of condensing water rushes through a set of nozzles, N I, N o, N s, and N t, inducing the steam and the air to follow, the steam at the same time being

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**DETAILS OF STEAM ENGINES.**

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condensed. The rotary air pump at the bottom discharges the water through the outlet-pipe, O P. other by tooth-wheels fastened on the end of the cylinder spindles.

Instead of a piston, the air pump has two tooth-wheel-like cylinders, the teeth of which fit accurately into the corresponding gaps. The one cylinder is driven by the engine or by a separate motor, and then drives the
discharge into the condenser. The quantity of condensing water required for a given size of engine can be calculated as follows:

Let the quantity of steam, in pounds, to be condensed, be denoted by $S$
Let the ratio of quantity of condensing water to that of steam to be condensed, be denoted by $\gamma$
Let the temperature of condensing water in degrees of Fahrenheit be denoted by $t''$
Let the temperature of condenser in degrees of Fahrenheit be denoted by $t'$
Let the pressure, in pounds per square inch, in the condenser be denoted by $p$

We may take the heat contained in 1 lb. of steam, reckoned from 32 deg. F., as 1,180 B.H.U., and we shall therefore have

$$1,180 \times S + \gamma S \times (t'' - 32) = S(1 + \gamma) \times (t' - 32),$$

and consequently

$$\gamma = \frac{1212 - t'}{t' - t''} \quad \ldots \quad (202)$$

Example 1.—Take $t' = 60$, $p = 2$, therefore $t = 126.3$, and we shall have $\gamma = 16.5$.

Example 2.—For $p = 1$, $t' = 102$ and $t'' = 60$, we find $\gamma = 26.5$.

Which of the two, non-condensing or condensing engines, will be the cheapest, depends upon the ratio of the local prices of fuel and water, and may be determined as follows:
Let fuel, in pounds, per I.H.P. hour for a non-condensing engine, be denoted by \( B_n \).

Let fuel, in pounds, per I.H.P. hour for a condensing engine, be denoted by \( B_c \).

Let steam, in pounds, per I.H.P. hour for a non-condensing engine, be denoted by \( S_n \).

Let steam, in pounds, per I.H.P. hour for a condensing engine, be denoted by \( S_c \).

Let the price of 1 lb. of fuel be denoted by \( P_f \).

Let the price of 1 lb. of water be denoted by \( P_w \).

For the same boiler and steam-pipe arrangement we must have

\[
\frac{S_n}{B_n} = \frac{S_c}{B_c} = \frac{S}{B} \quad \text{and consequently} \quad \frac{B_n}{B_c} = \frac{S_n}{S_c} = \delta.
\]

The cost of one I.H.P. hour for a non-condensing engine will therefore be

\[ S_n \times P_f + B_n \times P_c \]

and for a condensing engine

\[ S_c(1 + \gamma) \times P_f + B_c \times P_c. \]

We must therefore have

\[ S_n \times P_f + B_n \times P_c = S_c(1 + \gamma) \times P_f + B_c \times P_c. \quad (203) \]

according to whether the non-condensing engine is less, equally or more economical than the condensing engine. From (203) we obtain

\[
\frac{P_f}{P_w} < \frac{B}{B} \times \frac{1 + \gamma - \delta}{\delta - 1} \quad \ldots \quad (204)
\]

Example.—If the fuel be good coal and the boiler be an economical one, we may take \( \frac{S}{B} = 8 \). For \( \gamma = 20 \), we shall probably have \( \delta = \frac{4}{3} \), and consequently the right-hand side of (204) will be 472.

In London we may take the price of coal as eighteen shillings per ton, and that of water from water works as ninepence per 1,000 gallons; in this case

\[
\frac{P_f}{P_w} = 107.
\]

It is therefore more economical to use a non-condensing engine in London, except on the river side.

Surface Condenser.—In some cases it may be preferable to keep the condensing water and the steam apart; the condensing chamber is then filled with a great number of thin tubes of small diameter, through which the condensing water is passed by means of a pump—the circulating pump. The condensation of the steam takes place on the cold surfaces of the tubes, and the air pump has only to remove the steam-water and the air which might have leaked into the condensing chamber.

A surface condenser, designed by Messrs. Musgrave and Sons, is shown in Fig. 288. It is a cast-iron cylinder divided into five compartments, A, B, C, D, and E, through which seven sets of tubes are passed.

![Fig. 288.](image)

Each set consists of a 1 in. gas-pipe, \( T_s \), screwed into the partition between A and B, and two brass tubes, \( T_1 \) and \( T_2 \), of which the first is 3 in. in diameter, and is screwed at the bottom into tube-plate, \( T_2 \), and is provided at the top with packing and gland; \( T_3 \), whose diameter is 2 in., is screwed at the top into the partition between B and C, and is shut at the bottom by a cap which also keeps it from touching \( T_2 \).

The exhaust steam enters compartment C by inlet \( S \), and is condensed while passing through the annular space between tubes \( T_1 \) and \( T_2 \), and drops as water into compartment E, from where it is removed by the air pump through outlet \( S \). To secure good drainage, the floor of E has a fall of \( \frac{1}{4} \) in. towards the outlet.

The condensing water enters the condenser through inlet \( C \), filling up compartment D, from where it passes through the lateral channel into A, then down through the gas-pipes, up again between \( T_2 \) and \( T_3 \), and at last leaves the condenser through outlet \( C \). By this circulation, the condensing water is much more effective than if forced straight through a number of tubes.

The condensing chamber is thus composed of the annular spaces between tubes \( T_1 \) and \( T_2 \), which offer a total cooling surface of 48 square feet to the steam.

Figs. 289 and 290 are plans of compartments C and E, and the position of the condensing water inlet is
shown by dotted lines. Fig. 291 is a plan of tube-plate \( T P \). Figs. 292 and 293 are elevation and plan through compartment \( D \).

The Governor.

Engines required for driving dynamo machinery must run at a constant speed of rotation, independent of the load. This condition is impossible to fulfil absolutely, but by proper design, the variation of speed can be kept within limits which will not effect the purpose for which the engine is designed. There are two distinct apparatus which act as speed regulators.

1. To obtain a uniform motion, the effort must be equal to the resistance. This cannot be obtained in a steam engine, but we can arrange that the energy exerted on the crank-pin during one revolution is equal to the energy consumed by the load during the same interval of time. This is the function of the Governor.

2. The angular velocity of the crankshaft should remain constant, notwithstanding the variation of the crank effort during a revolution. This is the function of the Flywheel.

The action of the governor is to diminish the quantity of steam let into the cylinder, should the speed of the engine increase, and to increase the quantity of steam should the speed of the engine fall. The principle of the governor is therefore an imperfect one, as it requires the speed of the engine to rise or fall in order to act.

The governor commonly used in steam engines is the so-called centrifugal governor, designed on the principle of the conical pendulum, Fig. 295. This consists of a pendulum attached to the vertical axe, \( A B \), by a horizontal pin, thus allowing the pendulum to turn in a plane through \( A B \). By rotating the axle round itself, the pendulum will fly out until it makes an angle, \( a \), with the axe, the magnitude of which depends upon the speed of rotation. Suppose the angular velocity of the axe is \( \omega \); then the pendulum will be in equilibrium when the deviating force is

\[
P = \frac{W}{g} \times \omega^2 \times r \text{ pounds} \quad (205)
\]

where \( W \) is the weight of the ball in pounds, the mass of the arm being neglected.

But it is evident that \( P \) is also equal to \( W \times \tan a \), and, consequently,

\[
\tan a = \frac{\omega^2 r}{g} = \frac{r}{h'}
\]
by which we obtain
\[ \omega = \sqrt{\frac{g}{h}} \ldots \ldots (206) \]

Watt’s Governor.—A diagram of this governor is shown in Fig. 296. It consists of two pendulums suspended in \( b \) and \( b \). A sleeve, \( e e \), which can slide on the axle, rises and falls with the balls, and thereby actuates the apparatus which controls the quantity of steam let into the cylinder. Let \( Q \) be the weight which has to be overcome in lifting the sleeve, and \( W \) the weight of each ball, then the moment of the deviating force with regard to \( b \) will be
\[ \frac{Q}{2} \cos \beta \times b c \times \sin (\alpha + \beta) + W \times b d \times \sin \alpha. \]

On the other hand, the deviating force, \( P \), at the centre of the ball must be
\[ P = \frac{W}{g} \omega^2 \times f d, \]
and its arm will be \( b d \times \cos \alpha \). The governor will, therefore, be in equilibrium in the position shown in the diagram if
\[ \frac{W}{g} \omega^2 \times f d \times b d \times \cos \alpha = \frac{Q}{2 \cos \beta} \times b c \times \sin (\alpha + \beta) + W \times b d \times \sin \alpha. \]

Let now \( l, L, h \), and \( K \) denote \( b c, b d, f d \times \cot \alpha \), and \( \tan \alpha + \tan \beta \) respectively, then we shall have
\[ \omega = \sqrt{\frac{g}{h}} \left( 1 + K \times \frac{Q + F}{L \times W} \right) \ldots \ldots (207) \]

This formula shows that the loaded governor must be run at a higher speed than the unloaded one.

Besides the weight, \( Q \), the governor will have to overcome friction between the parts of the controlling apparatus, be it a throttle-valve or a cut-off valve. Assuming that this friction, \( F \), is the same in both directions, then the load on the sleeve will be \( Q + F \) when rising, and \( Q - F \) when falling. The governor will therefore not act until the angular velocity has been increased to
\[ \omega_2 = \sqrt{\frac{g}{h}} \left( 1 + K \times \frac{Q + F}{L \times W} \right) \ldots \ldots (208) \]
or diminished to
\[ \omega_1 = \sqrt{\frac{g}{h}} \left( 1 + K \times \frac{Q - F}{L \times W} \right) \ldots \ldots (209) \]
The three formulæ (207), (208), and (209) give us
\[ \omega_2^2 - \omega_1^2 = \omega_2^2 - \omega_1^2 \ldots \ldots \ldots \ldots \ldots (210) \]
The governor will evidently be more sensitive for overcoming friction the smaller we can make
\[ \frac{\omega_2 - \omega_1}{\omega} = \eta. \ldots \ldots \ldots \ldots (211) \]
The angular velocity, \( \omega \), will be approximately equal to the mean of \( \omega_2 \) and \( \omega_1 \), so we shall have
\[ \omega = \frac{\omega_2 + \omega_1}{2} \ldots \ldots \ldots \ldots (212) \]
The three formulæ (210), (211), and (212) give us
\[ \eta = \frac{\omega_2^2 - \omega_1^2}{2} = \frac{F}{L \times W} \ldots \ldots \ldots (213) \]
The last formula clearly shows that a governor loaded with dead weight will be more sensitive for overcoming friction than the original Watt’s governor.

Porter’s Governor.—A governor of this class is shown in Fig. 297. The pedestal, \( P_1 \), which carries the governor is bolted on the foundation-frame of the engine. Pulley, \( P_1 \), is driven by belt, and its rotary motion is transmitted to the governor spindle, \( S_p \), by bevel wheels, \( B W_2 \) and \( B W_1 \). The governor is loaded with a dead weight, \( D W \), which is cast in one piece with the sleeve, \( S_1 \); and the two pendulums, \( A_1, B_1 \) and \( A_2, B_2 \), are suspended on one pin, \( p \), at the top of the spindle. The sleeve and the dead weight move up and down with the balls, and thereby turn valve arm, \( V A \), by means of lever \( L_{1b} \), which has a fulcrum at \( F_c \), and the vertical rod \( K \). \( D P \) is a dash-pot to prevent sudden jerks. The governor spindle has a bearing, \( P B \), and rotates within the brass tube, \( B T \).

The application of formula (213) on this governor is very simple; we have \( L = l \), and as angle \( \beta \) is approximately equal to angle \( \alpha \), \( K \) will be equal to unity, and therefore
\[ \eta = \frac{F}{W + Q} \ldots \ldots \ldots \ldots (214) \]

The sensitiveness of this governor to overcome friction would be increased by adding a weight, \( W \), to \( W + Q \), as we should then have \( \eta = \frac{F}{W + Q + w} \); but it is evident that \( w \) should be added to the dead weight, and not to the ball, as in the latter case, the total weight added to the governor would be \( 2 w \). The sensitiveness of the Porter governor thus depends more on the dead weight than on the balls, which can, therefore, be made small.
The governor illustrated in Fig. 297 is made by Messrs. Browett, Lindley, and Co., of Salford, and is applied by them to drive their Lindley-Rider automatic expansion gear.

of the governor depends, therefore, on the variation of \( h \) being small as compared with that of angle \( a \), and the pendulum, Fig. 295 is consequently more sensitive than that in Fig. 298.

In Fig. 299, the curve in which the centre of the governor ball moves is a parabola. As the centre of curvature lies in the normal to the curve, \( h \) must be the projection on the axle of that part of the normal which is situated between the centre of the ball and the axle. This projection is the same for all points in a parabola, and consequently we have a governor which is perfectly sensitive. As the ball is in equilibrium at any point of the curve, it follows that the parabola must be specially constructed for the speed at which the governor is to be run. Should, however, the load on the engine be diminished, the engine will begin to race, the consequence of which will be that the governor ball will not be in equilibrium at any point of

Stability of Governors.—Formule (206) and (207) require that \( h \) shall diminish when the angular velocity increases; this condition is satisfied when the governor pendulum is suspended, as in Figs. 295 and 298. The pendulum in these two cases will take up a definite position corresponding to the velocity, \( \omega \), at which it is turned round the axle, and will not be in equilibrium in any other position unless the velocity be changed. The governor is therefore said to be stable, but it is evident that it cannot keep the speed of the engine constant, as a new position of the pendulum requires the engine to run faster or slower. The sensitiveness
the parabola, but will fly out as far as the mechanism of the governor permits. The steam will thus be shut off, the engine will run slower, but the governor ball will not move until the speed has fallen below that corresponding to the parabola. At this moment the ball will suddenly fall as far as it can, and open for the steam. The engine will begin to race, the ball will fly out and shut off the steam, and so on. The result will be that the engine will run unsteadily.

The pendulum might be suspended as shown in Fig. 300. The peculiar feature of this arrangement is that there is a certain position of the pendulum where \( h \) is a maximum. This position is determined by

\[
\sin \alpha_2 = \frac{3}{\sqrt{\frac{e}{L}}} \quad (215)
\]

where \( L \) is the length of the pendulum arm.

The governor will therefore be stable as long as \( \alpha > \alpha_2 \), and will be unstable when \( \alpha < \alpha_2 \). In the position 3, corresponding to \( \alpha_2 \), the governor will behave like a parabolic governor. The pendulum must be prevented from falling below position 2 in order to avoid the unstable positions.

*Parabolic Governor.*—Fig. 301 shows a parabolic
of rotation by $\alpha$, then the governor will be in equilibrium when
\[ \frac{Q}{2} \frac{l \times \sin(\alpha + \beta)}{W} \tan \alpha = \frac{W}{g} \alpha \frac{h^2 \times \tan \alpha}{g} \]
and therefore
\[ \omega = \sqrt{\frac{g}{h} \left( 1 + \frac{Q}{W} \frac{l}{l} \frac{\sin(\alpha + \beta)}{2 \sin \alpha} \right)} \]

We will also have
\[ \eta = \frac{F}{l} \frac{1}{W} \frac{\sin \alpha}{2 \sin(\alpha + \beta) + Q} \]

As $\frac{L^4}{l}$ is about 3, and $\beta = 30^\circ$, then in the position of the pendulums shown in the drawing, we shall have
\[ \frac{L^4}{l} \frac{2 \sin \alpha}{\sin(\alpha + \beta)} = 3, \text{ and therefore} \]
\[ \eta = \frac{F}{3} \frac{W + Q}{} \]

By comparing (216) with (214) for Porter's governor, it will be seen that the balls of the Paxman governor are three times as efficient as those of Porter's.

The Pickering Governor.—The governor shown in Fig. 305 is made by Messrs. R. Garrett and Sons, of Leiston, and is of the Pickering type. It has two or more balls, B, which are mounted on flat steel springs, S1g. These springs are fixed to discs, D1 and D2, which rotate with the balls. D3 is prevented from moving up and down by the collar, Cr, which is screwed to the tubular spindle, TS. The rotary motion of the horizontal spindle, S3p, is transmitted to the balls by two bevel wheels, of which the one is fixed to D2. The spindle, Sp, carries at the one end an equilibrium throttle-valve, TV, and at the other end it is fixed to D1, the lift of the throttle-valve being adjusted by nuts, n. Cv forms the cover of the valve-case, and Sp works steam-tight up and down in stuffing-box, S B.

The horizontal spindle, S3p, carries an adjustable spring, Sg, the one end of which is fixed to worm wheel, W, while the other end is fastened to the forked end of the spindle. By turning the worm screw, VS, the tension of the spring will be increased or diminished, and thus adjust the pressure of the forked end of the spindle against collar, Cr. As this pressure has to be overcome by the balls, the speed of the governor will in this way be adjusted.

The Acme Governor.—Messrs. Browett, Lindley, and Co.'s Acme governor is illustrated in Figs. 306 and 307. It consists of two half-balls, B1 and B2, which are hinged by pins, p1 and p2, to a cross-piece, which cannot move up and down. The balls are held together by springs, S1g, which supply the deviating force. These springs are connected to cross-piece, Cr, by links, L1 and L2. When the speed of the governor is sufficiently high to overcome the tension of the springs, S1g, the throttle-valve, which is attached to
Cr by spindle, Sp, will be pushed down and thus regulate the supply of steam.

The speed of the engine can be adjusted by a double bell-crank lever, Cl, which turns on pin, p. One arm
of this lever is at right angles to screw, Sc, and engages in a sleeve on spindle, Sp. The one end of spring, Sg, the position of the nut. The spring will thus cause a downward pressure on Sp when the nut is screwed is attached to nut, n, and the tension of this spring will turn Cl in the one direction or the other, according to upwards, and an upward pressure when the nut is screwed downwards.
The Throttle-Valve.

The most common way of regulating the quantity of steam to be admitted to the cylinder is by diminishing or increasing the inlet-opening by a valve—the throttle-valve. This valve is actuated by the governor, as shown in several of the preceding illustrations.

Figs. 309 and 310 illustrate an arrangement which is often used, especially in small engines. $SV$ is the stop-valve, which opens by turning the hand-wheel, $HW$; the throttle-valve, $TV$, is fixed on spindle, $Sp$, which is turned in the one or the other direction by the governor, as shown in Fig. 302.

The valve, $TV$, will be full open while the engine is stopped, and will be almost shut when the engine is running empty.

In Fig. 308 is shown a double-beat throttle-valve. It consists of two valves, $V_1$ and $V_2$, which are fixed on the same spindle, $Sp$. The governor is attached to lever, $L$, by a bolt through one of the holes, $h$. The valve openings will be larger or smaller, according to the load which the engine has to overcome.

The Flywheel.

The flywheel is a wheel of large diameter, having a rim of considerable mass, which moves at great velocity. The moving rim is the seat of a large quantity of kinetic energy, which can be augmented or diminished without causing an appreciable variation of velocity.

If the effort which produces the rotary motion is variable while the resistance to be overcome is constant, or vice versa, then there will be a period during which the energy exerted by the effort is greater than that consumed by the resistance. The excess of energy exerted will be accumulated in the flywheel as kinetic energy, whereby the velocity of the rim will be increased from $v_1$ to $v_2$. This period will be followed by another one, during which the energy consumed by the resistance is greater than that exerted by the effort; the flywheel will during this period give off the energy it received during the first one, and its velocity will thereby fall from $v_2$ to $v_1$.

Let us now by $W$ denote the energy which causes the irregularity of speed, by $M$ the mass of the flywheel, and by $R$ its radius of gyration; then we must have

$$W = M \times \frac{v_2^2 - v_1^2}{2},$$

and therefore

$$v_2 - v_1 = \frac{2 W}{(v_1 + v_2) M}.$$

As $(v_2 - v_1)$ must be small, the mean velocity of the rim will be

$$v = \frac{v_2 + v_1}{2},$$

and therefore

$$\frac{v_2 - v_1}{v} = \frac{W}{R^2 \lambda} = \lambda, \text{ and } M = \frac{W}{\pi^2 \lambda},$$

where $\lambda$ is a coefficient which must be the smaller, the steadier the engine is required to run. With engines driving dynamos for electric lighting, $\lambda$ should probably not be less than 0.005.

If the wheel makes $n$ revolutions per minute, we have $\frac{\pi R n}{60} = v$, and therefore also $M = \left(\frac{30}{\pi n}\right)^2 \times \frac{W}{R^2 \lambda}$.

If $W$ be given in foot-pounds and $R$ and $v$ in feet, then we shall have

$$M = \frac{32.187 \times W}{v^2 \lambda} = \left(\frac{30}{\pi n}\right)^2 \times \frac{32.187 W}{R^2 \lambda} \text{ pounds}. \quad (217)$$

We may take for $R$ the mean radius of the rim; $M$ will then be the mass of the rim plus about one-third of the mass of the arms of the wheel.

Strength of Flywheel.—The flywheel is made of cast iron, and consists of a rim carried by a number of arms the other ends of which are joined to a boss, by which the wheel is keyed to the shaft.
The rotating rim is subject to a centrifugal force, which tends to tear the rim along a diametrical plane through the axis of rotation, just in the same way as the steam pressure tends to burst a cylindrical boiler shell. The thickness, $\delta$, of the rim can therefore be determined by the same formula which we used on page 108 for calculating the plate thickness of a boiler shell—viz.:

$$\delta = \frac{D \times p \times f_s}{2T} \ldots \ldots (218)$$

where $D$, in this case, is the diameter of the wheel, $p$ the centrifugal force in pounds per square foot of facesurface, and $T$ the tensile strength of cast iron. Let $\delta$ be so small that each particle of the rim can be considered to move with the same velocity; then the mass of the rim per square foot of face-surface will be

$$M = \frac{\delta \gamma}{32\times187}$$

Where $\gamma$ is the mass in pounds of a cubic foot of cast iron, we shall also have

$$p = \frac{2M v^2}{D} = \frac{2 \delta \gamma v^2}{32\times187D}$$

pounds.

Inserting the latter expression for $p$ in (218), we have

$$v = \sqrt{\frac{32\times187 \times T}{\gamma \times f_s}}$$

feet per second,

which is independent of the dimensions of the wheel.

The ultimate tensile strength of cast iron may be taken as 2,255,000 lb. per square foot, and the maximum working stress as 615,000 lb. per square foot. Taking $\gamma$ as 450 lb., we shall have

$$v = 209 \text{ ft. per second}$$

as the maximum velocity for the rim.

In practice, the circumferential velocity of a flywheel does probably not exceed 100 ft. per second.

If the flywheel be used for driving with belt, then $v$ may be taken on an average as 45 ft. per second, and when it is used for driving with ropes, $v$ may be taken as 80 ft. per second.

**Determination of $W$.**—In practice, the number of revolutions the engine is made to per minute, as well as the diameter of the flywheel, are given; the mass, $M$, of the wheel can therefore be calculated when we have determined the energy, $W$, which causes the irregularity of speed.

Fig. 311 represents the theoretical indicator diagram of an engine taken at an early cut-off; $OV$ is the absolute vacuum-line, and $OC$ is the clearance-line. For simplicity's sake, we will assume that the length of the connecting-rod is great compared with that of the crank arm, in which case the diagrams taken from both ends of the cylinder will be identical. The effective steam pressures per square inch of piston area are represented by the ordinates to the diagram, Fig. 312, $a b c d e f a$, measured from the base-line, $a f$. The semicircle, $a k f$, represents the path of the crank-pin during one stroke. When the crank has turned through an angle, $\phi$, and the piston has moved through a distance, $a g$, then the crank effort per square inch of piston area will be represented by $h g \times \sin \phi$. It will be seen that the crank effort will be positive during that part of the stroke which is represented by $a d$, and it will be negative for the remainder of the stroke on account of the compression on the other side of the piston.

In Fig. 313 the length of the base-line, $a k f$, is equal to the length of the semicircle, $a k f$, in Fig. 312, and the ordinates to the curve, $a c h d f a$, are taken proportional to the crank effort as determined in Fig. 312; thus $h f$ and $a k$ are equal to $h g \times \sin \phi$ and $a k$ in Fig. 312. The work done during one stroke by the crank effort per square inch of piston area is, therefore represented by area $a c h d a$, minus area $d f a f d$. The ordinate, $a a'$, to the straight line, $a f'$, represents the constant resistance to be overcome by the crank effort. The area of rectangle, $a a' f' a$, will therefore represent the work consumed by this resistance per square inch of piston area, which must be equal to the work done by the crank effort per square inch of piston area. It is now evident that area $m o l n$, multiplied by the area of the piston in square inches, must represent the energy, $W$, which causes the irregularity of speed, and which must be subdued by the flywheel.

In the case just described, we have assumed the piston speed to be so low that the inertia-pressure
due to the moving masses can be neglected. With high speeds of revolution, however, the inertia-pressure will entirely alter the flywheel diagram. Let, for instance, the indicator diagram of a high-speed engine be that in Fig. 311, the stroke of the engine be 1 ft., the reciprocating masses reduced on the piston be 2 lb. per square inch of piston area, and let the engine make 800 revolutions per minute, then, according to (179), page 213, the inertia-pressure at the beginning of the stroke will be minus 30-25 lb. per square inch of piston area. At the end of the stroke, the inertia-pressure will increase the effective pressure by 30-25 lb., and at the middle of the stroke, the inertia-pressure will be zero. In Fig. 312 is drawn a straight line, e g, in such a manner that the ordinate, a q, equal to e f, represents 30-25 lb.

The effective pressure on the piston of the high-speed engine must therefore be estimated from the line e g, instead of from a f. When the piston has traversed distance a g, the effective pressure will thus be \( g^2 \frac{h}{2} \), and the crank effort per square inch of piston will be \( g^2 \frac{h}{2} \times \sin \phi \). In this manner, flywheel diagram, Fig. 314, has been produced. It will be seen that the energy to be subdued by the flywheel per square inch of piston area has been considerably reduced by the inertia pressure.

When the engine has two cylinders with cranks at 180 deg., then the energy, W, will be twice that due to one cylinder. If a two-cylinder engine has cranks at right angles, then the two crank efforts will assist each other, and the irregularity will be diminished. Fig. 315 represents the flywheel diagram for half a revolution of a two-cylinder engine with cranks at right angles and with indicator diagram, as in Fig. 311. As the resistance to be overcome is twice that of a single-cylinder engine, it follows that \( a a^1 \) in Fig. 315 is twice \( a a^1 \) in Figs. 313 and 314. It will be seen that the energy to be subdued by the flywheel is much smaller than in the single-cylinder engine, although the flywheel diagram of each cylinder would be that in Fig. 313.

In single-cylinder engines, as well as in two-cylinder engines with cranks at 180 deg., the maximum energy to be subdued by the flywheel will be produced when the ratio of expansion is about 2; whereas the greatest irregularity in two-cylinder engines with cranks at right angles will occur at an early cut-off.

It is worth noticing that in designing the flywheel and the governor for an engine, the governor should be less sensitive than the flywheel, or, in other words, \( \eta \) in (211), page 231, should be greater than \( \lambda \) in (217).

The Slide-Valve.

The piece of mechanism generally used for the purpose of regulating the distribution of steam in the cylinder is the slide-valve. Moving to and fro, the slide-valve shuts and opens the steam-ports, thereby allowing the steam to enter the cylinder alternately on the one and the other side of the piston, and again letting the steam already used escape into the exhaust chamber.

As the reciprocating motions of the steam-piston and the slide-valve are produced by the same form of mechanism—viz., "crank and connecting-rod"—it will be necessary to investigate the laws of this kind of motion, in order to understand properly the distribution of steam by the slide-valve.

In Fig. 316 is drawn a circle, with O as centre, and with the crank arm, r, as radius. \( C_1 B_3 \) and \( C_2 B_4 \) are two positions of the connecting-rod corresponding to the two positions \( C_1 C_2 \) and \( C_2 C_4 \) of the crank arm, and \( B_3 \) and \( B_4 \) of the cross-head pin. The other two positions, \( B_1 \) and \( B_2 \), of the cross-head pin correspond to the two dead-point positions of the crank arm.

When now the crank has turned through an angle \( \phi \), so that the crank-pin is at \( C_2 \), then the cross-head pin will have traversed distance \( S_1 \), which, by making \( B_2 N \perp L \), will be equal to \( C_1 N \); we have now

\[
C_1 N = r (1 - \cos \phi) - L \mp \sqrt{L^2 - r^2 \sin^2 \phi} = S_1. \tag{219}
\]

Formula (219) will thus express the motion of the cross-head pin, and therefore also that of the piston during the stroke from \( B_1 \) to \( B_2 \).

In the return stroke, the cross-head pin will traverse distance \( S_2 \), while the crank turns through an angle \( \phi \). By making \( B_2 N \perp L \), we have

\[
N^2 C_2 = S_2 = r (1 - \cos \phi) + L \mp \sqrt{L^2 - r^2 \sin^2 \phi}
\]

We can therefore express the motion of the cross-head pin by

\[
S = r (1 - \cos \phi) \mp L \pm \sqrt{L^2 - r^2 \sin^2 \phi}
\]

where the upper sign must be used for the stroke from \( B_1 \) to \( B_2 \), and the lower sign for the return stroke. As we have approximately

\[
L \approx \sqrt{L^2 - r^2 \sin^2 \phi} = \frac{r^2 \sin^2 \phi}{2L}
\]

we shall also have approximately

\[
S = r (1 - \cos \phi) \mp \frac{r^2 \sin^2 \phi}{2L}. \tag{220}
\]

In applying formula (220) to the motion of the slide-valve, we must substitute the eccentricity, \( \xi \), of the eccentric for \( r \), and angle \( \psi \), Fig. 319, for \( \phi \). At the
same time, as $\xi$ is very small compared with the length of the eccentric rod, the second term in (220) may be neglected, and the formula for the slide-valve will be

$$S = \xi (1 - \cos \psi) \quad (221)$$

We thus see that the motion of the slide-valve will be the same in both directions.

It may be remarked that the stroke of the slide-valve is termed the "travel" of the slide-valve, and is equal to the "throw" of the eccentric, or twice the eccentricity.

The motion of the steam-piston, however, will follow formula (220), and will therefore be different in the two strokes. It is for these reasons that the indicator diagrams taken from the two ends of the cylinder differ in shape and size. The longer, however, the connecting-rod is, compared with the crank arm, the smaller will the last term in (220) be, and the more will the two motions of the piston be alike.

Zeuner's Slide-Valve Diagram.—The slide-valve, SV, in Figs. 317 and 318 is an ordinary D-valve, which is placed at its central position in Fig. 317; $a$ and $c$ are the lengths of the steam-ports and exhaust-ports respectively.

$a$ is called the outside lap, and causes the steam-ports to be opened later and shut earlier.

$c$ is the inside lap, which increases the period of compression and delays the release.

Fig. 318 shows the valve moved through a distance, $x$, from its central position.

The line, $OX$, in Fig. 319 represents the direction of the piston-rod, as well as that of the slide-valve rod. $O$ is the centre of the crankshaft, and $OX$ is perpendicular on $OX$. $\xi$ is the eccentricity of the valve eccentric, and with that as radius, a circle, $D_1D_2$, is drawn.

When the crank is in the dead-point position, $OC_1$, then the eccentric centre will be at $D_1$, and the centre line, $OD_1$, of the eccentric will form an angle $\delta$, the angle of advance, with $OX$. The eccentric centre will be at $D_2$ and the centre line of the slide-valve will be in position $E_1$, as in Fig. 318, when the crank has turned through an angle $\phi$. The slide-valve will be at its central position, $E$, when angle $\psi$ is 90 deg.

The problem now is to find by a simple method the relation between the distance, $x$, which the valve has moved from its central position, and the angle $\phi$ through which the crank has turned.

This problem can be solved graphically by means of a diagram due to Dr. Zeuner, and which is shown in Fig. 320. Draw first the two lines $OC_1$ and $OY$ at right angles to each other, the former representing the
direction of the piston-rod; then draw line OZ, forming an angle \( \delta \), the angle of advance, with OY. With \( \xi \) as diameter, and with centres in line OZ, draw two circles describe circle \( V_1, V_2 \); then \( V_3 P_2 \) will be equal to \( z - a \) which is the opening of the port to steam. With the inside lap, \( c \), as radius and O as centre, describe circle through O—these circles are called the slide-valve circles; also draw \( OC_2 \) to represent the position of the crank when it has turned through an angle \( \phi \);

then it can be proved that \( OP_2 \) is equal to the distance, \( x \), which the slide-valve has moved from its central position.

With O as centre and the outside lap, \( a \), as radius, W; \( W_{10} \); as \( x - c \) is the opening of the port to exhaust, the inside lap circle will serve to find the positions of release and compression.

With O as centre, and \( a + b \) as radius, draw the circular arc through \( P_8 \), and likewise with \( b + c \) as radius, draw arc through \( P_8 \).

We will now proceed to discuss the diagram. When
the crank is in position $O C_0$—i.e., just before it reaches the dead centre—the port will begin to be opened to steam, showing that the steam will begin to enter the cylinder before the piston has completed its stroke.

In position $O C_0$, the port is full open to steam.

In position $O C_4$, the port is still full open, but the valve begins to close it.

In position $O C_5$, the cut-off takes place.

At the dead-point position, $O C_1$, of the crank, the opening to steam is $V_1 P_1$; the latter is called the "lead."

The various positions of the crank, which are of interest, are marked $O C_9$, $O C_4$, etc.;
In position O C₁₀. The compression begins.
In position O C₁₁. The valve is again in its central position.
In position O C₁₂. Admission begins.

We have now followed the crank round one revolution while we have discussed what takes place on the one side of the piston. The position of the piston corresponding to the various positions of the crank must be determined by means of formula (220).

Meyer's Variable Expansion Gear.—By the simple valve motion just described, the steam will always be cut off at the same point, whatever may be the load which the engine has to overcome. The speed of the engine can therefore only be controlled by throttling the steam before it enters the cylinder, and this is done, as already mentioned, by the governor shutting the throttle-valve more or less, according to the load. Moreover, the slide-valve diagram shows that the ratio of expansion is small. It is true that we could make the valve cut off earlier, by increasing the outside lap and the angle of advance, and also by diminishing the throw of the eccentric, but these can only be varied within narrow limits without causing practical difficulties in producing sufficiently large openings to the steam.

The principle of the Meyer's expansion gear now to be described is the application of a second valve, which slides on the back of the first valve. By the relative motion of the two valves, the second one will cut off steam from the first one, before the latter has reached the position at which it cuts off steam from the cylinder.

Fig. 321 is a drawing of a steam-cylinder to which the Meyer's expansion gear is applied. SV is the main slide-valve which, if it were alone, would distribute the steam to the cylinder in the same way as the D-valve in Fig. 318. The cut-off valve consists of two blocks, B₁ and B₂, which slide steamtight on the first valve, and are moved by a separate eccentric. The parts of the valve-rod, C V R, which pass through the two blocks, are screwed, but in such a manner that the thread through B₁ is left-handed and that through B₂ is right-handed; if we therefore turn the hand wheel, H W, which is fixed on the tail-rod, C T, one way or the other, the blocks will either be separated or be moved closer together. The action of the cut-off valve is now simply this, that the further the blocks are removed from one another, the earlier will they cover the ports, P₂, of the slide-valve, and the greater will the ratio of expansion be. By this arrangement, the ratio of expansion can be varied from about 10, down to that due to the slide-valve, SV, alone. It will be seen that C V R can turn freely in the cross-head C₁ H₁, whereas the slide-valve rod, S V R, is fixed in the cross-head C₂ H₂. By turning H W, a small pointer is made to slide along a scale fixed on the bracket, thus showing the relative position of the blocks, B₁ and B₂, and therefore also the cut-off.

In order to produce a relative motion of the two valves, the angles of advance of the two eccentrics must be different. The angle of advance for the slide-valve may thus be 15 deg., and that for the cut-off valve 88 deg. The motions of the two valves will therefore be in the same direction in some part of the stroke, and in another part of the stroke, the relative motions of the valves will be in opposite directions.

As the cut-off, as shown in the drawing, must be varied by hand, it follows that the engine must be controlled by a throttle-valve unless the attendant is always at the hand wheel. It is, however, possible to make the governor turn the cut-off valve-rod, and thus vary the ratio of expansion automatically, but the motion is very slow.

Paxman's Automatic Expansion Gear.—Fig. 322 is a horizontal section through the cylinder and valve-chest of an engine provided with an automatic expansion gear designed by Mr. Paxman. The distribution of the steam is done by a three-ported main slide-valve, S V, of a similar construction to that shown in Fig. 321, and by a separate double-ported cut-off valve, C V. Between the two valves is a stationary anchor-plate, A P, which is double-ported on the side next the main valve, and is four-ported on the side next the cut-off valve. Both valves are worked by valve-rods with two nuts at each end.

The main valve cuts off at 75 per cent. of the stroke, and is worked by a single eccentric, E₁, with a 23 in. throw, and an angle of advance of about 27 deg. The valve has a 9 in. outside lap, but no inside one. The stroke, or travel, of the cut-off valve is made to vary by means of a link motion, Fig. 323, which is worked by two eccentrics, E₂ and E₃, and which is controlled by the governor, as shown. The cut-off valve has no lap, and controls the steam to be let into the cylinder by opening and shutting the four ports on the anchor-plate.

The throws of the two eccentrics, E₂ and E₃, are 14 in. and 32 in. respectively, and their angles of advance are about 90 deg. and minus 90 deg.; they are therefore also termed the positive and the negative eccentrics. As the eccentric-rods are very long, the slot in the link, L K, will be almost straight, and as the throws of the eccentrics are very short, the obliquity of the link will be small, and consequently the force required for moving the link will also be comparatively small. The travel of the cut-off valve will thus be diminished when the balls of the governor fly out, and the valve will thereby increase the ratio of expansion. The cut-off valve-rod is forked at the end where it carries a slide-block, B, which fits into the slot of the link.

The length of each of the four ports of the anchor-plate, next the cut-off valve, is 9 in., whereas the length of each of the ports on the main valve side is 1 in. These ports have a 9 in. lap, and as the main valve has a 9 in. lap, it follows that the port of the main valve will open to the port of the anchor-plate, before it opens to the cylinder-port.

By this expansion gear the cut-off may be varied from 0 to 75 per cent.
Lubricators.

The object of lubrication is to diminish the coefficient of friction between the wearing surfaces of the engine. If the lubrication fails, the friction will increase and the efficiency of mechanism will diminish; besides which, the cooling surfaces will not be ample enough for the increased heat to be dissipated, the temperature will rise, and the wearing surfaces will seize.

The lubricator most commonly used for main bearings, connecting-rod ends, etc., consists of a box of gunmetal or iron, with a lid on the top to keep dust out. In the middle of the box are one or two tubes, which are continued down to the wearing surface to be lubricated. In each tube is a pin, at one end of which a wick is attached; the other end of the wick is immersed in the oil with which the lubricator is filled. The lubrication will thus continue by the capillary action of the wick, as long as there is any oil in the box. The rate of lubrication will vary with the height at which the oil stands in the box, and will thus diminish as the oil runs out. Such a lubricator will therefore require a great deal of attention, or else it will be either wasteful or not sufficiently efficient; and when the engine is stopped, the pin must be taken out of the tube, or the lubrication will continue.

It is for these reasons that great attention has been paid to the designing of lubricators with adjustable feed, whereby the rate of lubrication can be made constant and sufficient for the rubbing surfaces which are to be lubricated.

A lubricator of this class is the "Crosby Visible Drop-Feed Lubricator," which is illustrated in Fig. 324.

At the bottom of the glass cup, and inside the tube, is a small cone valve, which is held down on its seat by a spiral spring when the lever, C, is in a horizontal...
position. By turning the lever into the vertical position, as shown in the engraving, the cone valve is lifted and oil can pass out of the cup. The lift of the valve, and thereby also the rate of lubrication, can be adjusted by screwing nut A up or down. B is a lock-nut which prevents A from turning when adjusted.

Steam Cylinder Lubricators.—A very simple, but rather wasteful, apparatus for lubricating the cylinder and slide-valve of a steam engine is the grease-cup, illustrated in Fig. 325. It is screwed into the top of the cylinder. The oil which is contained in the chamber, V, will, when the cock C₂ is opened, or partly opened, be displaced by steam from the cylinder, and thus fall into the latter. The lubricator is refilled by shutting C₂, and gradually opening cock C₁. When steam has ceased to issue from the opening, oil is poured into the cup, C_p, until V is

The feed can be stopped and started by turning lever, C, without interfering with the adjustment. As the cup is made of glass, and the feed is visible, the driver can see at a glance whether the apparatus is in proper working order.
filled. C is then shut. The cylinder receives in this way a charge of oil now and then, and the rate of lubrication is most irregular.

In Dewrance's "Window Lubricator," which is illustrated in Figs. 326, 327, and 328, the rate of lubrication can be regulated by the cone valve on the end of the spindle, S. This lubricator is also screwed into the top of the cylinder, and when the cone valve is opened, the steam from the cylinder will pass through hole b, and tube, T, into the hollow space inside spindle, Sp. Some of the steam will condense and fall as water through the hole h into the container, V, which is filled with oil. The water will buoy up the oil, which will pass through hole h, and if now the steam pressure in the cylinder fails, then some of the contents inside spindle, Sp, will be drawn through tube, T, into the cylinder. This lubricator is thus designed to work where there is a variation of pressure such as is found in a steam-cylinder. It has a window of thick annealed glass, G, which is made tight with asbestos packing, and which enables the driver to see the rate of feed and to regulate it by means of the cone valve.

In order to fill the lubricator, the cone valve must be screwed up tight, and spindle, Sp, unscrewed four turns; the oil is then poured into cup, C, and runs through hole h into the lubricator. When the oil is gone, the water is discharged into the cylinder through hole h, by turning spindle, Sp, half a turn and opening the cone valve. When used where the steam is very hot and dry, the lubricator may be worked by unscrewing the spindle, Sp, one quarter of a turn, and regulating the feed by the cone valve; the oil will then pass through hole h, Figs. 327 and 328 are horizontal sections through hole h, and spindle, S, respectively.

The most rational, and therefore also the most economical, way of lubricating a slide-valve and a steam-cylinder is by the use of a sight-feed lubricator, in which the quantity of oil supplied to the cylinder is visible to the driver and under his control.

In Figs. 329 and 330 is shown a sight-feed lubricator, designed and made by Messrs. Chas. Winn and Co., of Birmingham. The lubricator is bolted to a bracket on the engine steam-pipe, with which latter two connections are made—one at A nearest the boiler, and the other at B, both on the boiler side of the stop-valve. Some steam from the steam-pipe will find its way through the connection at A into the condenser, C, where it will be turned into water. By opening the cone valve at D, water will pass from the condenser into the container, F, which is filled with oil. The water will now buoy up the oil, some of which will pass through pipe P, and when the regulating valve at J is opened, the oil will find its way through nozzle, N, and rise as drops through the water with which the sight-glass, K, is filled. The oil will accumulate underneath plug, L, and when the valve at M is opened, will find its way through the connecting pipe at B into the main steam-pipe, where it will be thoroughly mixed with the steam which is intended for the engine.

As the steam pressure is the same on both openings, A and B, it follows that the pressure by which the oil is forced out is due to the head of water in the condenser above the oil-pipe at B.

Fig. 330 is a section through the cylinder in a plane at right angles to Fig. 329. H is a gauge-glass to indicate the contents of oil and water in F, and I is a three-way drain-cock through which the container can be emptied.

To fill the lubricator, all valves must be closed, the lever of the drain-cock, I, must point upwards as shown in the drawing, the two plugs R and L must be taken out, and condenser and sight-glass filled with clear water. Then take out plug P and fill container with oil; if there is not sufficient oil at hand, fill up quite full with water. The plugs are then replaced and the lubricator is ready for working.

The lubricator is started by opening each of the valves D and M half a turn, and the feed is regulated by valve J.

To refill the container, close first valve J, then valve D; then run water out of container by placing the lever of the drain-cock, I, pointing downwards, then close drain-cock and fill container with oil.

Figs. 331-335 are drawings of the latest model of Dewrance's sight-feed lubricator. This lubricator has only one connection with the main steam-pipe. In Fig. 331, the pipe, P', connects the lubricator with a horizontal steam-pipe, whereas Fig. 332 is designed for connecting it to a vertical steam-pipe. For the purpose of making the action easily understood, the passage of the oil through the lubricator is shown by dotted arrows, whereas the flow of water is shown by full arrows.

The steam passes through tube T, opens check valve, C V 1, and enters the coil, C, where it is condensed; it then passes through the air-cock, A C, which is open when its lever points upwards; the water passes then through tube T 2, and shut-off cock, S C, which is open when its lever is horizontal, as shown in Fig. 333, passes then down tube T 4 to the bottom of the container, V, and buoy up the oil, which will fall through tube T 2. When the regulating valve, R V, is open, the oil will rise as drops through the water, with which the sight-glass, G, is filled. The oil will now pass between the glass and plug, P, open check-valve C V 2, Fig. 333, pass out of the lubricator through opening, b, Figs. 333 and 331, and will at last drop into the steam-pipe, whence it will be carried by the steam into the steam-chest and the cylinder.

The process of refilling the container is as follows: First shut regulating valve and shut-off cock, then turn water out through drain-cock, D C, then shut the latter and open filling-cock, F C, and fill the container with oil.

It will be noticed in Fig. 332 that the filling-cock cannot be opened before the shut-off cock is shut. The object of the air-cock, A C, is to relieve the apparatus from air, which will be blown through passage O, Fig. 335, by turning the lever.

Fig. 333 is a horizontal section through the shut-off
cock, Fig. 334 is a vertical section through same, and Fig. 335 is a vertical section through the air-cock.

The Barring Engine.
In order to start an engine with single cylinder, engines a special motor, the barring engine, is required for this purpose. In Figs. 336 and 337 is shown plan and elevation of a barring engine, designed by Messrs. Musgrave and Sons, of Bolton. It will be seen to

or a double-cylinder engine with cranks at 180 deg., or a compound engine, it is necessary to turn the crankshaft, so as to give the cranks a proper position. With small engines this is done by turning the flywheel by hand, or by using a bar; but with large engines have two vertical cylinders with cranks on a horizontal shaft; the quick motion of the latter is transformed into a slow one by means of a worm gear, as shown.

The flywheel of the main engine which is to be turned is provided with teeth into which the teeth
of the cam-wheel of the barring engine fit. Fig. 338 illustrates the barring engine in gear with the main engine; whereas Fig. 339 shows the two engines out of gear.
DESCRIPTION OF STEAM ENGINES.

Having given an account in the preceding pages of the working parts of a steam engine, it now only remains to describe a few types of engines designed for driving dynamo machines.

High-pressure cylinder... HPC
Low-pressure cylinder... LPC
Cylinder drain-cocks... dr
Main bearing... MB
High-pressure crank... HPCr
Low-pressure crank... LPCr
Crankshaft... CRS

In order to assist the reader in understanding the drawings now to be described, the following lettering will be adopted throughout.

Steam-pipe... SP | Girder trunk... GT | Receiver... R | Balance disc... BD
Exhaust-pipe... EP | Girder head... GH | Receiver drain-cocks... Rdr | Flywheel... FW
FP | Jacket... J | Flywheel race... FR
 | Piston-rod... PR | Foundation frame... FF
 | Base-plate... BP | Driving-rod... DR
High-pressure piston ... HPP
Low-pressure piston ... LPP
Cross-head ... CH
Connecting-rod ... CR
Guide blades ... GB
Lubricator ... L
Governor ... GR
Governor driving wheel ... GW
Dash-pot ... DP
Automatic expansion gear ... AEG

formed by an inner cylinder or bush, which is cast separately, accurately turned and bored, and forced into the outer cylinder as described on pages 209 and 210. The cylinders are lagged with hair felt, wood, and covered with sheet iron, and are provided with necessary drain-cocks and sight-feed lubricator.

Horizontal Compound Steam Engines.

Messrs. Davey, Paxman, and Co.—The engine shown in Figs. 340 to 343 is a 40 nominal horse-power horizontal compound engine of the receiver type, making 90 revolutions per minute. The cylinders are placed side by side, and mounted on a strong cast-iron girder or foundation frame.

They are made of special hard, close-grained cast iron, accurately bored and faced. The diameter of the high-pressure cylinder is 12\(\frac{1}{2}\)in., and that of the low-pressure cylinder is 20in. The stroke of the two pistons is 24in. The cylinders are jacketed, the jacket being

The pistons and piston-rods are shown in Figs. 22 and 230, on page 212, and described on page 211. The piston-rod glands are of cast iron, with gunmetal bush.

The guide-bars, cross-heads, and slide-blocks are shown in Figs. 234-238, and described on page 215. The connecting-rods and straps are of wrought iron, and are shown in Figs. 253-256, and described on page 217.

The crankshaft (see Figs. 269 and 270) is made of steel, and extends at both ends beyond the engine bed, so that the flywheel or a pulley can be put on either
end. The cranks are set at right angles. The crankshaft runs in three strong cast-iron plummer blocks, fitted with adjustable gunmetal bearings. The cranks are balanced by means of a balance-disc.

The flywheel is 8ft. 6in. diameter and 17in. wide, and is turned on the face to receive a driving belt.

The governor is of the Paxman adjustable high-speed type, shown in Figs. 303 and 304, and driven by a gearing consisting of tooth-wheels and a driving-rod, as shown in the drawings.

The high-pressure cylinder is fitted with Paxman's automatic expansion gear, consisting of two slide-valves—one main and one cut-off valve—precisely as described on page 243, and shown in Figs. 322 and 323. The eccentric working the main valve is marked SVE, and the two eccentrics for the link motion are lettered AEG.

The valve-chest of the low-pressure cylinder is placed between the two cylinders, and the steam is admitted to the cylinder by a single slide-valve, cutting off at about 53 per cent., and worked by an eccentric, LPS. The valve-chest is closed by cover, CC.

The engine may be started in almost any position of the cranks, by means of a small valve—the by-pass valve—which opens communication between the steam-pipe and the low-pressure cylinder.

_Undertype Compound Steam Engine and Boiler._—The engine shown in Figs. 344, 345, and 346 is precisely of the same size and construction as the one just described. The boiler, L B, which is of the locomotive type, is placed over the engine, the smoke-box end being supported by a rest, R t, on the cylinders, and the firebox end resting, as usual, on the ashpit-box, A P.

The boiler is made entirely of mild ductile steel plates. All edges of plates are planed. The front plate, firebox, and other plates are flanged from the solid with special machinery. The shell is double riveted in the longitudinal seams, and the boiler is well stayed throughout. The shell is 1 in. thick, the internal firebox 1\(\frac{1}{8}\) in. thick, and the tube-plates 1\(\frac{1}{8}\) in. thick. There are 100 tubes, F T, of 2\(\frac{1}{4}\) in. external diameter, made of lap-welded iron.

The boiler is usually fitted with 12ft. of chimney, Cy, on an uptake, UT, and with one double-lever
safety-valve, LiS V, and also with the usual and necessary fittings.

inch, and made for a working pressure of 120lb. per square inch.

Fig. 347.

The boiler is tested by hydraulic pressure to 220lb. per square inch, and by steam to 120lb. per square

The steam-pipe, being perforated within the boiler, acts as an anti-priming pipe and passes out of the boiler
through the smoke-box. The steam is admitted to the steam-chest of the high-pressure cylinder through the stop-valve, S V.

condenser, C, and the piston-rod, P R, of the air pump is coupled with the tail-rod of the low-pressure piston. The condenser is of the construction shown in Figs. 282, 283, and 284, and is described on page 227. The governor is driven by two straps of two sets of pulleys, G P.

When the engine is a condensing one, as shown in Figs. 347, 348, then the exhaust-pipe passes into the

The feed pump, F P, is driven by an eccentric, P Ec, on the crankshaft. The suction-pipe is fixed on the
flange, F S P, and the feed is regulated by an overflow cock, O P C. F W P is the feed-water pipe, and C V is the check valve.

Messrs. Davey, Paxman, and Co.—The engine illustrated in Figs. 349 to 352 consists of two separate engines coupled together. Each engine is of the girder type—i.e., the front cylinder cover, cross-head guide, main bearing for crankshaft, and foot for bolting to foundation, are cast in one piece, to which the cylinder with valve chest is bolted. The engines are placed side by side, and in such a manner that the high-pressure engine is on the right-hand side, and the low-pressure engine on the
left-hand side (standing at the cylinder end and looking towards the crankshaft). The distance between centre lines of the two engines is 11ft.

The size of the total engine is 100 nominal horsepower, and the crankshaft makes 60 revolutions per minute. The two cylinders are connected with a receiver, and are provided with drain-cocks and relief-valves.

The cylinders are made of hard close-grained cast iron. The diameter of the high-pressure cylinder is 22in., that of the low-pressure cylinder is 35in., and the stroke of both engines is 45in. The cylinders are jacketed in the usual manner.

The cross-heads are made of cast steel, and are shown in Figs. 239, 240, and 241, and are described on page 215.

The connecting-rods are made of wrought iron, with adjustable gunmetal bearings, and are shown in Figs. 257, 258, 259, and 260.

The crankshaft is made of steel, and is shown in Fig. 268. It runs in adjustable gunmetal bearings. The cranks are set at right angles.

The engine has two flywheels, 14ft. in diameter by 18in. wide, which are turned on the face to receive driving belt. They are made in two parts, connected by bolts C B.

The governor and slide-valves are precisely of the same type as described in the preceding engines made by the same firm. The main valve for the high-pressure cylinder is lettered H S V. A S P is a pipe for passing steam into the L P C from the by-pass valve.

The low-pressure engine may be fitted with an injection condenser in the same manner as shown in Figs. 347 and 348.

The Robey Compound Engine.

This engine, which is illustrated in Figs. 353, 354, and 355, is a coupled compound receiver engine with cranks at right angles, the two sub-engines being of the girder type. The diameter of the high-pressure cylinder is 183in., and that of the low-pressure cylinder is 30in., the stroke of both sub-engines being 40in.

The total engine will develop 200 indicated horsepower at its most economical load, and a maximum indicated horse-power of 320 with 80lb. pressure on the engine side of the steam stop-valve, and with the crankshaft making 63 revolutions per minute.

The cylinders are made of close-grained cold blast cast iron bored true, and the ends enlarged to receive the covers. Each cylinder is steam-jacketed, and is protected as well as the steam-chest with lagging and covered by blue steel plates. The cylinders are also provided with indicator cocks and relief-valves.

Inside the receiver is a heating coil, which is connected with pipes to the jackets of the two cylinders. By this means, steam from the boiler will circulate through the coil as well as through the cylinder jackets.

The pistons, which are described on page 212 and shown in Fig. 232, have phosphor bronze rings with steel springs in the high-pressure cylinder, and cast-iron rings with steel springs in the low-pressure cylinder, the diameter of the steel piston-rod being 3in. The crankshaft is made of steel with a diameter of 12in., and is enlarged in the middle to receive the flywheel. The two journals are each 18in. long by 9in. diameter, their bearings having already been described and shown on page 223. A cast-iron crank disc is forced under heavy pressure upon each end of the crankshaft, and is further secured by a steel key. The crank disc, into which a steel crank-pin is fitted, is a large circular plate of 4ft. 9in. diameter, and counter-weighted at the back to balance the moving parts.

The cross-heads and connecting-rods have been described on pages 216 and 217.

The cylinder-end of the tubular girder frame is circular, and being turned and faced true with the axis or centre line of the engine, forms the front cover of the cylinder. A rim upon this circular end enters some distance into the mouth of the cylinder; the joint between the two being an accurate fit, is secured by a number of steel studs and nuts. The girder head or crank end of the girder frame forms a plunger-block for the crankshaft bearing.
The most important feature of this engine is the peculiar manner in which the distribution of the steam is effected. The energy required for working the slide-valves of an engine is no doubt in many cases very considerable, especially where steam of high pressure is used. In this engine the usual slide-valve is dispensed with, and the steam is admitted from the steam-chest into the cylinder, and again cut off by double-beat lifting-valves, one at each end of each cylinder. These valves are situated close to the ends of the cylinders, so that the clearance to be filled with steam at each stroke is considerably reduced.

Fig. 356 is a section, at right angles to the piston-rod, through one of the valves, the steam-chest, and the cover CC. The end, E, of the eccentric-rod, EC R, will describe an arc, with centre at FC; during part of this motion, the tripper, TR, which can turn on the pin through E, will depress the outer end of the lever, LR, which, turning on its fulcrum, FC, will cause the gunmetal valve, DV, to be lifted from its seat, SV. The lifting of the valve begins just before the commencement of the stroke. Owing to the different arcs described by E and LR, the tripper will at a certain point slip out of contact with LR, and the valve will drop instantaneously and cut off the supply of steam. To prevent the valve from being injured by coming too heavily on its seat, its spindle, VB, ends in the piston of a dashpot, DP, which in Fig. 356 is cut away, in order to show the governor which is situated behind it.

The eccentric, which works the tripper, is fixed on the driving-rod, DR.

The lead of the valve, DV, can be adjusted by the nut, AN, on the valve spindle. If the nut be screwed upwards, the lead would be decreased; screwing it downwards towards the valve, will increase the lead. More lead can be obtained by shortening the eccentric-rods, ECR, by means of their adjusting nuts. If the rods be lengthened, the reverse will take place. The point at which the tripper slips out of contact with LR can be adjusted by screw Sc. In this way the ratio of expansion can be made to be the same for each stroke.

This mechanism is sufficient for admission and cut-off of the steam at fixed points of the stroke, and is all that is required for the low-pressure cylinder.

In the high-pressure cylinder, however, the cut-off of the steam should be automatic—i.e., should vary according as the load or steam pressure varies, so as to keep the speed of the engine constant. This is effected by the governor, which in rising lifts lever LR, and thereby moves the fulcrum, FC, of LR to the left, thus causing the tripper to slip out of contact at an earlier point. The opposite will take place when the flyers fall. The governor is loaded with a spring inside its spindle, and upon this spring the governor pendulums press. The speed of the engine may be varied a few revolutions by adjusting the compression of the spring by means of the nut, AN1. To make the engine run faster, screw the nut down, and unscrew it to make the engine run slower. A cord, OD, may be attached to the lever LR, and led away to any part of the building. In case of accident to life or machinery, by pulling the cord, the lever LR draws lever Lr completely clear of the tripper; no steam can enter the cylinders, and the engine is brought to a standstill.

The governor is driven by the driving-rod, DR, which again is driven by DR.

When the engine is used for electric lighting, an electric governor may be applied, which consists of two solenoids, Sd, Fig. 357, each of which has an iron core, Cr, fixed to an armature, Ar. The end of the governor lever, LR, rests on the screw Sc, which is attached to the armature. By proper adjustment of screw, Sc, and the movable weight, AW, the speed of the engine can be regulated by the strength of the current passing through the solenoid.

The exhaust-valves, EV, are placed underneath the cylinders, and, like the inlet-valves, close to the pistons, so as to reduce the clearance. The exhaust-valve is a gridiron valve, sliding upon a treble-ported face formed upon the upper surface of the exhaust branch, and worked by an eccentric upon the driving-rod, DR. Although these valves are slide-valves, they require comparatively little power to move, as the pressure upon them is small. On account of the position of the exhaust-valve underneath the cylinder, the latter is kept drained of any water which may accumulate within it. The exhaust-ports are closed when the piston has completed about seven-eighths of its stroke.

The engine can be turned by means of the bar, BR, Fig. 354. The engine stop-valve is lettered SV, in Figs. 353, 354, and 355, and the high-pressure exhaust-pipe is lettered HE, in Figs. 354 and 355; LS is the low-pressure steam pipe.

**Vertical Side-by-Side Compound Quick-Speed Engine.**

The engine illustrated in Figs. 358 to 362 is a compound receiver engine with vertical cylinders placed side-by-side, and made by Messrs. Browett, Lindley, and Co.

The engine is intended to make 200 or 250 revolutions per minute, as required, and is fitted with the "Acme" governor, which is described and shown on pages 234-236. The I.H.P. is 250, the high-pressure cylinder being 15\(\frac{1}{4}\) in. and the low-pressure one 23\(\frac{1}{4}\) in. in diameter, both having 16 in. stroke.

Figs. 358, 359, and 360 are sections through the cylinders and the valve-chests. The steam in the high-pressure cylinder is distributed by means of a piston-valve, PV, which is shown in detail in Fig. 363. It will be seen that the high-pressure steam, as well as the exhaust steam, surrounds the piston-valve, and therefore the friction which has to be overcome in moving the valve will only be that due to the pressure of the spring rings, SG, against the liner, LR.

The drawings also show that the steam from the boiler is let through S I into the space SS, which in ordinary engines is occupied by the exhaust steam. When the top piston-rings in the up-stroke of the valve have passed over ports h1 in the liner, steam
from the steam-space, SS, will pass through the ports h₁ and h₂ into the cylinder. At the same time, the lower piston-rings having passed over ports h₁ allow the low-pressure steam at the other end of the cylinder to exhaust through ports h₂ into the high-pressure exhaust space, H E S. The cut-off will take place at the moment the top piston-rings, in the down-stroke of the valve, shut ports h₁. The distribution of the steam during the up stroke of the high-pressure piston, H P P, is effected in the same manner.

The piston-valve is fixed to the rod, S P R, which moves steam-tight through a stuffing-box, S B₁, both for steam and exhaust. This valve has two internal steam passages, I P, which pass through the valve and thus communicate at both ends with the steam-chest. The rod, which works this valve, ends also in a cross-head, which slides on a pair of guide-blades. The eccentric, which actuates the low-pressure valve, is fixed on the crankshaft, and the cross-head end of the eccentric-rod is forked, as shown in Fig. 361.

The piston of the high-pressure cylinder is of cast iron, in one piece, and fitted with steel rings, which are sprung into place and are expanded by a cut steel coil. The low-pressure piston is of cast steel, and is fitted with rings and springs in the same manner as the high-pressure piston. This construction of the pistons dispenses with junk rings and screws, which are liable to jar loose and cause breakdowns. The piston-rods pass through stuffing-boxes, S B₁ and S B₂.

A special feature with this engine is the cross-head, which consists of a plain rectangular block of steel forged solid with the piston-rod, and slotted out to receive the cross-head brasses. The cross-head is closed at the top by a forged steel cap, which is slipped over at each end, and embraces the jaws to prevent
the latter from spreading. The cap bolts, which pass through the block, serve also to receive the slipper-slide on the back of the block.

The cross-head brasses are divided in two parts, and are tightened by a steel wedge of the same width as the brasses. The wedge is adjusted by a screw on the front
of the cap-plate. The cross-head pin is of steel, and is 3\(\frac{1}{4}\)in. in diameter by 6\(\frac{1}{4}\)in. wide, and has a hole through its centre, which is 2\(\frac{1}{4}\)in. diameter.

The connecting-rods are forked at the cross-head 10in. long, and the two outside ones 12\(\frac{1}{4}\)in. long. The cranks are slotted, and are fitted with cast-iron counter-balances. The diameter and length of the crank-pins are 6\(\frac{1}{4}\)in.

![Diagram](image)

end, and are of the same type as that shown in Figs. 265 and 266 on page 221.

The crankshaft is made of steel, and its diameter is 7in. at each end. It is carried by three bearings, the diameter of which is 6\(\frac{1}{2}\)in., the centre one being

The cylinders are cast with feet, Ft, which are bolted to the vertical standard, and they are further supported in front by three steel stays or columns, Cn. The two cylinders are held together by bolts, Bt.

The stop-valve, S V, is opened and shut by means
of lever, Lr. On the left-hand side of the stop-valve, Fig. 361, is a by-pass-valve, which opens and shuts by turning hand-wheel, H; and whereby high-pressure steam can be let through the steam-pipe, A S P, into the low-pressure steam-chest. Willans Central Valve Compound Engine.
The engine, Fig. 364, consists of two single-acting tandem engines with their cranks at 180 deg. The reciprocating parts are therefore well balanced.
At a steam pressure of 120lb. per square inch, and
the crankshaft making 460 revolutions per minute, the engine will develop 80 I.H.P. or 72 A.H.P.

The stroke is 6in., the diameter of the high-pressure cylinder is 9\(\frac{5}{8}\)in., and that of the low-pressure cylinder is 14in. The effective areas of the two pistons are 67 and 141 square inches respectively.

Where higher pressure is available, the engine can be arranged for a constant load of 100 I.H.P.

Each line of pistons is connected to its corresponding crank by two exactly similar connecting rods, with a space between, in which works an eccentric, Ec, forged solid on the crank-pin. The piston-rod, which connects the two pistons belonging to the same line, is hollow and provided with steam-ports through which the steam can enter and leave the cylinders. The distribution of the steam through the ports is effected by a set of piston valves, \(V_2\), \(V_4\), \(V_6\), and \(V_8\), moving inside the piston-rod and worked by the eccentric, Ec.

The reason why the eccentric is fixed on the crank-pin, and not on the shaft as usual, is that the required valve motion must be a motion relative to the piston-rod, and as the latter moves with the crank-pin, the eccentric must also move with the crank-pin.

\(V_1\) is a guide for taking the side thrust of the eccentric, and \(V_9\) separates the steam-chest from the cylinders, except when the top ports are open; it also serves to transmit the full steam pressure at all times through the line of valves to the eccentric, keeping the eccentric-rod in compression upon both the up and the down stroke, and preventing knocking in the eccentric strap.

\(V_2\), \(V_4\), \(V_6\), and \(V_8\) are provided with spring rings pressing against the inside surface of the piston-rod. In order to make the piston-rod move steamtight up and down through the covers which separate the cylinders, the glands, \(G_1\), \(G_3\), and \(G_5\), contain phosphor bronze packing rings with cast-iron spring rings, similar to piston rings, but pressing inwards against the piston-rod instead of outwards.

The lower end of the piston-rod is fixed on a guide piston, G P, which works inside a guide cylinder, G C, and takes the side thrust of the connecting-rods. The connecting-rod ends work on hardened steel pins, which are fixed inside the guide piston.

The engine being a single-acting one, the connecting-rods must always be in compression, never in tension.
For this reason, the upper crank-pin brasses, Br, Fig. 365, of the connecting-rods are wider than the lower ones, which are only intended to act as a stand-by in case of accident. As the working brasses never leave the crank-pins, it follows that no wear which can take place can lead to knocking, as the connecting-rods will follow up the wear automatically. But in order that the lower brasses may be useful as a stand-by, they should not be too far from the crank-pin; the wear should be taken up when it becomes excessive—say, as soon as it exceeds \( \frac{3}{16} \) in. Sufficient slack, however, should always be left to ensure an audible knock if the engine is allowed to race. In that case—i.e., if the speed is allowed to exceed that at which the momentum of the moving parts, upon the up stroke, is balanced by the cushioning, the moving parts will leave the crank-pin at some point before reaching the top of the stroke, and will strike it again with more or less force so soon as steam is admitted to the cylinder.

The wear of the brasses can be watched in the following manner:

A small hole is drilled in each guide piston, \( \frac{3}{8} \) in. in diameter. The hole is just visible below the bottom edge of the guide cylinder when the crank-chamber door is removed, and when the piston is at the bottom of its stroke; when the entire diameter of the hole is in view below the guide cylinder, it is time both to set up the brasses so as to reduce the play, and to pack up the connecting-rods by inserting packing-pieces between the big ends of the connecting-rods and the brasses. The connecting-rods, however, must not be packed up sufficiently to take the hole quite out of sight. Its lower side must still be in sight under the edge of the guide cylinder. If the hole goes out of sight entirely, there will not be enough clearance for safety between the pistons and the top of their cylinders.

The eccentric-rod is intended to work always in compression, in the same way as the connecting-rods, the holding-down power being furnished by the pressure of the steam in the steam-chest acting constantly upon the uppermost piston-valve, \( V_6 \). It may sometimes happen, if the engine is running without load but at full speed, that the pressure in the steam-chest is insufficient to keep the eccentric-rod in contact with the eccentric upon the up stroke. If so, a slight knocking may be heard, as the lower eccentric-strap is purposely left a very easy fit upon the eccentric. Such knocking will cease as soon as the engine is given work to do.

The cylinders are mounted upon the crank-chamber Cr C, which contains the bearings upon which the crankshaft rests. The crank-chamber is partly filled with a mixture of oil and water. The crank-pins dip bodily into the lubricant at every revolution, and in doing so they splash it to the upper ends of the connecting-rods and eccentric-rods, and into the guide cylinders, as well as into that part of the hollow piston-rod where the guide, \( V_1 \), works.

The main bearings, which have no top brasses, are at all times partly immersed in the lubricant. As the lubricant consists of oil and water, its temperature cannot rise above that of boiling water, and there is, therefore, a greater guarantee against hot bearings than in most other engines, so long as the supply of water is maintained.

It has, however, been found that when the larger non-condensing engines exhaust into the atmosphere, some of the heat of the exhaust steam in the exhaust-chamber, \( E \), passes by conduction down the sides of the crank-chamber, \( C \), and heats the lubricant. In the smaller engines, where the radiating surface is larger in proportion, this effect is not observed. Nor is it present in the larger engines, except after long runs, while in condensing engines the low temperature of the exhaust steam prevents any trouble. In large non-condensing engines, however, it is usual to fit two small cross tubes in the crank-chamber, to which a cold-water service may be connected. This may with advantage be a portion of the feed-water.

The oil used in the crank-chamber should be best castor oil or good olive oil, and must contain no acid. The quantity of lubricant in the crank-chamber can be ascertained by means of the gauge, Fig. 366. A pipe replacing the plug at \( O \) will serve as an overflow. A \( V \) acts as an air vessel, to prevent violent oscillations of the surface in the gauge. As the gauge communicates only with the lowest part of the crank-chamber, very little oil will pass into the gauge, and any overflow which may take place consists, therefore, principally of water, and can be caught in buckets and returned to the crank-chamber when cold. The surface of the lubricant in the gauge generally rises about \( \frac{3}{8} \) in. while the engine is running; this is due to the level being lowered where the revolving cranks scoop out a path in the lubricant. When water is required to be added, it should be poured through the open top of the gauge. Oil should be admitted through the funnel, \( F_n \). A tap is fitted at \( D \) for the purpose of occasionally drawing the lubricant from the crank-chamber for the purpose of cleaning the latter.

One sight-feed lubricator, fixed on the throttle-valve, is sufficient for the cylinders and the valves while the engine is running. Grease-cups are also fitted in the holes, which on the drawing are closed by plugs, \( F_5 \); but they are only used as a stand-by, or for giving the engine a flush of oil at starting and just before stopping.

The steam distribution is effected, as already mentioned, by the piston-valves shutting and opening the ports in the hollow piston-rod. In Fig. 364, the left-hand line of pistons is shown in section, and the line of piston-valves in elevation. The pistons are upon the down or steam stroke. Fig. 368 is a section through the line of piston-valves.

The high-pressure steam from the steam-chest, \( S \), enters the piston-rod through ports \( 6 \), passing between the piston-valves \( V_6 \) and \( V_5 \) into the high-pressure
cylinder through ports 5. This cylinder will continue to take steam as long as the ports 6 are still in the steam-chest; but on reaching the gland G2, the ports 6 will pass out of the steam-chest, and cut-off will take place. This will happen early or late, according as the ports are cut lower down or higher up in the piston-rod, or, what is the same thing, according as the gland rings, G2, are more or less raised above the cylinder cover by a distance-piece placed below them. Normally, the ports are so placed as to give cut-off at either 0.4 or 0.6 of the stroke, when the gland rings are as low as they can be fitted. The height to which the rings are raised determines the actual cut-off.

At about three-quarter stroke the ports 5 are closed by the (relative) upward movement of V5.

Shortly before the piston reaches the bottom of its stroke, V5, still moving upwards, begins to pass above the ports 5, thus putting the ports 5 and 4 into communication, and allowing the steam to be transferred upon the up stroke, with no practical change of volume parts 3 in the piston-rod and to the height of the gland rings, G2. Also here, shortly before the end of the stroke, the valve V3 will commence to uncover ports 2, and to allow the low-pressure exhaust steam to pass through the piston-rod, and out again through ports 1 into the exhaust-chamber, E Ch.

The right-hand line of pistons, shown in elevation, Fig. 364, are upon the up or exhaust stroke. The valves are necessarily invisible, but the course of the exhaust steam is indicated by arrows.

The water above the high-pressure piston drains
downwards through the ports into the receiver, and that above the low-pressure piston drains through the ports into the exhaust-chamber during the exhaust stroke.

The pistons, under a recent patent of Mr. Willans, are dished on the upper side, and as the exhaust-ports travel with the pistons, and are, so to say, at the bottom of the hollow, both the rush of the steam through the ports and the upward movement of the pistons combine to drive out the water during the exhaust stroke.

The valves, $V_a$ and $V_b$, by rising at each stroke above the bottom of the ports 1 and 4 respectively prevent the accumulation of water in any part of the valve motion.

Besides the relief-valves shown in the drawing, the partition between the low-pressure cylinder and the receiver is fitted with an unloaded valve, through which water in the cylinder can be discharged quickly into the receiver.

Both cylinders and receiver are provided with drain-cocks, which discharge into the crank-chamber.

The plugged holes, $P_g^a$ and $P_g^b$, are intended for fixing indicators.

Reference has already been made to the fact that the connecting-rods and eccentric-rods are constantly in compression—a condition rendered possible only by the fact that the engine is single-acting, giving no pull to the crank upon the up stroke, but only a push upon the down stroke. In any engine running at a high speed of revolution, however, the moving parts can only be kept in compression upon the up stroke by very powerful cushioning, which in most engines is obtained by an excessive compression of the steam.

Sometimes when the steam is exhausted into a vacuum, sufficient cushioning cannot be obtained by the usual means. In this engine, the cushioning is provided by the guide pistons, which, on the up stroke, compress the air contained in the guide cylinders. Thus any desired amount of cushioning can be obtained, according to the clearance allowed in the cylinder.

The energy expended in compressing the air is given out again by its expansion on the succeeding down stroke. There are holes, $h$, in the guide cylinders, which are uncovered by the guides at the bottom of the stroke, and

![Diagram of engine](image)

Fig. 370.

as the casing which surrounds the guide cylinders and forms part of the framing of the engine is open to the atmosphere, it is evident that the air compression always commences at atmospheric pressure, and is constant in its results whatever alteration may be made in the pressure of the exhaust steam.

Air or relief-cocks, A C, are fitted upon the guide cylinders, in order to avoid compressing the air in them when the engine is turned by hand, and to facilitate starting. If the cocks are opened at starting, they must be closed again immediately, and they must never be open when the engine is running at speed, or the necessary cushioning will be wanting. A drain-cock is fitted to the exhaust-chamber, which should be connected, by a copper pipe, with some convenient place for discharging hot water; but if the exhaust-pipe is led
downwards, and is itself properly drained, the exhaust-chamber drain may be dispensed with.

The high-pressure pistons can be inspected by first disconnecting the steam-pipe at SI, and the governor spindle by unscrewing nut N₂. The joints Jt² should then be broken, when the steam-chest and the high-pressure cylinders can be lifted off in one; the hollow piston-rods will draw through glands G₃.

If it be required to inspect one of the low-pressure pistons, then the bolts in the high-pressure piston should be unscrewed, and the catchers, which enter some of ports 4, should be removed. The high-pressure spindle should be disconnected, and the connecting-rod ends, as well as eccentric-strap, should be undone through the crank-chamber door. The joint at the level of the crankshaft should then be broken, and the upper part of the engine should be lifted; the crankshaft will then be left lying on the main bearings.

The governor, which is fixed on the crankshaft, consists of two flyers, Fl, attached to bell-crank levers with fulcrums at Fc. The springs Sg², which supplies the deviating force, cause the bell-crank levers to press against the sleeve, Si, which otherwise would be moved by the force of spring Sg¹ in the direction of the arrow. The action of the governor is, therefore, to release the sleeve, more or less, according to the rotary speed of the crankshaft, and thereby cause the throttle-valve to shut or open for the steam.

The tension of spring Sg¹ can be adjusted by screwing nut N₁ up or down, with the virtual effect of adding to, or decreasing the centrifugal action of the flyers, thus enabling a given opening of the flyers, and, therefore, a given opening of the valve, to be obtained at a somewhat increased or diminished speed as may be desired. The length of the governor spindle, which is in two parts, R₁ and R₂, can be adjusted.

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**Fig. 371.**
by means of the long nut, Fig. 367. The top part of this nut is split, and can be opened sufficiently to receive the part $R_2$ of the spindle; and by screwing the nut $N_2$ down, $R_2$ will be squeezed in the hole and held in position.

The "Windsor" Quick-Speed Engine.

This engine, which is made by Messrs. Davey, Paxman, and Co., and illustrated in Figs. 369, 370, and 371, is a compound receiver engine with inverted cylinders placed side-by-side, and with cranks at 180 deg. The cylinders are mounted on two cast-iron standards, Std, and are supported in front by two steel stays, Sy. The whole engine is securely fixed on a strong cast-iron bed-plate.

The size of the engine is 25 nominal horse-power, and is designed to work with a steam pressure of 120 lb. per square inch, and at a speed of 160 to 220 revolutions per minute. The diameter of the high-pressure cylinder is 10 in., and that of the low-pressure cylinder is 16 in., the stroke of both pistons being 12 in.

The details of this engine have already been described and shown: The pistons on page 211 and Figs. 229, 230, and 231; the cross-heads on page 218 and Figs. 242 and 243; the connecting-rods on page 221 and Figs. 255-267; the crankshaft on page 222 and Figs. 271 and 272; the governor on page 254 and Figs. 303 and 304; and the automatic expansion gear on page 243 and Figs. 322 and 323.

The governor is driven by a series of three wheels, G W, the first one of which is fixed on the crankshaft, the second one on a spindle, supported by bracket Br, and the third one is mounted on a spindle, which drives the governor-spindle by means of a pair of bevel-wheels. The governor is mounted on a bracket, Br, and its spindle is supported by a pivot bearing on bracket, Br. The governor works the link motion by means of the three levers $L_1$, $L_2$, $L_3$, of which the two first ones are fixed to the horizontal spindle, Sp, supported by Br.

The cross-head pins, as well as the crank-pins, are lubricated from the oil-box, O B, the oil being carried through the four tubes, O T.

The high-pressure and the low-pressure distributing sliding-valve gears are lettered H P S and L P S respectively, and the slipper guides, which are bolted to the front of the standards are lettered S G.
SSUMING that the engines and dynamos of the installation are all in order, it is seldom convenient to send the current direct from the terminals of the dynamo into the conducting wires. The intermediate apparatus in large central stations is often a rather complex affair; but in early days, and with series circuits, it often consisted of a single make-and-break switch. It will be better, in this brief description, to commence with the simplest case, and gradually continue more and more complicated arrangements till we come to those of the present time. For the most part, the study of the illustrations given will be sufficient information after the underlying principles have been discussed.

The switchboard, or rather the switch in its simplest form, merely consists of an apparatus to complete or to break the circuit. In Figs. 1 and 2 let D C represent a conductive circuit, with a break at A B. Suppose A B to be terminals which can be bridged or connected by the conductor, S. One end of S may be fixed to one terminal as a pivot, or fixed as shown. When the conductor, S, is in the position shown in Figs. 1 and 2, there can be no current, but when it is brought into the position shown in Fig. 3 the circuit is completed, and current is possible.

Switches that simply make and break contact at one point of the conductor, or rather at one point leading from one pole of the machine, are called single-pole switches; those that break and make contact at two points in the conductor, or rather at two points leading from the two poles, are called double-pole switches.

Figs. 1, 2, and 3 represent single-pole switches. Figs. 4 and 5 double-pole switches. The arrangement of these switches is shown in the figures, where A B, C D are the fixed contact-pieces in the circuit, E P F the moving piece pivoted at P carrying conducting pieces at E and F separated by non-conducting material. When E P F is in the position shown by the dotted line the circuit is closed. When it is in the positive, shown by the thick lines, there are two gaps in the circuit, one at each pole of the machine.

In turning the switch, and especially if it is worked by inexperienced hands, it is quite possible to hesitate, or to turn the switch slowly. We shall see shortly that it is necessary to avoid such slow action.

In the first place, however, a good switch, when used as a bridge to make contact, so completes the circuit that there is no increase of resistance other than that would be if the gap was completed by an unbroken continuity of the main conductor. Then it is of the greatest importance that when the circuit is broken the switch should act quickly, or an arc will be formed, which soon does a considerable amount of damage. Just examine the conditions existing when breaking contact. Suppose the pressure used is considerable, such as would send a current through a very high resistance. At one moment in the action of breaking the circuit the bridge-piece of the switch must necessarily be just leaving the contact-piece, and the air space, or gap between them, is infinitesimally small. The pressure is sufficient to send a current through this small increase of resistance, and it does, but in so doing tears off minute particles of the conductor, raises these particles to incandescence, and bridges over the gap with a bridge of these incandescent particles. This bridge is termed an arc, undoubtedly a corruption of arch. The particles are mostly torn from one side of the conductor, which, if the action occurs often, is soon burnt up. We require the most absolute contact between two conductors to avoid arcing. As the
distance between the conductors increases, the resistance increases and the current decreases, till at length the resistance becomes so great that the current ceases altogether. If then a break is made slowly so that the arc continues over an appreciable length of time, and the space is filled with incandescent particles, the conductor is soon burnt away and must be renewed. Again, the resistance decreases more slowly when the break is made slowly than when it is quick, because the bridge of particles can be more complete, and the length of the gap must be longer than would be necessary in their absence.

It would be a mistake under these circumstances to depend upon the hand alone for turning off the switch, hence it is usually supplemented by a strong spring, or, better still, the action of the spring alone is utilised. The switch piece may either be rigidly connected to its handle, when both hand and spring may aid in breaking contact, or the manipulating handle may not be rigidly connected, but be quite independent, and turn loosely upon the pivot. Then when moved, the handle moves a stud or projection of some kind releases the spring, which alone acts in moving the contact-piece. In the case where hand and spring work together, the hand may really, and often in practice does, retard the action of the spring, but where the handle merely releases the spring, the latter acts without interference.

In other cases the switch, when on, is held in position by a strong spring, and the hand in turning off the switch has to exert a considerable force, which, as in the case of the switches at the Post Office, renders it almost impossible to do other than break contact rapidly.

The metal of which the switch is made should be a
good conductor—hard copper or gunmetal for preference—or in some cases, for small switches, of brass. The pieces carrying the current must be of sufficient section to carry the largest possible total current without heating. The danger of heating in a switch is,

make the two functions independent, and so arrange the contact-piece that it shall be a pure electrical bridge-over from terminal to terminal. This is happily done in the Post Office switches referred to above and illustrated below. With the very best arrangement of contacts

however, more to be feared from accidental increase of resistance arising between the surfaces which make the contact. This may occur from separation of the contacts due to either wear and tear, or to loosening of the screws of the switch, or it may be due to dust, dirt, or oil getting between the surfaces. For the first of

there is still some danger of the parts heating, and it is therefore advisable to mount the whole upon an incombustible base, as of slate or porcelain. In addition, it is necessary to see that screws which fasten contact-

these reasons it is advisable to have the rubbing contacts large and the springs which press them together strong, and in large switches adjustable to take up the wear. For the second reason it is advisable never to allow the mechanical pivot of the moving contact-piece to act also as an electrical contact, but to

pieces do not pass through the base, but are countersunk and firmly bedded, where not open to inspection, in plaster or some similar incombustible material. The aim of all designs of switches, then, is to have:

1. Sufficient thickness of conductor in the contact-pieces to prevent the slightest heating.
2. A good broad rubbing contact for making the circuit: if possible double and adjustable for large switches, the contact-pieces being, of course, so insulated that no current leaks through moving parts.

3. A very quick and sufficiently long break when breaking the circuit—a loose handle moving independently of the contact-piece being preferable in order to ensure sudden spring off.

4. No circuit through the pivot, but a pure bridge-over.

5. Incombustible base.

6. Absence of metal screws, etc., at the back.

7. Simplicity in its parts, and ease in fixing. Besides which, for high-tension switches there should be:

8. Absence of all possibility of accidental contact with the conductors by any person standing near, or manipulating the switch.

Various devices are used to ensure good contact. There are two pieces of conductor required to obtain this contact. Let us call one the fixed piece, the other the moving piece. In the first place, both fixed and moving pieces are generally slightly bevelled, so that there shall be no jar or trouble of getting them one on the other. The fixed piece is frequently in the shape of a conical plug conductor is used, Fig. 6. In this case we have two fixed pieces so bored that the plug fits accurately. Contact is made by pushing the plug home, at the same time giving it a slight turn to ensure good contact.

Referring again to Figs. 1 to 5, it will be as well to show how the single and double switches are arranged in the circuit in practice. It is customary to call the wire going from the + terminal of the dynamo, the + lead; and the wire going to the – terminal, the – lead. Fig. 7 shows the use of the single switch. The – wire is broken and the ends fixed to the binding screws, A and B, of the switch. So long as A and B are not conductively connected, the circuit is broken and the lamp, L, is not lighted. Connecting A and B by means of the switch, the lamp is put into the circuit and receives current. The double-pole switch, Fig. 8, has both + and – wires, broken and connected to the terminals AB, CD, as shown. The switch is shown making contact, so that the lamp, L, is in circuit. The wire connections are usually made through perforations in the base of the switch, so that there is no possibility of accidental contact with the moving parts.

Switches are mounted on a variety of materials, the larger ones sometimes on wood faced with asbestos, or more usually upon slate, the smaller ones on porcelain. The smaller ones for internal work must, of course, be useful, but the principal aim of design is to make them both ornamental and useful. These will be dealt with when considering the fittings for interior work. Meanwhile the practice with larger switches will best be seen by illustrations. Then, in addition to switches for the purposes hitherto mentioned, switches are required for a number of purposes—for regulating the charging and discharging secondary batteries, automatic switches, multiple switches, etc., all of which entail some difference in design, but none in principle.

Fig. 9 shows a wedge contact switch, with loose handle. The spring of the contact-pieces, which clutch the moving piece as in the figure, is strong enough to cause a considerable power to be applied to the handle when a break is necessary. This results in contact being very sharp and abrupt.

Fig. 10 shows a double contact switch with brush contact-pieces, and Fig. 11 shows a multiple contact-piece similarly constructed. Figs. 12 and 13 show double-pole switches. The latter figure shows the switch in a case. In circuits where high pressure is used the switches should always be protected. Fig. 14 shows a ring contact switch; but instead of illustrating some scores of switches, for their name is legion, the engineer will prefer details of construction of one or two selected specimens. Such details are shown in the
accompanying illustrations, which, being drawn to scale, will require little or no explanation other than the figures themselves give. These details are of switches used for interchanging dynamos. All the drawings are one-quarter full size, the material used in this and in the other switch being slate for the base, generally used in the Post Office installation, under the control of Mr. W. H. Preece, F.R.S., and under the immediate supervision of Mr. Probert, to whose courtesy we are indebted for the drawings. Fig. 15 shows a switch bronze for the contact-pieces, and ebonite for the insulating parts. Fig. 16 shows a single-pole dynamo switch, also one-quarter full size, while Fig. 17 shows one switch section on the engine-room switchboard.
Here the plan is one-eighth full size, the details being one-quarter full size. A glance at either plan or details will show the simple and effective way in which contact through moving parts is avoided. A spring U piece is placed just in front of handle and pivot, the moving contact-piece falls into this U piece and into a second U piece at the centre, which forms the other contact terminal.

It is seldom, however, even in the simplest installation that a switch can be placed at every point where it might be required. For convenience sake the circuits are so arranged, and the wires so run, that the required switching apparatus is collected together and placed in a position that is easy of access to those in charge. Generally the switches are arranged upon a common back, behind and through which the necessary circuit connections are made, so that the whole or a large part of the installation may be under the control of one man. Switchboards are said not to repay the time and trouble spent upon them, yet they are necessary to a proper maintenance of the installation, and are often very complex and, with the instruments, very expensive. Consider the simplest case—one dynamo supplying current to one series circuit. The man in charge requires a means of putting on or cutting off the current. A switch enables him to do this. He also requires to know the current passing into the circuit—hence must have a current measurer (ammeter) provided; he also wants to know the pressure at which he is working, and therefore a voltmeter must be provided. Besides these instruments, provision has to be made in case of accidentally getting too high a pressure and too much current, which might destroy much valuable apparatus. To guard against this, a fusible plug or cut-out of some kind is provided, which acts automatically either by fusing or in some way breaking the circuit when the current reaches a dangerous quantity. Usually then the switch or switches, the necessary measuring instruments and the cut-outs are arranged upon the switchboard. In large installations arrangements have to be made for the exciter circuits, for the charging and discharging of batteries, for the shifting of the load from one dynamo, or several dynamos in parallel, to another or other dynamos. Each separate installation has to be studied, and its switchboard arranged according to the special requirements. It will not be necessary to describe in detail each switchboard illustrated, or to reiterate over and over again that each circuit needs its own ammeter, and so on. Fig. 18 then shows a simple type of switchboard as used for accumulator installations, and designed by Messrs. Drake and Gorham. The dynamos and lamp switches are of the ring contact pattern, the ammeter a steelyard ammeter, also introduced by this firm. The board is fitted with a simple form of combined charge and discharge regulator, so that lamps can be run and cells charged at the same time. The pressure at the battery terminals while being charged is greater than that required in the lamp circuit, and moving down the right-hand handle connects the proper number of cells to give the lamp circuit its required pressure. A four-way switch, as in the figure, is that usually employed for a 50-volt circuit, a six-way switch being used for 100 volts. Figs. 19 and 20 show a type of switchboard constructed by the General Electric Company. Fig. 21 also shows a switchboard by the same makers, in use at the installation at the Hotel Metropole, Brighton.

The accompanying illustrations, Figs. 22 and 23, represent one of Messrs. Crompton and Co.'s large central station switchboards of the most recent design.

The board, as shown, is composed of seven large slates, each 7ft. high, 3ft. 6in. wide, and 1\(\frac{1}{2}\)in. thick, all of which are mounted on a strong wrought-iron frame in panel form.

The whole framework is supported on heavy cast-iron brackets, bolted to the wall about 10ft. from the ground to economise space, and to enable the attendant on the platform to watch all that is going on in the engine-room below.

Ample space is left between the back of the slates and the wall for access to the connections, as will be seen from Fig. 24.

The switchboard is designed for a station similar to those of the Kensington and Knightsbridge Electric Lighting Company, working on the three-wire system, with accumulators. In this case, however, arrangements have been made for six large dynamos giving 500 amperes at 250 volts, for two smaller dynamos giving the same current at half the pressure, for two double batteries, and for eight pairs of feeders, each capable of carrying 500 amperes.

To minimise the chances of short circuits, and for
convenience in the connections, the switchboard is divided into three distinct parts. The three slates on the right-hand side are entirely positive, the three on the left-hand are negative, while that in the centre may be termed the intermediate slate. On the board the slates Nos. 1, 2, 6, and 7, Fig. 22, contain the large dynamo current indicators, automatic cut-outs, volt indicators, shunt resistance switches, and dynamo plug boards, as well as the cut-outs and current indicators and plugboards for the feeders.

On slates 3 and 5 are placed all the battery switches, while slate No. 4 contains the switches and instru-
ments for the two smaller dynamos, which can be
thrown, by means of the double-pole switch above and
the two small plugboards, on to either side of the
system for equalising purposes.

By means of the plugboards one pair of batteries
and any of the feeders and dynamos may be worked
entirely apart from the others, and, if necessary, at a
different pressure.

One of the advantages of this system is that any of
the switch contact-pieces may be quickly and safely
taken down for examination or repairs without
interfering in any way with the running of the
station.

The connections in the battery-room are made in a
similar manner, and the copper is in these places care-
fully painted to protect it from the acid spray.

The connections at the back of the board are made
with drawn copper rods of high conductivity, varying
in size from \( \frac{3}{8} \) in. to 2 in. in diameter. The joints in
these rods, and the connections with the fittings, are
made by means of copper flanges which are screwed
on to the rods. These flanges are carefully faced,
tinned, and drawn together by means of two bolts.

We will now follow through the connections of the
diagram, assuming in the first place that the station is
working under ordinary conditions.

Starting with dynamo No. 1, Fig. 23. The current
passes from the right-hand brush direct to the vertical
bar on the positive dynamo plugboard, \( D_1 \).

We will only take into consideration double battery
No. 1, which is composed of 112 cells, and is practically two 56-cell batteries coupled together in series. The 12-way switch will be in such a position on the battery that it remains practically inactive.

By plugging $D$, with the top horizontal bar $B_1$, we couple the dynamo with the 12-way battery switch, $R_1+$, and the bottom contact of the main two-way switch. The position of the large two-way switch will be as shown, and the current will consequently pass direct to the top horizontal bar of the positive feeder plugboard,
and thence by means of plugs through the current indicators and duplex cut-outs to the lamps, returning again through the negative duplex cut-outs and current indicators to the top horizontal bar of the negative feeder plugboard.

The current now passes through the two-way switch, as shown, connecting it with the 12-way battery switch, R₁⁻, which is also placed practically in a position of inactivity, and so on to the top horizontal bar of the negative dynamo plugboard, B₁. By plugging on to this bar the dynamo bar B₁ negative, the circuit is completed through the automatic cut-out and current indicator to the negative brush of the dynamo.

Any of the large dynamos may be similarly connected either separately, or at the same time, as desired. It will be readily seen that battery No. 2 may be employed in the same way as battery No. 1, by substituting in each case the second horizontal bar of the plugboards for the first.

By altering the position of the 12-way regulating switches in regard to the cells at either end of the batteries, these may assist the dynamos, or receive a charge themselves; and in cases where the dynamos are not running, the lights may be maintained for a time at the proper pressure by switching into circuit the available end cells.

Under the ordinary working conditions, it is, of course, impossible to charge these end cells, as the dynamos would have to run at too high a pressure for the lamps. This difficulty is overcome in the following manner.
The dynamos are coupled as before, and the end cells which require charging are put in circuit by the 12-way switches. Before this is done, however, the two-way switches are turned in the position in which they are shown with battery No. 2, which throws the feeders on to the small eight-way battery switches, by means of which proper pressure is kept on the circuits.

Before moving the two-way switch, care must be taken that the large and small regulating switches are on the same cell, otherwise a short-circuit would take place across the cells which the two switches overlap.

All the batteries have a common connection at the third wire, at which point the battery meters and current indicators are coupled; these are provided with two-way switches, as shown, to cut them out of circuit when the batteries are discharging.

In order to provide for the irregularities of load on either side of the system, the two 125-volt machines are employed.

It will be seen that a dynamo, by means of the double-pole switch, is coupled on to the third wire and the vertical bar of the small positive plugboard, while
B dynamo is coupled to the third wire and vertical bar of the small negative plugboard. By plugging the small horizontal bars with the vertical bars, either or both of these small dynamos can be made to assist either or both sides of the system.

The automatic cut-outs are a new combination of a magnetic and fusing cut-out, and are specially adapted for heavy currents.

The battery switches are so arranged that not the slightest flicker is noticed when a cell of the battery is passed into or out of circuit.

Fig. 25 may be given here, although it really illustrates another part of our subject. Hitherto we have been speaking of main switchboards, but other switchboards are used where, as in hotels, factories, or warehouses, large numbers of lamps are used. It is necessary to control such lamps from the room or the immediate vicinity in which they are used. This figure, then, illustrates a distributing switchboard in use on the ground floor of the Post Office, and is one-eighth full size, while Fig. 26 shows the details of this board, also one-eighth full size. That is, in this case, we have all the lamps upon this floor controlled from a switchboard in a convenient position. It may be that only a few lamps are needed—then the others can be switched out without trouble. The examination of the circuits is thereby facilitated. A lamp or lamps going wrong causes a glance at the measuring instruments, and it is at once known whether that particular circuit is taking too much or too little current, or the circuit where the difficulty arises can be at once determined. Of course, any movement of the switches upon any of the distributing boards is known in the dynamo-room because of the load taken off or put on the machines, and of the indications on the instruments of the main switchboard.

A different arrangement has been adopted at the new Opera House, and a little consideration will show that the ordinary switching on and off of lamps would be unsuited for theatrical purposes; and what is said here of the new Opera House applies equally well to almost all theatres. Hence special apparatus has to be designed and constructed to fulfil the varying conditions that arise in such installations. This apparatus, again, must be simple, and so unlikely to get out of order, for a panic in a theatre is one of the things to be avoided at all hazard. It is well known that the exigencies of theatre lighting necessitate great variations of light. In some brilliant scenes all the light possible is required,
and from these well-lighted scenes there must be every gradation of light to almost total darkness. In the opera of "Ivanhoe" the load varies some eight or ten times in the evening—from 1,400 to 300 amperes.
The manipulation of light is managed by a somewhat different kind of switch to any we have hitherto mentioned. It is done by means of a series of small wheels, supplied with handles fitted independently on an axle running through them all. These hand wheels communicate, by means of endless wire ropes, with switches which control the resistances by short-circuiting some of the coils in circuit. This method does away with all sparking, and if the switch should get out of order it does not put the light out, but merely introduces all the resistance into the circuit. A large lever, Fig. 27, at the end of the axle enables all the lamps in the building that are supplied with resistances to be raised or lowered, while the independent hand wheels can be utilised to vary any desired combination. The limits of variation in this particular installation are from 110 to 50 volts.

For quick changes of scene for which the curtain is not let down, but which have to be done in the dark, a large main switch is used to break the main circuits carrying 1,400 amperes. This switch is fitted with copper blocks to take the arc, and is short-circuited, after the circuit has been completed, by two large mercury cups and a connection. The object of the blocks of copper gauze in the switch is to facilitate renewal of the contacts, and they also have the effect of making the switch much more durable than if the contacts were made and broken on springs, as is usual, because the small globules of copper produced by breaking the circuit are flattened into the gauzy material when contact is next made. Thus, while breaking contact may be said to deteriorate the gauze, making contact assists to maintain it in an efficient state.

We have now given the details of switchboard construction, but it may not be out of place to refer to others; for, as we say, each installation needs its special
design, although the general type of design is similar throughout most of the switchboards constructed by the same maker. A type of a high-pressure central station switchboard has been designed and adopted by the Brush Company, as has also a type of low-pressure switchboard. The same idea forms the basis of both types of switches, being that of mechanical arrangement to allow of a certain number of dynamos to be connected with all or any of a given number of circuits in such a manner that these can be changed over with ease and certainty. In the low-pressure switch a solid heavy bar slides along, by means of an ebonite handle, into jaws consisting of split pieces of stout copper. To these are connected one end of the cable, and the other end is connected to stout springs, which press up underneath the sliding piece, thus making good contact. In the switchboard a series of these sliding bars are arranged in the centre of the board, and each one connected to its own dynamo. At the top and at the bottom are corresponding receiving jaws, to either of which they can connect. Each of these jaws has a handle, to which a movable contact is fitted; these contacts can be lifted and fitted down over either of the transverse bars. The transverse bars are joined in couples, top and bottom, each couple connected to a separate circuit. To throw over a dynamo to another circuit, therefore, the jaw not in use corresponding to that dynamo is lifted and pressed down to the required circuit bar. The switch handle is then pushed hard across, and the current is, of course, shunted to the new circuit.

In the high-tension switchboard the same arrangement of dynamos and circuits is made, but the switch is of a different pattern, giving a long break to obviate the spark. In this a handle on a loose pivot catches against a small trigger, and releases an arm carrying a contact-piece. This arm is actuated by a powerful spring, and the act of moving the handle causes it to fly round instantaneously, the break being, of course, twice the radius of the arm. The connection of dynamos to the various circuits is made in the same manner as the former to the transverse bar connection. A locking arrangement prevents the arm flying back accidentally, and is only unlocked by again altering the circuit contact.

Fig. 28 shows the connections of the switchboard designed by Mr. G. Kapp for use at the installation at Madame Tussaud's. Here there are three circuits—two main circuits and a panic circuit. As will be seen, each of the two main circuits has 10 switches, the panic circuit being controlled by its own switch. The switchboard is arranged to allow connection of either dynamo to either battery, of the supply of current direct to either circuit, or from the batteries, or for the charging of the batteries while partially lighting, or the discharge of the dynamos and batteries together. Fig. 29 shows a type of board used by Messrs. Poole and White for private and small installations. Fig. 30 shows the connections of this board, which are sufficiently distinct to explain themselves. It will be seen that the board is somewhat similar in type to that illustrated in Fig. 18.

Besides arranging for connecting circuits and measurements, it is necessary to provide also an automatic arrangement to break contact should the current by any means become too large. This, as has been said, is usually obtained by the insertion of a fusible piece of metal, called a cut-out or fuse,
Frequently a magnetic apparatus is adopted. We refer to the subject of cut-outs here only to give Figs. 31, 32, and 33, which show the elevation one-eighth full size and the details half full size of the fuseboard at the Post Office.

The Post Office installation, to which we have so frequently referred, has been so carefully designed and the details thought out, that it may well form a pattern for work of a similar character. The main switchboard is, of course, a collection of switches similar to that illustrated in Fig. 17, while Fig. 34 shows the connections of the dynamo switches.

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CHAPTER XIV.

MEASUREMENT.

Introductory.

The most important knowledge for an electrical engineer is that relating to measurement. It may be said, without fear of contradiction, that the instruments in the hands of electricians enable them to make more delicate and more exact measurements than is possible in any other branch of science, not even excepting chemistry, and far more delicate than in any other industry. Most of the instruments employed are the subject of patents, and thus at present cannot be generally manufactured. Many of the instruments, however, used in ordinary work wherein measurements to '1 per cent. are sufficiently accurate, are not controlled by patentees. All, however, are based upon similar principles, so the plan adopted here will be to deal, in the first place, with the scientific principles underlying the measurements, and subsequently with the application of these principles to the instruments. Frequently it will be best to give the principles and the application together, so a hard and fast plan cannot be followed. The history of the development of electrical measurement is interesting, but will form no part of these papers. The work of the British Association Committee is written in the annals of that association, and to the reports of that committee the reader desirous of knowing this history must be referred. Under that committee chaos has given place to order, and we have to use what is, not what was. The aim of the committee was to devise a system of measurement founded upon a firm scientific basis, and hence capable of general application. The system devised is known as the B.A., or the absolute, or the C.G.S. system. The meaning of B.A. is simply the initials of British Association. The term "absolute" indicates not absolute accuracy, by independence of the properties of any particular instrument, or of other physical quantities, except those of length, mass, and time. It is termed the C.G.S. system because the units involved are derived directly from the centimetre as the unit of length, the grammes as the unit of mass, and the second as the unit of time.

From the units adopted in the C.G.S. system are derived the units adopted in practice, so that something must be known about what may be termed the fundamental system before that used in practice can be thoroughly understood.

There are two systems of electrical units based upon the C.G.S. units, known respectively as the electrostatic and the electromagnetic. In this latter system all the quantities are expressed in units derived from a magnetic pole of unit strength, and unit pole is defined as "a pole which, placed at unit distance from an equal and similar pole, repels it with unit force."

Fundamental Units in the C.G.S. System.

Length, 1 centimetre = 3.93701 inches = about 1 in.
Mass, 1 gramme = 15.4323 grains = about 15/2 grains.
= 0.03574 ounce avoirdupois = about 1/27 ounce avoirdupois.
= 0.022151 ounce troy = about 1/27 ounce troy.
Time, 1 mean solar second, or \( \frac{1}{36525} \) part of the mean solar day.

A caution must be given here to the effect that weight is not the same as mass, although it is frequently assumed to be identical. Mass is invariably, weight is variable. The mass of a body is the same at the poles as at the equator, but the weight is not the same owing to the varying pull of gravity. To put this plainly, we may suppose the pull of gravitation to be towards the centre of the earth, and that the earth acts, far as gravity is concerned, as if it were concentrated at the centre point. The further a body is from the centre of gravity the less is the pull; so if we take a piece of iron and determine the pull of gravity upon it in a London laboratory, that pull will be found to differ very considerably from the pull determined upon the same piece of iron at the equator or the poles. The number of molecules which constitutes the mass of the iron is unchanged, but the pull of gravity upon each molecule, and therefore upon the whole iron, is changed.

In the C.G.S. system the unit of mass is taken as the
quantity of distilled water at the temperature of 4 deg. C. contained in 1 cubic centimetre, which under standard pull of gravity (usually represented by \( g \)) corresponds to 1 gramme weight.

In England—outside of pure science—the standard of mass is the Imperial standard pound avoirdupois, or rather a piece of platinum marked "P. S. 1844, 11b.," preserved in the Exchequer Office. The choice of these fundamental units is entirely arbitrary, and many would prefer a foot-pound-second system to the C.G.S. system. In engineering matters other units are required, especially dynamical units. The most important of these are the units of force and work. If we allow a body, such as a gramme weight or a pound weight, to fall fully for one second under the influence of gravity alone, it will have acquired at the end of that period a velocity of 981 cm. per second, or about 32-2 ft. per second. This does not mean that the body falls 981 cm., or 32-2 ft., but that at the end of a second, if allowed to travel uniformly upwards at the velocity thus acquired, it would move through 981 cm., or 32-2 ft. each succeeding second.

The actual space fallen through in the first second is \( \frac{1}{2} \) of 981 cm., or \( \frac{1}{2} \) of 32-2 ft.—that is, 490'5 cm., or 16'1 ft. It is easy to show that under the influence of gravity the actual fall of a body in the second second will be 1471-5 cm., or 48-3 ft. Now, if a body is constantly acted upon by a force less than gravity it will acquire a less velocity per second; if the force is greater, then a greater velocity is acquired.

The C.G.S. unit of force has been defined as "that force which, acting upon a mass of 1 gramme for 1 second, will impart to it a velocity of 1 cm." This unit is called the "dyne," and evidently is equal to \( \frac{1}{981} \) g.

When the foot-pound-second system is used, the unit of force is called the "poundal," and is that force which, acting for 1 second on a mass of 1 lb., generates a velocity of 1 ft. per second, and is evidently \( \frac{1}{32-2} \) g.

"Work" represents force applied through distance or length, and the unit of work in the C.G.S. system is called an "erg," and equals the unit of force \( \times \) unit of length; or equals the work done in lifting 1 gramme vertically against gravity through the distance of 1 cm.

In practical work, this unit being so small is of little use, and another, 10,000,000 times as large, called the "joule," is sometimes used, though as yet it has not commended itself to engineers.

In the foot-pound-second system the unit of work is termed a foot-pound—that is, an amount of work equal to that done in lifting a pound vertically against gravity through the distance of a foot.

Sir W. Thomson has suggested the use of the term "activity," as equivalent to the time rate of doing work. The unit rate of working adopted by engineers in this country is 1 horse-power, which is equivalent to 33,000 foot-pounds per minute, or 550 foot-pounds per second. This is a far more practical unit than the erg per second.

Some idea of the amount of work represented by an erg may be obtained thus: 1 gramme raised vertically against gravity a distance of 1 cm. = dynes \( \times \) cm. = 981 \( \times \) 1 = 981 ergs. In English measures it takes about 160 ergs of work in raising a grain vertically against gravity through an inch, or 1,920 ergs to raise 1 grain similarly through the distance of a foot. More nearly, a foot-pound = 13,562,600 ergs; which shows what large numbers would have to be dealt with if engineers adopt this unit.

So far as the amount of work is concerned it does not matter whether the pound is lifted in a second or in a year, but it does matter where "activity" is concerned.

The English unit horse-power is generally taken as equivalent to 7,460,000,000 ergs per second, for the horse-power is 33,000 foot-pounds per minute or 550 foot-pounds per second, and 550 foot-pounds = 76 kilogram-metres, i.e., 76 kilogrammes raised 1 metre in 1 second—hence

1 horse-power = 76 kilogram-metres.

= 76 \( \times \) 1,000 gramme-metres.

= 76 \( \times \) 1,000 \( \times \) 100 gramme-centimetres.

= 7,600,000 gramme-centimetres.

but we have seen that to raise 1 gramme vertically against gravity 1 cm. high requires an expenditure of work equivalent to 981 ergs.

Therefore 1 horse-power = 7,600,000 \( \times \) 981.

= 7,455,600,000 ergs per second.

As was said above, the round number 7,460,000,000 is generally taken as the equivalent.

Energy expended or gained is measured by the work done by or upon the body, and is measured by the same units as work.

The units referred to may again be tabulated:

<table>
<thead>
<tr>
<th>FUNDAMENTAL UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.G.S. (centimetre-gramme-second).</td>
</tr>
<tr>
<td>Foot.</td>
</tr>
<tr>
<td>Mass.</td>
</tr>
<tr>
<td>Time.</td>
</tr>
<tr>
<td>Force.</td>
</tr>
<tr>
<td>Work.</td>
</tr>
<tr>
<td>Energy.</td>
</tr>
<tr>
<td>Activity.</td>
</tr>
<tr>
<td>Velocity.</td>
</tr>
<tr>
<td>Acceleration.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DERIVED UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>P.S. (foot-pound-second).</td>
</tr>
<tr>
<td>Foot-pounds.</td>
</tr>
<tr>
<td>Pound.</td>
</tr>
<tr>
<td>Mean solar second.</td>
</tr>
<tr>
<td>Dyne.</td>
</tr>
<tr>
<td>Erg.</td>
</tr>
<tr>
<td>Erg per second.</td>
</tr>
<tr>
<td>Centimetre-second.</td>
</tr>
<tr>
<td>Centimetre-second.</td>
</tr>
</tbody>
</table>

It is necessary to reiterate that the measurements required by electrical engineers of to-day are very different from those required in telegraphy, either as regards land lines or submarine cables. The work done by currents used in either branch of telegraphy is very small compared with that done in electric lighting or transmission of power; hence the ordinary engineering units are more applicable than those used in telegraphic work. Foot-pounds, horse-power, etc., are terms in common use, appealing to the uneducated as well as to the educated, and not requiring a special training to make comprehensible. It may be that horse-power scientifically means nothing, except the conventional 33,000 lb. raised 1 ft. in one minute; that no horse will
continue to work, if it is able to work at all, at this rate, but for all practical purposes the horse-power is a very good unit, and needs not to be superseded by one that may be more in accord with the notions of pure science.

The Earth’s Magnetism.

In the vast majority of instruments used in practice, a magnet forms an important feature. It must be remembered that such a magnet is always subject to the influence of the earth’s magnetism, and, therefore, before the effect of any other influence can be measured, registered, or tabulated, it is necessary to know exactly the effect of the earth’s magnetism upon the magnet.

Any magnet so suspended as to be free to move in any plane will finally come to rest in a position pointing almost due north and south with one pole a little higher than the other. The geographical poles occasionally, and only after long intervals of time, coincide in direction with the magnetic poles of the earth. Thus, when we say a magnetic needle points north and south, the earth’s magnetic north and south is meant, and not the geographical north and south. The angle between the magnetic meridian and the geographical meridian of a place is called the “magnetic declination” of that place.

If a magnet, as above mentioned, be suspended, this magnet will set itself in a direction to the west of the geographical N and S, there being at the present time an angle of about 17°25’ between lines showing the two directions. That is, the magnetic north pole is at the present time 17°25’ west of the geographical north pole. The variation from the geographical meridian is termed the declination of the magnet, and the angle the angle of declination. The declination at any place, therefore, is the value of the angle in degrees at that place between the magnetic and geographical meridian of that place.

The nearer the magnet needle is carried to the magnetic pole, the more and more, if free to move vertically, does one end or pole dip downwards, till if carried quite to the pole the needle would point straight down. At the earth’s north magnetic pole the true south pole of the needle (commonly, but unscientifically, called the north pole of the needle because it points towards the north) is downward, and at the earth’s south magnetic pole the true north pole points downwards. The angle formed by the magnet pointing downwards at any place and a horizontal axis, is called the dip of the needle.

Both “dip” and “declination,” it must be remembered, change with position on the earth’s surface, and the declination, if not the dip, differs at the same position at different periods of time.

We assume, then, that the earth acts as a magnet, and, if so, we must assume that the lines of force, constituting the earth’s magnetic system, possess similar properties to the lines of force of any other system. Inasmuch as the lines of force of any two magnetic systems brought within each other’s influence always, when free to act, place themselves, or tend to place themselves, in the same or in parallel directions, it will be seen that other magnets under the influence of the earth’s magnetism merely obey this invariable rule.

If, then, we have a magnet, it naturally, if free to do so, as has been said, takes up a position pointing to the magnetic north and south. It is this directive influence of the earth’s magnetism upon small magnets free to move in a horizontal plane that gives us a most valuable aid to navigation in the compass. If a magnet is moved from its natural position of rest, it requires force to move it against the action of the earth’s magnetism, just as a lump of metal requires force to lift it against the action of gravity. We can measure the force employed, or the work done, in lifting a pound against gravity, and similarly we can measure the force employed, or the work done, in forcing a magnet out of its natural position against the force of the earth’s magnetism.

In considering the earth’s influence upon a magnet we shall notice:

1. How to find the magnetic meridian.
2. How to find the horizontal component of the earth’s magnetism.
3. How to find the vertical component of the earth’s magnetism.

Determination of the Magnetic Meridian.

The reader is not supposed to have at his command the apparatus usually found in physical laboratories, but to require a fairly correct method of determination sufficiently accurate, in fact, for all practical purposes.

Take an ordinary bar magnet. If the magnetic axis of the bar corresponds with the geometric axis, the meridian is easily found. At each end of the bar magnet, midway between its vertical sides, and therefore in the plane of the geometric axis, attach a small, short pointer—a bristle will do. Having determined the table or work bench upon which the meridian is to be marked, fix a hook in the ceiling above this place.

Fasten to the hook a silk thread or a small steel wire, according to the weight of the magnet, and by the silk thread or the wire suspend the bar magnet, which for convenience may be carried in a stirrup of light cardboard, Fig. 35. When suspended, the magnet should just swing freely upon the table, or rather over a piece of looking-glass, which should be placed upon the table face upwards. The glass may be kept in position by a
few pins, not by nails or screws of iron. In fact, the less iron in the vicinity of the magnet the better.

The suspending thread must be free from torsion. To obtain this, put a piece of lead, of equal weight, to the magnet in the stirrups, twist the hook in one direction or the other, till the lead hangs approximately in the magnetic meridian, a position which may be determined, as shown, by an ordinary compass needle. When the lead is perfectly stationary in this direction, hold the stirrup and replace the lead by the magnet, taking care that the N pole of the magnet is directed towards the north, otherwise, on freeing the stirrup, the magnet will swing halfway round, and give a twist on the thread of 180 deg. of torsion. The magnet being properly placed, set it vibrating through an arc of 5 deg. to 10 deg., and then allow it to come to rest. From above the magnet look down so that the image of the projecting bristle or wire, as reflected by the mirror, coincides with the object itself. By this means any error due to parallax is avoided. Mark the position of the images, at both ends of the magnet, on the surface of the mirror with dots, and call these dots A and A'. Now reverse the magnet in the stirrups so that what was the top face is put underneath—the north pole, of course, still pointing to the north. Repeat the observations at each end of the magnet, marking the images as before, calling these new marks B and B'. The object of this reversal of the magnet is to correct any errors arising from the magnetic axis of the needle not corresponding with its geometric axis.

Remove the magnet.

Join A A' and B B', with straight lines.

Draw a line bisecting the angle formed by these two lines, and the straight line thus bisecting the angle will be the plane of the magnetic meridian required, Fig. 36.

![Fig. 36.](image)

The table or bench, if fixed, can be permanently marked, or permanent marks can be placed along the floor and up the opposite walls of the room.

Having determined the line of the meridian, we are in a position to determine the horizontal component of the earth's magnetism, and from the value so found to calculate the total magnetic force.

To find H, the Horizontal Component of the Earth's Magnetism.

A freely-suspended magnet needle, if free to move in any plane, sets in the direction of the line of dip—that is, in the direction of the earth's lines of force. In other words, whatever force is acting upon it, is acting along the line of dip. The total force thus acting does not admit of being readily measured by any direct method, but by resolving it into components acting at right angles to each other, one vertically and one horizontally, according to the well-known principle of the parallelogram of forces, we can measure the force of either component, and so calculate the total force.

Let $n$ represent the magnet needle inclined to the horizontal by the angle of dip $d$; also, let $H$ represent the horizontal component, $V$ the vertical component, and $T$ the total force, Fig. 37.

Then
$$T = \frac{H}{\cos d}$$

or,
$$T = \frac{V_1}{\sin d} = \frac{V}{\sin d}$$

Of the two, $H$ and $V$, the determination of $H$ is less liable to error, and is therefore the one usually selected to measure.

![Fig. 37.](image)

Employing Gauss's method, which consists of determining two values:

First.—The product of the moment (M) of the magnet into the horizontal component of the earth's magnetism, $H = (MH)$, as shown by the period of vibration of a magnet freely swinging in a horizontal plane under the earth's magnetism alone; and

Secondly, the ratio $\frac{M}{H}$ as measured by the angle through which a short compass needle is deflected by the same magnet at a known distance.

The magnetic moment of a magnet is the product of the strength of either pole into the distance between the poles.

A convenient and inexpensive set of apparatus for determining $H$ has been designed by Mr. J. T. Bottomley, of Glasgow University. It consists essentially of two distinct parts:

1. A wooden chamber or box, the base of which is supported by levelling screws—one at each corner. This is used for determining the period of vibration.

2. A magnetometer, consisting of a small closed chamber, in which is suspended a short magnetised needle with mirror attached—similar to the arrangement in Sir W. Thomson's reflecting galvanometer. This is employed in measuring the angle of deflection produced by the magnet, whose period of vibration has already been ascertained.

Make a box, Fig. 38, about 12in. high, 6in. wide, and 6in. deep, with the top, bottom, and two sides...
made of wood, the two remaining and opposite sides being glass plates, capable of sliding in vertical grooves cut in the wooden sides. These glass plates when raised give access to the interior of the box, and when lowered into their ordinary position close the box and effectually prevent the vibrating magnet needles being disturbed by air currents. To a wooden peg, P, so fixed as to be able to be turned in a hole in the centre of the top of the box, is fastened a single unspun silk fibre of convenient length, which carries at its lower end a light paper stirrup, in which the magnet used in the experiment is placed. A fine pencil line, or preferably a fine scratch made with a diamond, must be drawn vertically down the centre of each glass side, so that when the box is carefully levelled in a true vertical position, the two scratches and the silk fibre are all in the same plane.

To Determine M H.

Place the box on the bench or table in such a position that the two scratches on the glass doors are in the magnetic meridian, as previously determined on page 294, and level the box until the silk fibre hangs in the same plane. Now raise one of the doors, and place in the stirrup a brass or copper rod of equal weight to the magnet which will subsequently replace it. If on the rod coming to rest its axis does not coincide with the magnetic meridian, it can be made to do so by a little manipulation of the peg at the top. The peg must be gently turned till the copper rod lies in the plane of the magnetic meridian.

Now raise one window, take hold gently of the stirrup, and replace the copper rod by a well-magnetised piece of hard steel wire of the same weight, and from 3 in. to 4 in. in length. Some care is required in this operation, and especially as to the poles of the magnet. If the student is standing on the south side of the apparatus the needle must be held by the south-seeking pole, and the north-seeking pole pushed through the stirrup, otherwise, on releasing the stirrup the needle will swing round and impart a torsion of nearly 180 deg., on to the silk fibre. If he stands on the north side of the apparatus the action must be the reverse of the above—the north-seeking pole will be held, and the south-seeking pole pushed through the stirrup. If the replacement of the copper by the magnet needle has been carefully done, the needle should hang in the magnetic meridian, but if it does not—that is, if it is slightly out—it may be brought into position by turning the peg. It is difficult to fix up a fibre absolutely without torsion, and the copper is first placed in the stirrup to get rid of any torsion that happens to exist. Assuming, then, we have the magnet in position, we want to make the needle swing slightly on both sides of the scratches on the glass. This we can do if we approach a small magnet with one pole pointing towards the centre of the suspended needle, giving a slight movement to the magnet, which will set the needle vibrating. When it is vibrating through an arc of about 5 deg. or 10 deg., let an assistant observe the times of successive transits, using a watch with a seconds' dial. To make this observation, place the eye in a line with the two scratches, and observe the transit made by the nearest end of the needle across the plane of the scratches. What we require to know is the time of a "complete vibration," that is, the time between one crossing the meridian to the next crossing of the meridian in the same direction—thus it is only necessary to notice the transits in one direction. The recurrence of the tenth, twentieth, thirtieth, fortieth transit (if the needle continues in vibration so long) should be recorded. The mean time of these readings divided by the number of transits, gives approximately the mean time of a complete vibration. A series of three or four such sets of readings should be made, and the mean of the series taken for the true value. The time, T, required by a magnet whose moment (vide next paragraph) of inertia = K, to make one complete vibration through a small arc, is found by the following formula:

\[
T = 2\pi \sqrt{\frac{K}{MH}}
\]

or

\[
T^2 = 4\pi^2 \frac{K}{MH}
\]

therefore

\[
MH = \frac{4\pi K}{T^2}
\]  \hspace{1cm} (A)

Moment of Inertia, K.

The moment of inertia of a material point, referred to an axis round which it revolves, is its weight multiplied by the square of its distance from the axis. The moment of inertia of a body round any axis is the sum of the moments of all its particles round that axis. The value of K depends only on the form and mass of the body, and is not altered by magnetisation. The following table gives the values of K for a few bodies of symmetrical form.

<table>
<thead>
<tr>
<th>K = moment of inertia, W = weight of body, r = radius.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of K</td>
</tr>
<tr>
<td>1. A long, thin, uniform bar, whose thickness and width are small compared with its length, l, suspended at its centre of gravity.</td>
</tr>
<tr>
<td>( K = \frac{Wl^2}{12} )</td>
</tr>
</tbody>
</table>
2 A rod of length \( l \), with square cross section, each side of breadth \( b \), the axis of suspension passing through the centre of gravity.

\[
K = W \frac{l^2 + b^2}{12}
\]

3. A cylinder of length \( l \), and radius \( r \), suspended by a perpendicular to the middle point of the axis.

\[
K = W \left( \frac{l^2}{12} + \frac{r^2}{4} \right)
\]

4. A hollow cylinder, inner radius \( r \), outer radius \( r_1 \), referred to its central axis.

\[
K = \frac{r^2}{2} - \frac{r_1^2}{2}
\]

5. A cylinder referred to its axis.

6. A ring whose thickness is small compared with its radius, \( r \), suspended at its centre of gravity and at right angles to plane of ring.

\[
K = W \frac{r^2}{2}
\]

In the case of the magnet needle, we deal with a body either of rectangular or circular section. If the former, carefully measure length, \( l \), and breadth, \( b \). If the latter, measure the radius, \( r \), and in both cases \( W \), the weight.

Then, for a rectangular-shaped needle or bar

\[
K = W \left( \frac{l^2 + b^2}{12} \right)
\]

For a cylindrical-shaped needle or bar

\[
K = W \left( \frac{l^2}{12} + \frac{r^2}{4} \right)
\]

Having thus ascertained the time of vibration, \( T \), and the moment of inertia, \( K \), we can proceed to the

**Determination of the Ratio \( \frac{M}{H} \).**

Another apparatus, termed a magnetometer, Fig. 39, is employed in obtaining this ratio. It consists of a circular wooden base, \( B \), supported on three levelling screws. To this base a vertical pillar is fixed, 6in. high, 2in. wide, and 1in. thick; having cut nearly along its face a narrow groove opening near the bottom into a flat circular chamber, and at the top continued by a small aperture to the outside. At the top of this small aperture is a peg. A single fibre of silk goes through the aperture, and the silk is fixed by means of the peg and a little wax. At the lower end of the silk fibre is fastened a small mirror, to which is attached a small magnet. The length of the silk thread is regulated before fastening at the top, so that the magnet hangs freely in the flat circular chamber near the bottom of the vertical piece. A glass plate covers the face of the vertical piece in front of the mirror. This plate can be kept in position by a couple of elastic bands, and it prevents any disturbance of the mirror from air currents.

Besides the magnetometer, we require a long flat rule at least a metre long, divided into centimetres and millimetres. Place this rule flat on the table so that its centre point, fiftieth centimetre, comes upon the meridian line marked on the table, Fig. 36. Set the magnetometer with its mirror facing \( E \) or \( W \), according to position of magnet needle on the back of the mirror—that is, so that the north-seeking pole points to the north. Take care that the suspended fibre is free from torsion, and hangs approximately over the point of intersection of the meridian and the flat rule.

Opposite the glass face of the magnetometer is placed a vertical screen, having upon it a scale in millimetres as shown in Fig. 40. This scale may be of paper pasted on the screen. Just below the central division of the scale is a small circular aperture having a thin wire across its vertical diameter. A paraffin lamp placed behind the screen, with its flame set edgewise, will send a circular beam of light through the aperture, and this falling on the mirror of the magnetometer, is reflected back on the scale of the screen, the shadow of the wire showing most distinctly the movement of the mirror. By interposing a convex lens between the hole and the mirror, and varying the distance of the lamp, a sharply-defined image of the cross wire is projected on the scale. It will simplify subsequent calculation if the distance between the mirror and scale be made exactly 1 metre.

Care should be taken that the stand carrying the vertical scale is placed parallel to the meridian line on the table, and that the spot of light and image of cross wire stands exactly at the zero point of the scale, if the divisions are numbered outwards from the centre, or at the 500 division if they are numbered consecutively from left to right (assuming the scale to contain 1,000 divisions).

Having satisfactorily arranged the magnetometer and
scale, take the magnetised needle, whose time of vibration has been determined, and place it “end on” — i.e., with one of its poles directed towards the magnetometer, and in such a position that its centre shall be directly over, say, the 200th * division of the horizontal ruler or scale, and supported by a convenient block of wood, at such a distance above the table that the axis of the needle produced would pass through the centre of the small magnet and mirror of magnetometer, Fig. 41.

![Fig. 41.](image)

Suppose the magnetised knitting needle to be placed on the W side of, and with its N pole turned towards, the magnetometer. Read off deflection of spot of light. Then reverse position of magnet so that the S pole is directed towards magnetometer, the centre of needle remaining at same distance as before, the spot of light will now be directed towards the other side of zero of scale. Again read off and take mean of the two readings. Now remove the needle and its supporting block to the other (E) side of the magnetometer, and place it so that its centre shall be at a distance from the centre of the magnetometer corresponding to that at which the two previous readings were taken (300 mm). To do this, evidently we must place the centre of the needle over the 800th division of the flat scale. Proceed to take the mean of two more readings, using alternate poles of the needle. The mean of the two means so obtained may be taken as the value of the deflection in divisions of the scale. Let it be called the “observed deflection.” But since the angular velocity of the spot of light is twice that of the mirror attached to the small magnets of magnetometer, half the “observed deflection” must be taken as representing the true value of the deflection at the distance of 300 mm. Assuming, as we have done, that both the horizontal and vertical scales are divided equally — i.e., in millimetres — then half the observed deflection divided by distance of scale from mirror will give us the tangent of the angle through which the magnet has been deflected by the magnetised needle at a distance of 300 mm.; call this tan d. By taking readings with magnetised needle alternately on each side of magnetometer, any error in distance arising from non-coincidence of the suspended magnet with the 500th division of the horizontal scale is corrected; and half the distance between the position occupied by the centre of the magnet during the two deflections (in the above case 200 mm. and 800 mm.) = \frac{800 - 200}{2} = 300 may be safely taken as the distance, r, of centre of magnet from centre of deflecting needle.

Then the ratio of \( \frac{M}{H} \) is given by the formula

\[
\frac{M}{H} = \frac{1}{2} r^2 \tan d \quad \ldots \quad (B)
\]

Instead of the deflecting magnet being placed “end on,” it may be placed “broadside on” — i.e., the horizontal metre scale may be placed so that its 500th division shall be immediately underneath the magnetometer as before, but this time parallel to the meridian instead of at right angles to it, and the needle, with its supporting block, placed alternately at equal distances on the N and S sides of the magnetometer, and with its poles pointing E and W, Fig. 42.

Two readings with poles reversed are taken at each position, and their mean value calculated as described in the “end on” method. Half this value in scale divisions divided by distance of magnet from scale, gives us tan d. In this arrangement, with tan d and distance r of centre of deflecting needle from magnetometer, \( \frac{M}{H} \) is found as follows:

\[
\frac{M}{H} = r^2 \tan d.
\]

From these data we can calculate in absolute measure either the value (H) of the horizontal component of the earth’s magnetism; or (M) the magnetic moment of the magnet employed during the investigation.

To Find H.

Divide first equation (A) by second equation (B) and extract the square root.

\[
\frac{M}{H} = \frac{4 \pi^2 K}{T^2} \quad \text{or} \quad \frac{4 \pi^2 K}{T^2}
\]

\[
\frac{M}{H} = H^2 = \frac{4 \pi^2 K}{T^2} \quad \frac{1}{2} r^2 \tan d
\]

or

\[
H = \frac{2 \pi}{T} \sqrt{\frac{K}{\frac{1}{2} r^2 \tan d}}
\]

To Find M.

Eliminate H by multiplying first and second equation together, and extract the square root.

\[
M H = \frac{M}{H} \cdot \frac{M H}{H} = \frac{4 \pi^2 K}{T^2} \cdot \frac{1}{2} r^2 \tan d
\]

or,

\[
= \frac{4 \pi^2 K}{T^2} \cdot \frac{1}{2} r^2 \tan d
\]

\[
\therefore \cdot = \frac{2 \pi}{T} \sqrt{\frac{K}{\frac{1}{2} r^2 \tan d}}
\]

* Any distance may be taken which will give a convenient deflection; the stronger the magnetism of the needle the greater the distance at which it can be placed from the magnetometer.
Example 1.—The following value of $H$ was obtained, employing the method and apparatus described in the text.

<table>
<thead>
<tr>
<th>Time of one complete vibration.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>First series.</td>
<td>Second series.</td>
</tr>
<tr>
<td>3h. 5' 40&quot;</td>
<td>3h. 22' 00&quot;</td>
</tr>
<tr>
<td>10th vibration 3h. 6' 41' 5&quot;</td>
<td>3h. 25' 02&quot;</td>
</tr>
<tr>
<td>20th ,, 3h. 7' 43' 5&quot;</td>
<td>3h. 24' 04&quot;</td>
</tr>
<tr>
<td>30th ,, 3h. 8' 46&quot;</td>
<td>3h. 25' 06&quot;</td>
</tr>
</tbody>
</table>

\[
\text{Mean } \frac{186}{0} \text{ minute.}
\]

Length of magnetised needle 8 cm. = \(l\)

Radius of magnetised needle 0.1 cm. = \(r\)

Weight of magnetised needle 1-848 grammes = \(W\)

Therefore, moment of inertia \(K = W\left( \frac{e^2}{12} + \frac{r^2}{4} \right)\)

\[
= 1-848 \times \frac{8^2}{12} + \frac{1^2}{4} = 9-99
\]

Distance of scale from magnetometer = 600 mm.

Observed deflection of spot of light = \(D = \ldots \ldots = 70 \ldots \ldots \) (scale divisions)

True deflection of magnet = \(D = d \ldots \ldots = 35 \ldots \ldots \)

Tangent of \(d = \frac{35}{600} = 0.0581\)

Distance of centre of deflecting magnet from centre of mirror 22 cm.

\[
r^2 = 10648
\]

\[
2 \pi = 6-2832
\]

Hence \(H = \frac{2 \pi}{T} \sqrt{\frac{K}{\frac{1}{2}r^2 \tan d}}\)

\[
= 6-2832 \sqrt{\frac{9.99}{309.3}}
\]

\[
= 1.013 \times 0.32
\]

\[
= 0.32
\]

Comparison of the Horizontal Intensities of Two Magnetic Fields.

The following method of measuring the strength of the field surrounding the pole of any given magnet at varying distances, or of comparing the forces or "fields" of two or more magnets at the same distance, depends upon the law of pendular vibrations, "that the force is proportional to the square of the number of vibrations executed in a given time."

Suspend in the paper stirrup of apparatus, Fig. 35, a short magnetised needle, about 1 in. long, following the instructions given on p. 295 as to the position of the chamber with respect to the meridian, absence of torsion, etc. Since the pole of a magnet vibrating in the field produced by fixed magnet is also under the influence of the horizontal component of the earth's magnetism, means have to be taken to ascertain the later quantity, in order to eliminate it. To do this, set the needle vibrating through a small arc by bringing a weak magnet near the outside of the case, taking care to prevent any swinging motion being given to the suspending fibre, and proceed to count the number of transits of the nearest pole of the needle across the plane of the scratches on the glass doors of the instrument during any convenient period of time, say, 1 minute; call this number \(n_1\), then the force of the earth's magnetism (or strength or field) acting on the needle is measured by \(n_1^2 = \frac{E}{H} \).

Now place a long bar magnet with its axis in the magnetic meridian, and raise to such a distance above the table that its axis produced would pass through the centre of the needle and paper stirrup, and remembering to place the bar magnet so that the pole nearest the vibrating needle shall be of opposite polarity to that of the needle. Again set the needle in vibration, and count the number of transits made in the same interval of time as before (1 minute) = \(n_2\), calling the force due to the pole of the bar magnet at distance \(d\) \(\mu M\); then the joint effect of the earth and magnet, or \(E + M\), is measured by \(n_1^2\); therefore \(M = E + M - E = n_2^2 - n_1^2\).

The distance \(d\), or the space separating the poles (not the ends) * of the needle and bar magnets, must now be carefully measured, and afterwards the pole of the magnet removed to a distance \(d_2\) and another observation made of the number of transits in 1 minute. Calling this number \(n_3\), and the force at \(d_2\) \(\mu M_2\), we have the combined force of the earth and magnet at \(d_2\) measured by \(n_3^2\); and, therefore, \(M_2 = E + M_2 - E = n_3^2 - n_1^2\); or, \(M_1: M_2 = n_3^2 - n_2^2 : n_2^2 - n_1^2\).

Since the same magnet has been employed during the whole time of the experiment and only the *distance* separating its pole from that of the needle has varied, we shall find, on comparing the distances \(d\) and \(d_2\) with the forces \(M_1\) and \(M_2\), that the latter vary inversely as the square of the former.

Example 2.—A short magnet suspended by the silk fibre, Fig. 38, when under the influence of the horizontal component of the earth's magnetism alone, made 17 complete vibrations per minute = \(n_0\). The N pole of a long bar magnet was then placed at a distance of 25 cm. = \(d_1\) from the centre of the vibrating magnet, when the number of vibrations executed in 1 minute was 24 = \(n_1\). On removing the pole of the

* In long thin steel magnets the pole is situated at a distance of from \(\frac{1}{3}\) to \(\frac{1}{6}\) the length of the bar from its ends.
bar magnet to a distance of 50 cm. = \( d_2 \), the number of vibrations in 1 minute fell to \( 19 = n_3 \).

Then as

\[
\begin{align*}
n_2 - n_1 : n_3 - n_1 & : : \frac{1}{d_1^2} : \frac{1}{d_2^2} \\
24^2 - 17^2 : 19^2 - 17^2 & : : \frac{1}{25^2} : \frac{1}{50^2} \\
576 - 289 : 361 - 289 & : : \frac{1}{1^2} : \frac{1}{2^2} \\
287 & : 72 : : 4 : 1
\end{align*}
\]

Measurements of the Magnetic Moments of the same Magnet after different increments of Magnetism have been imparted to it; or, Comparison of the Magnetic Moments of two or more Magnets with each other.

We saw on page 287 how the magnetic moments, \( M \), of a magnet might be determined in absolute units, the value of \( H \) being obtained at the same time. The following method, known as the "deflection method," enables us readily to compare the moments of a series of magnets if the value of \( H \) at the place of observation is known.

The magnetometer, scales, lamps, etc., are arranged, as in Fig. 41, for the "end on" method, only as we shall probably find the magnets we are using are more powerful than the magnetised knitting needle used in the determination of \( H \), they will necessarily have to be placed at a greater distance from the magnetometer; therefore, instead of placing the 500th division of the metre rule underneath the centre of the magnetometer, it will be advantageous to have the whole length of the metre rule on one side of the magnetometer, the suspending fibre hanging just over the zero end of the rule, as shown in outline in Fig. 43.

Having everything arranged with spot of light exactly over centre of vertical scale, place the deflecting magnet "end on" at such a distance from the magnetometer as will produce a suitable deflection. Let \( r \) = this distance between the centres of the magnet and the needle, and \( d \), the deflection obtained. Reverse the magnet so that its opposite pole is now directed towards the magnetometer, the centre of the magnet remaining at the same distance as before, and again note deflection, \( d \) (this time on the opposite side of zero). Take the mean of these two deflections \( \frac{d_1 - d_2}{2} \), and call it the "observed deflection" \( d_0 \), then the magnetic moment, \( M \), of the magnet is

\[
M = \frac{1}{2} HR^2 \tan d_0.
\]

Removing the magnet, and varying its magnetism by any of the known methods, and afterwards replacing it in its former position (or, in the case of comparing two separate magnets, replacing the first magnet by the second, and taking care that the distance between the centres of the magnet and needle is accurately maintained), take the mean of two other observations, with reversed poles, let this observed deflection be \( d_0 \), then, as before

\[
M_1 = \frac{1}{2} HR^2 \tan d_0.
\]

and since \( H \) and \( r^2 \) are common to both equations it follows that

\[
M : M_1 :: \tan d_2 : \tan d_6.
\]

It has been mentioned that the definition of a single magnetic pole was purely ideal, but that by taking a long thin bar and magnetising it, the distance between its poles becomes so great in comparison to the distance separating the poles of the neighbouring magnet that the effects due to the more remote pole may be neglected. It is only under such conditions that the law of "inverse squares" holds good. When the length of the magnet, and therefore the distance between its poles, is small, the needle of the magnetometer is influenced by both poles of the deflecting magnet, in which case it may be proved that the total action of the magnet must diminish in an inverse ratio to the third power of the distance, provided the action of a single pole really stands in an inverse ratio to the square of the distance.

Weber has by this means indirectly proved the law of inverse squares.

Arrange the apparatus and proceed as follows. Either the magnetometer, Fig. 38, or a delicately-suspended compass needle may be employed.

Let \( a \ b \) be a short magnet 10 cm. long, whose centre is placed at 100 cm. from \( C \), Fig. 48, the distance of one pole, say \( b \), will be 95 cm., and the other pole, \( a \), 105 cm. from \( C \).

If we call the attraction \( b.c = 1 \), at a distance of 1 cm., the attraction at 95 cm. will be \( 1 \frac{1}{95^2} = \frac{1}{9,025} \) if the action of the pole stands in an inverse ratio to the square of the distance.

From the same data, it follows that the repulsion of the pole \( a.c \) is \( \frac{1}{105^2} = \frac{1}{11,025} \); therefore the total action exerted by the short magnet \( a.b \) on the magnetometer, \( C \), is

\[
\frac{1}{9,025} - \frac{1}{11,025} = \frac{20}{9,950}.
\]

If now the magnet be removed to double its former distance, so that its middle be 200 cm. from \( C \), and the distance \( b.c \) being 195 cm., and \( a.c \) 205 cm., the attraction \( b.c \) will be \( \frac{1}{195^2} = \frac{1}{38,025} \), and the repulsion \( a.c \)

\[
\frac{1}{205} - \frac{1}{42,025} = \frac{1}{38,025} - \frac{1}{42,025} = \frac{20}{159,800}.
\]

Therefore, by removing the bar magnet from 100 cm. to 200 cm., its action diminishes in the ratio \( \frac{20}{9,950} \) to \( \frac{20}{159,800} \) provided the action of each separate pole stands in the inverse relation to the square of the distance.

But \( \frac{9,950}{159,800} = \frac{995}{15,980} = \frac{2}{15,980} = \frac{1,990}{15,980} = \frac{1}{8} \) or at double the distance the action is only \( \frac{1}{8} \) as intense; and \( b \) is the third power of 2.
Example.—Compare the magnetic moments of two magnets, \( A \) and \( B \), from the following data. In each case the centre of the magnets were 50 cm. from the magnetometer. A gave an "observed deflection" of 40 scale divisions, while \( B \) produced a deflection of 36. Distance of scale from magnetometer 600 mm.

Value of \( d = \frac{\text{Scale reading}}{2} \)

\[
\begin{align*}
\text{A} & : \text{B} : \tan \theta_A : \tan \theta_B \\
20 & : 600 & 18 & : 600 \\
\ldots & : 0.033 & : 0.030 & \\
\ldots & : 11 : 10
\end{align*}
\]

Determination of the Angle of Inclination or Dip.

The determination of the angle of dip is of great importance, as coupled with the previously obtained value of \( H \) it enables us to calculate the total intensity of the earth’s magnetism at the place of observation.

Place the instrument so that the graduated vertical circle is parallel to the magnetic meridian, and since the meridian line is already marked upon the table this is easily effected; but supposing the meridian were not known, its direction could be determined with sufficient accuracy by simply turning the inclination instrument through such an horizontal angle that the needle hangs vertically. When this is the case the plane of vibration of the needle is approximately east and west, and 90 deg. from this plane will be the meridian.

Set the needle in vibration by bringing pole of small magnet near it, remove magnet, and allow the needle to settle, and take readings at both ends of needle. Repeat the operation, and take the mean of the four readings.

By reading at both ends of needle, any error due to eccentricity of axis of suspension to centre of circle is corrected, and by repeating the observation and making the mean the probable error is still further reduced.

Take out the needle from its bearings and rotate it through an angle of 180 deg. round its own axis—i.e., so that the side formerly facing the observer is now turned away from him—and again take the mean of four similar readings. The object of reversing pivot on bearings is to eliminate any possible lateral displacement of centre of gravity from axis of pivot.

The needle must again be removed, and its magnetism reversed by carefully stroking it with a powerful bar magnet. This is effected by laying the needle on the table and bringing over, say, its N-seeking end—the S seeking pole of the bar magnet (the magnet being held in a vertical position) and gradually drawing the magnet along the needle to its other end. Now lift off the magnet and carry it back at a distance from the needle to its former position, and repeat the action; then turn the needle so that the side in contact with the table is now upwards, and repeat the stroking. The polarity of the needle will be completely reversed.

The needle is again mounted on its bearings, and another series of observations made as before—i.e., two with one face of the needle towards you and two with its face reversed, taking care to read at both ends of the needle each time. By reversing the magnetism of the needle any error arising from longitudinal displacement of its centre of gravity from the axis of the pivot is corrected.

The mean of these 16 observations will be the angle of dip = \( d \).

\[
\text{Fig. 44.}
\]

Example.—With a simple form of dip needle, constructed as in Fig. 44, the following results were obtained:

<table>
<thead>
<tr>
<th>S seeking pole</th>
<th>Mean of</th>
<th>N seeking pole</th>
<th>Mean of</th>
</tr>
</thead>
<tbody>
<tr>
<td>253:5 - 180 = 73:5</td>
<td>74:0</td>
<td>253:7 - 180 = 73:7</td>
<td>74:2</td>
</tr>
</tbody>
</table>

After reversing pivots on bearings.

<table>
<thead>
<tr>
<th>253:5 - 180 = 73:5</th>
<th>73:5</th>
<th>253:3 - 180 = 73:3</th>
<th>73:4</th>
</tr>
</thead>
<tbody>
<tr>
<td>244:0 - 180 = 66:0</td>
<td>63:5</td>
<td>244:5 - 180 = 66:5</td>
<td>64:0</td>
</tr>
</tbody>
</table>

After reversing magnetism, but on same bearings as in \( B \).

Angle of dip = \( \frac{276.6}{4} = 69.15 \)

If the plane of the dip circle be turned out of the magnetic meridian, the angle of dip increases until at 90 deg. from the meridian the needle stands vertically. This arises from the fact that while the vertical component, \( V \), of the earth’s magnetism remains constant, the horizontal, \( H \), has become nil, its effect being merely to put a strain on the pivot. At any intermediate angle, \( a \), say 60 deg., while \( V \) remains unchanged, \( H \) becomes diminished.

Resolving the horizontal force acting on the end of the needle into two components, \( H_1 \) in the present plane of the needle and \( H_2 \) at right angles thereto, the force \( H_1 \) merely acts as a strain on the pivot, while \( H_2 \) represents the new value of \( H \). But \( H_1 \) in this case equals \( H \cos \alpha \), and since \( \tan a = \frac{V}{H} \), the tangent of the new angle, \( a \), will be \( \frac{V}{H_1} = \frac{V}{H \cos a} = \frac{V}{H} \times \frac{1}{\cos a} \), and since the true angle of dip = \( d \), and \( a \) the angle through which the
plane of the needle has been turned, the tangent of the
new angle of dip, D, will be \(\tan \frac{d}{\cos a}\).

Example.—The angle of dip \(d\) being 69 deg. (see preceding example), the plane of the circle was turned through an angle of 69 deg. = \(a\), when the angle of dip increased to \(79^\circ 8\) deg. = \(D\).

By above formula, \(\tan D = \frac{\tan d}{\cos a} = \frac{\tan 69^\circ}{\cos 69^\circ} = \frac{2.625}{0.5} = 5.25\). Referring to table of tangents, we shall find that \(5.25 = 79^\circ 5\) deg.

Having now measured the horizontal force, \(H\), and the angle of dip, \(d\), the total force and its vertical component can be calculated.

For let any inclination needle free to vibrate in plane of the magnetic meridian take up its position, then if we let \(d\) = angle of dip, and \(T\) the total force, resolving this total force into two components, \(H\) and \(V\), at right angles to each other, we have \(\frac{H}{\cos d} = T\); \(\therefore T = \frac{H}{\cos d}\);

and, again, since \(\frac{H}{V} = \tan d\), \(\therefore V = H \tan d\).

Hence, \(H\) and \(d\) being determined by experiment, we have only to divide the value of the horizontal component, \(H\), by the cosine of the angle of dip in order to obtain the total force; or, multiply the horizontal component by the tangent of the angle of dip to get the value of the vertical component, \(V\).

Example.—The horizontal component, \(H\), having been determined and found equal to 182 dyne, and the angle of dip to be 69 deg. 15 min., what is the value of the vertical component, and also the total force of the earth’s magnetism?

The vertical component, \(V = H \tan d\).

\[= \frac{H}{\cos d} = \frac{182}{\cos 69^\circ 15\text{ min.}} = 182 \times 2.6396 = 480\text{ dyne.}\]

The total force, \(T\),

\[= \frac{H}{\cos d} = \frac{182}{\cos 69^\circ 15\text{ min.}} = 182 \times 0.3527 = 51\text{ dyne.}\]

The Tangent Galvanometer.

When a current of electricity flows through a conductor we have seen that a magnetic field is produced in the space surrounding the conductor, the effect being to cause any magnet capable of movement in its immediate neighbourhood to set with its magnetic axis at right angles to the conductor.

If the wire be bent into an arc of a circle and a current passed, the centre of the arc behaves exactly like the pole of an ordinary magnet, and any pole of a magnetic needle placed there will be attracted or repelled according to the direction of the current. If the conductor, hereafter called the wire, be bent into a circular shape, with radius of circle = \(r\), then length of wire in circle \(l = 2\pi r\), and current = \(C\), the force acting at centre of circle,

\[F = \frac{C}{2\pi r} = \frac{2\pi C}{r}.\]

If a magnet pole of strength \(M\) be placed at the centre of the circle, the force will be represented by the product of the strength of pole and the intensity of the field, or

\[F = \frac{M}{r}.\]

It is impossible to have a magnet with only one pole, but we can approximate to the ideal by having a magnet relatively small to the radius of the coil in the centre of which it is suspended, the force exerted upon either pole by the current being then practically the same.

This is the principle adopted in the tangent galvanometer.

This instrument consists of a vertical ring of wire; in some instruments several coils of thick and thin wire. The thick coils are used for large currents; the thin coils are for use with smaller currents, and can be used in series, in parallel, or separately. The coils are carried on a base supported by levelling screws, so that they may be kept in a vertical plane irrespective of inequality of surface upon which the instrument stands.

Fig. 45 shows one form of the instrument. At the centre of the coil, suspended on a delicate pivot, or by a silk thread, is a small magnet, whose length should not be more than \(\frac{h}{3}\) or \(\frac{h}{4}\) of the diameter of the ring. The magnet carries a light pointer at right angles to its axis, so as to enable the graduated card just underneath the magnet to be easily read.

In setting up the instrument the plane of the ring must be placed in the magnetic meridian, when the pointer should point to zero on the scale.

Since the magnetic field produced at the centre of the ring is very uniform, and the length of the magnet small in comparison to the radius of the coil, we may without serious error assume the poles to be at equal distances from the ring; whence a current through the wire will act upon each pole of the magnet with equal and opposite forces. The effect of this couple is to rotate the magnet round its point of suspension. When
a current passes, the magnet is rotated through a
deflection, \( d \). The extent of the rotation depends upon
the ratio of the force due to the current in the coils, and
the horizontal component of the earth's magnetism. In
all questions relating to a magnet we must consider the
effect of the earth's magnetism, or in some way
neutralise the effect. Roughly speaking, the earth acts
as a magnet with its poles near to but not quite in the
same direction as the geographical poles. The position
of the earth's magnetic poles is constantly, though
through small periods of time, slightly changing. Just
as we term the imaginary lines passing through any
place, and through the geographical poles, the geo-
graphical meridian of that place, so an imaginary line
drawn through a place and through the earth's
magnetic poles is called the magnetic meridian of that
place. The action of the earth's magnetism upon the
suspended needle is to direct the axis of the needle
into a position parallel to the magnetic meridian—in
other words, to make the needle point north and south
between the north and south magnetic poles. If the
needle be moved out of the meridian, the horizontal
intensity, \( H \), of the earth's magnetism tends to pull it
back into the plane of the meridian.

Now we are in a position to determine the law which
governs the needle under the action of a current in the
coil. It must be remembered that the action on one
pole is equal and opposite to that on the other.

Let \( N, S \), Fig. 46, represent the magnet in the plane
of the coil, both magnet and coil being in the plane of
the magnetic meridian.

Let \( N, S \), be the new position of the magnet when a
current is sent through the coil.

Let \( d \) be the angle through which the needle is
deflected.

\( H \), as before, is the horizontal intensity of the earth's
magnetism.

Let \( F \) be the force due to the current.

Then the moment of couple due to earth's magnetism
is \( \mathbf{H} \times \mathbf{AB} \).

And the moment of couple due to current is \( F \times \mathbf{DE} \), but when the magnet is at rest these couples are
equal.

That is, \( F \times \mathbf{DE} = \mathbf{H} \times \mathbf{AB} \)

whence \( F = \mathbf{H} \times \frac{\mathbf{AB}}{\mathbf{DE}} \)

\( = \mathbf{H} \times \frac{\mathbf{AO}}{\mathbf{DO}} \)

\( = \mathbf{H} \tan \phi \)

which gives the law: “The magnetic force which,
acting at right angles to the magnetic meridian,
produces on a magnet the deflection \( d \) is equal to
the horizontal force of the earth's magnetism at
that point multiplied by the tangent of the angle of
deflection.”

At the same point \( H \) may be taken as constant,
hence the current varies as the tangent of the angle
of deflection. It must be noted that the strengths of
current are relative only. Currents can thus be com-
pared with one another.

In using a tangent galvanometer the aim should be
to get deflections as near to 45 deg. as possible, because
this is the most sensitive deflection of the instrument.
If two currents are to be compared, obtain deflections
as near as possible at equal distances on the two sides
of 45 deg. Thus if it is desired to get a current double
of another, let the apparatus be so arranged as to give
with the smaller current, say, a deflection of 30 deg.

\( \tan \) of 30 deg. = \( \frac{1}{2} \) \( \frac{\mathbf{H}}{\mathbf{DE}} \).

A current of double strength will give a deflection in
degrees of which

\( \tan = 2 \times \frac{\mathbf{H}}{\mathbf{DE}} \).

The tangent galvanometer enables us readily to
determine strength of current in absolute measure, and
then a division by 10 gives us strength of current in
amperes, because the practical unit of electrical current
is \( 10^{-4} \) or \( \frac{1}{10^4} \) of the C.G.S. unit of current. To obtain
the value of the current in absolute measure, or in

amperes, it is necessary to know the reduction factor or
the constant factor of the galvanometer for converting
indications of the galvanometer into absolute measure,
which is \( \frac{\mathbf{H}}{2 \pi} \) with one turn of wire in the coil, and

\( \frac{\mathbf{H}}{2 \pi n} \) with \( n \) turns of wire in the coil.

The formula for current then becomes

\[ C = \frac{r}{2 \pi n} H \tan d \]

and for current in amperes \( C = \frac{r}{2 \pi n} \tan d \times \frac{1}{10^4} \).

With the foregoing theoretical considerations we are
in a position to define “unit current”; it is “that
current which, flowing through a wire formed into
a circle of unit (1 cm.) radius, acts on a unit magnetic
pole placed at the centre with unit force (1 dyne) per
unit (1 cm.) length of the circumference.”

Hence, if the length of the arc be equal to 1 radian,
or 57 deg. 17' then unit current will repel a unit magnetic
pole with a force of 1 dyne, whereas, if the wire forms
a complete circle, the force at the centre will be \(2\pi \times \text{62832}\) dynes.

The relation of the forces acting on the poles of a short magnet placed at their centre by currents flowing through coils of different radii is very clearly illustrated by the following arrangement, due to Professor Poynting, of Mason College, Birmingham.

On a wooden base, supported on three levelling screws, is fixed a vertical board, about 18 in. square, having a circular hole bored through its centre. The diameter of the hole must be sufficiently large to allow the small mirror with attached magnet belonging to the magnetometer to swing freely, when suspended by a silk thread attached by a brass pin to the face of the board. An iron nail must not be used, as it would probably affect the magnet, and the silk thread must be kept a little distance from the face of the board, to enable the magnet and mirror to vibrate freely.

With a radius of 4 in. from the centre of the hole, a single layer of silk or cotton covered wire is attached to the face of the board either by some kind of cement, or by a few brass wire staples, the two ends of the coil being led down to the base, and soldered to two binding screws. A second coil of wire is also attached to the board in a similar manner, but with a radius of 5 in., and making two complete turns, its two ends being led down and secured to two other binding screws. At a suitable distance in front of the board and its rings (which, as in the case of a tangent galvanometer, must be set in the plane of the magnetic meridian) is placed the scale and lamp. When all is arranged satisfactorily, and the spot of light is focussed on the zero division of the scale, join up a single Daniell cell (and sufficient resistance to keep the spot of light well on the scale) with the terminals of the inner ring, and note deflection produced. On removing the connecting wires from the terminals of the outer circle of wire, the same deflection will be produced, for though the current now goes twice round the magnet, it does so at twice the distance. Therefore, the force at centre of first coil will be

\[
-C\frac{2\pi \times \text{C}}{r^2} = C \times \frac{2 \times 3.1416 \times 10}{10^2} = C \times \text{62832},
\]

and at centre of second coil

\[
-C\frac{2\pi \times \text{C}}{r^2} = C \times \frac{2 \times 3.1416 \times 2 \times 20}{20^2} = C \times \text{62832},
\]

as before, and since we are using equal currents in each case, \(C\) cancels out, and we see at once that the two forces are equal to each other. This fact can be still more strikingly shown by joining up the two coils "in series," but so that the current will flow round the two coils in opposite directions, when no deflection of the magnet will occur, the effect of one coil being exactly neutralised by that of the other.

If the student has grasped the fundamental principles on which the tangent galvanometer is based, he will be in a position to follow the directions given in the following pages as to the method of using the instrument, and as it is important that every student should possess one of these useful pieces of apparatus, we insert the following description taken from the South Kensington syllabus of the course of practical instruction in physics, whereby those students who are not prepared to incur the expense of purchasing an instrument from a professional maker can make one for themselves, which will be quite good enough for ordinary purposes.

"Cut three strips of thin card 1 in. wide, and long enough to go round a wood block 6\(\frac{1}{2}\) in. diameter. Lay on the first piece dry and fix the other two with weak glue; the joints should just meet, but not overlap, wind round with string and leave during the night to dry. On the middle \(\frac{1}{2}\) in. of the card wind 20 turns of thin insulated wire in two layers of 10 turns each. Tie the ends together, leaving them about 6 in. long. On either side of the thin coil, and touching it, wind one turn of thick wire and leave the ends about 8 in. long. Varnish, and leave to dry. Divide the card ring into four equal quadrants, taking care that one of the divisions is opposite the ends of the wire. This, when the card is mounted, will be the lowest point in the ring.

To the middle of the opposite division, which will be the highest point for a minute ring of fine wire, on either side of the remaining two divisions, fix a small block of wood so as to hold a 6\(\frac{1}{2}\) in. disc of card between them exactly at right angles to the plane of the ring. Mark each block with a central line, so that when a diameter of the card meets these lines the card is fixed centrally also. Divide the card into degrees and tangents. The degrees may be marked from a protractor, but the tangents are best found thus: Fix the card on a table and put a pin through its centre. At exactly 10 in. from the centre of the zero line fix a scale of inches divided into tenths, exactly at right angles to the zero line—say a straight edge against the pin and over each division of the scale, and where the straight edge cuts the circle of the card make a mark. These marks will form a scale of tangents. Make a hole in the centre of the card \(\frac{1}{2}\) in. in diameter. Fix the card in the ring, so that the diameter at right angles to the zero line is in the plane of the ring. Fix the ring vertically in the centre of an 8\(\frac{1}{2}\) in. square of wood, using blocks of wood to hold it in position; pass the ends of the wires through holes in the board, bringing the ends of the thin wires to binding screws at one corner of the board, and the thick wires to the opposite corner. Support on three levelling screws. Cut a piece of steel \(\frac{1}{2}\) in. thick; harden and magnetise. Fix with thin wire at right angles to steel a capillary glass pointer about 5 in. long. Support magnet and pointer by single silk fibre to small ring at top of card ring. Adjust length of silk so that magnet hangs in central aperture of card disc with pointer free to move. Turn ring into plane of magnetic meridian, and twist levelling screws till magnet swings freely in central hole.

With weak currents use thin wire coil, and with strong the thick wire."
Electromotive Force, or Electrical Pressure, and Resistance.

In the preceding pages we have defined the electromagnetic unit of current, and briefly explained how currents can be determined in absolute measure; it now remains to define the absolute units of electromotive force (pressure) and resistance, and from these and the unit of current to derive the practical units—i.e., volt, ohm, ampere, coulomb, watt, joule, and farad.

Ohm's law teaches us that the strength of a current flowing through a wire whose resistance is $R$, the ends of such wire being maintained at a difference of potential $V_1 - V_2$, is expressed by the formula

$$C = \frac{V_1 - V_2}{R} = \frac{E}{R}$$

where $E$ represents the electromotive force due to the difference of potential $V_1 - V_2$. Evidently in above equation the unit representing any one of the three quantities is dependent upon the other two. This connection between the three quantities will be made apparent by considering the action of an imaginary dynamo.

Suppose that in an uniform magnetic field—such as that due to the earth's magnetism—we place two parallel rails so that their plane is at right angles to the line of dip, Fig. 47. Let one end of each rail be connected to the terminals of a galvanometer, and the circuit completed by means of a metal slider, free to move along the rails. Assume for a moment that the system has no resistance. The slider being stationary, insert the N-seeking pole of a bar magnet between the rails, and therefore in the line of dip, when, supposing the rails to extend in a N and S direction, there will be a reverse current—that is, in the opposite direction to that in which the hands of a clock move—induced in the circuit, flowing from the east rail through the slider to the west rail, and thence through the galvanometer back to the east rail again.

On withdrawing the N-seeking pole of the magnet, a "direct" current—that is, in the same direction as the hands of a watch move in—will be produced. Now on inserting the N pole of the magnet, the effect is simply to increase the number of lines of force enclosed within the system comprising the rails, slider, and galvanometer, and withdrawal is accompanied by a corresponding decrease.

Hence we see that "increasing the number of loops or lines of force in a given area gives us a 'reverse' current," and decreasing the number furnishes a "direct" current.

Dispensing with the magnet, and simply using the magnetic field due to the earth, it is obvious that we can vary the number of lines of force enclosed by moving the slider. Suppose the slider to move with a velocity of 1 cm. per second, and call the electromotive force developed $E$, then a velocity of 2 cm. per second will yield an electromotive force of $2E$—in other words, the electromotive force increases with the velocity of the slider.

If the field be of unit strength, the distance between the rails, and therefore the length of the slider, 1 cm., and the distance travelled in unit time (1 second) be 1 cm., then the difference of potentials, or electromotive force, will equal one absolute limit.

Having our units of electromotive force and current fixed, it becomes an easy matter to define the remaining unit of resistance.

Referring again to our rails and slider, we see (since we have assumed that they are without resistance) that, in accordance with Ohm's law, as we increase the electromotive force by increasing the velocity at which the slider moves, we increase the current in the same ratio. Now letting the slider move 1 cm. per second as before, let us put so much resistance into the circuit that unit current flows; the resistance so added will equal one absolute unit of resistance, or we may define unit resistance as that resistance which under unit electromotive force conveys one unit of current per second, $C = \frac{E}{R}$.

If, therefore, we increase the velocity of the slider, we must, in order to keep the current equal to unity, increase the resistance in the same proportion, or $C = \frac{E}{R} \cdot \frac{n}{n}$.

These absolute units of electromotive force and resistance are far too small for actual work, therefore multiples of these absolute units have been taken to form a practical series—i.e.:

The Volt, or unit of electromotive force, is equal to 100,000,000, or $10^8$ absolute units, so that our ideal slider, in order to produce a difference of potentials equal to 1 volt, would have to traverse one hundred million centimetres per second.

The Ohm, or unit of resistance, would, as we have seen above, in order to maintain unit current, have to equal $10^8$ absolute units, for $C = \frac{E}{R} = \frac{E \cdot 10^8}{R}$. But, as before mentioned, the practical unit of current (the
ampere) is only one of an absolute unit, therefore we must, in order to reduce the current $\frac{1}{10}$, increase the resistance 10 times, or our slider must move with a velocity of 10° centimetres per second.

It would be impossible to construct our ideal rails and slider, but a closed circuit consisting of a coil of wire, in the centre of which a small magnet is suspended, may be easily constructed and caused to rotate in the magnetic field due to the earth’s magnetism.

Then, knowing the velocity of rotation, the strength of the field, length and resistance of the wire, and the deflection of the needle, it becomes possible to calculate the electromotive force, and therefore the resistance, necessary to permit unit current to flow. This was the method employed by the committee of the British Association in the determination of the “B.A.” unit of resistance, or “ohm.”

The Coulomb, or unit of quantity, represents the quantity of electricity conveyed by unit current in unit time—i.e., by a current of 1 ampere in 1 second. It is equal to $10^{-3}$ or $1 \frac{1}{6}$ of an absolute unities of quantity.

The Farad, or unit of capacity. A condenser has unit capacity if it contains unit quantity at unit difference of potential, or 1 coulomb under an electromotive force of 1 volt. It is equivalent to $10^{-9}$ or one thousand millionth of an absolute unit of capacity. Since the farad is too large for general purposes, the microfarad $= 10^{-6}$ absolute unit (or one millionth of a farad) is usually employed. The Atlantic cables have, on the average, a capacity of about 35 microfarad per knot.

The Watt, or unit of power, equals 10$^7$ ergs, or 1,000,000 absolute units of power. It represents the power conveyed by an ampere of current under a difference of potentials of 1 volt, or the power done by a current of 1 ampere through a resistance of 1 ohm. It is equal to $\frac{1}{16}$ horse-power.

The Joule, or unit of work or heat. Like the watt, or unit of power, it is equal to 10$^7$ ergs, but the factor time is introduced. It represents the work done, or heat generated by an ampere flowing through a resistance of 1 ohm or 1 coulomb falling through a difference of potential of 1 volt in 1 second. It will heat 2405 grammes of water 1 deg. C.

The Wheatstone Bridge.

For the measurement of resistances some form of Wheatstone bridge is essential, it being far more convenient and expeditious than any of the substitution or differential methods.

We shall first describe the method of using the ordinary Post Office form of bridge, and subsequently the kind known as Kirchhoff’s “slide wire or metre bridge,” a form of bridge that can be made by anyone possessing ordinary mechanical skill, and which, in combination with a set of resistance coils, will enable anyone to make the greater portion of the measurements described in the following pages.

For a detailed explanation of the theory of the Wheatstone bridge, the student must consult some standard text-book, such as Kenyon. We shall confine ourselves to practical details, merely remarking that the Wheatstone bridge is an arrangement of a series of resistances, by varying which we can, as in an ordinary proportional sum (three of the values being known), determine the fourth.

Theoretically, the resistances are placed as in Fig. 48. The three known resistances being placed in the arms A B, B C, and A E, while the unknown resistance, whose value is to be determined, occupies the fourth arm, C E. The poles of one or more cells of a battery (Daniell’s are very suitable) are connected to the points B E, having a key, $K_1$, in circuit. A delicate galvanometer, G, and key, $K_2$, are joined up with the points A C, and a certain ratio being given to A and B, $K_1$ is depressed. The resistance, D, is varied until, on closing $K_2$, no deflection of the galvanometer needle occurs. When this is the case it can be proved that as $B : A : : D : X$,

$$X = \frac{AD}{B}.$$

Assuming that the ordinary Post Office form of bridge is available, the connections are made as indicated in Fig. 49, where the lettering is similar to the theoretical diagram, Fig. 48.
The wires leading from the battery are joined to terminals B, E. These are usually marked “copper” and “zine.” This arrangement is useful in testing telegraph lines, but for measuring ordinary resistances it is immaterial to which of the two terminals, B, E, the copper is attached. The galvanometer is joined up to the two terminals, A C and the resistance to be measured is connected to the two terminals C E. Having everything arranged, take out the two 1,000-ohm plugs in the arms A B, B C, and also one of the infinity plugs.

Close the right-hand key, K 1, so as to complete the battery circuit, and immediately afterwards the left-hand key, K 2 (to bring in the galvanometer). The object of closing the battery key before the galvanometer key is to prevent the violent throw of the needle due to self-induction in the resistance coils.

The keys being held down, note the direction in which the needle of the galvanometer is deflected. This enables us to judge, when making subsequent adjustments, whether the resistance unplugged in A E is too high or too low. Suppose that, with the infinity plug removed, the deflection was to the right-hand side of the observer. Then a similar deflection obtained during the actual measurement shows that the resistance, A E, is greater than the unknown, C E, whereas a deflection to the left informs us that A E is less than C E. A E can then be varied till balance is obtained, and the needle remains stationary.

Having ascertained this necessary information, reinsert the plugs, and proceed with the actual measurement.

If the resistance to be measured is small, the two 10-ohm plugs in the arms A B, B C should be removed and A E adjusted till balance is secured, while with higher resistances the two 100, or 1,000, ohms should be employed instead of the two 10 ohms, as the nearer the values of the resistances in the four arms approximate to each other, the greater is the accuracy obtained. If with the resistances in the two arms, A B, B C equal—i.e., 10 : 10, 100 : 100; or 1,000 : 1,000, as the nature of the case may require—we find, on introducing a certain resistance in A E, that balance is obtained; then it follows that the unknown resistance equals that in A E, which is known, for as 10 : 10 : A E : C E.

But it will frequently happen that balance cannot be secured by altering the value of A E, the arms A B and B C remaining equal. Suppose that with A B and B C = 10 ohms each, that 25 ohms in A E is too low, and 26 ohms is too high, obviously the true value of C E lies between these two values. Replace the 10-ohm plug in A B, at the same time removing the 100-ohm. On making A E 250 ohms, we shall find it is too low and 260 too high, but increasing the value of the 250, unit by unit, we shall probably find that balance is obtained, say, when A E = 256 ohms; then the value of the unknown resistance will be as

100 : 10 : 256 : 25.6 ohms.

Supposing we still fail to obtain a balance, say, 256 is too low and 257 too high, change the ratio of the arms A B, B C to 1,000 : 10, and make A E 2,560, and increase step by step, as before, until balance is obtained, suppose when A E = 2,569 ohms then the unknown resistance, C E, is

1,000 : 10 : 2,569 : 25.69 ohms.

Should the resistance to be measured be greater than the whole resistance in the box, usually about 11,000 ohms, its value may be ascertained by varying the ratio of A B : B C, but in the opposite direction to that described above.

Suppose that with A E = 10,000, the deflection shows that it still falls short of that necessary to balance by making A B = 100 and B C = 1,000, we could get any value up to 100,000 ohms, for as 100 : 1,000 : 10,000 : 100,000, and by making A B 10, and B C 1,000, we have a range of 1,000,000 ohms, but with these high ratios the results can only be considered approximately true.

With the bridge properly adjusted, proceed as follows to measure the resistance of three lengths of wire.

(1) Separately.
(2) In series.
(3) In parallel.

Calling the three wires respectively A, B, and C, fasten the two ends of A to terminals C E, and measure its resistance, and the same for wires B and C.

Next join the three wires end to end “in series,” and measure the combined resistance; it should be equal to the sum of the separate resistance A, B, and C.

Care must be taken that the ends of the wires do not overlap more than is necessary to form a junction, otherwise the total length of the wires will be reduced and the resistance too low.

Next proceed to measure the resistance of the wires in “parallel”—by pairs—and prove that the resistance of two wires in parallel equals the product of their separate resistances divided by their sum, or

\[ R = \frac{A \times B}{A + B}. \]

Lastly, join the three wires in parallel, and show that the total resistance corresponds to that given by the formula

\[ R = \frac{A \times B \times C}{(A B) C + A B}. \]

Example.—Three wires measured separately gave the following resistances:

\[ A = 2.43 \]
\[ B = 4.09 \text{ ohms.} \]
\[ C = 4.65 \]

Measured in series the resistance was

\[ A + B + C = 11.16 \text{ ohms.} \]

With two of the wires in “parallel” the resistances were:

By actual measurement.  By calculation from

\[ \begin{align*}
A + B &= 1.592 \text{ ohms} \quad A + B \\
B + C &= 1.596 \quad 1.595 \\
B + C &= 2.180 \quad 2.181 \\
\end{align*} \]
Lastly, the three wires in parallel gave

\[ = 1.149 \text{ ohms} \quad 1.148 \text{ ohms}. \]

If the student has not a properly constructed bridge of the kind already described, he can readily make for himself one of the "slide wire" or metre bridge pattern. This is a very valuable and efficient form of bridge, and if carefully made will yield very satisfactory results.

To a well-seasoned board, 110 cm. long, 10 cm. wide, and 2\(\frac{1}{2}\) cm. thick, are attached, by screws, three thick strips of copper. One, 90 cm. long, having three binding screws soldered to it, one at each end, the other at the centre, is fastened parallel to the length of the board; the other two strips are each 6 cm. long, and have one binding screw soldered to one end of each strip. These two short strips are fixed transversely to the length of the board, and at a distance of exactly 1 metre between their inner faces. To the free ends of these strips of copper, the galvanometer wire replaces \(K_2\) in the Post Office bridge. In the more elaborate kinds of the slide wire bridge the galvanometer wire is attached to a movable block and spring key, \(A_2\). This block slides along the German silver wire, and by depressing the spring contact is made.

![Fig. 50.](image)

To make a measurement, place the set of resistance coils in the gap \(A\), and the unknown resistance in the other gap, \(X\), and slide the contact wire along till balance is obtained; then, as before,

\[ \frac{B}{D} = \frac{A}{X} \]

or,

\[ X = \frac{AD}{B}. \]

As with the other kind of bridge, it is necessary to ascertain whether a deflection of the galvanometer, say, to the right, indicates the resistance in \(A\) as being too high or too low. Of course, this is done making \(A\) or \(X\) infinitely great at first.
Having made the slide wire bridge, a set of resistance coils is necessary. It is better to obtain them from makers who are accustomed to the work, but there is nothing difficult in constructing such resistances. With the slide wire bridge the number of coils need not be so large as with the Post Office bridge for this reason: in the latter form we only have three ratios between the arms, \( a \) \( b \)-viz., 10 : 10, 10 : 100, and 10 : 1,000; whereas with the former we can get any ratio ranging between 1 : 999 and 999 : 1, although the values obtained when the slider approaches the ends of the slide wire are not comparable to those obtained when it is nearer the centre. A set of six coils of the following values will be found useful: 1, 5, 10, 25, 50, and 100 ohms. The wires for the three smaller values may consist of silk-covered copper, but for the remaining coils silk-covered German silver wire must be used, as the length of copper wire necessary to give the required resistance would be considerable. Should the worker have access to a set of coils, he may measure off his wires directly; but if not, he must procure from some dealer or manufacturer of resistance coils a length of wire of known resistance.

"Measure off (by bridge) lengths of wire having resistances in ohms or fractions of ohms, as above mentioned. Double the wire in middle, and laying this middle part on a cotton reel, commence winding until all the wire is laid on except a few inches at each end; soak in melted paraffin. In order to ensure the greatest accuracy, some makers, instead of measuring in the first instance the full length of wire, measure a length of wire which will be about (very slightly over) half the required resistance. Two lengths of such wire are laid side by side, and at the ends which represent the point where the bend would come in a single wire, a drop of solder connects the two wires in series. The resistance of the whole is now measured, and if too great the wires are soldered a little farther up, and so on until great accuracy is obtained. It is said that this plan is more practical than the doubling plan, and answers the same purpose. Make mercury cups 1\( \frac{1}{2} \) in. apart in a row along one edge of the board. Fasten the bobbins of wire along the centre of the board in a row opposite interspaces between the mercury cups. Through a hole in each mercury cup push a flat-headed copper rivet, so that the head forms the bottom of the cup, Fig. 52.

"Lead one end of the first coil of wire under the board, and solder to the rivet of the first mercury cup. Lead the second end of the first coil and also the first end of the second coil to the rivet of the second cup—the second end of the second coil and the first end of the third coil to the rivet of the third cup, and so on. Make thick copper wire staples 1\( \frac{1}{2} \) in. long and turned down 1 in. at each end for connecting the cups. Make some longer staples, 3 in., 4\( \frac{1}{2} \) in., and 6 in. long. Mark the value of the coil connected with each pair of mercury cups on the board between them; amalgamate the loose copper connections."

We may supplement the above concise description by saying that the reason why the wires are bent in the middle and then wound on the reels, so that the two halves lie side by side, is to prevent self-induction, and also any action on the needles of galvanometers placed in the neighbourhood of the set of coils.

The amalgamation of the copper connections is to ensure good contact with the mercury filling the cups, and for this reason the flat-headed rivets mentioned in above quotation ought to be amalgamated likewise.

In order to amalgamate the loose contacts, the copper must first be cleaned by dipping the ends into a little nitric acid, and afterwards into some nitrate of mercury, washed, and burnished up.

Another indispensable piece of apparatus (indeed without it the Wheatstone bridge will be valueless) is a sensitive galvanometer. For ordinary bridge work a carefully made astatic galvanometer answers exceedingly well; but for determinations of capacities a mirror galvanometer is necessary. The construction of the astatic form of the instrument is so simple and so thoroughly explained in most textbooks that it need not be referred to here; but a few words respecting the mirror galvanometer may not be out of place. To construct a highly-sensitive mirror galvanometer, and accompanying box of shunts, require considerable technical skill; but an instrument possessing sufficient delicacy for ordinary purposes may be made without much difficulty.

Get a boxwood reel turned to shape and size shown in section on Fig. 53; place this reel in a lathe, or on an horizontal spindle capable of being rotated by a handle, and carefully wind on No. 36 silk-covered copper wire until the reel is filled, leaving about 2 ft. of each end of the wire projecting to be attached
to two terminals. It will be found an improvement to have these projecting ends of thicker wire carefully soldered to the thin wire, as by doing so there is less risk of their being broken by any strain they may be accidentally subjected to owing to their exposed situation.

The reel being filled with the wire, it may be mounted on a suitable pillar and fixed to the top of a strong flat box, 8in. × 8in. × 2in., the two wires being led down into the box.

The object in using a box instead of a solid board for the base is that it forms a convenient receptacle for the "shunt coils," which must be prepared as follows:

Carefully measure the resistance of galvanometer coil. Let us suppose it to be 1,000 ohms. It will frequently happen that if the whole of the current we may be dealing with at the time is sent through the galvanometer, the deflection will be so great that the spot of light will be thrown off the scale. To prevent this, part of the current is "shunted"—i.e., allowed to traverse our derived path lying between the two terminals of the galvanometer.

![Fig. 55](image)

The proportions of the total current which will under these conditions pass through the galvanometer and shunt, will depend upon the ratio of their respective resistances.

A short reference to the theory of shunts will not be inappropriate at this point.

The joint resistance of two or more wires in "parallel" is equal to the reciprocal of the sum of the reciprocals of the resistances of the several wires measured, separately; or,

$$ R = \frac{1}{\frac{1}{r} + \frac{1}{r_1} + \frac{1}{r_n}}. $$

If the galvanometer terminals, G, be connected by a shunt, S, and if a current, C, be made up of G + S parts, then $C \frac{G}{G+S}$ will be the value of that portion of the current going through the shunt, and $C \frac{S}{G+S}$ the value of the remaining portion going through the galvanometer.

Obviously, if we make $S = G$, then the current through the galvanometer will be $C \frac{G}{G+G} = \frac{C}{2}$; and making $S = \frac{G}{n-1}$, the current through the galvanometer will be

$$ C \frac{G}{n-1} = \frac{G}{n-1} = \frac{C}{n}. $$

Hence, to reduce the galvanometer current to $\frac{1}{n}$-th of its former value, the shunt employed must have a resistance of $\frac{1}{n-1}$-th of that of the galvanometer, or,

$$ S = \frac{G}{n-1}. $$

Usually a set of shunts are supplied with the galvanometers, whereby the current may be reduced to its $\frac{1}{10}$ and $\frac{1}{100}$ or $\frac{1}{1000}$ part, the resistance of these shunts being, according to above formula, $\frac{1}{10}$, $\frac{1}{100}$, and $\frac{1}{1000}$ that of the galvanometer.

The combined resistance of a galvanometer and any given shunt may be calculated by the method of reciprocals, or by the simpler method depending upon the fact that $R = \frac{GS}{G+S}$, or if the value of the $\frac{1}{n}$ power of the shunt used be known, by dividing the galvanometer resistance by the value $\frac{1}{n}$ or $R = \frac{G}{n}$.

If with an unshunted galvanometer the deflection is found to be too large, and a shunt has to be employed, the relative value of the current $C$, which flowed through the unshunted galvanometer to the current $C_1$, flowing after the shunt is inserted, is found by the equation

$$ C = C_1 \times \frac{G+S}{S}. $$

This value $\frac{G+S}{S}$ is called the multiplying power of the shunt.

Assuming the resistance of our galvanometer, G, to be 1,000 ohms, as before mentioned, we find the respective resistances of $\frac{1}{10}$, $\frac{1}{100}$, and $\frac{1}{1000}$ shunts must be as follows, since $S = \frac{G}{n-1}$.

For the $\frac{1}{10}$ shunt $S = \frac{1000}{10-1} = \frac{1000}{9} = 111$ ohms.

For the $\frac{1}{100}$ shunt $S = \frac{1000}{100-1} = \frac{1000}{99} = 10.1$ ohms.

For the $\frac{1}{1000}$ shunt $S = \frac{1000}{1000-9} = \frac{1000}{991} = 1$ ohm.

The wire for the shunts should be of the same metal as that used for the galvanometer coil—i.e., copper—but the error will not be great if German silver be used, thereby reducing the length of wire required; and since space is not of so great importance here as it was with the galvanometer coil, cotton-covered wire may be employed. Having cut off the necessary lengths of wire, and measured the resistance of the wires for the shunt, bend each wire in its middle, and laying the middle point of the wire on a bobbin, proceed to wind
the two halves side by side, allowing a few inches of the ends to hang free from the bobbin.

Screw the three bobbins by brass screws (on no account must iron screws be employed, as they may become magnetised by the currents circulating through the coil and affect the needle of galvanometer) to under surface of top of box, and solder the ends of the shunt and galvanometer wires to a set of brass strips fixed to top of box, Fig. 54.

The shape of these strips and the method of connecting up the wires will be easily understood from the diagram.

A and B are two L-shaped pieces of brass, their longer sides being about 4in. and the shorter 1in. in length, and having a semi-circular notch cut out of the ends of the shorter sides, so that when they are placed in position inserting a conical plug will make contact between the two strips. On the inside of B three similar semi-circular notches are cut, and opposite each notch a short brass strip is placed having corresponding notches cut in their ends facing B. The ends of the wires belonging to the coil and shunts are soldered to the bottom of the strips, as indicated in the diagram. I, 2 are two terminals to attach the wires leading from the other parts of the circuit.

In its normal condition (with the plug out) the whole of the current goes through the galvanometer. Inserting the plug at a, b, and c successively, \( \frac{1}{2} \), \( \frac{1}{3} \), and \( \frac{1}{6} \) part of the total current passes through the galvanometer, while putting the plug in d the galvanometer is “short-circuited,” the whole current flowing direct through the plug from 1 to 2 or 2 to 1 as the case may be.

The galvanometer and shunts being satisfactorily arranged, we require to mount the mirror and its accompanying magnet. For the mirror, a circular microscopic glass cover, about \( \frac{3}{4} \)in. in diameter, may be taken and silvered by following process:

A. Dissolve 154 grains of silver nitrate in 17oz. of distilled water. Add ammonia till precipitate first formed is nearly redissolved. Filter and dilute to 34oz.

B. Dissolve 31 grains of nitrate of silver in 34oz. of distilled boiling water. Dissolve 23 grains of Rochelle salt in a little water. Add to boiling nitrate till precipitate formed becomes grey. Filter and allow to cool.

Clean glass object with nitric acid and caustic potash, well washing with water before and after the potash, wash in alcohol, and, lastly, well-distilled water; place in clean dish, and while still wet pour over equal quantities of A and B. In about two hours silvering is complete; take out of dish, dry, and varnish back.

To the back of the mirror is attached, by a little cement, a piece \( \frac{3}{4} \)in. long of well-magnetised watch spring, the whole being suspended by a single unspun silk fibre, in such a manner that the magnet hangs in a horizontal position, Fig. 55.

A cardboard (or, better still, a thin brass) tube, 1in. long and \( \frac{3}{4} \)in. diameter, has a small hole drilled midway between its ends, and the silk fibre carrying the mirror and magnet is threaded through the hole and secured by a bit of cement, so as to allow the mirror to vibrate freely in the centre of the tube when lying in a horizontal position, Fig. 56.

The tube carrying the mirror slides freely into the circular aperture in the centre of the galvanometer.

The only thing remaining to complete our galvanometer is the controlling magnet. The object of this magnet is to diminish or neutralise the effects of the earth’s magnetism.

A brass rod placed behind the galvanometer with a ring (similar to a retort stand), capable of being clamped at different positions along the rod, will answer exceedingly well. The ring arm should project over centre of galvanometer, and the controlling magnet being placed upon it, Fig. 57, its height can be varied at pleasure, and a slight movement in a horizontal plane will serve to bring the spot of light to the zero of the scale whenever necessary.
The scale and lamp used with the magnetometer, Fig. 41, can be employed with the galvanometer, a lens being used to focus the spot of light on the scale.

Figure of Merit of Galvanometer.

By the "figure of merit" of a galvanometer is understood the reciprocal of the current necessary to produce a deflection of 1 deg. under a given electromotive force.

Join up a Daniell cell, resistance-box, and tangent galvanometer in simple circuit, Fig. 58, and unplug resistance till a suitable deflection is obtained, \( d \); the figure of merit can then be easily calculated as under.

Example.—A tangent galvanometer, \( G \), of 2.5 ohms, gave a deflection, \( d \), of 36 deg., when joined to a Daniell cell (whose electromotive force = 1 volt, and internal resistance, \( r \), = 3.5 ohms) by means of a wire of 10 ohms resistance = \( R \). What is its figure of merit?

Since the current necessary to produce a deflection of 36 deg.

\[
C = \frac{E}{r + R + C} = \frac{1}{3.5 + 10 + 2.5} = \frac{1}{16} = 0.0625 \text{ amperes,}
\]

the current required to give a deflection of 1 deg. is 0.0625 \( \tan \) 1 deg. = 0.0175 \( \tan \) 36 deg. \( \approx \) 0.0015 \( \tan \) 36 deg. = 0.0015 amperes, and its figure of merit is \( \frac{1}{C} = \frac{1}{0.0015} = 666 \).

Another way of regarding the figure of merit of a galvanometer is to ascertain through what resistance an electromotive force of one Daniel cell (practically 1 volt) will produce a deflection of 1 deg. In the above example this would be 666 ohms.

With a sensitive mirror galvanometer the deflection due to the current from one Daniell, with all the available resistance in circuit, will generally be sufficient to throw the spot of light off the scale. In this case the galvanometer must be shunted, and the resistance, \( R_s \), in current calculated according to following formula.

Let \( r \) = integral resistance of cell.
\( R \) = interposed resistance.
\( G \) = galvanometer resistance.
\( S \) = resistance of shunt.
\( d \) = observed deflection in scale division.

Then to get the amount of resistance necessary to obtain a deflection of 1 deg. we must have, if the galvanometer be unshunted,

\[
R_s = d (r + R + G)
\]

Since it is obvious that if a given resistance, \( R \), we get a deflection of \( d \) divisions, the resistance necessary to reduce this to one division must be \( d \) times as great.

Should a shunt, \( S \), have to be employed the formula becomes

\[
R_s = d \frac{G + S}{S} \left( \frac{r + G}{G + S} \right),
\]

\( G + S \) and \( G S \) being the multiplying power and the resistance of the shunted galvanometer respectively.

With a mirror galvanometer, \( r \) will be so small in comparison to the high resistance in circuit that it may be neglected.

Example.—A Thomson galvanometer, \( G \), of 6,000 ohms resistance, and an interposed resistance of 9,000 ohms \( (r \) being neglected) gave a deflection of 330 scale divisions when joined with one Daniell cell = 1 volt. What was its figure of merit?

\[
R_s = d (R + G)
\]

\[
= 330 (9,000 + 6,000)
\]

\[
= 330 \times 15,000
\]

\[
= 4,950,000 \text{ ohms.}
\]

Example.—Using the same galvanometer and cell, but inserting the \( \frac{1}{10} \) shunt \( S = 666 \text{ ohms} \), and an interposed resistance of 14,400 ohms, \( d = 33 \) scale divisions, therefore

\[
R_s = d \frac{G + S}{S} \left( \frac{r + G S}{G + S} \right)
\]

\[
= 33 \frac{6,000 + 666}{666} \left( \frac{14,400 + 6,000 \times 666}{6,000 + 666} \right)
\]

\[
= 33 \times 10 (14,400 + 600)
\]

\[
= 330 \times 15,000
\]

\[
= 4,950,000 \text{ ohms.}
\]

N.B.—The value of \( \frac{G + S}{S} \) is simply the reciprocal of the denomination of the shunt \( \frac{1}{10} = 10 \); and the value of \( \frac{G \times S}{G + S} = \frac{G}{n} \) (see page 309).

Determination of the Reduction Factor of a Tangent Galvanometer.—By the reduction factor of the galvanometer is understood that constant by which the value of the angle of deflection obtained must be multiplied in order to obtain the value of the current in absolute measure, or in amperes.

Supposing the value of \( H \) at the place of experiment to be known, and also the mean radius, \( r \), of the coil, and the number of complete turns, \( n \), made by the wire, then the reduction factor, \( K \), can be calculated from the following formula,

\[
K = \frac{r H}{2 \pi n}.
\]
Example.—A certain tangent galvanometer, whose coil consisted of 40 = n complete turns of wire, the mean radius, r, being 11·75 cm. Assuming the value of H to be 176 dyne. Required, the reduction factor in absolute units.

Answer.—\[ K = \frac{11\cdot75 \times 1\cdot76}{2 \times 3\cdot14159 \times 40} = 0\cdot08228 \] in absolute units, or \( 0\cdot08228 \times 10 = 0\cdot8228 \) in amperes.

Hence the value of any current (in amperes) producing a given deflection, \( d \), with this particular instrument would be

\[ C = K \tan d = 0\cdot8228 \tan d \]

If the dimensions of the galvanometer are not known, its reduction factor may be ascertained by the following method, which depends upon a knowledge of the quantity of a metal liberated from a solution of one of its salts by a known quantity of electricity—i.e., the electro-chemical equivalent of the metal:

Take two pieces of clean sheet copper about 15 cm. \( \times 3 \) cm., and place them between three dry strips of wood, with their copper ends projecting sufficiently above the wood strips to allow of a wire being attached to each, by means of a clamp, the whole being held firmly together by two strong indiarubber bands.

Rest the wooden support on the top of a beaker containing a saturated solution of copper sulphate \( (\text{CuSO}_4) \) so that from 6 cm. to 8 cm. of the copper plates are immersed in the liquid; join up with a good Daniell cell, a key, and the tangent galvanometer whose reduction factor is to be determined.

Before connecting up, the copper plate which is to serve as the cathode—i.e., the one connected with the zinc pole of the battery, must be carefully weighed on a good balance, and its weight in grammes = \( W_1 \), recorded. After ensuring that the galvanometer is properly adjusted, close the circuit and read the deflection of the pointer at intervals of 10 minutes for one hour, and take the mean of the six readings as the true value of the deflection, \( \delta \).

By taking these readings at short intervals, any variation in the strength of the current will be detected and the average current estimated. At the expiration of the hour disconnect the copper plates, and after carefully washing the cathode, first with distilled water and then with alcohol, and lastly with a little ether (by this treatment the plate dries quicker and there is less danger of the copper becoming oxidised) it must be placed at once into an air bath or oven, and exposed to a temperature of about 100 deg. C., until it is thoroughly dried. After cooling under a desiccator, or if this is not available, under an inverted beaker, the cathode is to be again carefully weighed; call this \( W_2 \).

Let \( W = \) weight of metal liberated, or \( W_2 - W_1 \).
\( C = \) current in amperes.
\( \epsilon = \) electro-chemical equivalent of metal (copper)
\( \tau = \) time.
\( \delta = \) deflection.

If \( W_1 \) be weight of cathode at commencement, and \( W_2 \) be weight of cathode at end of experiment, we have

\[ W_2 - W_1 = \epsilon \cdot C \cdot \tau \]

and

\[ C = \frac{W}{\epsilon \cdot \tau} \]

But

\[ C = K \tan \delta, \]

whence the reduction factor, \( K \), is known, for

\[ K = \frac{C}{\tan \delta} \]

Example.—With the galvanometer referred to in last example the following data were obtained:

\[ W_2 = 10\cdot383 \quad \epsilon = 0\cdot00033 \]
\[ W_1 = 10\cdot285 \quad \tau = 60 \times 60 = 3,600 \text{ seconds} \]
\[ W = 0\cdot098 \quad \delta = 45 \text{ deg. } 30' \text{ (mean of six readings)} \]

Then

\[ W = C \cdot \epsilon \cdot \tau \]
\[ 0\cdot098 = C \times 0\cdot00033 \times 3600 \]
\[ = C \times 1\cdot188 \]
\[ \therefore C = \frac{0\cdot098}{\epsilon \cdot \tau} = \frac{0\cdot098}{0\cdot00033 \times 1\cdot188} = 0\cdot825 \text{ ampere.} \]

But we saw above that \( C = K \tan \delta \), and substituting for \( C \) the value \( 0\cdot825 \), we get

\[ C = 0\cdot825 = K \tan 45\cdot30 \]
\[ = K \times 1\cdot0176 \]
\[ \therefore K = 0\cdot825 \times 1\cdot0176 = 0\cdot81, \]

instead of \( 0\cdot8228 \) as calculated from the known dimensions of the instrument.

Arrange battery power and resistance so that the deflection is as near 45 deg. as possible—as that is the angle of maximum sensitiveness.

Electro-Chemical Equivalent.

One of the phenomena connected with electrical currents is the decomposition of chemical solutions, and the weight of a substance in solution decomposed by the passing of one ampere for one second is called the electro-chemical equivalent of the substance. The following table gives the electro-chemical equivalent of the more important substances usually dealt with:

<table>
<thead>
<tr>
<th>Substance</th>
<th>Electro-chemical equivalent in grammes per ampere per second</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>0·000001035</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0·000008968</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0·0008675</td>
</tr>
<tr>
<td>Sodium</td>
<td>0·0002881</td>
</tr>
<tr>
<td>Gold</td>
<td>0·0006790</td>
</tr>
<tr>
<td>Silver</td>
<td>0·0011180</td>
</tr>
<tr>
<td>Copper</td>
<td>0·0003861</td>
</tr>
<tr>
<td>Zinc</td>
<td>0·0003864</td>
</tr>
<tr>
<td>Lead</td>
<td>0·0010684</td>
</tr>
</tbody>
</table>

This table is given not because we believe in its accuracy to even a fifth decimal place, but because it
shows a most curious example of the desire of modern science to get exact numerical values in its investigations, whenever possible. The figures can only be taken as approximately accurate.

Experimental Illustrations of Ohm's Law.

The relation to each other of the three quantities which constitutes Ohm's law may be verified by the following simple experiments:

\[ C = \frac{E}{R}, \]

where \( C \) = current, \( E \) electromotive force, \( R \) = resistance of cell and external resistance.

First Case.—\( R \) remaining constant, \( C \) varies directly as the electromotive force.

Join up in circuit, Fig. 58, a good Daniell cell, a Thomson galvanometer of known resistance, and a box of resistance coils, and note deflection, \( d \), obtained.

A tangent galvanometer might be employed, but in this case the internal resistance of the cell must be ascertained by any of the methods to be subsequently described, as, owing to the resistance of an ordinary tangent galvanometer being generally low, the internal resistance of a Daniell cell becomes too great a factor of the total resistance to be neglected. Whereas, with a Thomson's high-resistance galvanometer, the internal resistance of the cell is negligible.

Increase the battery power from 1 to 2 and 3 cells when the values of the deflections will become \( 2d \), \( 3d \), etc., or, with a tangent galvanometer, \( \tan d \) becomes \( 2 \tan d \), \( 3 \tan d \), etc., and since these values are proportional to the currents producing the deflection, we have

\[ C_n = \frac{E_n}{R}. \]

Example.—With a Thomson galvanometer of 6,000 ohms shunted down \( \frac{1}{6} \), the total resistance being 5,000 ohms, one Daniell cell gave a deflection of 36 scale divisions, while two cells gave 71.5 divisions.

Second Case.—\( E \) remaining constant, \( C \sim \text{inversely as} \ R \). With one cell and a total resistance, \( R \), in circuit, note deflection, \( d \). Increase the resistance to \( 2R \), and subsequently to \( 3R \), when the deflections will be reduced to \( \frac{d}{2} \) and \( \frac{d}{3} \) respectively.

Example.—With the same shunted galvanometer and one Daniell cell, with 5,000 ohms in circuit the deflection was as before—36; on doubling \( R \) to 10,000 the deflection fell to 17.8.

Third Case.—The current remaining constant, the electromotive force varies directly as the resistance.

Note deflection, \( d \), obtained with one cell and resistance, \( R \), in current. On introducing two and three cells, we must, in order to keep \( C \) constant, increase \( R \) to \( 2R \cdot 3R \) respectively, or

\[ C = \frac{nE}{nR}. \]

Example.—Again employing the same galvanometer and cells, one Daniell yielding through 5,000 a deflection of 36; when two cells were used in series, the value of \( R \) had to be increased to 10,000 in order to maintain the same deflection.

Should the deflection produced in either of the preceding measurements be so great that the spot of light moves off the scale, the galvanometer may be shunted with one of the sets of shunts supplied with it, as in the examples given; in this case the resistance of galvanometer and shunt combined will be equal to their product divided by their sum \( R = \frac{G \times S}{G + S} \), which is equivalent to the

Resistance of the galvanometer \( = \frac{G}{n} \)

Resistance of the multiplying power of shunt \( = \frac{n}{G} \)

Measurement of Galvanometer Resistance.

We shall describe four methods of measuring the resistance of a galvanometer, from which the student can select the method most suitable to the kind of instrument he has to deal with. We shall assume that he has provided himself with an ordinary astatic galvanometer to use with the bridge. This need only have a coil composed of a few turns of comparatively thick wire, the resistance of which will be so small that it need not be known, but the resistance of the tangent and mirror galvanometer ought to be accurately determined.

A. Direct Bridge Method.—Place the galvanometer in the fourth arm of the Wheatstone bridge, and measure it as an ordinary resistance, Figs. 59 and 60. This is the only trustworthy method for low-resistance galvanometers.

Example.—A tangent galvanometer, whose resistance being required, was placed in the fourth arm of the Post Office bridge, and on making \( B = 100 \) and \( A = 10, \)
it was necessary to make $D = 280$ before balance was obtained. What was the resistance?

$$X = D \frac{A}{B} = 280 \times \frac{10}{100} = 28 \text{ ohms.}$$

A mirror galvanometer was substituted for the tangent galvanometer, and making $B$ and $A 1,000$ ohms each, $D$ had to be made 6,000 ohms. Required its resistance.

$$X = 6,000 \times \frac{1,000}{1,000} = 6,000 \text{ ohms.}$$

B. Half Deflection Method.—Join up the galvanometer with a cell of low internal resistance, and a box of resistance coils, Fig. 58. If the resistance of the galvanometer be low, the resistance of the cell should be known, as it may form an appreciable part of the total resistance in circuit; in the case of a high resistance galvanometer it may be neglected. Note deflection, $d_1$, produced with a resistance, $R_1$, unplugged in box. Increase $R_2$ to $R_2^n$, so that the new deflection, $d_2$, is equal to half $d_1$. Then,

$$G = R_2 - 2 R_1.$$

**Example.**—The tangent galvanometer before mentioned, using a cell of very low resistance, gave a deflection of 47 deg. (tan 47 deg. = 1.07) when $R_1 = 1$ ohm. In order to reduce this deflection to one-half, or 28 deg. (tan 28° = .53) $R_2$ had to be made 90 ohms.

$$G = R_2 - 2 R_1 = 30 - 2 \times 1 = 28 \text{ ohms.}$$

The mirror galvanometer, in order to keep the spot of light on the scale, had to be shunted down to $\frac{1}{10}$. Its actual resistance would therefore be $G = \frac{6,000}{10} = 600$ ohms (see page 309).

The value obtained by this method was

- $R_1 = 5,000$ ohms. $d_1 = 64$ scale divisions.
- $R_2 = 10,600$ ohms. $d_2 = 32$

$$G = 10,600 - 2 \times 5,000 = 600 \text{ ohms.}$$

Note.—Make $R_1$ and $R_2$ as low as possible, but remembering that with the tangent galvanometer the best results are obtained when $d_1$ and $d_2$ have equal values on either side of 45 deg.—i.e., tan 55 deg. and tan 35°.5 deg.

The connections are shown theoretically in Fig. 58, and practically in Fig. 61, using the Post Office bridge. The arms, $A$ and $B$, play no part in the arrangement, only the set of resistance coils, $D$, being utilised; in fact, the bridge becomes a simple resistance-box. The infinity plug, I P, being removed.

C. Equal Deflection Method.—Join up galvanometer cell of low resistance, and resistance, $R_1$, as in last method, only interposing a shunt, $S$, between the terminals of the galvanometer, $G$. Note deflection, $d$.

The shunt, $S$, is now removed, causing an increased deflection, $d_2$. Increase $R_1$ to $R_2^n$, so that $d_2$ is again produced, then

$$G = S \frac{R_2 - R_1}{R_1}.$$

With the Post Office resistance-box, to insert the shunt, $S$, put in the infinity plug, I P, and remove one of the plugs between $B$ and $A$. To remove $S$ we have simply to unplug I P, Figs. 62 and 63.

Make $S$ as small and $R_1$ as large as possible.

**Example.**—By this method the tangent galvanometer gave the following data: $d = 16$ deg., $R_1 = 20$ ohms, $R_2 = 77$ ohms, and $S = 10$ ohms.

$$G = S \frac{R_2 - R_1}{R_1} = 10 \frac{77 - 20}{20} = 10 \frac{57}{20} = 28.5 \text{ ohms.}$$
\[ G = \frac{7100 - 1000}{1000} \]
\[ G = 610 \text{ ohms.} \]

Thomson's Method.—Connect up galvanometer in fourth arm of bridge, and place battery and key, \(K_2\), between the points A C. Join up B E through \(K_1\), unplug resistance in A and B, and adjust resistance \(d\) till no alteration in the deflection of the mirror is produced either by opening or closing \(K_1\), Figs. 64 and 65.

With the Post Office bridge, hold the left-hand key firmly down to bring in the battery, and having given a suitable ratio to \(b d\), adjust \(d\), closing \(K_2\) at intervals. When the proper value has been given to \(d\), closing \(K_2\) will produce no effect on the galvanometer. Attention must be directed to one very important point.

Since on closing \(K_2\) and bringing in the current the mirror is permanently deflected, the spot of light moving off the scale, some means must be employed to counteract this effect of the current. This is best secured by placing a bar magnet on one side of the galvanometer, and at such a height and distance from it that the attraction due to the magnet exactly balances the repulsion arising from the current; when this is done the spot will return to zero, the magnet of the galvanometer being at the same time exceedingly sensitive to any alteration in the strength of the current.

Then, as in ordinary bridge measurements of resistances,
\[ G = \frac{A D}{B^2} \]
Make \(B\) greater and \(A\) less than \(G\).

With a slide wire bridge the connections would be as follows: Make \(A\) small and \(D\) large, Fig. 66.

Example.—In measuring the resistance of Thomson galvanometer shunted down \(1/10\). With \(b = 1,000\) and \(a = 100\) ohms, it was necessary to make \(d = 6,090\) ohms.
\[ G = \frac{6,090 \times 100}{1,000} = 609 \text{ ohms.} \]

Example.—With a slide wire bridge, and tangent galvanometer, no effect was produced on needle when \(A\) was 25 ohms, and contact made at the 470 division of \(B\).
\[ G = \frac{25 \times 530}{470} = 28.2 \text{ ohms.} \]

Summary.

Of the above four methods, the first with the Wheatstone bridge is to be preferred when a second galvanometer is at hand; when such is not the case, and especially when measuring a high-resistance galvanometer, Thomson’s method is very satisfactory. Since, as in ordinary bridge determinations, it is a null method, the measurement being taken when the needle is undeflected; it is therefore independent of the values of the graduations of the galvanometer scale, and also of the internal resistance of the battery.

Of the remaining two methods (B and C), that of “equal deflection” has the advantage of being applicable to any kind of galvanometer, since we have only to reproduce a given deflection, therefore its value.
need not be known, whereas with "half deflection" method is restricted to those instruments in which the values of the different deflections are comparable. In either case the internal resistance of the battery must be exceedingly small in comparison to that of the galvanometer.

For this reason they are not adapted for measuring low-resistance galvanometers; in fact, the only reliable method for this class of instruments is that first described with the Wheatstone bridge.

We shall see that the tangent galvanometer as described is very little used in the ordinary work of electric lighting, but the principle of the tangent galvanometer underlies many, if not most, of the instruments used. In many operations it is not of very great importance to read resistance, say, to the hundredth of an ohm—it is sufficiently practical to read to tenths; the same may also be said with regard to amperes and volts. Hence it will be found that the practical instruments are often of such a character that they most admirably fall in with this laxity of accuracy. They are only approximate. A well-known electrical engineer goes even further than this, and maintains that the best-known makers are not too particular in measuring the accuracy of the resistances in the resistance-boxes they send out. Be that as it may, the user, when necessary, ought to be able with a Kirchhoff bridge and a good galvanometer to ascertain for himself whether his apparatus is accurately described or not.

We have already said that to Sir W. Thomson more than to anyone we are indebted for the great advance that has taken place since 1850 in electrical measuring instruments, and we cannot do better than to briefly and rapidly describe the most recent forms of his standard instruments.

**Standard Direct Reading Electric Balances.**

These instruments are founded on the mutual forces, discovered by Ampère, between movable and fixed portions of an electric circuit. The shape chosen for the mutually-influencing portions is circular, and each such part will be called for brevity an ampere ring; or sometimes simply a ring, whether it consists of only one turn or of any number of turns of the conductor; or an arc when it consists of less than a whole turn.

In each of the balance instruments, except the kilo-ampere balance, each movable ring is actuated by two fixed rings, all three approximately horizontal. There are two such groups of three rings—two movable rings attached to the two ends of a horizontal balance arm pulled, one of them up and the other down, by a pair of fixed rings in its neighbourhood. The current is in

![Fig. 67.—Centi-ampere Balance.](image-url)
sighted position, for the sake of stability, is above it at one end of the beam and below it at the other, in each case being nearer to the repelling than to the attracting ring by such an amount as to give about $\frac{3}{8}$ per cent. more than the minimum force.

In the balance instruments to measure alternate currents (which may be also used for direct currents) of from 1 ampere to 600 amperes the main current through each circle, whether of one turn or of more than one turn, is carried by a wire rope of which each component wire is insulated by silk covering, or otherwise, from its neighbour, in order to prevent the inductive action from altering the distribution of the current across the transverse section of the conductor.

The balancing is performed by means of a weight which slides on an approximately horizontal graduated arm attached to the balance; and there is a trough fixed on the right-hand end of the balance into which a proper counterpoise weight is placed, according to the particular one of the sliding weights in use at any time.

From a book carried by a sliding platform, which is pulled in the two directions by two silk threads passing through holes to the outside of the glass case.

Four pairs of weights (sliding and counterpoise), of which the sledge and its counterpoise constitute the first pair, are supplied with each instrument. These weights are adjusted in the ratios of 1 : 4 : 16 : 64, so that each pair gives a round number of amperes, or half-amperes or quarter-amperes, or of decimal sub-divisions or multiples of these magnitudes of current, on the inspectional scale.

The useful range of each instrument is from 1 to 100 of the smallest current to which its sensibility suffices. The ranges of the different types of this instrument regularly made are

I. Centi-ampere balance: from 1 to 100 centi-amperes (Fig. 67).

II. Deci-ampere ,, 1 to 100 deci-amperes.

III. Deka-ampere (Fig. 68) from 1 to 100 amperes.

IV. Hekto-ampere balance ,, 6 to 600 ,,.

V. Kilo-ampere ,, 25 to 2,500 ,,.

VI. Composite ,, 0.02 to 500 ,, and from 100 to 50,000 watts (at 100 volts).

The following table shows for each type of instrument the value per division of the inspectional scale corresponding to each of the four pairs of weights:

<table>
<thead>
<tr>
<th>I. Centi-ampere</th>
<th>II. Deci-ampere</th>
<th>III. Deka-ampere</th>
<th>IV. Hekto-ampere</th>
</tr>
</thead>
<tbody>
<tr>
<td>per div.</td>
<td>per div.</td>
<td>per div.</td>
<td>per div.</td>
</tr>
<tr>
<td>1st pair of weights...</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>2nd</td>
<td>50</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>3rd</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>4th</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

The fixed inspectional scale shows, approximately enough for most purposes, the strength of the current;

---

For the fine adjustment of the zero a small metal flag is provided, as in an ordinary chemical balance. This flag is actuated by a fork, having a handle below the case outside, as shown in the drawing, Fig. 67. To set the zero the left-hand weight is placed with its pointer at the zero of the scale, and the flag is turned to one side or the other until it is found that, with no current going through the rings, the balance rests in its sighted position.

To measure a current, the weight is slipped along the scale until the balance rests in its sighted position. The strength of the current is then read off approximately on the fixed scale (called the inspectional scale), with aid of the finely-divided scale for more minute accuracy, according to the explanations given below. Each number on the inspectional scale is twice the square root of the corresponding number on the fine scale of equal divisions.

The slipping of the weight into its proper position is performed by means of a self-releasing pendant, hanging
the notches in the top of the aluminium scale show the precise position of the weight corresponding to each of the numbered divisions on the fixed scale, which practically annuls error of parallax due to the position of the eye. When the pointer is not exactly below one of the notches corresponding to integral divisions of the inspectional scale, the proportion of the space on each side, to the space between two divisions, may be estimated inspectionally with accuracy enough for almost all practical purposes. Thus we may readily read off 34.2 or 34.7 by estimation with little chance of being wrong by 1 in the decimal place. But when the utmost accuracy is required, the reading on the fine scale of equal divisions must be taken, and the strength of current calculated by aid of the table of double square roots appended to these instructions. Thus, for example, if the reading is 392 we find 34.18, or say, 34.2 as the true scale reading for strength of current; or, again, if the balancing position of the pointer be 301 on the fine scale, we find 34.70 as the true reading of the inspectional scale.

The centi-ampere balance, with a thermometer to test the temperature of its ampere rings, and with platinoid resistances up to 1,600 ohms, serves to measure potentials of from 10 volts to 400 volts.

**Constant of the Centi-Ampere Balance when used as a Voltmeter.**

<table>
<thead>
<tr>
<th>Weight used</th>
<th>Resistance in circuit</th>
<th>Volts per division of fixed scale.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st pair of weights</td>
<td>400</td>
<td>1.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>800</td>
<td>2.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>1,200</td>
<td>3.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>1,600</td>
<td>4.0</td>
</tr>
</tbody>
</table>

* Including resistance of the instrument, which is about 30 ohms.

If the second pair of weights is used the constants will be double of those noted above.

When using, the instruments should be levelled in accordance with the indications of the spirit-level attached, by means of the levelling screws on which the sole-plate of the instrument stands.

In the centi and deci-ampere balances, the beam can be lifted off its supporting ligaments by turning a handle attached to a shaft passing under the sole-plate of the instrument. This shaft carries an eccentric, on the edge of which rests the lower end of a vertical rod which is fixed at its upper end to a tripod lifter. When the instrument is to be removed from place to place, the lifter should be raised; but when it is fixed up for regular use it is advisable to keep the beam always hanging on the ligaments. In the deka, hekto, and kilo-ampere balances there is no lifter, but the beam is packed by placing distance-pieces between the two halves of the suspension traction and screwing them together by means of milled-headed screws provided for the purpose. When the instrument is unpacked and prepared for use, these distance-pieces must be taken out and placed in receptacles provided for them in the weight box.

A set of four sliding weights, of which the carriage constitutes one, is supplied with each instrument. The carriage is fitted with an index to point to the movable scale, and is intended to remain always on the rail. One or other of the weights is to be placed on the carriage in it in such a way that the small hole and slot in the weight pass over the conical pins. The weights are moved by means of a slider, which slides on a rail fixed to the sole-plate of the instrument, and carries a pendant with a vertical arm intended to pass up through the rectangular recess in the front of the weight and carriage. The slider and weight are shown in position in the figures. The slider is moved by silk cords which pass out at the ends of the glass case. When the cords are not being pulled for shifting the weight their ends should be left free, so that the pendant may hang clear of the weight. When a weight is to be placed on or removed from the carriage the slider should be drawn forward at the top until it is clear of the weight, and then pushed to one side until the weight is adjusted, when it may be replaced in position in a similar manner.

Cylindrical counterpoise weights with a cross-bar passed through them are supplied for the purpose of balancing the sliding weights when they are placed at the zero of the scale. The sliding weight should be placed so that the index of the carriage points to the zero of the scale, and the proper counterpoise weight should be placed in the trough, fixed to the right-hand end of the beam, with its cross-bar passing through the hole in the bottom of the trough. The flag which is attached to the cross trunnion of the beam should then be turned by means of the handle projecting from under the sole-plate, until the index on the end of the movable scale points to the middle one of the five black lines on the fixed scale opposite to it. Care must be taken when making this adjustment that the fork which moves the flag is not left in contact with it, as this would impede the free swing of the beam. The fork should be turned back a little after each adjustment of the flag, and, when the flag is being adjusted, it is better to watch the flag itself, and make successive small adjustments until the beam stands at zero, than to make successive trials by pushing round the handle while watching the position of the index.

If the ligament has stretched since the instrument was standardised, the index at one end of the movable scale will be found to be below the middle line on its vertical scale, when the index at the other end is correctly pointing to the zero position. The error so introduced would be a small one, but it may be easily put right by slightly loosening the screws fixing the pillared frame, which supports the movable beam, to the base-plate, and raising it by slipping one or two thicknesses of paper below it until the indices simultaneously point to their zero position.

A lens is supplied with each instrument for facilitating accurate observation either when reading the position of the weight or adjusting the zero.

The vibrations of the beam may be checked so as
to facilitate reading by bringing the pendant, which moves the weight, lightly into contact with it in such a way as to give a little friction without moving the weights.

In using the centi-ampere balance as a voltmeter, when great accuracy is required, care must be taken that the effect of change of temperature in changing the resistance of the coils of the instrument, and of the external resistance coils, is allowed for; and in this use of the instrument it is advisable to employ currents such as can be measured by the lightest weight on the beam. When the instrument is to be used as a voltmeter, four resistances are provided, three of which are each 400 ohms, and the fourth is less than 400 ohms by the resistance of the coils of the instrument at a certain specified temperature. The smallest resistance is intended to be included by itself in the circuit when the lowest potentials are being measured, and in series with one or more of the others when the potential is so high as to give a stronger current than can be measured with the lightest weight on the beam. The correction for temperature is, for the copper coils of the balance about 0.38 per cent. per degree centigrade, and for the platinoid resistances, about 0.024 per cent. per degree centigrade.

Composite Balance.—The instrument is similar in form to the centi and deci-ampere balances, but the pair of fixed coils at one end of the beam are made of a rope of insulated wires similar to that used for the coils of the hekto-ampere balance. Separate electrodes are provided for the rope coils, and for the fine wire coils. A switch which allows the movable coils either to be included in the circuit by themselves or in series with the fixed fine wire coils, is attached to the under side of the sole-plate of the instrument. When the handle of the switch is turned to “Watt,” the movable coils alone are in the circuit; but when the handle is turned to “Volt,” both the movable and the fixed fine wire coils are in the circuit.

The composite balance can be used as hekto-ampere balance, or as a wattmeter, or as a voltmeter, by following the instructions given below.

In using this balance it should, like the standard balances, be levelled and the stop screws turned back out of contact with the cross trunnion and the front plate of the beam so as to leave it free to oscillate.

To use the instrument as a centi-ampere meter or as a voltmeter the switch is turned to “Volt,” and one or other of the weights marked V.W₁, V.W₂, V.W₃, used. The current flowing through the instrument is then to be calculated from the constant given in the certificate sent with the instrument. The volts on the terminals are calculated from the current in amperes and the resistance in ohms (including the anti-inductive resistance, if any) in circuit. If V be volts, C current, and R resistance,

\[ V = C \cdot R \]

The anti-inductive resistance is arranged so that the instrument reads a round number of volts per division.

To use the instrument as a hekto-ampere meter the switch is turned to “Watt” and the thick wire coils inserted in the current circuit in such a way that the right-hand end of the beam is repelled up. Either the sledge alone or the weight marked W₂W₃ is to be used in this case. A measured current is then passed through the suspended coils and the constants given in the certificate for the balance used in this way are calculated on the assumption that this current is, as there stated, 0.25 amperes. Any other current which is convenient in the circumstances may be used, and if this current be C amperes the corresponding constant is obtained by multiplying the constant given in the certificate by C/25 or 4C. The current through the suspended coils may be measured by means of the instrument itself arranged for the measurement of volts. This may be done by first measuring the current which the difference of potential between the supply conductors of an electrical installation, or between the poles of a battery, causes to flow through the coils of the instrument and its external resistance, and then turning the switch to “Watt,” and at the same time introducing a resistance into the circuit equal to the resistance of the fixed coils.

To use the instrument as a wattmeter one terminal of the fine wire coils is joined to one end of the anti-inductive resistance and the other terminal to one of the leads, the other end of the resistance being joined to the other lead. The thick wire coils are inserted in the main circuit as described in the previous paragraph. With the instrument thus joined up, the current through the suspended coils and the electromotive force between the leads may be obtained by the operations described two paragraphs above, since the presence of the thick wire coil in the circuit causes no appreciable error; or the electromotive force may be taken from the electrostatic voltmeter used on the circuit, and from its indications the current in the suspended coil circuit calculated. The watts are then to be calculated from the electromotive force on the leads and the current through the thick wire coils by the formula

\[ W = V \cdot C = e \cdot C \cdot R, \]

where e is the current in the suspended coil circuit, C the current in the thick wire coils, and R the resistance in the circuit.

The weights sent out with the instrument are arranged to give a round number of watts per division of the scale with a known anti-inductive resistance in series with the fine wire coils.

Portable or Marine Voltmeter.

For the measurement of potential in connection with electric lighting or power installation on board ship, the mass of the moving part of the balance voltmeter and engine-room voltmeter is too great to be convenient for accurate use. The marine voltmeter now to be described is specially suitable for such a purpose, but it is also equally useful as a portable voltmeter for general use, Figs. 69 and 70.
The instrument consists of a small oblate of soft iron supported on a stretched wire in the centre of a solenoid of fine copper wire connected in series with platinoid resistances, variable according to the potential to be measured; and is founded on the principle that an oblate spheroid of soft iron, movable round a diameter, tends to turn its equatorial plane parallel to the lines of force in a uniform magnetic field. The pointer is fixed relatively to the oblate in such a manner that, when the pointer is at the zero position of the scale, the equatorial plane of the oblate is inclined about 45 deg. to the lines of force of the solenoid.

The suspending wire is stretched between the two ends of a brass tube, being fixed at the bottom end and carried at the upper end by a torsion head, which is secured by screwing down upon it the movable cap of the top resistance coil (vide second paragraph below). Portions of the tube are cut away to permit of easy access to all parts of the instrument for adjustment or inspection. In order to prevent damage to the suspending wire or accidental disturbance of the torsion head, two brass cylinders, which also serve to carry the resistance coils (vide second paragraph below), are placed covering the two ends of the supporting tube, and are fixed by screws to the sheath.

The scale is graduated from zero to 140, but for convenience of observation the first marked division is 50. It is placed in a horizontal box with a glass cover fixed to the sheath, and the pointer shows, by inspection, direct reading of currents of from 50 to 140 milliamperes.

The resistances to enable the instrument to be used as a voltmeter are wound anti-inductively on two brass cylinders (vide above), and the lower one of these may be arranged to serve as a convenient means of supporting the instrument on a table or shelf. When, as is most commonly the case, the mean potential to be measured is 100 volts, the platinoid resistance is adjusted to make up, along with the fine copper wire solenoid (of which the resistance is about 60 ohms), a total resistance of 1,000 ohms. Thus, the direct reading of potential on the scale is in volts.

In order to save time in taking readings a checker is provided. A brass arc, capable of moving in a vertical direction, is placed parallel to and slightly below the plane in which the pointer moves, and by means of a handle this arc may be brought gently and momentarily into contact with the pointer so as to quickly stop its oscillations.

When the instrument is to be used for very accurate work, a means of observing and annulling any error due to residual magnetism in the oblate may be provided by a reversing key placed below the scale box, and two magnets screwing into the sheath. The current through the instrument is made in one direction when the handle of the reversing key is in the top position, and made in the opposite direction when the handle is in the bottom position. The current is broken when the handle is on either side. The residual effect in the instrument is very small, and it is found to be sufficiently accurate for all practical purposes without this adjustment.

When in use this instrument should be supported
with its scale approximately horizontal. For use as a marine voltmeter it is found convenient to place the instrument in a bracket, and secure it by passing a collar over the upper end of the tube.

The adjustment for annulling any effect due to residual magnetism in the oblate may be tested by taking two readings with a constant current passing through the coil, first in one direction and then in the other. If the readings so obtained do not agree, the current should be reversed through the coil several times by turning the handle of the reversing key—in most cases this will be found sufficient to restore the adjustment. Should it not do so recourse must be had to the two compensating magnets in the case, which should be simultaneously screwed out or in as required until the desired equality of readings is obtained. When this is done, the magnets should be again clamped by means of the nuts provided for that purpose. When it is found necessary to screw out the magnets to make the above compensation, and on screwing them out as far as possible a perfect adjustment cannot be obtained, the two magnets should be interchanged, and the desired compensation will then be speedily secured by screwing them in a little.

The adjustment of the zero is made by the maker, and it will rarely, if ever, require revision. Should such be found necessary at any time it may be very easily effected as follows:

(a) Unscrew the movable cap of the top resistance coil.
(b) Turn the torsion head until the needle points to zero.
(c) Replace the cap, screwing it down firmly.

Adjustable Magnetostatic Current Meter.

The magnetostatic current meter, Fig. 71, consists essentially of a small steel magnet or system of magnets suspended in the centre of a uniform field of force due to two coils, each having one or more turns of copper ribbon or wire, and also under the directive influence of two systems of powerful steel magnets. The suspended system of magnets is attached to one end of a vertical shaft passing down centrally through an opening in the soleplate of the instrument from an indicating needle, which is supported by a jewelled cap resting upon an iridium point. The two systems of directive magnets are circular in form, and each ring is composed of two semi-circular magnets placed in a brass cylindrical frame with their similar poles together. Each system is securely fixed to a circular brass frame, which fits on to the cylindrical case of the instrument in such a manner that the systems are capable of being turned round, together or separately, as explained below. The instrument has a "tangent scale," which is adjusted in its position before the instrument is sent out, so that the needle indicates equal differences of readings for equal differences of current. The scale consists of a hundred divisions, and for most purposes it is convenient to set the field magnets in such a position that the needle points to 0, and to use the scale from that point upwards towards 100. Sometimes, however, it may be found convenient to measure currents, whose direction is being occasionally reversed, without being at the trouble of reversing the electrodes in the contact clip; in that case the zero should be set to the division 50 at the middle of the scale, and readings taken on each side of it. It must be remembered that when the point taken as zero is changed, the constant, by which the indications of the instrument have to be multiplied to give the current in amperes, is changed in proportion to the cosine of the angle between the zero point and the middle of the scale: and as this angle is 60 deg. the constant with the zero at 50 on the scale is exactly double the constant with the zero at 0 on the scale.

The instrument is provided with a "lifter," which serves to raise the needle off the iridium point when it is being moved about from place to place. This lifter is in the form of a ring placed below the needle, and

Fig. 71.
The instrument has an advantage, important for some practical purposes, of being available as an accurate direct-reading current meter, through a continuous range of from 1 to 100 times its smallest current, which may be anything from half a milliampere to 4 amperes, according to the number of turns in the coils supplied with the instrument. It is not, however, available as an alternate-current instrument, and it must be remembered that the magnetism of the steel directing magnet does not remain absolutely constant. With good quality of steel, a proper preliminary ageing of the magnet (by heating it several times in boiling water and cooling again, and subjecting it to somewhat varied rough usage) brings it to a condition in which its magnetism is found to remain exceedingly nearly constant month after month and year after year. Still it should never be relied upon as absolutely constant, and for accurate laboratory work it is therefore necessary to have some means of retesting the instrument at any time. This is always easily done with the utmost accuracy if one of the balance instruments is available as a standard.

Another advantage which the instrument has is that, when a standard instrument is available, its constant is capable of being varied to any desired value down to one-tenth of that which it has with its directive magnets in their strongest position. Thus, if the constant should be 3 amperes per division of the scale, with the similar poles of the magnets coinciding, it may be adjusted to any value down to 0·3 ampere per division.

One very convenient use of the instrument is to act as a lamp-counter for indicating the number of incandescent lamps in use in an installation. For this purpose it is best to standardise it by putting on a known number of lamps and adjusting, as described below, until the desired reading is obtained on the scale. Of course this numbering of lamps is not possible to any great accuracy, because the lamps themselves are not all rigorously equal in the amount of current which each takes, but the lamp-counter serves the important practical purpose of showing at any time the number of lamps in use nearly enough for practical purposes. In private houses this is very useful as a check against some lamp or lamps being left accidentally alight in a cellar, or safe-room, or box-room, or other place where the fact of its being alight might escape observation for days or weeks together.

To count larger numbers of incandescent lamps up to 1,000 or more, the instrument is made with smaller rings of more massive conductor, and the same proportionate accuracy is attained as with the 100 lamp-counter.

The milliampere-meter, on account of the low resistance of its copper coil—about 40 ohms—may conveniently be used as a voltmeter. To adapt it for this purpose a copper cylinder, wound anti-inductively with two platinoid resistances, is supplied. The first of these, together with the resistance of the instrument, makes up 100 ohms, and the second alone is 900 ohms. Thus, taking the constant of the instrument at 2 milli-}

amperes per division, by joining the smaller in series with the instrument, the reading on the scale will be 1/5 of a volt per division. With both resistances in series with the instrument the reading will be 2 volts per division.

The magnetostatic current meters when used should be levelled, and the pointer adjusted to zero. The adjustment is made by

(a) Loosening the two lower milled-headed screws clamping the magnet frame, and turning the frame round till the pointer stands at zero;

(b) Then reclamp the frame by tightening the two screws.

The scale is firmly clamped in its place before sending the instrument out, and this position is marked by two lines on the outside of the case, one horizontal and the other vertical, just below the 0 of the scale. The horizontal line is engraved below the movable top of the instrument, and the vertical one on the side of the case. Should the top of the instrument have been inadvertently moved, and the scale thus put out of adjustment, it may be set right by slightly loosening the two slotted screws and turning the top round till the extremities of the two lines coincide.

If the needle should by accident be bent, it may firstly be made as straight as possible by the hand, and finally adjusted as follows: Set the zero, by the field magnets, to the division 50 at the middle of the scale, then join the instrument in series with another current instrument of convenient form, and pass a current through both sufficient to give a deflection of about 40 divisions on the magnetostatic instrument. Reverse the current on the magnetostatic instrument only, and set the scale so that equal deflections, read in divisions, are given on each side of the zero for equal currents, as indicated on the auxiliary instrument. The zero must, of course, be reset by the magnets every time the scale is moved. When the scale has been adjusted to this position, firmly clamp the top of the instrument by the two slotted screws, and again mark the position of the horizontal line on the outside of the case.

The constant may be quickly varied as follows: Join the instrument in series with any reliable current instruments of known accuracy, such as the deci-ampere balance, and pass a convenient current through both instruments, observing the readings. Break the current, loosen the two upper pair of milled-headed screws, and turn the top system of magnets relatively to the lower, so that the similar poles of the two systems are brought closer together or moved further apart, according as it is desired to make the instrument respectively less or more sensitive. Reclam the screws and adjust the zero as previously described. Again, make the current and note the reading on the two instruments. The desired reading on the magnetostatic may be obtained quickly after one or two approximations, care being always taken to readjust the zero after each movement of the top magnets.

When convenient it is always best to standardise the instrument in the place where it is to be used, but when
it is intended to move it from place to place it should be standardised in such a position that when the needle is pointing to zero it is in a direction approximately east and west.

**The Ampere Gauge.**

The ranges of the different types of this instrument usually made are:

I. From 25 to 5 amperes.
II. " 1 " 20 "
III. " 5 " 100 "
IV. " 10 " 200 "
V. " 25 " 500 "

The instrument, Fig. 72, is of simple construction, having a vertical slate base-plate, to which are attached:

(a) A solenoid of special form.
(b) Brass bearing-plates supporting a balance which carries a soft iron plunger on its one arm, and a brass counterpoise weight on the other.
(c) A brass arc having a scale graduated to give direct readings in amperes.
(d) A hinged arm which bears a light checker.

An indicating needle, or pointer, formed from a strip of platinooid, passes down from the trunnion of the balance to the brass arc bearing the graduated scale. As the plunger is attracted upwards, this pointer passes round the scale and indicates the strength of current passing through the solenoid.

When the instrument is packed for carriage, the brass counterpoise on the arm of the balance and the weight hung on the end of the plunger—which is the larger of the two—should be removed and placed in the receptacles provided for them. The pointer should also be placed in the slot at the left-hand side of the scale and secured by the button.

The instrument should be secured to a wall by means of its brass support provided for the purpose, so that the pointer is in the same plane with the scale and stands at 0 when no current is passing through the solenoid. When the instrument is thus supported, the plunger should be found hanging parallel to and between the two white lines engraved on the slate base-plate.

**The Electrostatic Voltmeters.**

These voltimeters have the great advantage of being available as accurate measures of potential on direct and alternating systems, and, being electrostatic, they use no current, and consequently require no temperature correction. They are therefore free from the causes of error so prevalent in instruments of the electromagnetic type, whose accuracy is impaired by variations of temperature, and which when used on alternating systems are affected by errors due to self-induction varying with the period of alternation. The chain of electrostatic voltimeters measures from 40 to 100,000 volts, and is composed of three distinct types—viz., the multicellular electrostatic voltimeters, the vertical electrostatic voltmeters, and the electrostatic balance.

The ranges of the separate instruments as usually made are:

**Multicellular Electrostatic Voltmeter**

- Range: 40 to 160
- Best of range: 50 to 100
- Range: 60 to 240
- Best of range: 70 to 130
- Range: 80 to 400
- Best of range: 100 to 240
- Range: 200 to 800
- Best of range: 300 to 600
- Range: 500 to 1,600
- Best of range: 700 to 1,300

**Vertical Volts**

- Range: 200 to 4,000
- Range: 400 to 8,000
- Range: 800 to 12,000
- Range: 2,500 to 50,000
- Range: 5,000 to 100,000

**Electrostatic Balance**

The instruments are made on the principle of an air condenser, having one of its parts movable about an axis, so as to increase or diminish the capacity. The condenser is enclosed in a metal case, for the double purpose of protecting the movable part from air currents, and from the disturbing influence of any electrified body, other than the fixed portion, differing from it in potential. In all the instruments, except the electrostatic balance, the fixed portions consist of two sets of quadrant-shaped cells in metallic connection with each
other, and formed by a number of parallel brass plates. These cells are fixed by an insulating support to the case of the instrument, and a terminal passes from them to an insulated binding screw on the outside of the case.

The movable portion in all the instruments is in metallic connection with the surrounding case. In the multicellular voltmeters this connection is made through the suspending wire, and in the vertical scale voltmeter and electrostatic balance through the knife-edges which support the movable part. The movable portion carries the pointer which indicates by direct readings the difference of potential between the two parts of the condenser.

The action of the instrument, shortly stated, is as follows: When the fixed and movable plates are connected respectively to two points of an electric circuit, between which there exists a difference of potential, the movable plate tends to move so as to augment the electrostatic capacity of the instrument, and the magnitude of the force concerned in any case is proportional to the square of the difference of potential by which it is produced. In the use of the vertical and electrostatic balance instruments this force of attraction is balanced by the horizontal component of a weight of any convenient amount hung on the knife-edge in connection with the movable part, while in the case of the multicellular it is balanced by the torsion of the suspending wire.

The arrangement of the parts of the multicellular electrostatic voltmeter is shown in Figs. 73 and 74. These figures apply to an early form of the instrument, and differ in two matters of detail from the voltmeter as now made. For simplicity in manufacture the cells are now made with straight backs, and the plates looked at in plan are, therefore, triangular instead of square, as shown in Fig. 74. A coach spring has now been interposed between the suspending wire and the spindle carrying the vanes, as explained below.

The insulated cells are formed of triangular brass plates fixed into saw cuts in a brass back piece so as to be equal distances apart and accurately parallel to each other. Two sets of these cells, $C$, are fixed relatively to each other, as shown in Fig. 74, by a vulcanite support to the sole-plate, so that their plates are horizontal, and are completely enclosed within the brass cylindrical case of the instrument.

On the top of this cylinder is a shallow horizontal circular scale-box containing the scale of the instrument, and having a glass cover, which serves to protect from currents of air the movable indicator, $I$, and the scale and interior parts from dust.

For the movable part a number of vanes, $V$, similar in form to those of the quadrant electrometer are used. These vanes are placed parallel to each other on a spindle with distance pieces between them. The top end of this spindle passes through a small hole in the sole-plate of the instrument, which forms the bottom of the scale-box, and is attached to a small coach spring, which in turn is secured to one end of a fine iridio-platinum wire suspended from a torsion head at the top of a vertical brass tube. The torsion head may be turned by means of a forked key provided for the purpose, and is clamped, to protect it from accidental displacement, by a cap which screws on to the end of the tube. The coach spring has sufficient resilience to allow the spindle to touch a guard stop, and so saves the suspension from injury in event of the instrument being roughly set down.

Two vertical brass repelling plates, which also act as guard-plates to prevent the movable part from turning
beyond its prescribed limits, are fixed to the bottom of the sole-plate. These two plates carry a guide-plate, G, with a circular opening in it, through which the lower end of the spindle passes. A little brass disc, or head, D, is attached to the end of the spindle, sufficiently large to prevent its passing back through the hole in the guide-plate. Thus the movable part is effectively secured from swinging about so as to be injured, and by no possibility can it come into contact with the insulated quadrants. When the instrument is level the spindle hangs free by the suspending wire, so that the vanes are horizontal, and each is in a plane exactly midway between those of two contiguous condenser-plates.

An aluminium needle attached to the top of the spindle indicates, on the horizontal circular scale fixed to the upper side of the sole-plate, the difference of potential between the movable and fixed portions of the condenser by direct readings in volts.

![Fig. 75.](image1)

To enable the multicellular to be used as an inspectional instrument capable of being read from a distance, as across an engine-room, a mirror, supported in a frame which passes over the vertical brass tube, and rests upon the glass cover of the instrument, is supplied. When this mirror is in position, it is at an angle of 45° with the plane of the sole-plate, and by reflecting the scale and pointer gives the instrument all the advantages of a vertical scale. The instrument is shown in Fig. 75 with its mirror in position. A small thumb-screw is placed in the centre of the base-plate below the instrument, which can be screwed in so as to lift the weight of the spindle and vanes from the suspending wire and clump the disc on the end of the spindle against the guide-plate. A lifter or checker is also provided similar to that used in the magnetostatic instruments. A switch is attached to the upper terminal of the instrument by which the voltmeter can be taken out of circuit when desired. The switch, after breaking circuit, puts the case and the insulated cells in metallic connection. When received from the maker the indicator needle with attached vanes will be found supported by means of the thumb-screw below the instrument, and also by the circular lifter, or checker, turned up so that the weight of the needle and vanes is taken off the suspending wire. The scale is graduated to read directly in volts.

To set the instrument up for use (a) unscrew the thumb-screw, and turn down the checker, so that the needle swings clear; (b) level the instrument so that the spindle of the vanes passes down centrally through the intersection of the two black cross-lines on the sole-plate. To adjust the zero, if necessary, unscrew the cap on the top of the tube, remove the washer, turn the torsion head by means of the forked key until the pointer stand at 0 on the scale. Replace the washer and screw on the cap again. Before adjusting the zero turn the switch so that the insulated cells are in metallic connection with the case. When the instrument is to be removed from place to place, see that the needle is lifted by turning up the checker, and when it is packed for use as a portable instrument, always screw up the thumb-screw as mentioned above.

As aluminium is electro-positive to brass, the instrument reads about \( \frac{1}{4} \) of a volt too low when the positive pole of a battery or dynamo is attached to the upper or insulated terminal of the instrument; and about \( \frac{3}{4} \) volt too high if connected in the opposite direction. With alternating currents it is correct.

The vertical electrostatic voltmeter is shown in Fig. 76, and, as will be seen, the insulated quadrants are supported with their plates vertical, and only one
large vane is used. This movable plate is supported in a vertical position on knife-edges, so that the plane of its motion is parallel to the two fixed plates which form the insulated quadrants. Its upper end has a fine prolongation which serves as a pointer for indicating the deflections on the scale of the instrument, and at its lower end is fixed the knife-edge for the weights, having its length perpendicular to the plane in which the plate moves.

In order to save time in taking readings, an arrangement is provided for checking the oscillations of the movable plate, and stops are placed to limit its range and prevent damage to the pointer. One of these stops, the left-hand one, is made to act as a support for the vane in the arrangement for portability described below.

The scale is graduated from 0 to 60, and the divisions represent equal differences of potential—the actual magnitude of the difference per division being dependent upon the weight in use at the time. A set of three weights is sent with each instrument, providing for three grades of measurement in the proportion of 1:2:4. Thus the instrument shows one division per 50 volts with the link (the lightest weight) alone on; one division per 100 volts with the medium weight hanging on the link, and one division per 200 volts with all three weights on.

To set up the electrostatic voltmeter in working order, remove the glass door of the case, place the movable plate or vane on its knife-edge support, handling it very carefully unless it be bent or twisted in the operation. A line, drawn lengthwise on the surface of the movable plate, and passing through its intersection with the knife-edge, divides the portions above and below the knife-edge into unequal parts. When the movable plate is properly placed, this line is just seen behind the vertical edge of the fixed plate when the pointer indicates zero, and the smaller segments of the movable plate are then hidden from a front view by being between the fixed plates.

To detect, and if necessary correct, any accidental bending of the pointer, with reference to the attracted portion of the movable plate, hang one of the weights on the lower knife-edge; take the round pin sent inside the case and with it press the movable plate in between the fixed plates, until it rests in the two V-notch near the upper end of the vertical edges of the fixed plates; holding the pin so, rotate it about its axis, and observe that the pointer indicates a small red line seen on the scale in the neighbourhood of division number 33.

Remove the weight and see whether the movable plate is in neutral equilibrium. If it is so, the index will move very slowly along the scale, and will come to rest somewhere within its range. If the index rests against one of the stop-pins, screw out, or in, the nut on the horizontal screw attached to the lower end of the vane until the pointer comes to rest on the scale. If the index rests very definitely at one point of the scale and vibrates about it, the movable plate has too much stability; if it is found that the index will rest against both of the stop-pins, but will not rest at any other point on the scale, the movable plate has too little stability. The stability can be adjusted by screwing up or down the nut on the vertical screw attached to the lower end of the vane. These adjustments are made by the maker, and will generally be found to be nearly enough correct.

After hanging on the weights, adjust the pointer to zero by means of the screw levelling feet on the case of the instrument.

The Electrostatic Balance.

The arrangement of the parts of this instrument is shown in Fig. 77. The fixed portion of the condenser in this instrument is a brass disc, B, which is supported from a slate base, S, on three glass pillars, P. The disc is provided with the well-known Thomson "hole, slot, and plane" arrangement, so that it always rests in exactly the same position on its supports.

![Fig. 77.](image)

A wire thickly covered with indiarubber passes from a terminal, T, through a glass tube, C, C, C, and makes connection with the disc by a spring contact; the glass tube being filled with paraffin to prevent the lodgment of moisture and give great resistance to disruptive discharge. A sheath formed by a short piece of glass tube pulls up over the terminal, T, and protects it from being touched by accident. The slate base-plate is provided with three screw levelling feet. A brass case fits upon the slate base-plate, and fixed to its top is a metal scale-box with a glass front, which contains the indicator and scale. The movable part, V, is a round aluminium plate, supported by two long links, which pass through a slit in the top plate of the case to two knife-edge stirrups on one end of the counterpoised indicator, I. The whole movable portion is supported by knife-edges on two brass pillars and has a short arm, A, with a knife-edge stirrup at its extremity attached to its axis. The weights which fix the constant of the instrument hang on this stirrup.
The instrument has a scale with divisions corresponding to equal differences of potential. The scale is graduated from 0 to 50, and three weights are provided such that, with the first alone hung on, the constant is 250 volts per division, with the first and second weights on, it is 500 volts per division, and with all three weights on, 1,000 volts per division.

The following precautions ought always to be taken for safety in the use of Sir W. Thomson’s electrostatic voltmeters in connection with dynamos, whether for direct or alternating currents.

In all applications in which one of the two conductors connected with the voltmeter is kept permanently connected with the earth, this conductor should be connected with the outer case of the voltmeter. The other is to be connected with the insulated terminal, and must be carefully guarded against accidental contacts.

To provide for use in any application not fulfilling this condition, all the electrostatic voltmeters are supplied with thoroughly insulating feet; and the precautions stated below must be observed.

The vertical scale voltmeter for from 400 to 12,000 volts, when set up for permanent use, should be enclosed in a case (which may be of wood with a glass front) preventing any person from accidentally touching the metal case or the terminals of the instrument. The vibration checker is worked with perfect safety by a silk cord passing through the wood or glass of the protecting case to the front outside. For temporary or experimental applications the user must take his own precautions; an outer enclosing glass case might be found too cumbersome. For ordinary domestic electric lighting or other applications to less than 200 volts, the multicellular voltmeter may be left unprotected so far as personal danger is concerned; but, to avoid chances of damage to instruments or wires, or of melting a fuse, its outer case, as well as its terminal insulated from the outer case, ought to be perfectly guarded against accidental contacts when the instrument is set up for permanent use. Glass and vulcanite sheaths are provided for this purpose by the instrument maker when desired.

Never open the case of the vertical scale voltmeter, to change its weights, nor touch its terminal to connect or disconnect (or to secure either connection if imperfectly made), without being sure either that the dynamo is not running, or that both the conductors leading to the voltmeter are safely disconnected from its circuit.

It may be asked, with reference to the vertical scale voltmeter, why is the inner case made of metal? The answer is, that the electric conditions for definiteness of measurement require the vane to be protected all round from sensibly disturbing influence of any substance, other than the air around it, differing in potential from itself unless at the same potential as the quadrants. Why, then, not coat the metal inner case with wood or vulcanite, or other non-conducting material? Answer: The protection thus imagined might be delusive when 10,000 volts is dealt with.

Safety is more surely secured by an outer case an inch or so from the inner metal, unless, which is always best when it can be arranged for, one of the conductors is kept connected with the earth, and with the metal case of the electrometer also connected with the earth.

New Engine-Room Voltmeter.

This instrument is intended for installation work on either direct or alternating circuits, where it is convenient to have a direct-reading voltmeter with large scale divisions.

The instrument, as shown in Fig. 78, depends for its action upon the repulsion of a movable coil, M, by a fixed coil, F. The fixed coil, F, bears all the other portions of the instrument attached to it, and is in its turn supported from a vulcanite block fixed to the instrument case. This vulcanite block also bears the terminals of the instrument. The movable coil is supported on knife-edges, and the circuit through it from the fixed coil of the voltmeter is made by two spirals of fine copper wire. A pointer attached to the movable coil indicates by direct readings in volts the difference of potential between the terminals of the instrument. Attached to the pointer on one side, and perpendicular to it, is a short arm, with a screw nut, N, which, together with the sliding weight, S, on the pointer, serves to adjust the balance of the movable parts. To
Missing Page
instruments, costing from £20 to £30; considerable
trouble and expense are incurred in the first place
to adjust the coils with perfect accuracy; and an elaborate
but unnecessary finish is indulged in to do justice to it.
A bridge costing £3 or £5, suitable for ordinary instal-
lalion work, cannot be obtained. It is by no means
intended to depreciate accuracy. An accurate instru-
ment is better than an inaccurate one, other things
being equal; but it would be absurd if a grocer could
buy nothing cheaper than a chemical balance to weigh
with, because scale makers found they were capable of
very great accuracy and had plenty of room for
unnecessary finish. Accurate bridges are required for
such work as localising faults in telegraph lines, but
rough resistance-boxes right within, say, ½ per cent.,
would be good enough for ordinary work. As it is,
an installing engineer, who would not scruple to
dispose with a voltmeter and judge the electromotive
force by the look of the lamps, searches for ground
contacts with a 40-guinea bridge in conjunction with
one defective Leclanché cell and a pivoted detector
which sticks."

A very useful and at the same time inexpensive
form of galvanometer is

The Holden-d’Arsonval Galvanometer.

This galvanometer, as shown complete in Fig. 79, and
with its cover removed in Fig. 80, is a development of
the well-known d’Arsonval dead-beat zero instrument.
In the improved galvanometer we have a powerful
laminated permanent magnet of circular form, and
placed horizontally. The poles of this magnet are
brought round to face one another, and are turned out
so as to encompass the moving coil. In the centre of
the magnetic field, and midway between the poles,
a cylindrical rod of very soft iron is placed, serving as a
medium for concentrating the lines of force, and making
the magnetic field quite uniform. The moving coil is
built upon a light silver frame, and is wound
with No. 40 silk-covered copper wire, and when
mounted with its suspending wires it has a total
resistance of about 16 ohms. The current is led into
the coil by means of the suspended platinoid or
phosphor bronze wire, starting from a spring at the
top of the instrument and passing out through another
wire fixed at the bottom and attached to a mill-headed
screw. The spring holding the top wire serves to give
the necessary tension. The bottom screw-nut is used
to produce the desired torsion to bring the mirror to
its zero mark. A special point about this instrument is
an arrangement for lifting out the coil and its
enclosed iron core, and thereby affording a ready
means of renewing the suspension wires or mirror,
and making other adjustments. By simply unscrewing
a clamping screw, and removing one connecting wire
from a binding clamp, the whole coil system can be
removed. The advantage of this arrangement is
apparent, as a number of different resistance coils may
be supplied with each instrument, and at the same
time it reduces the chances of damage in transit. With

a coil having a resistance of 16 ohms and an added
resistance of 100,000 ohms, a deflection of the coil
equal to an angle of 1 deg. may be obtained with a
pressure of 1 volt. As the scale is found to be of
practically equal divisions, the instrument may be used
as an ampere or volt meter by the addition of suitable
shunts or resistances.

Measurement of the Internal Resistance of Batteries.

Having ascertained the resistance of our tangent and
mirror galvanometers, the data so obtained will assist
us in measuring the internal resistance of the battery
we are using. The student will notice the points of
similarity between the methods here given for
measuring battery resistance with those for measuring
galvanometer resistance, page 313.

Galvanometer. Battery.

Direct bridge method. Direct bridge method.
Half deflection method. Half deflection method.
Equal deflection shunt method. Equal deflection shunt
method.
Thomson’s method. Mance’s method.

A. Direct Bridge Method.—This is a very inferior
method to either of the others to be described. It
necessitates the employment of two similar cells having
exactly equal electromotive force. The two cells are
joined up so as to oppose each other, and are then
placed in the fourth arm of the bridge, and the
resistance of the pair measured in the ordinary way.
This value divided by 2 is taken as the resistance of
the cell—a pure assumption, as we have no proof that
the resistance of one cell equals that of the other.
The arrangement is shown in Fig. 81.

B. Half Deflection Method.—Join up the battery by
means of short thick wires with resistance-box and
tangent galvanometer, and introduce such resistance,
\( R_t \), as will allow of a deflection of about 55 deg. = \( d \).
Increase \( R_t \) to \( R_s \), until the deflection is reduced
one-
half = \( d \) = \( \frac{d}{2} \), then

\[
r = R_s - (2R_t + G)
\]

The connections are the same as for the determination
of galvanometer resistance by "half deflection
method," Figs. 82 and 83.

"To avoid mistake in calculation, first double the
smaller resistance, to the result add the resistance of
the galvanometer, and then deduct the total from the greater resistance."—Kempe.

If with the lowest resistance we can give to \( R_1 \) the deflection should exceed 55 deg., the sensitiveness of the galvanometer may be reduced by employing a shunt, in which case the resistance of galvanometer will be

\[
\frac{G \times s}{G + s}
\]

**Example.**—With a tangent galvanometer, \( G \), whose resistance was known to be 28 ohms, the internal resistance of a Daniell cell was found by the half deflection method to be as follows:

When \( d_1 = 50 \text{ deg.} \) \( \left( \tan 50 \text{ deg.} = 1.23 \right) R_1 = 90 \text{ ohms.} \)

\[
\frac{d_1}{2} = 30 \text{ deg.} \quad \left( \tan 30 \text{ deg.} = 0.57 \right) \quad R_2 = 74 \text{ ohms}
\]

\[
r = R_2 - 2 R_1 + G
\]

\[
= 74 - 2 \times 90 + 23
\]

\[
= 74 - 68 = 6 \text{ ohms}
\]

**C. Equal Deflection Shunt Method.**—Join up galvanometer, resistance-box, and cell whose resistance, \( r \), is required with a shunt, \( s \), between its poles, and note deflection, \( d_1 \), produced with resistance, \( R_1 \), in circuit.

**D. Mance’s Method.**—Place cell whose resistance is to be measured in the fourth arm of the bridge (Fig. 86) connecting the galvanometer (which should be a Thomson’s mirror) in usual manner to terminals, \( C \), \( A \), \( E \), \( B \), interposing a key between \( B \) and \( E \). Then adjust resistance \( a \), \( b \), and \( d \).

\[
r = \frac{a d}{b}
\]

With a Post Office bridge the connections would be made as in Fig. 87. Having arranged suitable resistances in \( b \) and \( d \), bring in the galvanometer by firmly pressing down \( K \), and then vary the resistance in \( d \) till no alteration in the deflection is produced by closing or opening \( K \).

The great advantage of this method is that the electromotive force need only be constant during the short time necessary to close and open key.

Make \( b \) as high and \( a \) as low as the resistances at command will permit.

The student will not fail to notice the similarity of this method with that of Thomson for measuring the resistance of galvanometers—the galvanometer and battery simply change places. The directions to be followed are the same in both cases.
Example.—The Daniell cell previously referred to required 630 ohms in d, b and a being 1,000 ohms and 10 ohms respectively, therefore

\[ r = \frac{a \cdot d}{b} = \frac{10 \times 630}{1,000} = 6.3 \text{ ohms}. \]

A "slide wire" bridge may be employed for this test instead of the Post Office form; in which case the connection will be as in Fig. 88.

![Fig. 87.](image)

Placing the cell in \( r \) and resistance coils in \( d \), move slider along the wire until on closing the key no change in the deflection of galvanometer is produced, then

\[ r = \frac{a \cdot d}{b} = d \left( \frac{d}{1,000 - a} \right). \]

Make \( d \) greater than \( r \), so that \( b \) may exceed \( a \).

In Mance's as in Thomson's method, a controlling magnet must be employed to bring the permanent deflection to the zero of scale.

Example.—In measuring \( r \) of the Daniell cell, \( d \) being 10 ohms, balance was obtained when \( a = 380 \) divisions of the scale.

\[ \therefore r = d \left( \frac{d}{1,000 - a} \right) = \frac{380}{1,000 - 380} = \frac{10 \cdot 380}{620} = \frac{3,800}{620} = 6.1 \text{ ohms}. \]

Summary.—Of the four methods of determining the internal resistance of batteries described above, the equal deflection method has the advantage that any sensitive galvanometer may be used, since we have only to reproduce a given deflection—also, in common with Mance's, the resistance of the galvanometer need not be known.

Where a Thomson reflecting galvanometer is at hand, Mance's method leaves nothing to be desired.

With a good tangent galvanometer of moderate resistance, very good results can be obtained with the half deflection method. In every case the higher the figure of merit of the galvanometer, the greater is the degree of accuracy attainable.

Determination of Electromotive Force.

The measurement of electromotive force has the disadvantage that, unlike the measurement of resistance, there exists no procurable standard of the practical unit, or volt. Still, the electromotive force of a well-made Daniell cell so nearly approximates to the theoretical value of the volt that we may safely take one of these cells for our standard.

The Daniell cell is made in a variety of forms, but the one known as "Wheatstone's standard cell" will be found very suitable for our purpose.

Into an outer glass or glazed earthenware pot (Fig. 89) is placed a cylindrical sheet of copper with a wire attached (for positive pole), and inside this a small porous pot, the space between the porous and outer pot being filled with a saturated solution of copper sulphate.

A few small pieces of zinc are put into the porous pot, and sufficient mercury added to nearly cover them.

![Fig. 89.](image)

The porous pot is then filled up with water to the same height as the copper sulphate in the outer jar, and a short length of gutta-percha-covered wire, with the end uncovered, so as to make contact with the mercury and zinc, serves to form a negative pole for the cell.

When not in use the cell should be dismantled, and after placing the porous pot in nitric acid for a short time it should be well washed, and then allowed to stand in water until again required. The mercury and zinc may be repeatedly used. The electromotive force of this cell is 1.079 volt.

All the following methods of determining electromotive forces are based upon the principle of comparison against this standard cell:

- A. Equal deflection method.
- B. Equal resistance method.
- C. Wiedeman's method.
- D. Wheatstone's method.
- E. Poggendorff's method.
- F. Latimer Clarke's method.
**Equal Deflection Method.**—As in the case of measuring the resistances of galvanometers and batteries by the equal deflection method, any kind of sensitive galvanometer may be used, as we have merely to reproduce a given deflection.

Join up standard cell, \( E_1 \), resistance-box, and galvanometer in simple circuit, Figs. 83 to 85, and unplug resistance, \( R_1 \), till a suitable deflection, \( d \), is obtained.

Replace standard cell, \( E_1 \), by the one whose electromotive force has to be measured, \( E_2 \), altering resistance in box to \( R_2 \) till the same deflection is secured as with the standard cell.

![Fig. 90.](image)

Then, if \( C \) = resistance of galvanometer, and \( r_1, r_2 \) the internal resistances of the two cells, \( E_1 \) and \( E_2 \), it follows, since the deflections are equal, the currents must be equal also, and by Ohm's law we get

\[
C = \frac{E_2}{r_1 + R_1 + C} = \frac{E_2}{r_2 + R_2 + C}
\]

or, calling the total resistances in each measurement \( R_1 \) and \( R_2 \),

\[
C = \frac{E_1}{R_1} - \frac{E_2}{R_2} = \frac{E_1}{R_1} = \frac{E_2}{R_2}
\]

\[
E_1 : E_2 : : R_1 : R_2
\]

\[
E_2 = E_1 \frac{R_2}{R_1}
\]

from which we see (as proved on page 313, "Experimental Proofs of Ohm's Law") that the electromotive forces of the two cells are directly proportionate to the total resistances in circuit.

With a high resistance in circuit, \( r_1 \) and \( r_2 \) may be ignored.

The greatest accuracy is obtained when \( R_1 \) and \( R_2 \) are made as high as possible.

**Example.**—In the following examples the electromotive force of a Leclanché cell, \( E_2 \), was compared with that of the standard Wheatstone-Daniell, \( E_1 \).

Using a tangent galvanometer, we obtained

\[
d = 25 \text{ deg., } R_1 \text{ 30 ohms, } R_2 \text{ 40.}
\]

\[
E_1 : E_2 : : R_1 : R_2
\]

\[
1 : E_2 : : 30 : 40
\]

\[
E = \frac{1 \times 40}{30} = 1.3 \text{ volt.}
\]

**Example.**—Employing the mirror galvanometer, the values of \( R_1 \) and \( R_2 \) were 7,000 ohms and 9,000 ohms respectively.

\[
E_2 = \frac{1 \times 9,000}{7,000} = 1.28 \text{ volt.}
\]

**Equal Resistance Method.**—Join up standard cell, \( E_1 \), resistance-box, and galvanometer, as in preceding method, Figs. 83 to 85. Adjust resistance till a suitable deflection, \( d_1 \), is obtained. Note this deflection, and also the total resistance in circuit. Substitute \( E_2 \) for \( E_1 \), and if it has a different internal resistance the resistance in the box must be readjusted so as to maintain the total resistance the same as when \( E_1 \) was in circuit. Note new deflection, \( d_2 \).

Then, if \( C_1 \) be the current producing \( d_1 \), and \( C_2 \) the current producing \( d_2 \), we have, by Ohm's law,

\[
C_1 = \frac{E_1}{R} \text{ and } C_2 = \frac{E_2}{R}
\]

And since the deflections are proportional to the currents producing them, we have

\[
E_1 : E_2 : : C_1 : C_2 : : d_1 : d_2
\]

or

\[
E_2 = E_1 \frac{d_2}{d_1}
\]

If the tangent galvanometer scale is graduated into degrees of arc, then the tangents of \( d_1, d_2 \) must be taken.

![Fig. 91.](image)

Make \( R \) as high as possible, and with a tangent galvanometer let \( d_1, d_2 \) have equal values on each side of 45 deg.

**Example.**—Using a tangent galvanometer and making the total resistance \( R = 30 \) ohms, the standard
cell gave a deflection, \( d_1 \), of 41 deg., and the Leclanché a deflection, \( d_2 \), of 45 deg.

\[
\therefore E_2 = E_1 \tan 48\text{deg.} \\
= \frac{1.11}{0.87} = 1.27 \text{ volt.}
\]

The mirror galvanometer (shunted down to \( \frac{1}{8} \) in order to obtain a convenient deflection) gave with the standard cell, \( E_1 \), and 10,000 ohms in circuit, a deflection, \( d_1 \), of 40 divisions. On substituting the Leclanché cell, \( E_2 \), a deflection, \( d_2 = 50\cdot5 \) divisions was obtained through the same resistance; therefore

\[
E_2 = \frac{E_1 \times 50\cdot5}{40} \\
= \frac{1 \times 50\cdot5}{40} \\
= 1.26 \text{ volt.}
\]

Wiedeman's Method.—This is a very good method, since it is entirely independent of the internal resistance of the battery, but a sensitive galvanometer and high resistance should be employed.

Join up both cells in series, Fig. 92, and adjust the resistance so as to allow a high deflection, \( d_1 \), to be obtained.

The current, \( C_1 \), producing this deflection with a total resistance, \( R_t \), in circuit is

\[
C_1 = \frac{E_1}{R_t}
\]

Now reverse the weaker cell, \( E_2 \), so that the two oppose each other, and note the smaller deflection, \( d_2 \), due to \( E_2 \) and \( R \) remaining same as before.

\[
C_2 = \frac{E_1 - E_2}{R}
\]

therefore

\[
E_1 = E_2 \left( \frac{C_1 + C_2}{C_1 - C_2} \right) \\
\therefore d_1 = d_2 \left( \frac{E_1}{E_2} \right)
\]

N.B.—Since the weaker cell has to be reversed in above method, \( E_1 \) represents the Leclanché and \( E_2 \) the standard Daniell, whereas in each of the other methods described the reverse is the case.

The above formula is applicable to mirror galvanometers, etc., with tangent galvanometer tan \( d_1 \) and \( d_2 \) must be taken.

Example.—With the tangent galvanometer, the Leclanché cell, \( E_1 \), and the Daniell, \( E_2 \), in series, gave a deflection, \( d_1 = 54\cdot5 \) deg., and with the Daniell reversed a deflection \( d_2 = 10 \) deg.

\[
E_1 : E_2 : \tan d_1 = \tan d_2 : \tan d_1 - \tan d_2 \\
E_1 : 1 : \tan 54\cdot5 + \tan 10 : \tan 54\cdot5 - \tan 10 \text{ deg.} \\
\therefore 1:40 \text{ deg.} + 176:1\cdot19 - \cdot17 \\
\therefore 1:576:1\cdot224
\]

\[
E_1 = \frac{1\cdot576}{1\cdot224} \\
= 1.28 \text{ volt.}
\]

Example.—The shunted mirror galvanometer with \( R = 10,000 \), gave \( d_1 = 105 \) and \( d_2 = 11 \) scale divisions.

\[
\therefore E_2 = \frac{1\cdot105 + 11}{1\cdot105 - 11} \\
= 1\cdot116 \cdot\frac{1}{94} \\
= 1\cdot24 \text{ volt.}
\]

Wheatstone's Method.—This method, like the preceding one, is independent of the battery resistances, and any sensitive galvanometer may be used.

Join up in simple circuit, as in Fig. 93, the standard cell, \( E_1 \), galvanometer, and resistance in box until a moderately high deflection, \( d_1 \), is obtained. Increase the resistance by an amount = \( R \), so that a diminished deflection, \( d_2 \), is produced.

Replace \( E_1 \) by the cell, \( E_2 \), whose electromotive force is to be measured = \( E \), and readjust initial resistance in circuit till deflection \( d_1 \) is obtained, as with \( E_1 \). The resistance is now increased by an amount = \( R \), sufficient to again reduce the deflection to \( d_2 \), as in first case. Then

\[
E_1 : E_2 : R_1 : R_2
\]

or the electromotive forces of the two cells are directly proportionate to the added resistances. Make the initial resistances as high as the galvanometer will admit of, and the added resistance approximately double this.

Example.—With an astatic galvanometer and an initial resistance of 10 ohms the standard cell, \( E_1 \), gave a deflection of 25 deg. = \( d_1 \), which was reduced to 25 deg. by the addition of 20 ohms = \( R \).

Substituting the Leclanché cell, \( E_2 \), it required 19 ohms to reproduce the deflection \( d_1 \), and to reduce this to \( d_2 \) an addition of 25 ohms = \( R_2 \) had to be made.

\[
E_2 = \frac{E_1 \cdot R_2}{R_1} \\
E_2 = 1 \times \frac{25}{20} \\
= 1\cdot25 \text{ volt.}
\]

Example.—Employing the mirror galvanometer, it required 2,000 ohms = \( R_1 \) to reduce \( d_1 \) to \( d_2 \) with the Daniell cell in circuit, whereas the Leclanché required 2,550 ohms.

\[
E_2 = 1 \times \frac{2\cdot550}{2\cdot000} \\
= 1\cdot27 \text{ volt.}
\]
Poggendorff's Method.—With this method, the reading is taken when no current is flowing through the galvanometer, the electromotive force of the cell to be determined being balanced against that of the standard, therefore the relative values of the divisions on the galvanometer need not be known. Hence any form of instrument can be used, a low-resistance astatic combination being very suitable.

Again, since no current is flowing, all possibility of errors arising from polarisation is prevented. Also, by varying the resistances and taking a second reading and combining the two values, we eliminate the internal resistance of the cell under investigation.

Join up the two cells, galvanometer, and resistance-box, as shown in Figs. 94 and 95.

The standard cell, \(E_1\), should be stronger than the one, \(E_2\), to be measured, hence two or more Daniell cells in series must be used as occasion may require.

Unplug the two 100-ohm \(= r_1\) in A C and adjust the resistance, \(R_1\), in A E until no deflection is produced on closing the key, \(K_2\). Reduce resistance \(r_1\) to \(r_2\) by inserting one of the 100-ohm plugs in A C, and again vary resistance to \(R_1\) in A E, so that balance is again obtained, then

\[
E_1 : E_2 : (R_1 - R_2) : (r_1 - r_2) : (R_1 - R_2)
\]

or

\[
E_1 = (R_1 - R_2) + (r_1 - r_2)
\]

or

\[
E_2 = (R_1 - R_2)
\]

Example.—On placing two Daniell cells, \(E_1\), and whose electromotive force = 2 volts, between C E and the Leclanché cell, \(E_2\), to be measured with galvanometer between A E, and making \(r_1 = 200\) ohms, it required a resistance of 500 ohms in A E to prevent deflection of the needle of an astatic galvanometer.

On \(r_1\) being reduced to \(r_2 = 100\) ohms; \(R_1\) had to be lowered to \(R_2 = 300\) ohms.

\[
E_1 : E_2 = (R_1 - R_2) : (r_1 - r_2)
\]

\[
2 : E_2 = (500 - 300) + (200 - 100) = 200 + 100 = 300
\]

\[
3 : 2
\]

\[
E_2 = \frac{2 \times 2}{3} = 1.3\text{ volt.}
\]

If the electromotive forces of the two cells compared be equal, the test is impossible, and the greater the difference in their electromotive forces the more accurate becomes the measurement.

Latimer Clarke's Method.—In the development of Poggendorff's method both the standard and the trial cell are compared when no current is flowing in either. The initial difference of potential, to the fall of which the electromotive forces of the two cells are to be compared, is set up and maintained by a third battery, \(E\), of greater electromotive force than either of the two under comparison.

Instead of an ordinary box of resistance coils, which might be damaged by the heat produced by a strong continuous current, a slide wire resistance may be employed as follows: Take about 20 ft. of thin German silver wire and stretch it in a series of zig-zags between two rows of pins stuck into a dry board, the end of the wires being fastened to two binding screws, A and B, Fig. 96. If the length of each diagonal be 1 ft, it will facilitate subsequent measurement.

To terminal A connect the wires leading from the zinc poles of three batteries—\(E\), the one maintaining the difference of potential in the wire; \(E_1\), the standard cell; and \(E_2\) the cell to be measured.

Connect wire from positive pole of \(E\) through \(K\) to terminal, B, of slide wire, and from the corresponding poles of \(E_1\), \(E_2\) lead wires through two galvanometers, \(G_1\), \(G_2\).

Close K and move end of wire from \(E_1\), \(G_1\) along the slide wire from A towards B. At a certain distance = \(P_1\), the needle of \(G_1\) will come to rest. Measure the length of wire from A to \(P_1\).

Next touch slide wire with the end of wire from \(E_1\), \(G_2\). Note position, \(P_2\), at which \(G_2\) comes to rest, and
measure length of wire, \( A \ P_2 \). Then, assuming that
the resistance of the slide to be uniform, and to vary as its length, the distances \( A \ P_1 \) and \( A \ P_2 \) may be
taken as giving the relative resistances, \( R_1 \), \( R_2 \). The slide wire included in the two circuits of \( E_1 \) and \( E_2 \), and if \( C \) = current produced by \( E \) flowing through \( B \), then
\[
E_1 = C R_1, \quad E_2 = C R_2;
\]
\[
\frac{E_1}{E_2} = \frac{R_1}{R_2};
\]
and since \( C \) is common to both measurements, we get
\[
\frac{E_1}{E_2} = \frac{R_1}{R_2},
\]
or the electromotive forces of the two cells compared,
are proportionate to the lengths of the slide wires,
\( A \ P_1 \) and \( A \ P_2 \).

Messrs. Glazebrook and Shaw have suggested a very
useful modification of above arrangement, by which
one galvanometer suffices, a consideration of importance
to amateur experimentalists.

The arrangement is very similar to the preceding
one, except that the two positive wires from \( E_1 \) and \( E_2 \)
are connected to the two terminals, \( a \), \( b \), of a three-
point switch, the remaining terminal, \( c \), being joined
to the galvanometer and wire for making contact with
the slide wire, Fig. 97.

Close \( K \) and switch \( E_1 \) on to galvanometer by
inserting the peg between \( a \), \( c \), slide the free end of the
wire from galvanometer along \( A \) \( B \) till needle comes to
rest—note this point \( P_1 \). Switch \( E_2 \) on to galvan-
ometer and ascertain position \( P_2 \).

Measure \( A \) \( P_1 \) and \( A \) \( P_2 \), and proceed as previously
described.

Example.—Using a Grove cell, \( E \), to maintain
the difference of potential on the wire, a standard Daniell
cell required contact to be made at a point, \( P_1 \), 11ft. 6in.
from \( A \), whereas with the Leclanché cell \( P_2 \) was at a
distance of 14ft. 9in.: therefore, as
\[
11\text{ft. } 6\text{in.} : 14\text{ft. } 9\text{in.} :: 1 : E_2,
\]
\[
E_2 = \frac{14.9}{11.6} = 1.28 \text{ volt.}
\]

Summary.—Of the above methods of comparing the
electromotive force of cells, “the equal deflection method” has the advantage that any delicate galvano-

meter may be used, but either the internal resistance
of the cells must be known, or the interpolar resistance
must be so great in comparison, that it may be
neglected; when this is the case it is a very ready
and useful method. With the “equal resistance
method” the same remarks apply as to internal
resistance of cells, in addition to which the values
of the deflections must be comparable; with a good
mirror or tangent galvanometer it works well.
Place one of the boards on the table, and lay upon it two sheets of the paraffined paper; then a sheet of tinfoil, laying on the sheet a strip of foil sufficiently long to project over one of the edges of the paraffined paper; next, two more sheets of paraffined paper, then a second sheet of foil with a projecting strip, but with the strip this time turned towards the opposite edge of the paraffined paper. Continue the process until some 40 sheets of foil have been laid, each sheet separated by two layers of paraffined paper, taking care that the ends of the strips belonging to the odd numbers lie over each other on one side of the pile, and the corresponding strips belonging to the even numbers forming another group on the other side of the pile. Lastly, place two sheets of paraffined paper on top of last foil, and bend the whole of the “odd” strips up on to the top at one side, and the whole of the “even” strips up on the top at the opposite side; folding the ends of each bundle of strips round the ends of two short wires, pass these wires through two holes in the top board, which must be carefully placed on the top of the pile, and by means of suitable screw clamps compress the whole firmly together. This being accomplished proceed to compare the capacity with that of a standard condenser by one of the methods subsequently described; should it be found too small, unclamp and insert some more sheets of foil and paper until on further trial the capacity of the condenser is found to equal that of the standard.

When this is attained, screw the top and bottom boards securely together by brass screws (in the holes previously alluded to), and fill up the space between the edges of the boards with melted paraffin.
The two wires coming through top board must now be soldered to two brass terminals screwed on to the board, and when not in use these terminals should be connected by a loose brass strap.

**Direct Discharge Method.**—The kind of galvanometer most suitable for the measurement of the capacity of a condenser is Thomson’s reflector, and before commencing the determination the controlling magnet should be turned so that its field tends to neutralise that due to the earth. If this neutral point is arrived at, the spot of light will not always return to zero—hence, although the galvanometer is in its most sensitive state when these conditions are fulfilled, it is necessary to regulate the position of the magnet so that the magnetism of the earth slightly predominates.

Having adjusted the galvanometer, connect it up with a standard condenser (½ or ¼ microfarad will be sufficient), a good Daniell cell, and a Morse key, as in Fig. 100.

On depressing K a current rushes into the condenser, charging it to the potential of the battery employed, accompanied by a momentary deflection of the spot of light on the galvanometer scale. Note value of deflection, \( d_1 \), produced, and continue holding the key down until the spot of light has returned to zero, then release the key and the condenser will be discharged through the galvanometer, the deflection, \( d_2 \), this time being in the opposite direction. If the galvanometer has been correctly adjusted, \( d_1 \) will equal \( d_2 \); should they slightly differ the mean of \( d_1 \) and \( d_2 \) may be taken as the true value, but if the discrepancy be considerable, proceed to readjust the galvanometer and scale. Take the mean of five or six sets of readings obtained in this manner and call it \( D_1 \).

Now substitute for the standard condenser the one whose capacity is to be measured, and take the mean of a similar number of readings obtained in the same way as with the standard condenser. Calling this value \( D_2 \), and the capacities of the standard and trial condensers \( C_1 \) and \( C_2 \) respectively, we have

\[
\frac{C_1}{C_2} = \frac{D_1}{D_2}
\]

or

\[
C_2 = C \frac{D_2}{D_1}
\]

Usually the galvanometer is placed as in Fig. 101, in which case we only get a deflection when the condenser is discharged, but in all other respects the manipulation is the same as in the previous arrangement.

Since, in this method, the galvanometer is not affected on charging, there is no necessity for holding the key down while the spot of light returns to zero, therefore a short, firm contact suffices to charge the condenser, and the discharge may follow immediately—a point of great importance, as we thereby prevent the phenomena known as electrification.

**Example.**—Required, the capacity of a newly-made condenser, \( C_p \), from following data, obtained by the
"direct discharge method." Using two Daniell cells in series, \( C_2 \) gave a deflection of 19.5 scale divisions, whereas a standard 5 mf condenser, \( C_1 \), gave under similar conditions a deflection of 18 scale divisions.

\[
\frac{5}{C_2} = \frac{18}{19.5}
\]

\[ C_2 = \frac{5 \times 19.5}{18} = 5.42 \text{ mf.} \]

**Thomson's Method.**—This method, which is far more accurate than the direct deflection method, is now very generally employed. The theory of the process is very clearly shown in the following diagram, which is but slightly altered from that given in Messrs. Munro and Jamieson's "Electrical Tables."

On closing \( K_1 \) the poles of a well-insulated battery of one or more Daniell cells are joined through the two resistances, \( R_1 \) and \( R_2 \), at the points \( D, B \).

Calling \( V_1 \) and \( V_2 \) the potentials at junctions, \( D, B \), of the battery wires with the two resistances, \( R_1 \) and \( R_2 \), we have

\[
V_1 : V_2 = R_1 : R_2.
\]

Now depress simultaneously the two keys, \( K_2 \) and \( K_3 \), whereby charging the two condensers, \( C_1 \) and \( C_2 \), respectively to the two potentials, \( V_1 \) and \( V_2 \).

If \( C_1 \) and \( C_2 \) represent the capacities in microfarads of these two condensers, and \( Q_1 \) and \( Q_2 \) the quantities given to them, then

\[
Q_1 : Q_2 = V_1 C_1 : V_2 C_2.
\]

Next release the two keys, \( K_2 \) and \( K_3 \), and allow the two opposite charges of + and - electricity to mix through the wire, \( W \), then if \( Q_1 = Q_2 \) on bringing the galvanometer, \( G \), into circuit by closing \( K_4 \), there will be no deflection. Should, however, a deflection occur, it shows the capacities are unequal, and the ratio of \( R_1 \) to \( R_2 \) must be changed until on trial no deflection is produced.

Then

\[
V_1 C_1 = V_2 C_2,
\]

or

\[
V_1 : V_2 = C_1 : C_2.
\]

But

\[
V_2 : V_1 = R_2 : R_1,
\]

\[
\therefore R_2 : R_1 = C_1 : C_2.
\]

or

\[
C_2 = \frac{R_1}{R_2} C_1.
\]

Where accuracy and dispatch are essential, some form of key is necessary (such as Lambert's) which combines the movements required for charging, mixing, and discharging the condensers; but for ordinary experimental work a Post Office Wheatstone bridge, supplemented by two Morse keys, will be found sufficient, as seen in Fig. 103, in which the connections are lettered and numbered with those in Fig. 102 for the sake of comparison.

To make a measurement:

1. Arrange apparatus, as in Fig. 103, and commence by taking out the 1,000-ohm plug between \( D \) and \( E \). Call this \( R_1 \). Then unplug 2,000 ohms between \( E \) and \( B \), and proceed as follows = \( R_4 \).

2. Firmly close \( K_1 \). This brings the battery in circuit.

3. Firmly close \( K_2 \) and \( K_3 \), simultaneously, so charging both condensers, but with electricities of opposite sign.

4. Release \( K_3 \) and \( K_4 \), and afterwards \( K_1 \). This allows the two charges to mix, and cuts out the battery at the same time.

5. Depress \( K_2 \) and allow the surplus charge (if any) to pass through galvanometer, \( G \).

Note direction in which the deflection occurs, and keeping \( R_4 \) constant, make \( R_5 \) considerably less than \( R_1 \), say 100 ohms, and repeat the experiment. If the deflection is now in the opposite direction, it shows that the true value to be given to \( R_5 \) lies between 100 and 2,000. The resistance, \( R_5 \), in \( E \) \( B \) must then be varied until no deflection is produced.

**Example.**—In comparing the capacities of the two condensers mentioned in last example, putting the standard 5 mf. at \( C_1 \) and the unknown at \( C_2 \) with \( R_1 = 1,000 \text{ ohms} \), it was necessary to make \( R_2 = 910 \text{ ohms} \), in order that no deflection should occur, hence

\[
C_1 : C_2 = R_1 : R_2
\]

\[
C_2 = \frac{C_1 R_1}{R_2} \]

\[
= \frac{5 \times 1,000}{910} \]

\[
= 5.49 \text{ mf.}
\]

A modification of the above method, given in Messrs. Glazebrook and Shaw's "Practical Physics," p. 476, has the great merit of considerably simplifying the manipulation, and in which the resemblance to the Wheatstone bridge method of measuring resistances becomes at
once apparent. Fig. 104 shows the theoretical, and Fig. 105 the practical arrangement, using the Post Office bridge as in last method.

Join up as in Fig. 105 (K may be an ordinary Morse key), the wire from E being joined to central terminal of key, while the back terminal against which the key rests in its normal condition is in connection with the point a, thereby keeping the plates of the two condensers in metallic circuit, and therefore discharged, while on depressing the key the battery is brought into circuit and the condensers charged. Unplug resistance R₄, and adjust R₅ until no deflection occurs when K is either closed or opened, then, as before, C₁ : C₂ :: R₅ : R₄.

**Example.—** Employing the same two condensers as in previous examples, putting the ’5 mf. at C₁ and the unknown at C₂, and giving R₅ a value of 2,000 ohms, no deflection occurred on closing or opening K when R₂ =1,800 ohms; therefore

\[ C₂ = C₁ \frac{R₂}{R₁} = \frac{5 \times 2,000}{1,800} = \frac{10}{9} = 55 \text{ mf.} \]

**Measurement of the Combined Capacities of Two Condensers.**

When \( n \) condensers are arranged in parallel or multiple arc, Fig. 106, similarly to the so-called quantity arrangement with voltaic cells, the capacity of the combination is the sum of the several individual capacities, or

\[ C = C₁ + C₂ + \ldots \]

but if they are joined up in series, Fig. 107, analogous to the “cascade” arrangement with Leyden jars, then the joint capacity is the reciprocal of the sum of the reciprocals of the separate capacities, or

\[ C = \frac{1}{\frac{1}{C₁} + \frac{1}{C₂} + \ldots} \]

**Example.—** When the two condensers previously used, and which gave separately by the direct discharge method deflections of 8 and 19.5 scale divisions respectively, were joined “in parallel,” the discharge reading was 37 divisions; but when joined up “in series” the deflection was 9.5 divisions, the same battery being used in each determination.

Calculating from above formula, the deflections should have been:

In parallel, \( D = 18 + 19.5 = 37.5 \)

In series \( D = \frac{1}{0.0555 + 0.0512} = 0.0512 = 9.4 \)

**Measurement of Resistances by Fall of Potential.**

If the two poles of a cell whose electromotive force = E be joined by a wire of resistance R, then the fall of potential may be shown graphically, as in Fig. 108.

If internal resistance of the cell, r, be small in comparison to R, it may be neglected, and only the difference of potential between the two battery terminals taken into consideration. The fall will vary directly with this external resistance, therefore, taking any two points on this connecting wire, the resistance enclosed between them will bear the same relation to the differences of potential existing between such points as the total resistance of the wire bears to the total difference of potential between the two poles of the battery.

Or, again, consider the wire divided into two lengths, A B, B C, then the resistance, R₂, of A B is to the resistance, R₃, of B C as the difference of potential, \( V - V₁ \), between A B is to that existing between B C or \( V₁ - V₂ \).

\[ R₁ : R₂ :: V - V₁ : V₁ - V₂ \]

Hence if we have the means of comparing these potential differences, and a known resistance, R₃, we can readily ascertain the value of R₂. We can do this
either by employing a Thomson quadrant electrometer or a mirror galvanometer, having a high resistance in circuit. Employing the galvanometer, and touching the points A B on the connecting wire (so as to put the galvanometer in parallel or derived circuit), the current passing through the galvanometer, and therefore the deflection, \( d_1 \), will depend upon the difference of the potentials at A and B. Similarly touching B and C the deflection, \( d_2 \), will represent the difference of potential between B C or

\[
R_1 : R_2 : : d_1 : d_2
\]

To make a determination, join up a good Daniell cell of very low resistance, the standard resistance, \( R_1 \)—which may conveniently consist of a moderately thick iron wire of 1 ohm resistance stretched on a board as in Fig. 96—and the object, \( R_2 \), whose resistance has to be determined in simple circuit. This ensures the same current passing through \( R_1 \) and \( R_2 \), Fig. 109.

Connect galvanometer wires to A B and note deflection, \( d_1 \), with \( R_1 = 1 \) ohm circuit; remove to B C and observe deflection, \( d_2 \); lastly, replace wires on A B and take another reading, \( d_3 \).

![Fig. 109.](image)

The object of taking two readings at A B is to correct any error arising from any possible alteration in the electromotive force of the battery during the test. If \( d_3 = d_1 \) it may be rejected, but should a discrepancy appear, then the mean of the two values must be taken, or

\[
R_1 : R_2 : : \frac{d_1 + d_2}{2}
\]

This method is very applicable to the measurement of low resistances, such as the armatures of dynamos, etc.

**Example.—** A Daniell cell, a 1-ohm resistance, \( R_1 \), and short length of German silver wire were joined in circuit. On bringing the terminal wires from the galvanometer, with a total of 18,000 ohms in circuit, in contact with the ends of \( R_1 \), a deflection, \( d_1 \), of 52 scale divisions was obtained. On touching the ends of the German silver wire the deflection \( d_2 = 100 \) divisions.

\[
\begin{align*}
R_1 : R_2 : : d_1 : d_2 \\
1 : x : : 52 : 100 \\
x &= \frac{1 \times 100}{52} \\
&= 1.92 \text{ ohms.}
\end{align*}
\]

The ordinary bridge method gave for the same piece of wire a resistance of 1.95 ohms.

**Joule’s Law.**

When the circuit of a voltaic battery is closed, chemical action ensues, the fall in the potential energy of the zinc and acid being accompanied by the evolution of an equivalent amount of energy in some other form, such as mechanical work, chemical decomposition, magnetism, light, or heat. Joule’s law shows that the heat developed in a conductor is directly proportional to

1. Its resistance;
2. To the square of the current strength; and
3. To the times during which the current flows;

or,

\[
H = C R t
\]

Now since Ohm’s law teaches us that \( C = \frac{E}{R} \), if we substitute this new equivalent for one of the C’s in the above equation, we get

\[
H = \frac{E C t}{R} = \frac{E C t}{R}
\]

or the amount of heat equals the product of the electromotive force, the current, and the time.

Replacing the remaining C by \( \frac{E}{R} \) we obtain another expression of the law—i.e.: 

\[
H = \frac{E E}{R} R t = \frac{E^2 t}{R}
\]

from which we see that the heat developed equals the product of the electromotive force and the time divided by the resistance.

Finally, Q, the quantity of electricity flowing, equals the current (or rate of flow) into the time \( C t = \frac{E}{R} t \), and substituting in above equation for the value \( E t \) its equivalent \( Q \), we see that \( H = E Q \), or the heat equals the electromotive force into the quantity.

The mechanical equivalent of heat, as demonstrated by Joule, proves that the heat necessary to raise the temperature of 1 gramme of water from 0 deg. to 1 deg. centigrade, would suffice to lift the same weight of water through a vertical height of 42,400 centimetres.

But to lift 1 gramme through 1 centimetre requires an expenditure of 961 ergs, hence the mechanical equivalent of heat expressed in ergs = 42,400 \times 981 = 41,994,400.

The electrical unit of heat, or “joule,” equals \( 10^6 \) ergs. It is defined as the heat generated in one second by a current of 1 ampere passing through a resistance of 1 ohm = \( \frac{E}{R} \), or 10,000,000 ergs.

Assuming that the mechanical equivalent of heat equals in round numbers 42,000,000 ergs, we see that 1 “joule” would raise \( \frac{42}{10^6} \) = 238 gramme of water 1 deg. C.

If, therefore, the current be expressed in amperes, resistance in ohms, and the time in seconds, multiplying
the right-hand side of equation by 238 gives the heat generated in any conductor in ordinary thermal units, or

\[ H = C^2 R t \times 238. \]

The proper quantitative demonstration of Joule's law requires an amount of apparatus, such as delicate thermometers, calorimeters, and care in manipulation, as places it beyond the scope of these "outlines," and the student desirous of prosecuting the subject further must consult some standard works on the subject, such as those by Tyndall, Balfour Stewart, or Clerk-Maxwell, but the facts on which the law is based may be experimentally proved with sufficient accuracy by the following simple piece of apparatus:

Take two ordinary test tubes, one about 6in. and 1\(\frac{1}{2}\)in. wide, the other 6in. long by \(\frac{3}{4}\)in., and fix the smaller tube inside the larger by means of an annular bung of indiarubber, Fig. 110, closing the mouth of the smaller tube with a good bung of the same material, but having two holes bored through it, one for the insertion of the end of a piece of glass quill tubing—bent once at right angles—forming an index tube, the other for a short piece of similar tube closed by a short indiarubber tube and pinchcock. Through the annular bung are bored four holes, one wide enough to admit the shank of a small funnel or pipet, the other three sufficient to allow short lengths of thick copper wires being passed tightly through \(a\), \(b\), and \(c\).

A coil of thin platinum wire of exactly 2 ohms resistance has its ends soldered to \(a\), \(c\), and its middle to \(b\)—it is thus divided equally into two lengths of 1 ohm each.

The test tube should be supported on a small wooden stand, and a cardboard scale placed upon the horizontal tube.

To use the apparatus, pour into the space between the two test tubes, by means of a small funnel or pipet, a measured volume of water at a known temperature—\(\text{i.e.}\), that of the room in which the experiment is made. The quantity of water should be sufficient to cover the whole of the platinum wire. Next, open pinchcock, and placing the mouth to the end of the indiarubber tube, at the same time dipping the end of the index tube into a little coloured water, gently exhaust the air in the inner tube. This will draw a globule of the coloured water along the tube forming an index. When the globule has reached the zero of scale, close pinchcock, and any noncoincidence between the index and zero can be rectified by slightly moving the scale along the tube.

Connect up one or two constant cells of low internal resistance, such as Grove's or Bunsen's, the resistance-board, A B, Fig. 96, a tangent galvanometer and key, to the thick copper wires, \(a\) and \(b\). On closing \(K\), a current, \(C\), equal tan \(d\), will flow through the first half of the platinum wire = 1 ohm, heating the water surrounding the wire. This in its turn will heat the air inside the inner tube, causing it to expand, and forcing the index along the tube carrying the scale.

Note deflection, \(d\), of tangent needle, time, \(t\), during which the current flows, and \(l\) the number of divisions on the scale over which the index has moved. Open \(K\) and proceed to make another determination, as follows:

Remove the warm water by means of a small syphon made out of a piece of narrow quill tubing, through the hole in the annular bung, and again pour in an equal quantity at the same temperature as the previous charge; open pinchcock and bring index to zero \(a\) before, close \(K\) again for a period = 2 \(t\), when the index will have moved through a distance approximately = 2 \(l\).

It will not be exactly 2 \(l\), for the outer glass vessel is radiating heat all the time, and a correction would have to be made accordingly, but the approximate value will be quite near enough to show that "the heat varies directly as the time."

Recharge the apparatus and connect the leading wires to \(a\) and \(c\), and send the same current as indicated by the tangent galvanometer through the two ohms of platinum wire—for an equal time, \(t\), the index will move through 2 \(l\), showing that the "heat varies directly as the resistance."

Since we have an additional resistance of 1 ohm introduced between \(a\) or \(c\), we must, in order to keep the current the same value, reduce the length of the German silver wire (stretched on the board A D) in the circuit, until the same deflection is produced = tan \(d\).

Lastly, recharge the instrument, and arrange the connection to include \(a\) and \(b\), but vary the resistance on the board, \(R\), or, if need be, electromotive force, by addition of other cells, until a deflection, \(d_2\), is produced showing that the new current, \(C_2\), is equal to 2 \(C_1\). If this current, \(C_2\), flows for the original time, \(t\), the index will be moved through \(d\) time \(l\), proving that the heat varies as the square of the current.

The relative amounts of electromotive force and resistances necessary for the production of \(C_1\) and \(C_2\) when \(a\) and \(b\) or \(a\) and \(c\) are in circuit may easily be
ascertained by a few preliminary trials; or an ordinary wire of one or two ohms resistance may be inserted in circuit instead of a, b, c, and when the exact conditions for producing $C_1$, $C_2$ are attained, replacing the trial wire by the platinum coils, a, b, c.

Students who desire to understand the whole theory and practice of testing must, as we have said before, read and study Mr. Kempe's excellent treatise, which is far and away the best book on the subject ever issued. In the ordinary work of a central station, or an isolated electric lighting plant, less elaborate instruments are used. Generally the switchboard contains ammeters, fairly accurate and easily readable, always in circuit, also voltmeters. The latter are not always permanently in circuit, but can be switched on and off as desired. As full details will be given later on it will be unnecessary to do more here than describe some types of instruments to be found on the switchboards.

The coil is supported by two screws, and by means of nuts it can be moved as above described. On unscrewing the base board the magnet and coil of the instrument are exposed, and the adjustment can then be made.

To calibrate the commutator ammeter turn the commutator to series, and send a current from a standard cell of known electromotive force through the ammeter, obtaining a deflection $D$. Pull out the 1 ohm plug, the deflection will now be reduced to $d$. If $E$ is the electromotive force of the cell in volts, then current

$$E \frac{D - D}{D}$$

ampere sin series, or $10 \frac{E}{D} \frac{D - D}{D}$ amperes in parallel.

The adjustment of the coil must be made until the desired value per degree is obtained.

To calibrate the simple ammeter place it in series with a standard instrument having about the same range, and let the current flow through both, adjusting the coil of the former until the desired value per division is obtained.

Ayrton and Perry Permanent Magnet Ammeters.—In these instruments (Figs. 111, 112, and 113) the shapes of the magnet pole-pieces, needle, and coil are such as to render the deflections proportional to the current flowing. They are calibrated direct in amperes, and the readings given consequently require no multiplication by a constant. The needle being placed in a powerful magnetic field, the instruments are rendered extremely dead-beat, and unlikely to be influenced by the presence of dynamo machines. By the lightness of the needle and the excellence of the jewelling and pivoting great sensibility is obtained. These instruments are made of two types, which are known respectively as simple and commutator instruments. In the commutator instrument the galvanometer coil consists of 10 strands of wire, which may be placed either in parallel or series by the simple turning of the commutator, Fig. 112. This gives 2 deg. of sensibility, and enables the instrument, by the aid of a resistance coil inserted in it, to be calibrated with a current having one-tenth of that which the instrument can measure.

An amphere-meter designed to measure 50 amperes when the commutator is placed so as to put all of the 10 strands of the coil in parallel, will give, when it is moved to place them all in series, the same deflection with a current of 5 amperes. In the simple instruments there is no commutator. They must, therefore, be calibrated from time to time by comparison with a standard instrument, and adjusted to read correctly. The adjustment is easily effected, and is performed by moving the needle from a strong part of the field to a weaker, or vice versa, Fig. 113.
Simple Ammeters with Permanent Magnets.—This, as the name implies, is a simpler and less expensive form of instrument, suitable for indicating the current under circumstances in which the great accuracy obtained by the use of the more expensive types is not required (Fig. 114). The deflection of the pointer is proportional to the current flowing; the dial is marked direct in amperes, and the magnet is fitted with adjusting screws for recalibration.

Electromagnet Instruments.—Instruments in which the permanent magnets are replaced by electro-

magnets have come greatly into favour in recent years, for the very obvious reason that their construction does not necessitate the employment of a magnet which, though called permanent, is liable to a change of strength with time. In the electromagnet instrument as usually made, the same circuit which produces the deflection by means of a galvanometer coil circulates round a soft iron bar, and so produces an electromagnet to act as the controlling force. But in instruments so designed the controlling force is necessarily small, or, in other words, the field is weak, and besides the disadvantage which the instruments have in being very far from dead-beat, they are extremely likely to be influenced by the presence of dynamo machines near them. In Paterson and Cooper's instruments these defects have been overcome, and this has been done by substituting for the weak force exerted by an electromagnet the powerful force of a spiral spring. The deflecting soft iron needle attached to the spring forms part of a magnetic circuit, and in its normal position lies nearly at right angles to a soft iron ring, which comprises the other part. On this ring the wire through which the current is to flow is wound, and when the ring is magnetised by the current the needle tends to set itself in such a way as to close the magnetic circuit. Since its movement to effect this is against the spiral spring, and the deflection actually observed is a measure of the force exerted by the current on the spring, and therefore the dial being properly graduated of the current flowing. Fig. 115 shows the ordinary form of the instrument for measuring currents up to 400 amperes, the magnetic system with the controlling spring being plainly visible. Fig. 116 is a modification of the instrument suited for the measurement of large currents, the wire carrying the current in the smaller instrument being here replaced by a single bar of copper 1½ in. in diameter, the soft iron ring nearly embracing this bar and leaving only sufficient space between its open ends for the soft iron deflecting needle to lie in. This type of the instrument is made to measure currents from 500 to 2,000 amperes.

Ayrton and Perry Permanent Magnet Voltmeters (Figs. 117 and 1 of the magnet p as to render the current flowing. They readings given consequently require no multiplication by a constant. The needle being placed in a powerful magnetic field, the instruments are rendered extremely
dead-beat and unlikely to be influenced by the presence of dynamo machines. By the lightness of the needle and the excellence of the jewelling and pivoting great sensibility is obtained. These instruments are made of two types, which are known respectively as simple and commutator instruments. In the commutator instrument the galvanometer coil consists of 10 strands of wire, which may be placed either in parallel or series by the simple turning of the commutator. This gives 2 deg. of sensibility, and enables the instrument, by the aid of a resistance coil inserted in it, to be calibrated with a voltage equal to one-tenth of that which the instrument can measure. A voltmeter designed to measure 100 volts when the commutator is placed so as to put all of the 10 strands of the coil in series, will give, when it is moved to place them all in parallel, the same deflection with a difference of potential of 10 volts. In the simple instruments there is no commutator. They must, therefore, be calibrated from time to time by comparison with a standard instrument and adjusted to read correctly. The adjust-

![Fig. 118.](image1)

![Fig. 119.](image2)

**Cardew Voltmeter.**—This instrument, Fig. 119, has been greatly improved in points of detail from time to time, and may now be considered as perfect as this class of apparatus can be made. Essentially the Cardew voltmeter consists of a fine platinum silver wire 0.025 in. in diameter, which is heated by the current passing through it. The wire is kept stretched by a spring, but expands on being heated, the expansion given by different temperatures due to different potentials being indicated by a pointer in conjunction with suitable gearing. Since there are no magnets or coils in the instrument, and no retardation due to self-induction, it is equally applicable to the measurement of alternating current; in fact, it is the only instrument that for the latter kind of work gives a reliable reading. The dial is graduated direct in volts. When there is an alternating difference of potentials, the indication shows the square root of the mean square of the volts. In the instrument there are four lengths of wire, making about 12 ft. in all, these forming two continuous lengths of 6 ft., which pass over two small pulleys at the top of the tube, whose pivots turn in jewelled centres. An instrument having 12 ft. of wire will measure a difference of potentials of 120 volts, this being 10 volts per foot. To save the working wire from fusion, a still finer wire, 0.015 in. diameter, is inserted in the path of the current.

**Pocket Voltmeter.**—These instruments, Fig. 120, no larger than a good-sized watch, are very convenient for the measurement of small differences of potentials. Though sometimes wound for 120 volts, they are really not recommended by the makers for more than from 80 to 100. They are constructed with permanent steel magnets, and connection is made to the points between which it is desired to illustrate the difference of potentials by flexible silk-braided wires supplied with the instrument. The graduation on the dial is in volts
and the instrument is particularly applicable for testing the electromotive force of accumulators.

Ordinary Lineman's Detector.—This handy instrument, Fig. 121, consists of an astatic combination with the axle lying horizontally, one needle serving as a pointer, the other moving between two coils inside the mahogany case. The system is slightly weighted to give the needles a vertical bias. In the detector illustrated there are only shown two terminals for a low-resistance winding, but the instrument is frequently supplied with three terminals being wound with two coils, one of high and the other of low resistance.

Portable Galvanometer.—This instrument, Fig. 122, is very sensitive in its action. The needle has an agate cup inserted at its centre and the moving system is balanced on a polished steel point, the deflection being read off by means of an aluminium pointer. The instrument has a brass case, and is fitted with a bevelled plate-glass top. It is very suitable for portable use with a Wheatstone's bridge, where the ordinary Thomson galvanometer would be useless on account of the difficulty in setting it up.

Some instrument makers have devised portable testing sets. The best known are those of Mr. Blackburne, made by Messrs. Clark, Muirhead, and Co., and the Silvertown instrument. The latter may be described, and the instructions issued with it given.

The Silvertown Portable Testing Set.

This set consists of a small collection of the necessary instruments for testing electrically such insulated conductors as are used in telegraph, telephone, or electric light work.

The whole set is contained in two small wooden boxes, of which one holds the batteries and the other the galvanometer, resistance coils, key, and commutators required for making the two most important measurements on such circuits. These are measurements of the resistance of the conductor, and the efficiency of the insulation.

For connecting the battery to the testing instruments convenient leads are provided terminated in brass plugs with insulated handles for inserting in the proper plug holes. The instruments are connected up together in their own box in such a way as to secure the greatest economy of space, and to enable the two tests to be taken with the greatest readiness.

The battery consists of two parts: one—commonly called the bridge battery—is a set of Leclanché cells of low resistance intended to be used in testing conductor resistances only, a purpose for which currents of electricity of sensible magnitude are required. The other part is a set of 30 small Leclanché cells having a total electromotive force of 45-50 volts intended exclusively for measuring insulation resistances, or other resistances of considerable magnitude. These cells are designed to give only very small currents of electricity, and care should be taken not to connect them inadvertently to the Wheatstone's bridge or otherwise put them on a circuit of low resistance. This battery, called the insulation battery, is subdivided into three sections of 10 cells each, so that electromotive forces of about 15 volts, 30 volts, or 45 volts can be employed as may be found convenient.

Of the box containing the instruments, the diagram, Fig. 123, shows all the connections and resistance coils.

The only part of the instrument which requires detailed description is the galvanometer. This consists of a coil of fine wire on a brass bobbin, in the centre of which a small magnetic needle with an aluminium pointer is hung in the same way as is usual in compasses. The pointer projects through the opening in the end of the coil, and the excursions of the needle
are limited by the size of the opening to about 45 deg. on each side of the centre. On removing the glass cover, the needle on its point may be taken out by withdrawing the slide on which it is pivoted from inside the coil. The scale, which is a scale of equal currents, is approximately a scale of tangents, and is obtained empirically by calibrating the instrument. The north end of the magnetic needle points to the left-hand side of the box when it is swinging freely in its zero position.

On the left-hand side of the box is placed the controlling magnet, and the position of this affects the sensitiveness of the galvanometer. When the north pole of the controlling magnet is uppermost, the galvanometer will be most sensitive; on turning the magnet round so that the south pole is uppermost, the deflection of the needle due to any given current will be reduced by about 40 per cent. Generally in testing the insulation of well-insulated wires, the galvanometer is required to be as sensitive as possible, and the north pole of the controlling magnet should be at the top; but for measuring conductor resistances, for which the galvanometer is generally amply sensitive, it will be found more convenient to bring the south pole uppermost, thereby causing the galvanometer needle to oscillate more rapidly.

Besides thus affecting the sensitiveness of the galvanometer, the magnet is also used to adjust the needle to the zero in its position of rest by turning it slightly in one direction or the other.

In preparing the test the box should be placed on a table, or some other approximately level surface in front of the electrician, he facing the magnetic east, and the controlling magnet being in a vertical position.

The pointer of the galvanometer will then be found to be swinging near its zero, and may be brought exactly to it by slightly turning the controlling magnet.

If at any time the galvanometer needle should become insensitive and sluggish it may be due to one of several causes.

It may be that the needle has become demagnetised. This can be remedied by withdrawing and remagnetising it with an ordinary horseshoe magnet, care being taken that this is done in the same direction as before.

It may be that some dirt has found its way into the jewel. This may be removed with a piece of soft wood cut to a fine point.

It may be that the jewel or needle point is injured, and must be repaired by competent workmen. This will probably have occurred either through the whole instrument having received a blow when the lid is open and the jewel resting on the needle point, or through the brass spring in the lid of the box being bent so that it no longer presses on the lifter when the lid is closed, and the needle has consequently been resting on the point while the box has been carried about.

**Testing Conductor Resistance.**

The method used of measuring the resistance of the conductor of the circuit under examination is that of Wheatstone's bridge.

The diagram, Fig. 124, shows only those parts of the instrument which are employed in this test, and omits the parts, and their connections, which relate only to insulation testing. The parts employed are the following:

The adjustable resistance. This, it will be seen, consists of two sets of nine coils each connected to
circular plug commutators or dials. One set of coils has nine resistances of 10 ohms each, making 90 ohms in all; the other has nine resistances of 1 ohm each, making 9 ohms in all. If the hole marked with any number—say, 5—is plugged in the 10-ohm dial, a resistance of 50 ohms is inserted between the connecting leads entering and leading away from the dial; and a similar rule applies to the 1-ohm dial. Hence, if the hole 6 be plugged in the 10's dial and the hole 8 be plugged in the units dial, a total resistance is inserted in the two in series of 68 ohms. The lowest resistance that can be obtained is given when both the 0 holes are plugged, when the coil resistance inserted is zero. The highest resistance is obtained by plugging the two 9 holes, when the total resistance is 99 ohms. If no plug is inserted in the two ends of the Wheatstone's bridge by depressing the contact key. It will be noticed that the shunt coils, with their plug commutator, are omitted from the diagram. This is done because they are not essential to the test, though they may be conveniently used when the balance of the bridge is not yet approximately correct, and very large deflections are being obtained.

The battery, as has been already described, consists of four Leclanché cells, having an electromotive force of about six volts. One pole of the battery is connected in the usual way to the middle of the Wheatstone's bridge, and the other to the point where the end of the adjustable dial coils is connected to one of the terminals, to which the conductor under test is attached. The connections are made by inserting the

one or both dials, the circuit is broken, and the resistance is infinity.

The second part of the apparatus is the double set of proportional resistances, consisting of two coils of 10 ohms each, two of 100 ohms, and two of 1,000 ohms, these constituting what is known as Wheatstone's bridge. Of these only one on each side of the centre is to be unplugged for any given test, and a rule is given later on for selecting the resistances to be employed to obtain the greatest possible sensitiveness; that is to say, for selecting those coils which will give the largest deflection on the galvanometer, when the resistance plugged in the dials varies by a given error from that of the circuit under test.

The third part is the galvanometer, which has been already described. Its two terminals are connected to plugs at the ends of the battery leads, in the two holes marked "bridge," and immediately this is done the current is established in the coils; the galvanometer circuit is of course not completed till the key is depressed.

The ends of the conductor to be tested are to be secured under the two terminals marked "bridge terminals," and in measuring low resistances care must be taken that they are very securely attached.

The test is begun by selecting the coils to be unplugged in the Wheatstone's bridge; to do this it is necessary to know approximately the value of the resistance to be measured. Generally some idea of its value can be formed, but if it is quite unknown, two coils on the bridge may be chosen at random and a preliminary measurement made. This measurement
will enable the correct coils to be chosen for a further test. The following pairs of coils are to be selected:

For resistances between 1 ohm and 10 ohms, left-hand coil, 100 ohms; right-hand coil, 10 ohms.

For resistances between 10 ohms and 100 ohms, left-hand coil, 100 ohms; right-hand coil, 100 ohms.

For resistances between 100 ohms and 1,000 ohms, left-hand coil, 1,000 ohms; right-hand coil, 1,000 ohms.

In all these cases coils will be employed in both dials, and a result giving two significant figures will be obtained; a third figure can always be found in measuring resistances between these limits—viz., between 1 ohm and 1,000 ohms—by observing the deflections of the galvanometer needle on both sides of the zero for different adjustments of the dial resistances near the balancing point.

For example, we will suppose that the 10-ohm coil in the right-hand side of the bridge and the 100-ohm coil on the left-hand side are unplugged, and that when 45 ohms are plugged in the dials, and the key depressed, a throw of three divisions of the galvanometer needle is observed to the right; and when 46 ohms are plugged we get a throw of two divisions to the left on the galvanometer scale. It is clear that the resistance to be measured lies between 4·5 and 4·6, and is nearer to 4·6 than 4·5, as two is less than three; that is, the resistance is 4·66 ohms. As a further example, suppose 100 ohms to be unplugged on each side of the bridge, and 82 ohms to be plugged in the dials; on depressing the key, no deflection of the needle is observed. On plugging 81 ohms in the dials, a throw of six divisions to the right is obtained, and on plugging 83 ohms we get the same deflection to the left. We are then amply justified in putting the third figure in the result as 0, and the resistance to be measured is 82·0 ohms.

Resistance from 1 ohm to 10 ohm may be measured either with the same bridge coils as are used for resistances of 1-10 ohms—viz., 10 ohms in the right side, and 100 ohms on the left, but only to two significant figures, since the 10's dial will be plugged at 0.

 Resistances of from 1 ohm to 1 ohm may also be measured to three figures by using the bridge coils of 1,000 on the left side and 10 on the right, and resistances from 1,000 ohms to 10,000 ohms by using the bridge coils of 10 on the left and 1,000 on the right. For both of these tests, however, more battery power is required than is provided in the ordinary portable battery supplied.

For making this test attention may be called to the following points, some of which have been noticed before.

Except in testing at the extreme range of the instrument—i.e., quantities less than 1 ohm or greater than 1,000 ohms—the galvanometer will be found amply sensitive, and it is better to place the south end of the controlling magnet uppermost, thereby reducing the time of the oscillations of the galvanometer needle.

The battery should be in circuit as short a time as possible to avoid running down the cells, and it is well to take out one of the battery lead plugs when any alterations are being made in the plug commutators, only replacing it just before pressing the galvanometer key.

Care should be taken to connect the conductor to be tested very securely to the bridge terminals. This may be done, for very large or stranded conductors, either by soldering to their ends thin brass plates with holes in them of a suitable size to go under the heads of the terminals, or the connection may be made by means of finer wires soldered to the ends of the main conductor. The resistance of these must be independently ascertained and subtracted from the gross result.

Measurement of Insulation Resistance.

This is a measurement of the electrical resistance of the insulating material of a cable to the passage of a current from the inside conductor through the insulation to the lead sheathing, wet yarn, armour, or other outside conducting surface, and the inverse of the insulation resistance is the insulation conductivity, or, as it is generally termed, the leakage.

This measurement is effected by a method known as that of direct deflections. It consists in passing a current from a battery through a galvanometer into the conductor of a cable whose farther end is free and disconnected, thence through the insulating material to the outside coating or earth, and so back along a temporary conductor to the other end of the battery, the deflection of the galvanometer needle produced by this current being noted. Replacing that part of the circuit which was formed by the insulating material of the cable by a standard resistance of known value, we obtain a new deflection of the galvanometer needle.

The quotient obtained by dividing the deflection produced by the current through the standard resistance by that through the cable insulation is a measure of the insulation in terms of the standard.

Thus, for example, suppose that a given battery produces on the needle of a galvanometer placed in series with the insulation of a cable in the manner described, a deflection of 10·3 divisions, and that on substituting a resistance of 1 megohm for the insulation we get 4 divisions, we find that the insulation resistance is \( \frac{10.3}{4} \) megohms = \( \frac{1}{4} \) megohms approximately.

The diagram, Fig. 125, shows only those parts of the apparatus and their connections that are used in this measurement, those which relate only to the measurement of conductor resistances being omitted.

The arrangement, it will be seen, is as follows: One pole of the battery—a battery of 30 Leclanché cells giving an electromotive force of about 45 volts is normally employed—is connected by a conductor ending in an ebonite-headed plug to the lower of the two plugholes marked "insulation." Thence the current passes along a connecting wire to a block marked "shunts," and thence through the galvanometer to the upper block on the other side; we may
observe, in passing, that these two main blocks, one on each side, are practically the terminals of the galvanometer. If a shunt is plugged, \( \frac{1}{4} \)th, \( \frac{1}{8} \)th, or \( \frac{1}{16} \)th only of the current passes through the galvanometer, the remainder finding its way through the corresponding shunt coil.

From the upper block on the left-hand side, the current may take two paths, according as the hole marked "insulation," or that marked 10,000 ohms is plugged; if neither is plugged, the circuit is broken, and no current can pass. This plug forms consequently a convenient make and break key. If the hole marked "insulation" is plugged, the current passes to the terminal marked "insulation," so through the insulating covering of the cable to the outside sheathing or earth, back to the terminal marked "earth" and produced by the current passing through a known resistance—this is called taking the constant of the galvanometer. It will be found in practice that with the battery of 30 cells supplied, it is necessary to use the highest shunt power available, giving a multiplying power of 100; and we may note here that the passage of the current through a galvanometer shunted thus, and then through 10,000 ohms, gives the same deflection as passing the whole current through the galvanometer not shunted, and through a constant of 1,000,000 ohms. In short, the deflection thus obtained is the deflection given by the battery through 1 megohm.

(2) In transferring the plug to the hole marked "insulation," and again noting the deflection obtained, the galvanometer being shunted if necessary to give a convenient reading.

The plughole marked E, and then along the lead to the other pole of the battery. If, however, the hole marked 10,000 ohms be plugged, the current will pass through a coil of 10,000 ohms, then along a connecting wire to the plughole E, and so back to the battery.

In beginning this test, the conductor of the cable, or insulated wire, or a temporary lead attached to it, is connected to the terminal of the instrument marked "insulation" and another lead, connected to the outside sheathing of the cable, or the wet soil in which it lies, is attached to the terminal marked "earth," care being taken that these leads are separated, and that no circuit exists between them except through the insulation of the cable. The test then consists in—

(1) Noting the deflection obtained when the 10,000-ohm hole is plugged—i.e., obtaining the deflection on dividing the deflection on the scale obtained when taking the constant by the deflection obtained in the second part of the test, and multiplying the deflections by the shunt or shunts employed, we obtain the insulation resistance of the cable in megohms.

For example. Suppose that the current from the battery when passed through a constant resistance of 10,000 ohms gave a deflection of 42 divisions on a galvanometer shunted to \( \frac{1}{8} \)th, and that when passed through the cable insulation it gave 28 divisions with the galvanometer shunted to \( \frac{1}{16} \)th, the insulation resistance would be \( \frac{42}{28} \times \frac{1}{8} \) megohms = 0.37 megohms approximately.

For another example: If having found the same galvanometer constant, we obtained from the cable insulation a deflection of 10 divisions with no shunt
employed, the insulation resistance of the cable would be \( \frac{3}{4} \) megohms = 4\( \frac{1}{2} \) megohms.

It will be observed that when all the holes in the straight commutator near the front of the box are plugged, that the key on the left-hand side, which is used in the bridge test as a galvanometer make and break key, becomes for the insulation test a short-circuit key, and is useful for checking quickly the oscillations of the needle.

In making this test the following points may be called attention to :

(1) Too much care cannot be taken in preparing the ends of the cable. Since we are measuring a very small current of electricity passing from the conductor to the outside sheathing, through the insulating covering, it is clear that our results will be entirely misleading if any current be allowed to pass over a dirty surface at the ends where the conductor is exposed. These ends should be looked at before testing, and in the case of indiarubber or other firm material, the section of the insulator should be pared all over with a sharp and perfectly clean knife.

(2) Care should be taken not to short-circuit the battery, which may easily occur in two ways. One is by allowing the two battery plugs to touch one another, when the other ends of the leads are attached to the battery terminals; and another is by allowing the leads attached to the earth terminal to touch that attached to the insulation terminal.

In both cases the battery of small cells will be for a time much overworked, and in the second the needle may become bent or demagnetised.

(3) Another point that may be noticed is, that in deducing the insulation resistance per statute mile from a test on any given length, the result obtained from a test on the latter is to be multiplied by the length of the piece in miles, and not divided by it.

For example, if the insulation of a cable 3 miles long be 15 megohms, the insulation per mile will be 15 \( \times \) 3, or 45 megohms; or, again, if the insulation of a piece of cable, whose length is 350 yards, be 7,520 megohms, the insulation per statute mile will be \( \frac{7,520 \times 3}{1,760} = 429 \) megohms = 1,490 megohms.

From the switchboard, which, with the apparatus it carries, has now been described, are led the main cables. Of such cables the Silvertown Company says:

The accurate testing of electric light mains before and after laying, and periodically during use, is a matter of great importance if the efficient working of a system is to be obtained and maintained.

It is surprising that, while the experience of manufacturers of submarine cables has resulted in a thorough and systematic method of electrical testing being adopted, yet electric light engineers are in many cases content to lay down expensive mains without any reliable tests having been made, and they are therefore completely ignorant of the true value of the insulation resistance, which can only be obtained by a careful test made while the cable is immersed in water.

As a result breakdowns may occur, due to faults which in all probability existed in embryo at the time of laying the mains, and which are developed under the strain of working.

New methods of insulating, laying, and jointing conductors are being continually devised, with small effect beyond adding to an already dearly-bought experience; yet there undoubtedly exist methods which, when carefully carried out, have given very satisfactory results when worked under the heavy strain produced by high-tension alternating currents.

Very frequently when the daily tests show a continually decreasing insulation resistance, the station electrician comes to the conclusion that the cables are giving way, and is inclined to wait for a dead earth to develop before seeking the fault; he should, however, set to work systematically to find out where the fault lies, and to remove it before the cable becomes unworkable.

To do this it becomes necessary to carry out tests in a systematic manner to ascertain the true condition of the mains before and after laying and jointing, so that it may be quite certain that, at all events when ready for work, the whole system of insulated conductors may be as perfect as possible. Unfortunately but little can be said with respect to the localising of a fault in distributing mains or cables having numerous ramifications, but it is quite possible to localise a fault in a feeder main or other length without branches.

For the purpose of accurate testing, each station should be provided with a sensitive high-resistance mirror galvanometer, a shunt-box, a resistance coil of not less than 10,000 ohms (if possible a megohm), a condenser, keys, and a battery of not less than 100 Leclanché cells. For tests during laying this battery should consist of 400 to 600 cells.

The shunt-boxes usually supplied with the mirror galvanometers are fitted with shunts having for that particular galvanometer multiplying powers of 10, 100, and 1,000. For the varying insulation resistances which have to be measured in electric light testing, a resistance-box having coils of units, tens, hundreds, and thousands is most convenient for a galvanometer shunt-box, as it enables work to be done between very wide limits, and the obtaining of the deflection upon any part of the galvanometer scale.

The instruments should be erected and adjusted before the work of laying or pulling in is commenced, so that tests may be taken on the arrival of the drums of cable and the specified insulation resistance assured.

The test should be taken with the drums of cable immersed in water wherever possible, but where this cannot be done they must be well wetted.

The preparation of the ends of the cable is of the utmost importance if the real insulation resistance of the dielectric is to be obtained, the difference in the results given with properly and improperly prepared ends being very great.

For vulcanised rubber cables the tapes, braiding, or other covering should be removed for at least 6 in.
from the ends, and the tape next the rubber should be carefully removed, the surface of the rubber washed with naphtha, and well scraped to remove any fragments of the tape. The rubber should be tapered off with a pair of clean bent scissors, the length of the taper being 1 in. to 2 in. Next thoroughly dry the whole of the prepared end by means of a spirit lamp, allowing the flame to play round the rubber, care, however, being taken not to burn it. If the test cannot be taken immediately, the prepared end should be well warmed and lapped with clean warm pure indiarubber tape well stretched.

The most accurate and convenient method of obtaining the insulation resistance is by means of the direct deflection method—i.e., by a comparison of the deflection of the galvanometer needle produced by a given battery power working through a known high resistance with the deflection produced by the same battery power working through the insulation of the cable.

First, to take the constant—i.e., the deflection when the battery is connected up through the galvanometer and known high resistance. The galvanometer (with its shunt) is connected in series with the battery and known high resistance, and the circuit being completed through a suitable key the shunt is adjusted to give a convenient deflection, and this deflection noted—call it θ.

If the high resistance is less than half a megohm, it will be found impossible to keep the spot of light on the scale when the full testing battery is connected up, unless a shunt of very low value is used, and this is undesirable. It is therefore necessary to take the constant with a portion only of the battery, the number of cells used depending upon the value of the high resistance; if a 10,000-ohm coil, one cell will be sufficient. Having obtained a deflection, it is necessary to take the battery ratio—i.e., the ratio between the portion of the battery used for the constant and the full battery to be used for the actual test. For this purpose a condenser having a capacity of one-third microfarad and a discharge key are required. The condenser is first charged from the cell or portion of the battery used to take the constant; the discharge through the galvanometer is taken and noted—call it β. Next take a discharge from the same condenser from the full battery—call it B—then \[ \frac{B}{\beta} \] is the battery ratio, and we multiply the "constant" deflection, θ, by this ratio in order to obtain the deflection which would be given by the full battery through the high resistance.

The test upon the cable itself is now taken: one pole of the battery being put to earth, the battery itself being well insulated, the other pole is connected through the galvanometer and key to the cable. Of course the tank or drum containing the cable is to earth. A short-circuit key must be connected across the galvanometer terminals, and must always be closed so as to short-circuit the galvanometer at the beginning of each test, otherwise the rush of current from a high battery power will probably demagnetise the galvanometer needle. Close the battery key, and after half a minute open the short-circuit key, which may be used to check the swing of the galvanometer needle. At the end of the minute note the deflection—call it D. Still keeping the circuit closed, note the deflection at the end of the second minute, which shows a considerable decrease over that of the first. If the insulating material is high-class indiarubber, the battery should be kept on for 15 minutes, readings being taken every minute.

When a certain insulation resistance per mile is specified, it should be given by the first minute test.

The insulation resistance is calculated out as follows:

\[
\text{Total insulation resistance} = \theta \times \frac{G + S}{S} \times HR \times \frac{B}{\beta}
\]

where θ = deflection when taking the constant.

G = the resistance of the galvanometer.

S = the resistance of the shunt used when taking the constant.

S₁ = the resistance of the shunt used when taking the test.

HR is the value of the high resistance—If in ohms, the resulting insulation resistance will be in ohms; if a megohm, it will be in megohms.

D = the deflection obtained when taking the test, less the leakage deflection on test leads, instruments, etc., which should always be obtained at the beginning of the test.

\[ \frac{B}{\beta} \] = battery ratio, which equals unity when the full battery is used throughout.

The expression \( \frac{G + S}{S} \) gives the multiplying power of the shunt—i.e., the number by which the observed deflection must be multiplied in order to obtain the true value of the deflection.

When the usual 10, 100, and 1,000 shunts are used, those numbers denote the value of \( \frac{G + S}{S} \).

Example 1.—The deflection obtained when taking the constant with 100 cells through a megohm was 300 divisions, the shunt having a value of 20 ohms. The deflection D obtained when taking the test with 100 cells was 22 divisions, no shunt being used. The leakage from instruments, testing wires, etc., gave two divisions: \( 300 \times 22 - 2 = 20 \), the true value of D. The galvanometer resistance was 7,000 ohms.

\[
300 \times \frac{7,000 + 20}{20} \times 1 = 105,300
\]

\[
\frac{105,300}{20} = 5,265 \text{ megohms.}
\]

= the total insulation resistance of the cable, which
multiplied by the length in miles gives the insulation resistance per mile.

Example 2.—When D is obtained with the galvanometer shunted.

Let \( \theta = 300 \) with a 20-ohm shunt as above.

Let \( \Delta \) = 50 with a 100-ohm shunt.

\[
\frac{300 \times 7,000 + 20}{20} = \frac{20}{105,300} = 29.66 \text{ megohms.}
\]

Example 3.—When the constant is taken through 10,000 ohms, using one cell, the test being taken with the full battery.

Let \( \theta = 250 \) deg. and the shunt used 400 ohms.

\( \beta \) the discharge deflection from the 1 cell = 220 deg.

B the discharge deflection from 100 cells = 150 deg., and the shunt used 50 ohms.

Let \( \Delta = 20 \) with the galvanometer unshunted.

The galvanometer resistance \( G = 7,000 \) ohms.

\[
\text{Then } \frac{250 \times 7,000 \times 400}{10,000 \times 50} = \frac{200}{220} = 222,231,250 \text{ ohms, or say } 222 \text{ megohms.}
\]

For testing short lengths of highly-insulated cable a battery of least 400 Leclanché cells should be used.

If the battery is kept on for 15 minutes during which readings are taken every minute, it will be noticed that the deflection falls rapidly the first two or three minutes, the fall per minute becoming gradually less, till at the end of 15 minutes the deflection is falling very slowly. It would thus appear as if the insulation resistance rises during the test; but the chief reason is that when the battery is first connected, and after the first rush of current, the dielectric electrifies or absorbs current, and this absorption naturally becomes less and less as the cable becomes fully charged.

The great use of this test is that it shows the existence of minute faults in a cable which on a one-minute test would pass the specification, as if there is little or no electrification, or the existing electrification proceeds unsteadily, it is certain the dielectric contains undeveloped faults.

For this test it is absolutely necessary that the cable should be in water, as no reliable results could be obtained even from a well-wetted drum, and, of course, it cannot be taken on a system connected up to transformers, etc., though frequently before connecting up the electrification is very pronounced.

The method of testing having been explained, we proceed to the system which should be adopted during the laying of the cables.

All insulated conductors should be tested after at least 24 hours' immersion in water, and none but those giving the specified insulation resistance should be accepted. When laid or drawn in, but before jointing, the section having one end in the station should have its ends prepared, the distant end being well warmed and lapped, and a careful test taken; if all right prepare section 2, and, having by means of a short piece of fine wire connected it to section 1, test both sections together. If the insulation resistance per mile is found to be correct, the two sections may be jointed, after which they should be again tested, and if not up to the previous tests the joint must be remade. Sections 1 and 2 being jointed and passed, section 3 may be temporarily connected and tested, jointed, and the three sections tested, and so on till the entire system is jointed and the final test taken.

If this method is carried out, the engineer in charge will have a record of tests: first, upon each section in water; second, upon each section after laying; third, upon the system as each length is jointed on, and he will feel satisfied that the cables are up to the specification, that they have not been damaged in laying, and that the joints are all well made.

With vulcanised indiarubber joints, in a vulcanised indiarubber insulated cable, there is no difficulty in keeping the completed system up to the specified insulation resistance per mile of the cable.

It is manifestly absurd to lay down high-class mains and by means of inferior joints reduce the insulation resistance to a few thousand ohms.

If a section cannot be tested from the station, or if jointing cannot be commenced at the station end of the mains, a portable testing set should be employed, and when all sections are jointed up a final test should be taken with the station instruments.

If the daily tests (which should always be taken) show any decrease in the insulation resistance, the cause should at once be sought for and removed.

Of course, when transformers are used in the system, and are connected up, there will be a very decided fall in the insulation resistance. This is in a great measure unavoidable, but could be greatly decreased by more careful methods of insulating the transformer, fuses, etc.

In feeder mains running to a distributing centre it is possible to localise an earth by means of the loop test if suitable instruments are available. The ordinary P.O. pattern Wheatstone's bridge and resistance coils are quite unsuitable, the instruments required being a sensitive low-resistance Thomson's mirror galvanometer, a few low-resistance cells, together with a finely adjusted set of slide resistances and resistance-box.

The conductors should be looped by amalgamating the ends and immersing them in a large mercury cup containing clean mercury.

The copper resistance of the loop is first taken, by means of the slide resistances and resistance-box, connected up so as to form a Wheatstone bridge.

Then connect the conductors to the two free terminals of the slide ratio coils, across which the
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galvanometer must be connected. One pole of the battery is put to earth, the other pole is connected to the terminal at the junction of the two ratios. The balance is obtained by varying the ratios.

Let \( R \) = the total resistance of the loop.

\[ A = \text{the resistance when the balance is obtained of the ratio coils connected to the faulty side of the loop.} \]

\[ B = \text{the resistance when the balance is obtained of the ratio coils connected to the sound side of the loop.} \]

Let \( \tau \) be the resistance per yard of the conductor, then

\[ \text{the distance of the fault in yards} = \frac{R \left( \frac{A}{A+B} \right)}{\tau}. \]

All connections should be made by means of mercury cups, to which the conductors must be brought; no leading wires should be employed. If no special instruments are obtainable, the distance of the fault, if an earth, may be found by the fall of potential method, and if carefully taken good results should be obtained.

The instruments required are a high-resistance Thomson mirror galvanometer, shunt, condenser, discharge key, and a resistance capable of carrying, say, 30 amperes, and having a resistance of, say, 1 ohm. The wire composing the resistance should be of German silver or platinoid, and of sufficient section to carry 30 amperes without any appreciable rise in temperature. Loop the conductors at the distributing centre. Connect one pole of a battery or accumulators, or, failing these, of a continuous-current dynamo, to earth, the other through an adjustable resistance and the standard resistance described above, to the conductor of the cable forming the faulty side of the loop, the end of the side being insulated.

Now, by means of the adjustable resistance, adjust the current from the accumulator or dynamo, arranging it to be as high as possible, as if owing to the fault having a high resistance only a small current passes, it will be very difficult to localise the fault.

If possible use a condenser having a large capacity, one side of which is connected to earth and to one of the galvanometer terminals, the other side being connected to the movable lever of the discharge key, the two free terminals of which are connected—one to the remaining terminal of the galvanometer, and the other to a wandering lead, which for the first test is connected to the terminal of the standard resistance nearest the dynamo or accumulator. A discharge deflection is taken, call it \( D_1 \).

Remove the wandering discharge key lead, and connect to the other terminal of the standard resistance to which the conductor of the cable under test is also connected. Take a discharge deflection and call it \( D \).

Remove the wandering lead and connect it to the insulated end of the sound side of the loop. Take a discharge deflection and call it \( a \).

\[ \frac{D_1 - a}{D - D_1} = \text{distance of the fault in yards, where} \quad \tau = \text{the resistance per yard of the conductor.} \]

If no condenser is available, the galvanometer in series with a suitable resistance may be connected between earth and the various points as mentioned above, and the permanent deflection values used in the formula.

The distance of a contact may be obtained by measuring the resistance of the conductor, first from the station end, the distant ends being insulated, and afterwards from the distant end, the station end being insulated.

Let \( R \) equal the resistance as taken from the station.

Let \( R_g \) equal the resistance as taken from the distributing station.

Let \( R_c \) equal the conductor resistance of the faulty mains.

\[ \frac{R_1 + R - R_2}{4} = \text{resistance of one conductor to the fault,} \]

and \[ \frac{4}{\pi} = \text{distance of the contact in yards,} \]

when \( \tau \) = the conductor resistance per yard.

The instruments used for the loop test will be suitable for the above test, which should be taken when there is no traffic on the roads under which the mains are laid. It need hardly be said that as all measurements with a view to localising a fault are greatly dependent on the state of the joints in the system, to ensure a satisfactory test the joints must be sound and reliable.

It is very desirable that a proper distributing station should be arranged inside some building and fitted with arrangements for disconnecting the distributing from the feeder mains, so that the condition of any feeder or distributing main with its branches can be accurately obtained. Test-boxes in the street should be avoided, as they are of small practical value and a continual source of trouble.

It is unfortunately impossible to localise earth faults by direct testing in branch wires without disconnecting from the distributing main, and the existence of this difficulty should be the strongest possible reason for using the very best known means of insulating, jointing, and laying underground mains.
CHAPTER XV.

ELECTRIC LIGHT MAINS.

The various methods of laying electric light mains will now be described:

The Crompton System.

The system of underground mains used by Messrs. Crompton and Co., Limited, is that of bare strips of solid copper stretched upon glass insulators in an underground culvert, and strained in air from point to point by means of specially constructed straining apparatus. The Crompton system is in use for the low-pressure distribution of electricity for direct currents, with or without the use of accumulators, and is principally used upon the three-wire system of mains, though it is also applicable where desired for ordinary parallel distribution. The system has been in successful operation for about four years, and besides the original Crompton central station at Kensington and Knightsbridge, where it was first developed, and where over 12 miles of mains are now laid, it is in use or is being laid for the Notting Hill Electric Light Company, the Westminster Electric Company, at Northampton, at Birmingham, and also in France. Nearly 100 miles of mains in all are now in use or are being laid.

In principle, the system may be considered as a return to the ordinary methods of running telegraph wires, but applied to heavy copper mains, and underground. Mains for electric light were originally heavily insulated, afterwards cased in lead, then passed through protecting iron pipes, and finally run in conduits or culverts. To make these culverts such that bare conductors of sufficient thickness could be strained in air—which, after all, is the best as well as the cheapest insulator—thus doing away with costly insulation, has been the aim in the Crompton system, and, in point of fact, this system is one of the earliest attempts at a practical solution of the question of underground distribution on a large scale, and its success has given a great impetus to the planning of central distributing systems.

The development of the Crompton system of electric mains has been, roughly speaking, through the following stages: First, a solid square bar was carried upon a wheel insulator fastened sideways in a culvert, changed afterwards to an upright cup insulator having a slot in its head, carrying first a bar, then modified to a bundle of wires, and again modified to a set of strips placed sideways on their edges. The alteration of the position of the strips, placed next on the flat, brought the method to one much as now in use, its later development being mostly in the mechanical form and the practical method of placing the insulators, and in the system of straining. At first this straining was brought about by the use of a right and left handed screw on the solid copper bars, which drew the lengths together; the alteration was soon made of having each length strained separately, and connected together by a by-pass of solid copper. As at present used, Figs. 126 and 127, each length of copper strip is separately strained, and the overlapping ends are then tightly screwed together by a screw connecting piece, the strain being taken by specially constructed straining-pieces in the manner hereafter described.

The mains on the Crompton system are made to three standard sizes. These represent (1) the usual three-wire distributing main; (2) the distributing main with one pair of feeders; and (3) the distributing main with two pairs of feeders. It is seldom that other sizes than these are necessary; if such cases arise, two separate culverts would be run for the distance required.

The principle of the three-wire system of distribution is now sufficiently well known. With a total pressure of say 210 volts between the outside wires, the pressure between the inner and either of the outer wires is 105 volts. The wires to the houses are connected alternately in such a manner that the number of lamps on one side balances that on the other, so that no current (or only the slight difference between the two halves) is flowing through the central wire. To keep the pressure the same over all parts of the circuit, feeder mains, going to certain determined points where the demand is heaviest, are connected directly from the source of supply, and thus the potential is kept constant.

In laying out a system of mains the position of the generating station is taken as centrally as possible. The streets are laid out with mains in the simplest and most direct manner, and feeder points are then determined upon at various points upon the plan. In the streets, were no feeders are required, a culvert for three wires only is laid; but where one pair of feeders go alongside the mains, a culvert for five wires (the three wires and one pair of feeders) is necessary. Near the station where feeders in two directions are required, culverts for seven wires (three wires and two pairs of feeders) are laid, and so for other parts of the circuit. These three sizes are shown in the illustrations, Figs.
128, 129, and 130. The sizes inside are respectively 1ft. 3in., 1ft. 8in., and 2ft. wide.

The trenches for the culverts are made, wherever possible, under the pavement, and the usual type of Crompton system is 2ft. 5in. wide, and for the largest culvert 3ft. 2in. wide by 1ft. 9½in. deep.

The first process, when actual laying is begun, is the digging of the trenches and the construction of the boxes are made for this situation. Occasionally, however, it is necessary to lay the mains in the roadway for some length, or to cross the road from one side to the other, and the culverts and boxes are then made extremely strong to withstand the ordinary traffic or even the passage of a steam roller.

The size of trench for the ordinary main on the culverts. These are laid in concrete, of the required width of opening, with the walls biassed outward at the base for strength; first the floor is laid in concrete, and then the walls of the culvert, which are kept up by rough boarding till firmly set.

The second part of the work is the construction of insulator boxes. At every alternate house along the
road—roughly, at the distance of every 15 yards—arrangements for an insulator box are made. This box serves both for allowing inspection of the insulator, and as a junction box for either of the houses. An oak baulk, 4in. by 6in., for supporting the insulators, these box covers are previously filled in level with the concrete so as practically to form one continuation of the pavement itself.

At certain distances along—from 20 yards up to 100 yards if the road is straight—provision is made...

is imbedded in the concrete, each baulk having round holes drilled in its centre for the after reception of the insulator. These insulator baulks are marked with the letters IB on the figures.

Thick York flagstones are now placed along over the culverts, and the surface is filled in and rammed down and the pavement replaced. At the places for insulators a metal frame is bedded in the concrete. Each of these frames has a properly fitting lid or box cover, B C, and is 4in. by 4in. for ordinary mains, 4in. by 6in. for mains with one pair of feeders, 4in. by 6in. for mains with two pairs of feeders. These straining baulks are marked SB in the illustrations. After they are laid the spaces above are covered in with...
cast-metal boxes and covers of the same type as the others.

When the culverts are finished, the next process is the actual drawing in of the mains. These come in the ground by the workmen's feet, and the length between the straining-boxes is measured and cut off.

In the first place a cord is passed through the culvert, and usually for this an ingenious and simple method is adopted. At the Kensington station may be seen a curly-haired black dog, a permanent official of the mill. They are uncoiled and stamped out straight copper strip 1 in. wide by ½ in. thick, just as rolled from the mill.
works. This dog, with a cord attached to his collar, is put into the culvert and the top closed in. The men then go to the next box and call the dog, who creeps along, drawing the cord, and so on to the end. The cord is then attached to a chain, and the chain in its turn to the copper strip, which is then drawn in by the men.

At each insulator box the glass insulators are now pressed into the holes (1\(\frac{1}{2}\)in. diameter) in the timber into its position upon the insulator. The three or more strips are thus successively drawn in.

The copper strips having been passed into the culvert are yet lying along the bottom. They have now to be stretched sufficiently taut to be everywhere in air, except where they touch at the insulating supports. A sag of about 2\(\frac{1}{2}\)in. in the mains is usually allowed between the insulators.

The straining pieces, S, each consist of a bridge or baulk. These insulators, I, are of the form shown in the illustrations, Figs. 127, 132, and 134, with five deep rings to give a long length of insulating surface, and thus to guard against leakage by moisture creeping. The insulation is still further increased by each insulator being previously dipped in hot copal varnish. The head of each insulator is slotted out of a width to receive the copper strip. As each strip is drawn past, a man stands at each insulator box along the route and lifts the strip arch made of gunmetal, of the shape shown in the illustrations, Figs. 126, 131, and 133, and in detail in Figs. 138 and 139, and carefully designed to afford the requisite stability, both for resistance to the strain of the copper mains and for holding these latter absolutely fixed, while at the same time obtaining the highest possible insulation. The insulation is assured by the use of glass insulators with deep grooves, similar to those already mentioned, but more solid, and squat to withstand the strain.
In placing them into position, a ring or pad of solid indiarubber is placed over indiarubber, R, Figs. 126 and 131, is first placed each insulator, which are thus evenly bedded and against the straining baulk, upon these are placed the glass insulators, I I, Fig. 137, and then a enabled to withstand the heavy end strain without the edges chipping off. The gunmetal bridge straining
pieces, $S$, are then placed in position, and the copper main, $C$, is passed through the slot in the centre. It should be noticed that this slot is made with the lower side sloped, or wedge-shaped. A loose piece inside the slot screws down tightly upon the copper main, which is thus slightly bent, and becomes firmly fixed or wedged in position, so that by this simple means the more the strain on the main the tighter it is gripped. The pinching screws are made of aluminium bronze or Delta metal, or in dry situations of steel.

The straining is accomplished in various ways. The most scientific and certain is that often used of a hydraulic jack, made to form a lever to draw the mains up tight. Placed in position at the side of the trench, bedded against the concrete edge, a few strokes of the

hydraulic handle tightens up the main, and the pinching screws are then screwed tightly down upon the wedge-piece, $W$, Figs. 126 and 131. The straining for shorter lengths is also often done by the simple means of ropes and pulleys, or by a crowbar strained against a baulk, or sometimes by a righ or left-handed screw. The means employed are mainly dependent upon the length of the strip, and thus upon the necessity for greater or less force.

When the copper strips are properly tightened from straining-box to straining-box, the ends are overlapped and tightly connected together by a grip-box or connecting-box, $C$, Figs. 126 and 133, which simply means pressing the ends of the flat strips firmly together by means of pinching screws. This grip-box is usually large enough to hold four strips, but can be made to hold six strips if necessary. It is shown in detail in Fig. 140.

The culverts when going under roadways have to be made of extra strength to carry the heaviest traffic without fear of the covers breaking or the side walls crushing in. Certain regulations have been issued by the London County Council, and the designs of culverts and covers given are constructed fully to comply with these requirements. The trenches in these cases are about 4ft. deep. The illustrations, Figs. 132, 133, and 136, show cross sections and longitudinal sections of a 2ft. culvert under roadway. The smaller culverts are of similar construction, the only difference being in the width. The culverts have

a solid cement bottom, and the walls are of 9in. brickwork set in cement and with an inside coating of cement to prevent any percolation of moisture. They are also sometimes constructed entirely of cement 9in. thick. Two methods of covering the culverts are adopted according to judgment. They are either covered in with two thicknesses of 2½in. York stones; or in some cases with cast-iron covers having ribs on the upper surface and filled in with concrete. Both these methods are shown in the illustrations, Fig. 132 being a longitudinal section of a culvert, half of which is covered with thick York stones, and the other half indicating the culvert as covered with ribbed iron plates and concrete. Fig. 141 is a reproduction from a photograph of the work of trenching.
The covers to the boxes under the roadway have, of course, to be adapted to the nature of the rest of the roadway surface. Both the insulating and straining boxes are dealt with in the same way. The covers, Fig. 135, are made of a cast-iron frame, hollow on the upper side, fitting into the boxes and easily removable for inspection. The hollows in the upper surface are filled in with concrete, cement, asphalt, or other materials, to match both the colour and the rate of wear of the material of which the roadway itself is constructed.

The joints of these covers are made water-tight, and at cases heavily-insulated cables drawn into pipes are used for the distance required, each cable having its own separate pipe. The ends of these pipes are brought into insulator or straining boxes (Fig. 142) of the same form as those used for the culverts, and the cable is screwed tightly to the copper strips in the manner shown. Similar arrangements are adopted for connecting the house mains to the three-wire mains. They are led to the nearest insulating box, and are connected respectively to the inner main and one of the outer mains. If it is

![Image](https://example.com/image.png)

Fig. 142.

the same time noiseless, so as not to vibrate under the traffic, by inserting a serving of tarred rope in the framework of the box before the cover is put on. Where wood pavement is in use, the cover is made with ribbed openings of the necessary size to match the rest of the pavement, and hard wood blocks are cemented in, as shown in the illustration, Fig. 134. The arrangements for connecting a culvert under a roadway with that under the pavement are seen in Fig. 133.

It sometimes happens that the space under the footway is so small that culverts cannot be built. In such ever necessary to alter the balance of the current in the two halves of the three-wire mains, it is a matter of a few minutes' work to lift the cover, unscrew one end of the house main, and screw it upon the opposite outer main strip.

The Callender-Webber System.

Two systems of underground mains for electric light distribution are carried out by Callender's Bitumen Telegraph and Waterproof Company, Limited, of Leadenhall-street, London. These two systems are
known respectively as the Callender-Webber system and the Callender Solid system. In both of these, highly-insulated copper cables are used, laid under-

In the Callender-Webber system the bitumen is moulded into solid casings having holes throughout the length, and through these the insulated cables are

ground in trenches and protected by bitumen. The method of using the bitumen constitutes the difference between the systems.

drawn in. This gives facilities for the removal of cables and the substitution, if necessary, of others; and for the provision of spare space to be occupied by
other cables as the demand increases, without the necessity for again taking up the streets.

In the Callender Solid system the insulated cables are laid in an iron trough and the whole filled in solid with melted bitumen, the cables being held practically immovable when once laid.

The decision as to which of these two systems is the most suitable depends largely upon conditions of cost and of locality. The solid system will in most cases be the cheaper, if the cable is for a certain stipulated transmission of current which will never be exceeded, or if the demand for current is known or can be estimated closely, so that necessity for alteration or addition is not likely to occur.

The Callender-Webber system is most suitable for central station work with feeders where the addition of other mains as the demand increases will be certain to be required.

Many large contracts on one or other of these plans have been carried out in all parts of the kingdom, both for central station distribution or for feeders at isolated installations, and also in combination with the various systems of bare copper mains for use in special situations. The numerous practical details, which are so necessary for the success of any system of distribution, have thus been worked out as the result of actual experience, and the precautions fully learnt which must be taken to ensure high insulation and safe and uninterrupted supply, as well as to assure ease in laying and in the connection of branch or house mains.

We will first describe the Callender-Webber system of underground electric mains, this being the system most applicable to networks of new central stations likely to increase in size. The system is the outcome of the joint inventions of the Callender Company and Major-General Webber, R.E., and its essential distinction lies in providing a solid yet insulating protection to the cables, and a separate way or passage for each cable run.

The general arrangement is well shown in the descriptive section and plan, Figs. 143 and 144, of the roadway, showing six feeding mains, laid under the street among a bewildering array (not at all uncommon in towns) of gas and water pipes and main sewers, with a distributing main on the three-wire system laid under the footpath, feeder boxes and service boxes being constructed flush with the pavement.

The appearance of the bitumen casing is clearly indicated in Fig. 145. It is made in 6ft. lengths of blocks of bitumen concrete, pierced in the manufacture by a varying number of holes or ways. The standard sizes of these cable cases are shown in Fig. 146, and are for two, three, four or six ways, of either 1½in., 1⅜in., 2⅜in., or 3in. diameter.

The bitumen concrete is composed of natural bitumen (one of the most durable materials known) mixed with 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 gas or acids found in the ground, and is a non-conductor of electricity. It does not expand or contract, and is capable of withstanding, when embedded in the ground, the weights of heavy traffic. It can be made to any shape, and the cases can be bent up or down, or to curve to the right or left on the job in the work of
laying, and the process of laying is comparatively simple. When laid each way is a closed passage, completely separated from all the other ways and from earth by an insulating wall of bitumen, and the cables are, therefore, subject to no unfavourable conditions from contact with each other, or from deleterious or conducting substances.

When constructing the conduit it is easy to lay the casing with a larger number of holes than is necessary for present requirements, the additional cables being easily drawn in as the demand on the network increases without opening the roadways or disturbing the traffic.

The following table gives the stock sizes, with the size of cable taken:

<table>
<thead>
<tr>
<th>Size</th>
<th>1½in. ways, taking up to ½ in. cable.</th>
<th>1½in. ways, taking up to ¾ in. or ¾ in.</th>
<th>2½in. ways, taking up to 2¾ in. cable.</th>
<th>3½in. ways, taking up to 5 in. or sect. area, insulated.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 way</td>
<td>4½in. by 2½in.</td>
<td>3½in. by 2½in.</td>
<td>3½in. by 2½in.</td>
<td>5½in. by 5½in.</td>
</tr>
<tr>
<td>3 way</td>
<td>6½in.</td>
<td>5½in.</td>
<td>4½in.</td>
<td>6½in.</td>
</tr>
<tr>
<td>4 way</td>
<td>4½in.</td>
<td>4½in.</td>
<td>4½in.</td>
<td>8½in.</td>
</tr>
<tr>
<td>6 way</td>
<td>4½in.</td>
<td>6½in.</td>
<td>6½in.</td>
<td>10½in.</td>
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</table>

In laying mains underground, whatever the system, it is advisable to carry them as near to the houses as the cellars will admit, and as far as possible the trenches are made under the footpath. When the pavement is of a costly nature and the roadway is of macadam, it is better to run the trenches along the road, but usually the pathway, if not already occupied by telegraph mains or large cellars, is best and cheapest.

Under paved footpaths the depths at which the mains are run need only be sufficient to be just below the higher gas and water service pipes, the concrete foundation of asphaltite, or the flagstones of the pavement. In practice, the bottom of the trench is usually 1½in. to 2½in. below the pavement level, but in cases where space is limited the casings can be run with perfect safety in 3in. or 4in. of depth. This adaptability of the system for limited space, combined with its high mechanical and electrical protection and its power of curving up, or down, or to one side, make it extremely convenient in many places where more rigid systems would be inapplicable.

In the roadway it is customary to have the trench 3ft. deep. Under an ordinary macadamised road this depth will be quite safe for all ordinary traffic and for temperate climates. If the roadway is concreted as for wood or asphaltite paving, it is sufficient to have the mains laid immediately below the level of the concrete.

The actual process of laying the Callender-Webber mains is as follows:

The course of the main is first laid out, and the trench dug to the required depth. The trench is made in as straight a line as possible, and is somewhat carefully levelled, a good foundation being secured by ramming down the soil. Occasionally rough concrete is employed in the trench to bed the conduit, but this is necessary only in exceptional circumstances. As long lengths as are permitted by the authorities are opened at a time, arrangements being made to avoid interference to the traffic by bridging the trench where necessary. At crossings, however, the work is done in short sections to avoid blocking the traffic. The surplus earth is everywhere carted away regularly.

The bitumen casing is next laid upon the bottom of the trench and jointed together. This jointing is carried out length by length to form one solid and continuous casing. Each fresh 6ft. length is placed on the ground, with 2½in. to 3½in. interval between it and the one already laid. In the meantime, some bitumen concrete is being heated in the large iron cauldron. Mandrels are pushed through each of the holes in the casing, joining the two sets of holes together. Then the bitumen concrete is run in, stamped into position, and shaped into the same shape as the original casing. The joint is thus made absolutely waterproof, and the mandrels ensure the holes being smooth and continuous. The result is practically one solid bitumen casing, and except for the newness of the material a person passing along can hardly tell where the joint has been made. The mandrels are then pulled out, the earth thrown in again, rammed down, and the road repaved.

In certain circumstances, where the mandrels cannot be used, a different method is adopted. The ends of the casing are butted together (see Fig. 147), and saddle pieces of material similar to the case itself are placed at the joint, which is made tight by a little bitumen seared with a hot iron.
The next detail is the construction of the drawing-in boxes. These are constructed in a simple manner by the building of a pit in brickwork at the places required, in the manner shown in Fig. 148. In the larger sizes these are made 3ft. by 3ft., and about 4ft. deep. The bottom is not concreted, but left in ordinary brickwork, so that any moisture that may get in may easily drain away. The walls of the pit are built up, and the bitumen casings are so arranged that they project about 6in. into the pit. Above them the brickwork, overlaid and tapered up, as shown, forms a manhole in the surface of the street, having a cast-iron box, and removable lid.

The cover plates are generally made 18 by 12, 20 by 15, 24 by 15, or 24 by 24 inches, according to the size of the pit. The plate on the footpath is filled in with cement to resemble the paving in which it is placed. In some cases, where access is not often required, it is often found desirable to seal in these boxes. For this purpose the boxes are cast in a special form (see Fig. 149), so that a second lid can be placed on the inner rim there seen under the pavement lid, and the box then made absolutely watertight by sealing in the false lid with red lead or asphalte.

Three different kinds of boxes are in use:
1. Feeder boxes, for the connecting of feeders to distributing mains.
2. Service boxes, for the connection of mains to customers' mains at points where large supplies of current are to be taken off.
3. Supply boxes, for the supply of householders, put in, if required, when service boxes are too far away. These latter are usually constructed of cement or brick built round the conduit after it is laid, so that the conduit is cut at the point most convenient for tapping the cables.

When the conduit is all laid and the various boxes properly built, the drawing-in of the cable itself follows next. In the smaller sizes of casing a cord is passed in as the conduit is laid. The mandrels are specially made with a hook at the end, to which the cord is fastened as each length of casing is laid and the mandrel withdrawn, the cord is therefore drawn through. With the larger sizes of holes such a precaution is not necessary, and when the conduit is laid a jointed rod—something like a sweep's rod—can easily be pushed through from box to box. This is attached to a cord, which in its turn is drawn through and pulls in a rope. The rope is attached to a cable, which is
pulled in either by a number of men hauling or by the aid of a winch. The ways are quite smooth inside, and as these would only be used for feeders or for supply mains in the country, and for town supply the lengths

500 or 600 yards (½ mile) in one length of cable can be drawn in without any great difficulty. Lengths such would be of from 50 to 100 yards, or often less where the demand was heavy and service boxes numerous.
The cables that are used are Callender cables of high insulation with dielectric of vulcanised bitumen, and are made as follows: The conductor is of stranded copper cable of not less than 96 per cent. conductivity. This is first covered by a solid sheath of bitite (bitumen vulcanised under the Callender process) put on under heavy pressure at one operation. This core is then served with tape and insulating compound, and again served with either jute yarn or additional tapes, finally braided with hemp yarn and passed through a bath of asphalt compound. The cables are thus made extremely durable, resisting perfectly themselves all action of moisture or coal and sewer gas. When laid in the solid casing of bitumen, therefore, they are practically indestructible.

The bitumen is also, it appears, a thorough protection against rats, for although these mains have been laid now for several years, the rats have never been found to bite either the cables or the casings, although it is known they have made in some cases the spare holes in the casing their mode of travel.

In connecting the mains to branch or service supply circuits, the course is often adopted of building what are termed fuse-boxes, Fig. 150, in the ground, in which the junction of the service line is safeguarded by the insertion of a solid fuse. The outer pit is made of a depth to suit the position of the casing with its wires. The inner box is made watertight, and is placed inside the pit with air space around it. The bitumen casing projects a few inches inside the inner box, to which it is carefully sealed with bitumen. The upper lid or manhole of the whole street box is set flush with the pavement, and any little moisture that might get in simply drops to the bottom of the pit and filters away.

The method of connecting the feeders to the mains is simple and ingenious. It is the same in both systems.

The Callender Solid System.

In the Callender solid system of underground electric mains, the cables, heavily insulated, are laid in suitable troughs, generally of cast iron, placed in trenches under the street, and the whole of the vacant space in the trough round the cables is run in solid with refined bitumen. All the bitumen employed is genuine natural Trinidad bitumen, free from any admixture of gas, tar, and pitch.

The whole forms a solid and compact mass, into which neither gas nor water can possibly penetrate, and which itself forms a very high electrical insulation. There are few substances more durable than this bitumen, and with cables thus embedded there is little probability of any deterioration taking place in mains when once laid, while the thorough mechanical protection which is ensured reduces to a minimum the liability of injury from exterior causes.

Mains laid on this plan are permanent, and form a sound engineering job. It is of course clear that such mains should only be laid when the conditions do not require that the capacity of the cables should be afterwards altered. The Callender solid system is especially suitable for connecting mains for isolated plants where the conditions are settled and well known; for heavy mains in large cities where the consumption is likely to attain its maximum at once; for heavy distributing networks; and for the heavy feeders which are run to various points of the system of three-wire distribution. It is also peculiarly suitable for arc lighting on the series system where long lengths of single or double mains are required to be run.

The combination of vulcanised bitumen as the insulation for the cable itself, with plain bitumen run around it as a sheath in the trough, is one that ensures an absolutely safe and constant insulation, on which faults are unlikely to appear. Repairs, when necessary, are easily and rapidly made. Altogether, it forms one of the most trustworthy and satisfactory methods of placing cables underground, and has a certainty of being more permanent and lasting than most of the other parts of an electric lighting plant. The work of laying, once done, is thorough and complete.

The troughs for the mains are made of cast iron. For town work this is especially preferable, as it offers a permanent protection from the picks of workmen of other companies. In some cases the upper surface of the trough having been filled nearly to the level by bitumen, is covered by a layer of cement. In others the trough is covered in with cast-iron lids. The thickness of the metal is from \( \frac{1}{8} \) in. to \( \frac{1}{4} \) in., varying with the size of the trough and the liability of the soil to disturbance. These iron troughs are made in lengths of 6 ft., having socket pieces cast on one end, so that when fitted together the surface inside the trough is of one level. For carrying the mains round corners, and for changing levels at crossings, circular pieces and curved troughs are made, but considerable deviation from the straight line is possible with the ordinary type.

In country roads, and in places where wood is plentiful, troughs of sound timber are often substituted for those of cast iron, care being taken to select wood which will stand underground without rotting. The planks should not be less than \( \frac{1}{2} \) in., and the lid should be of 1 in. stuff. It is not advisable to use creosoted wood, as the action of the products of coal-tar distillation are found to be injurious to nearly every form of dielectric.

Brick and cement trenches are occasionally used for special situations, but they are expensive, and offer no advantages over those of cast iron.

The ordinary shapes and sizes of mains on the Callender solid system are shown in Fig. 151, which comprises sections of four-way and six-way insulated mains, laid in bitumen in iron troughs, and covered over at the top with cement.

A very usual case in a distributing network is where a pair of heavy feeders to a distant point are run along with the distributing mains in the same trough. This arrangement is shown in Fig. 152. In both cases the position of the cables in the trough is kept by bridges of hard bitumenised wood of the shape shown, which
are first thoroughly dessicated and then saturated with bitumen. These prevent the cables from touching the bottom of the trough, or of accidentally shifting their relative positions.

In Fig. 153 is shown a pair of heavy feeders, 91 strands of No. 9 wire. These are highly insulated, and each covered with outer lead casing; then laid one above the other in solid bitumen in a narrow iron
trough, and covered in with cast-iron lid. The joint of the trough is shown in section below.

While still molten, the bitumenised wood bridges are pressed into place across the trough at intervals of 18in.

In actual practice the method of laying is as follows:
The trenches in the ground having been dug and levelled, the iron troughs are laid therein, and are jointed together in one length with countersunk bolts and nuts, Fig. 154.

When the bitumen is set, the cable, which has been brought on huge drums, is paid out into the trenches, and laid along into the spaces of the wooden bridges. The cable is then drawn taut, and melted
bitumen is poured in between the cables and between the cables and the sides of the trough.

This is done by moving the bitumen cauldron on wheels along the trench, and by means of a large ladle, pouring a little molten bitumen in at a time. When this first layer is cool, the men come back again and pour in a little more, and so on, for about six times, thus allowing the bitumen to fill up every cavity round the cables. In the case of cables above one another, the whole process is, of course, repeated along the length. The bitumen is run in to within an inch of the top of the trough.

When the bitumen is quite cold a layer of Portland cement from 1in. to 3in. thick, according to circumstances, is put upon the top of the bitumen, and where crossing a roadway a brickwork, cast-iron, or other protection is placed over the top, to guard against damage from heavy traffic.

We now come to an interesting point, the connection of feeders, mains, and service lines, the second or changeable method in very many cases where the solidly insulated junction used to be employed.

In connecting the mains together, two different methods have to be considered: (1) those in which the joint is solid, permanent, and covered in with insulation in the same manner as the rest of the cables; and (2) those in which the connections of feeders to distributing mains and of those to house service mains are sometimes required to be altered or disconnected easily, either for change of load or for testing.

We will first of all take the solid connection, premising, however, that it is now found desirable to use

![Figure 155](image-url)

Fig. 155.
one piece, with an inner and an outer box, shown in plan and section, having their corresponding lids. This double box is pierced on all four sides with openings for the mains to be connected. The two larger mains are now cut to the requisite length to just pass a few inches into the inner box, and their copper ends, E E, are bared. A solid round copper socket, P, having a flat connecting piece projecting upwards, is securely sweated or soldered on each of these bared ends. The second pair of distributor cables, D D, are passed right through the junction box without cutting, and a space of some inches is bared to the copper upon each of them, these spaces being not opposite to each other, but opposite to the mains to which they are to be connected. Similar copper pieces, P', P', are sweated to each of these bare places, one copper piece being fixed on the main, D, on a line with the ends of the first main, E E, and the other piece being fixed on a line with the second main cable and projecting upward to the same height as the copper pieces thereon.

All that has now to be done is to place solid lengths of copper bar, L L, across the mains, securely fastened by nuts and bolts, the positive main, E E, to the distributor, D, passing over the other distributor within touching, and the negative to the negative distributor, D, passing over the positive without touching.

The cables and the connecting pieces are then insulated by semi-vulcanised material, and then protected by tape; the inner box is filled in with molten fine bitumen, and the cover placed on. The outer box is then similarly filled in with bitumen, thus forming a perfect protection from moisture getting into the joints in the inner box. The last lid is placed in its place, and the whole covered up with earth and finished off level to the road with the same paving as the roadway.
In certain cases these four-way boxes are left without the inner space being filled in with bitumen to allow junctions of house mains to be easily made. This type of box is, however, designed to be filled in solid and permanent, and, if accessible junction-boxes are required for the junction of house service mains or of a branch distributing main, a solid main fuse is used in a fuse-box with accessible manhole, as shown in Fig. 150. These accessible fuse-boxes are applicable to either system, solid or otherwise, and therefore need not be again described.

We now pass to the system of connecting mains and feeders in an ordinary central station network. In an extensive area of supply, the mains, both of feeders and distributors, will spread over a considerable area. Two things may happen to necessitate change in the connections. In the first place, a fault may be found, unscrewed, can be swung round off the bar, and thus disconnected at once, without interfering with or touching any of the others.

The way in which this is carried out is easily seen in the illustration. A double cast-iron box similar to those already described for the simple four-way junction, has leading into it the ends of the main, M M. To each of these is sweated or soldered copper socket pieces, P, having a broad solid lug of copper, L, which is pierced for a bolt. The broad solid omnibus bar, O B, is bolted closely to these lugs, having a short piece of similar thick copper, S P, through which the full connection across is made. It can easily be seen that by unscrewing this swing-piece, S P, and swinging it back, the main, M, becomes disconnected.

In the same way the ends of the distributing mains are led into the junction-box, each having its end bared in which case tests would require to be made, and a certain length of cable might be required to be cut out of circuit; and, again, the demand for current may be altered in certain districts, and the points at which the feeders should feed into the distributors may require to be changed into some other point. It will be seen from this that a ready and rapid method of disconnecting mains, and of connecting up others in their place, is desirable on both grounds.

A simple yet ingenious method is used in the Callender system, shown in plan and section in Fig. 156, which illustrates a single-pole junction-box, having the ends of a network of four subsidiary mains connected to the feeding main. The principle of the arrangement is that of having, on the ends of each main, lugs of solid copper, which can be screwed to a copper "omnibus" bar, and so arranged that each, if
bitumen can be easily removed by the use of a heated tool.

Ordinary sizes of cables are: for feeders \( \frac{4}{15} \) in., equaling one square inch sectional area, \( \frac{4}{15} \) in., equalling \( \frac{3}{8} \) in. sectional area of copper, and both can be laid up to 250 yards length; for heavy feeders \( \frac{4}{15} \) in., equalling \( \frac{3}{8} \) in. sectional area, laid in 150-yard lengths. The distributors are usually \( \frac{3}{8} \) in., sectional area, or \( \frac{2}{15} \) in., \( \frac{1}{4} \) in. sectional area, laid, according to circumstances, up to 600 or 700 yards. The latter size is usually employed for the house service lines.

The Callender solid system is particularly applicable to high-tension systems for arc lighting in series where the mains have to be led from lamp to lamp under the streets, and the strength of current remains constant, without necessitating increase of cable section even if the number of lamps is increased.

The method of connection of the arc lampposts in series is seen in section and plan in Fig. 158, where a junction-box at a street corner is shown. The cables are laid in the trough with sufficient spare length to go up the lamppost without joint, a junction-box being let in under the pavement and covered with a steel plate lid. These high-tension mains can be easily laid in lengths up to one mile without joint.

The Brooks Oil Insulation System.

This system, the invention of the late Mr. David Brooks, of Philadelphia, embodies the use of heavy mineral oil—one of the best of insulators—as the dielectric for high-tension underground mains. The system has recently been brought prominently to the front in England by Messrs. Johnson and Phillips. The system has, however, been well known for many years, and has received much favourable commendation, in Great Britain from no less an authority than Mr. Preece, and in America numerous experts have testified to its efficiency, and dating back as far as 1877, in which year Mr. Brooks laid some experimental wires in Philadelphia.

In 1887 a line of 1 1/4 miles was laid by Mr. Brooks on the Pennsylvania Railroad. In this cable there were 18 splices and 53 conductors, and a very high insulation value was obtained, and an important feature in reference to telegraph and telephonic circuits was practically demonstrated—viz., its low inductive capacity, which in this case gave a mean value of about 1.12 microfarad per mile.

The experience in America of over 10 years, though almost exclusively telegraphic, amply demonstrated the permanence and efficiency of the system. It is claimed in reference to these circuits that while other multiple cables have frequently broken down and developed faults due possibly to lightning and other causes, the Brooks circuits have never given way, and continue to this day to give values as high as when the lines were first put down.

In the earlier experiments Mr. Brooks employed ordinary fluid mineral oil as insulating medium. This, however, was found to have a very high penetrating power, and continual care was needed to keep the oil confined. The oil now adopted, produced from the waste products of rosin oil, is a thick sticky mass less liquid than treacle, and has the advantage of being extremely cheap.

Practical details have now been carefully worked out, and it may be confidently stated that the Brooks system, well carried out, has the best claims of permanency and efficiency of any underground high-tension system, and that it will probably contrast favourably as to cost with any other system of anything like similar insulation and permanency.

The dielectric is a pure homogeneous thick fluid of extremely high insulation value. It does not oxidise when exposed to the air, and when occupying the whole of the space in an iron pipe beyond that occupied
by the conductors and their fibrous covering, possesses all the elements of permanency—in fact, theoretically the system seems to exclude all the ordinary factors of decay, and the permanence of the system seems only limited by the life of the containing pipes, which, in ordinary cases, we believe have been known to last over 20 years when used for gas or water, where it must be remembered both the inside as well as the outside of the pipe is exposed to influences tending to cause decay; whereas in the Brooks system it is evident that no decay of the pipes could go on from the inside, and any deterioration that took place would be limited to the oxidising and perishing process from the outside only. Hence it is urged with much show of reason that the Brooks system must rank well, not on the score of insulation alone, but on that of permanency.

The mechanical details of the Brooks system are seen in the accompanying cuts, larger details of which are given further on.

The iron pipes are used in the usual lengths made and kept in stock, and have their ends carefully bell-mouthed, and connected together by T-sockets, as shown in the small cut, Fig. 159, and at suitable distances draw-in boxes, Fig. 160, are provided, which may or may not have glands for the cables to pass through, according to circumstances. Branch circuits are taken off by means of junction boxes fitted at points determined upon. The junction-boxes are in all cases provided with glands for the cables to pass through, so that the fluid dielectric may be removed from the junction-box for the purpose of making a branch connection, or for testing purposes, the glands then preventing the dielectric from flowing into the box from the pipes containing the mains.

The branch connections connected thereto are preferably lead-covered cables of the ordinary type, which also pass through glands. The junction-boxes may
also contain fuses between the branch circuits and the mains. The terminals are formed of cast-iron boxes of special form, provided with glands with suitable vulcanite sleeves, through which the ends of the cables are brought, Fig. 161. At the highest point of the prepared and all joints in the pipes carefully made, the cables, which consist of ordinary stranded copper conductors, covered to a suitable thickness with raw jute or hemp strand, preferably by braiding, and again wound over all with a sewing of braiding, are coiled on

drums and placed in a tank of the fluid dielectric and carefully heated up to about 300 deg. F., and maintained at this temperature sufficiently long to drive off all moisture. The cable may be of suitable size, and composed of varying number of strands; that shown
in section, Fig. 162, consists of four cables of $\frac{19}{3}$ in. with four pilot wires of No. 12 gauge. The end or ends are attached to a hauling-in strand of wire or rope previously passed into the pipes, and the cable is drawn in direct from the hot dielectric, Figs. 163 and 164, by means of a winch.

Messrs. Johnson and Phillips have made several very severe tests of the system at their works, and continue to have the strongest convictions that it is a reliable and efficient one. A line of 700 ft. in length was laid at Charlton, Kent, under the supervision of Mr. David Brooks, who visited England in order to convey to Messrs. Johnson and Phillips his experiences in the carrying out of his method. The cable consisted of seven No. 18 wires, each wire double cotton-covered, and braided with cotton twisted into a cable and braided over all; this length of cable was drawn into a lin. iron pipe, and the whole system filled with hot fluid dielectric. The line has now been down for about two years, and it is to-day as perfect as when first completed.

During the interval many searching tests of the line have been made, and on many occasions six of the wires have been grouped into two circuits of three wires each, and a Kapp alternator giving 2,000 volts has been connected to one end of the line, and a group of incandescent lamps lighted at the other end for several hours continuously. Measurements made before and after the run showed no fall in the insulation, and it must be remembered that in this case a pressure of 2,000 volts was exerted between wires whose covering of cotton did not exceed $\frac{1}{32}$ in., intimately twisted together.

Another line was afterwards put down at Charlton, one-tenth of a mile in length, containing two cables, each of $\frac{7}{14}$ wires, braided with a fibre to a diameter of about $\frac{1}{16}$ in. These were drawn into the pipe in two lengths, and the whole system filled with dielectric. This line has frequently had, under the direction of Mr. Kapp, a pressure of 14,000 volts for five hours at a time upon it. The test was made by transforming up from a 2,000-volt Kapp alternator to 14,000 volts, and at the
other end transforming down again to 2,000 volts, and then lighting 20 100-volt incandescent lamps in series to full brightness. This potential gave a sparking distance between points of ½ in. at the dynamo end of the line, and at the far end a somewhat greater distance. The line tested immediately before and after the run showed no change in the insulation value.

A recent communication from America dealing with this system gives particulars of underground mains with liquid insulation laid for the Heisler Electric Company, which gives entire satisfaction, having been in constant use for nearly a year in circuits using very high electromotive force, varying from 2,400 volts up to 4,000 volts, and the remarkable feature is the fact
that the insulation resistance is higher to-day than when first installed. Repeated efforts have been made to break down the insulation by subjecting it to various and unusual strains, such as suddenly breaking the circuit when the dynamo was running at its greatest speed, and also subjecting lengths of the line to a static jute, and enclosed in an iron pipe, with liquid insulation, are used for connecting the church with the overhead high-tension wires. The Brooks main goes under the graveyard to obviate the use of overhead mains. The wires have carried the full pressure of 2,000 volts for a period of over 14 months.

In England the Brooks system has been used for a short length in the Keswick central station system. Two single No. 14 copper wires, twice braided with jute, and enclosed in an iron pipe, with liquid insulation, are used for connecting the church with the overhead high-tension wires. The Brooks main goes under the graveyard to obviate the use of overhead mains. The wires have carried the full pressure of 2,000 volts for a period of over 14 months.

They have also been used on low-tension work in a large private installation for Lord Windsor, where 500 yards of four strands of $\frac{7}{18}$ are worked two each in parallel as main conductors under the grounds from the dynamo-room to the house, to entirely do away with the necessity for overhead wires. Various other private installations have adopted the system. Besides
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In this system it is seen that there is no space left for the accumulation of explosive gases, or gases injurious to the dielectric, as might be the case when a solid dielectric is used in conduits or iron pipes; and Messrs. Johnson and Phillips themselves believe that the only other system that could compare on the score of efficiency and permanency with the Brooks mains, is that in which the cables highly insulated with india-

rubber or gutta-percha are drawn into iron pipes kept full of water.

Experience in America for a period of at least 10 years has already demonstrated that, in the Brooks telegraphic and telephonic mains, the cost per wire in a cable of many conductors is less than the cost per wire insulated with gutta-percha or indiarubber, even including the additional charge of conduit-pipe and boxes, or other device.

It has also been abundantly proved at Charlotte that mains for the distribution of electric light and power will stand the severest tests that are ever likely to be required with even far higher voltages than at present are anywhere employed.

Probably one of the largest fields of usefulness for the Brooks mains will be in connection with the high-pressure three-wire alternate-current distribution for lighting, and for alternating-current motors, of which the installation to transmit several hundred horse-power a distance of 12 1/4 miles at 25,000 volts, at the Oerlikon Works, Zurich, is the first and most noteworthy example.

The general scheme of the use of the Brooks system for public lighting at Hong Kong is shown in Fig. 167, where the overhead lines are seen coming to tall posts bearing insulators with an arc lamp above the wires. In the crowded streets, where overhead wires would not be advisable, the high-pressure wires for the arc lamps in series, carrying 2,000 volts, are taken down and under the streets in iron pipes filled with the Brooks liquid insulation, are then run along the streets and up a series of lampposts—one of which is shown in the illustration—and then up vertical pipes again to the overhead wires.

The details of the junction-box and insulator for the top of the posts, where the overhead and underground wires are connected, have been carefully worked out,

part of the progress of the work. In laying, the cables are drawn through from point to point at these boxes, into which the liquid insulation is afterwards poured, and the lid securely fastened down.

Fig. 166 shows the terminal-box, which stands directly under the switchboard at the generating or at the receiving end of the line. Glands are provided when required in the case shown for two cables and pilot wires.

These two illustrations are shown in perspective elsewhere; they are quarter full size, and being reproduced from the working drawings, practically explain themselves.

...this, the system has been for many years in use on certain railways in England for telegraph wires with very marked success.

Fig. 165 shows the details of the junction-box which is laid under the street level. The exits or glands for the cable are arranged so that they can be packed and can also be plugged inside to prevent oil escaping, if the box is required to be left at any
and are shown in Fig. 168. The wires are pulled through the box, and the ends soldered together and insulated, and a screw cap fixed over them. The overhead line passes to an insulator specially adapted for oil insulation. The underground mains descend an ordinary pipe, and the whole is filled up with oil insulation.

We now pass to another and important application of the Brooks system. The drawings are almost self-explanatory. The junction-box, shown in Figs. 169, 170, and 171, is for the distribution in a number of directions of the three-phase current. Each pipe contains a three-strand cable, the strands of which on entering the junction-box are separated and led through glands to separate terminals, or omnibus bars, to which the other distributing cables can be connected. Provision is made for fuses, if desired, between the mains and branches within the junction-box.

Now that the enormous pressures, at one time considered beyond control, are being handled without much greater trouble, save for insulation, than the currents of ordinary voltages, a system such as this seems to be should become more and more valuable to electrical engineers.

Ferranti Mains.

Among the various systems of mains for the distribution of electricity few are more important, and certainly none are more interesting, than those of Ferranti. Mains for the use of 2,000 volts having been in use for transformer distribution some years, Mr. S. Z. de Ferranti, then chief engineer to the London Electric Supply Corporation, determined to transmit current at the enormous pressure of 10,000 volts to London from the company’s generating station at Deptford, a distance of 7½ miles. The difficulty of accomplishing this was the more enhanced in that it was necessary to lay these mains to a considerable extent underground, whereas the previous high-pressure distribution had been principally overhead. Several systems of ordinary electric cables were first tried, at 5,000 and 10,000 volts, but none of these were successful. Mr. Ferranti, therefore, undertook to construct his own mains, and, after exhaustive trials, the desired result was obtained in a singularly simple manner, by the proper combination of concentric copper conductors, covered with a cheap and easily-procured insulating material, together with the perfection of a special method of jointing. Mr. Ferranti determined upon the use of concentric copper tubes as conductors, to be placed one inside the other, and separated by 1/16 in. of the most durable insulation that it was possible to find. Mr. Ferranti resolved to manufacture the mains in short lengths of 20ft., necessitating an immense number of joint.

Scepticism as to the result was rampant, and it is safe to say that no living electrical engineer beside himself would, at the time he started this work, have dared to propose or attempt to carry out such a system. The insulating materials finally selected were paper and black ozokerite, or earth wax. It will be interesting here to give Mr. Ferranti’s ideas upon the subject of insulation of high-tension mains, a subject to which he has naturally given more than ordinary attention.

The necessary points to consider are two: durability of substance and the factor of safety. No one can definitely tell how the insulation may change in course of time, but what can be at once tested is the factor of safety of such insulation. No fault will develop in the insulation unless the dielectric is sufficiently strained to produce enough mechanical effect to cause a gradual change; in other words, unless it is strained beyond the limit of elasticity. Strained below the limit, the insulation will not give way; strained above its limit, the breakage is but a question of time. The Ferranti mains are made with a very large margin of safety, a margin that has been accurately determined by direct experiment. From these experiments it is found that a thickness of 1/8 in. of paper saturated with the black wax, is pierced within one hour by 20,000 volts—some specimens will go within 10 minutes, and nearly all within the hour; above that thickness the insulation is not pierced. This being so, with the present mains, which have 1/8 in. of insulation, there is eight times that thickness, and with half the number of volts we have 16 as the factor of safety. In the Ferranti mains there are 60 layers of waxed paper wrapped one above the other, and the factor of safety is so large, even if one or two layers were partially faulty, it may be trusted to the remainder to give perfect safety. In point of fact, no failures of tested mains have yet been experienced by reason of direct failure of the insulation. Fifteen faults in all were experienced in the thirty miles already laid, mostly of want of continuity. Only two faults were found with 20,000 volts, both of these due to water in the joint at the time of making.

With regard to the jointing, this is a most important part of the whole system. The mains are constructed ready for laying in the ground. The weight is heavy, and the length is kept to 20ft., so that a few men can handle them. In the thirty miles of mains there are therefore seven or eight thousand joints. To allow this the joint must be absolutely safe when once properly made. This indeed is what renders the whole scheme practicable. To make such a joint in the insulation was an achievement long doubted, but is now proved perfectly possible. The desiderata were a very long jointing surface and perfect contact. These were achieved by making a long slanting cone-like surface, the protruding point of one main fitting into the hollow of the next, these surfaces being accurately and truly turned and polished to gauge, and then heated and forced together by hydraulic pressure, by which means the insulation becomes practically one solid piece.

Briefly, then, the Ferranti mains consist of tubes of high conductivity copper cut into 20ft. lengths, and straightened. The usual size of tube to carry up to 350 amperes is of 1/8 in. section, and the size 1/16 in. inside
diameter, and \(\frac{1}{4}\)in. outside diameter. Lengths, 20ft. long, of brown paper are cut off from a roll 3ft. wide, and a length of this paper is glued by its edge to the bath of hot melted black mineral wax, drawn over rollers and through the air for some distance until dry; they are then cut into 20ft. sheets and placed for use.

copper tube. Meanwhile, other rolls of paper are passed over long iron plates heated below by open fires, and thus thoroughly dried; these are passed through a

on shelves. The copper tube has squared pieces of wood knocked into its end, and is then placed in sockets of a slowly-revolving roller on a table which
has at the back a set of rollers, a bath of hot wax, and revolving gear. As the tube revolves, lengths of the prepared paper are inserted between it and the wax is made to flow up and saturate the sheets. When the required thickness is served the wax is made to flow back, the insulation compressed still more upon the

![Diagram](image)

**Fig. 175.**

the brown paper, sheet after sheet, until 60 sheets are served in. During this time heavy rollers come down upon the tube, compressing the paper, and at the same time by displacement boxes dipping into the bath, the copper tube, and a tape is wound spirally over the whole. The tube covered with its insulation is then removed, the wooden pieces knocked out, and the whole slipped into a second tube of copper. Thi.
tube is of the same total cross-section as the first—
viz., \( \frac{1}{2} \) in.—but being larger in diameter is proportionately thinner. The size of this tube is \( \frac{1}{16} \) in. inner diameter, and \( \frac{1}{16} \) in. outer diameter. The tube is left a little larger, so as to slip easily over the inner tube with its insulation, and is then passed through a die and drawn down upon the insulation. This outer tube is now served with the insulation in the same manner as the inner tube: first a length of brown paper glued by one edge, then several sheets of waxed paper to the thickness of \( \frac{1}{8} \) in., compressed and taped as before. The whole is slipped into an outer iron tube to act as a protecting shield. Melted wax is forced by a pump through a small hole in the centre beneath this iron casing till the inner space is completely filled. The whole is then sawn off at the ends into exact 20ft. lengths. The section of the main is shown in Fig. 172.

The next process is the preparation of the joint. One end of each length is formed into a projecting cone, and the other end into a hollow cone, by means of a special hollow coned end. A tight-fitting sleeve of copper, \( F \), is driven for a distance of 8in. on the outer conductor of the main to which it is to be jointed, and this sleeve firmly gripped on by means of a special tool by three or more circular corrugations, as shown. The two cones are then inserted one within the other, the surfaces being previously warmed, and are forced together and driven home by screw clamps, a total pressure of about three tons being employed, and when still under compression the copper sleeve is firmly locked to the other outer conductor by means of circular corrugations as before described. The sleeve, \( F \), and the outer insulation, \( E \), are wrapped at the junction with insulation material until they become of the same external diameter as the iron tube, \( D \), when an iron sleeve, \( G \), 30in. long, is passed over the joint and corrugated down at both ends. In order to fill up any air space in the outer insulation, hot wax is forced in through the boss, \( H \), of the sleeve, \( G \), the whole being finally closed with a gas plug.
The laying of concentric mains is thus relatively a very simple matter; they are supplied ready for jointing together, and may be cut out and laid as gas-pipes are, no cement channels or specially-prepared conduits being necessary. It is usual, however, in crowded streets to lay them in a wooden trough, with wooden separating slips, the trough being filled in with pitch, with an upper layer of concrete for extra protection. When laid in this manner they are subject to variations of temperature, to compensate for which all that is necessary is to give them at certain points a slight wave in laying. To bend a main to go round a corner an ordinary rail bender, as used on railways, is employed; a curve of 6ft. radius being made in this way with but little trouble. In bending, it is found there is no appreciable drag between the layers of insulation and conductors.

For making branch connections a special T-joint is employed; this consists mainly of a cast-iron box with suitably-designed base and cover arranged to fit water-tight. These joints do not, of course, appear on the road surface, being inserted in the run of the mains as required. The joint has three stuffing-boxes through which the ends of the mains are brought in. A screw bolt from the centre of the branch main connects to the inner conductor of the main itself, and the joint is wrapped with paper insulation; the outer conductors are connected with a gunmetal bridge-piece of the shape shown, Fig. 175. Street boxes are also placed in the run of the mains at distances of about 200 yards. These are iron boxes similar in principle to the T-joint boxes, but are placed in small brick chambers, having removable covers flush with the road surface, Fig. 176. The interior is thus accessible for testing and other purposes, while the arrangement of the connections is such that the joints can be easily and quickly connected or disconnected. These joint and street boxes may be filled with rosin oil, by means of which very high insulation is insured at these points, and the full pressure of 10,000 volts may be safely used. While the above description applies more particularly to mains for parallel distribution, the system may be employed with equal advantage for series work.

With regard to the resistance of long lengths of these mains, a length of 7½ miles (i.e., 15 miles of lead and return) between London and Deptford was tested by Dr. Fleming, and the actual resistance was found to be 2·20 ohms, while the calculated resistance of a length of copper of that section was 2·16 ohms, thus showing that the resistance of joints is inappreciable. The mains can be touched on the outside and handled with impunity when a current at the highest voltage is flowing, without the possibility of anyone receiving a shock, the metal covering being to earth and acting as a complete discharge shield. In the event of a fault occurring between the inner and outer conductors, the current can only return direct to the machine, where the safety fuses prevent it doing any harm. The fuses employed are also illustrated here-with. The smaller one, Fig. 177, has a 12in. break, and is used in houses for the primary circuits of transformers; the larger fuse, Fig. 178, is identical with the first, except that it is adapted for main currents, and has a multiple fuse with a 24in. break. The plugs are arranged for separating the multiple fuse wires.

The absence of necessity for channels or conduits in the Ferranti system is an item which should be taken into account, and has, further, the immense advantage of avoiding the possibility of explosions from an accumulation of sewer or lighting gas, which have occurred so frequently with both high and low tension systems throughout Europe and America. Explosions of this kind have already occurred in London. In fact, when a conduit or line of pipes is opened, the presence of gas (which is found, moreover, to impair the insulation of cables laid in that manner) is very frequently detected. Such methods are also liable, sooner or later, to dangers which arise when water is present. For instance, when bare conductors are used and water gets access to them, they are liable to be short-circuited or injured by electrolysis. With insulated cables in pipes or conduits, the alternate presence and absence of water affects the insulation, damaging it in time, and when it is present in winter, it is liable to freeze—the ice crushing or piercing the insulation and causing partial or total short-circuitings. This occurred in London during the late winter of 1890-91.

With regard to safety the following experiments were carried out: In the presence of representatives of the Board of Trade, the Post Office, and local authorities, a main which had been running continuously under a pressure of 10,000 volts was submitted to two engineers, who, with a cold chisel and sledge-hammer, managed, after considerable time and much deliberate labour, to cut through from the outer to the inner conductor while 200 h.p. at that tension was being transmitted through it. They did not feel the slightest shock, although they were standing on a large metal plate making earth. A similar trial has been made with a pickaxe. The mains have also been submitted to a lengthened test, after laying, with 30,000 volts, and have given no trouble. It has thus been forcibly demonstrated that this system of conductors offers every possible guarantee of human safety.

We have referred to the Ferranti mains more particularly, perhaps, in connection with high-tension distribution, but it is apparent that they are also adapted for 100-volt or other low-tension distribution, or where a large mass of copper is required. By their construction the greatest amount of copper conductor is contained in the least space, the cables are buried direct without the use of conduits, and can be carried anywhere and under pavements, where there is no room for conduits. The house connections are rapidly and cheaply made, perfect insulation is obtained, there is no fear of any short-circuiting from water, and no fear of explosions. For three-wire distribution the cable is manufactured with three concentric conductors instead of two, and is laid and jointed exactly as above described.
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