THOMAS HAWKSLEY LECTURE.*

HEAT ENGINES.

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I have chosen Heat-Engines as a subject for this Lecture because my principal work has been connected with them, and also because Thomas Hawksley's activities were largely concerned with pumping engines, which were amongst the very first application of heat engines, and which until quite recently held the record for fuel economy. The consideration of heat engines, however, covers a very wide field, and I have had some difficulty in choosing amongst the numerous possible themes one which would be of general interest to all classes of engineers, and would enable me to avoid matters dealt with by specialists in this subject. A purely historical account of the progress made with the different types of heat engines would not have much merit, but I thought that I might combine with such an account a statement of some of the reasons which have led to the various changes, some of which have come about gradually and others more or less suddenly. I have, therefore, prepared a number of diagrams which show, in a general manner, the progress made in various heat-engines of the steam, gas, and oil types. Certain characteristics have been shown, such as power (i.h p., b.h.p. or kw.) speed (r.p.m.) economy, weight and power per square foot of floor space, but none of the diagrams comprise all these characteristics.

Owing to the difficulty experienced in getting full and reliable data, these diagrams do not pretend to any great accuracy, but the

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* *First* Thomas Hawksley *Lecture*, by E. B. Ellington, Proc. I.Mech.E., 1913, page 1215. *Second Lecture*, by W. B. Bryan, 1914, page 811. *Third Lecture*, by Dugald Clerk, D.Sc., F.R.S., 1915, page 591. *Fourth Lecture*, by Harry E. Jones, 1916, page 631.

approximation is sufficient to show the general trend of the changes. As regards power, that of the largest engine of each period has been plotted, and as regards economy the best results. Before considering these various diagrams, some general remarks will be made descriptive of the causes which have produced changes in the power, in the speed, and in the improvement of fuel consumption.

Power.—The change in power has generally been an increase being brought about by an increase in requirements, as, for example, in the case of marine engines, pumping engines, textile mills, rolling mills, locomotives, or by the introduction of new requirements, such as the driving of electric generators, motor-cars or aeroplanes. In some cases, however, a decline has taken place in the power of some particular type, owing to the introduction of another type better able to cope with the requirements, for example, the reduction in power of reciprocating engines for driving dynamos, owing to the introduction of steam-turbines.

Speed.—The desire to increase speed is due to the fact that a smaller, and in many cases cheaper, engine can be built, but this tendency is checked because, as a rule, at any rate in the case of reciprocating engines, mechanical difficulties increase rapidly with speed and often the fuel economy is impaired. For some purposes high revolutions are necessary, as in the case of motor-car and aeroplane engines. In the case of mill-engines, for example, high revolutions are unnecessary and even undesirable, and for this reason steam-turbines could not be introduced into mills until, in 1907, speed reduction-gear was made with the accuracy and efficiency that is now possible. The advantage of the direct connexion of a dynamo to its engine was a principal cause in increasing the speed of steam-engines.

Economy.—In its true sense, the economy of a heat engine includes many factors beyond the cost in fuel consumption, such as interest on capital expenditure, both for the plant and for the building in which it is placed, repairs and maintenance, cost of attendance, lubrication and such like. In this Lecture, however, only the fuel consumption will be dealt with, and the unit of measurement adopted in the various diagrams follows generally the prevailing custom for such engines. When, however, a comparison is made between steam, gas, and oil engines, the only true and reliable unit is one based on the heat used per unit of power, such as "B.Th.U. per B.H.P.-hour," and this unit has been adopted for such comparisons.

In the case of steam-engines the prevailing commercial custom is to state the number of lb. of steam per i.h.p., per b.h.p. or per kw.-hour. This custom leads to serious error in the case of engines running with highly superheated steam, and is contrary to the recommendation of the Committee on Engine and Boiler Trials of the Institution of Civil Engineers. This point was originally referred to in the preliminary report of the Thermal Efficiency Committee of the Institution of Civil Engineers, dated 12th April, 1897, one of the paragraphs reading as follows:—

"That the statement of the economy of a steam-engine in terms of feed-water per i.h.p. per hour is undesirable."

The point was further considered in the report of the Committee on Steam-Engines and Boiler Trials, and it was stated that "pounds of steam per i.h.p. hour does not give a true criterion of the economy of a steam-engine because the thermal units required to evaporate each pound of steam will vary with the boiler pressure, whether the steam is saturated or superheated, and also with the back pressure." This decision was confirmed in the Report of the re-appointed Engine and Boiler Committee and the term "Equivalent Feed" was then adopted. This "Equivalent Feed" is calculated by the formula:—

$$\text{Equivalent feed} = \frac{\text{lb. of actual feed} \times \text{I.H.P. per hour} \times \text{Heat required per lb. of steam}}{1{,}100^{*}}$$

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* 1,100 is the heat (B.Th.U.) required per lb. of steam when the steam is saturated at 150 lb. per square inch pressure and the vacuum 27 inches.

I would point out that in early days, when boiler pressures were low, it was the custom to state the economy of a boiler as so many pounds of steam produced per pound of coal. Later, when steam pressures were increased it was found that, owing to the greater amount of heat required to produce each pound of steam, the number of pounds of steam per pound of coal was greatly reduced, although the boiler was equally efficient. This obviously was a commercial disadvantage, and accordingly the well-known expression "from and at 212° F." was invented. When, however, superheat was introduced, the fact that one pound of superheated steam required more heat units to produce it than the one pound of saturated steam at the same pressure was not taken into account; it was not commercially advantageous to do so. With low degrees of superheat the error is not very great (for instance, with a superheat of 50° F. it is about 2 per cent.) but with high degrees of superheat it is considerable, as the two following examples will show:—

Example I.—The following are the test figures given for a Rateau Steam-Turbine of 7,200 b.h.p. running at 3,000 r.p.m.:—Steam-pressure 195 lb. per sq. inch gauge. Superheat 200° F. Vacuum 28·7 inches. Steam consumption 8·5 lb. per b.h.p.-hour. From Tables it is found that the heat required per lb. of steam under the above conditions is 1,240 B.Th.U. Hence the "equivalent feed" per b.h.p. is

$$8{\cdot}5 \times \frac{1{,}240}{1{,}100} = 9{\cdot}6 \text{ lb. per hour,}$$

so that the error is 11·5 per cent.

Example II.—Recently it has been suggested to withdraw the steam from a turbine about half way down the expansion and superheat it again. The thermodynamic effect of this process gives some theoretical gain, but practically there is no heat economy; if expressed in pounds of feed, however, an enormous apparent economy is shown. In a case I have worked out in which the steam was initially highly superheated and re-superheated to the same temperature, the feed-water was 9·0 lb. per kw.-hour, whereas the equivalent feed was 12·5 lb. per kw.-hour, so that the error is 28 per cent. This steam consumption is equivalent to 1·5 lb. coal. It is quite obvious, therefore, that the heat economy of steam-engines should not be quoted in terms of actual feed but in terms of equivalent feed or, preferably, by the number of B.Th.U. required to produce one b.h.p.-hour.

In the case of steam-engines, the improvement in steam-consumption over a period of years is due principally to increase of pressure, to the adoption of superheat and of better vacuum, and to a certain extent to the increase of power of each unit; a great deal is also due to improved knowledge and better manufacture.

Increase of Pressure.—Except in the case of locomotives, steam-pressures were very low during the first half of last century, and did not even exceed 50 lb. per square inch until 1868. As long ago as 1854 the economical benefits due to the adoption of the principle of expanding the steam in more than one cylinder was realized, and a compound engine was actually tried; it failed in practice because the steam pressure then available—that is, 30 lb. per square inch—was insufficient. When a considerable increase in pressure took place in 1868, expanding in two cylinders (compounding) produced a marked improvement in steam economy. With a further increase in pressure, expanding in three or even in four cylinders (tripling and quadrupling) was adopted with advantage. To-day, pressures of 180 to 240 lb. per square inch are common.

Vacuum.—Originally what would now be called a very bad vacuum was deemed sufficient, and it has always been accepted that for reciprocating engines a vacuum of about 25 to 26 inches is the best, the reasons being that a reciprocating engine cannot make use of steam at a higher vacuum owing to the very great increase in volume requiring enormous low-pressure cylinders, and further, there is a heat loss due to the reduction in the temperature of the feed. It is quite otherwise with steam-turbines, owing to the fact that a steam-turbine uses steam in the form of velocity, or rather velocity energy, and, therefore, can deal with large volumes quite readily, and it is only when vacua of 29 inches and over are reached that the volume of the steam becomes somewhat unmanageable. The result of this change in vacuum requirements has led to the invention and adoption of numerous new kinds of air-pumps and to great improvements in condensers.

Superheated Steam.—Comparatively recently the use of highly superheated steam has come into general use, and great improvement in fuel economy has been effected thereby. Superheated steam was originally introduced in the year 1828 by Trevithick, and gave remarkably economical results with pumping engines. It was abandoned probably owing to difficulties in regulating the temperatures. Hirn in Alsace was the first to discover the real cause of the advantage of superheating, and he did much pioneer work in this direction in 1855, and since that time the use of superheated steam has been firmly established in Alsatian mills.

Messrs. Humphrys and Tennant applied superheat to the P. & O. s.s. "Ceylon," and reduced the fuel consumption per voyage from 1,500 to 1,100 tons of coal. In 1864 *The Engineer* records that at that time 30 ships used superheated steam; nevertheless, after many years' extended use on board ship, superheat disappeared owing to difficulties with the lubricating oils then available. In 1893 the call for greater economy caused the re-introduction of superheating, and, as hydro-carbon oils had then become available, lubricating difficulties disappeared. At first only moderate degrees of superheat were used, but to-day a high degree is common for all important types of steam-engines. It is interesting to note that our President, Mr. Michael Longridge, stated as far back as 1896 that 600° F. of superheat might be used with real benefit.

Internal-Combustion Engines.—The heat economy of gas and oil engines is considerably greater than that of steam-engines, because a greater range of temperature is available by the use of an explosive mixture produced from gas or oil.

Extravagant ideas of economy were entertained in the early days of gas-engines because the Carnot cycle of the perfect heat-engine was assumed to be possible with a gas-engine. It is easy to show that the thermal efficiency of the Carnot cycle is of the order of 80 per cent. with the large range of temperatures available, which is about double the *theoretical* thermal efficiency of a modern gas-engine. The thermal efficiency of a gas-engine increases with the pressure to which the explosive charge is compressed, as was pointed out in 1861 by M. Million, and also by Beau de Rochas in 1862. In the early days, however, the economical advantage due to high compression of the charge could not be realized, because the then somewhat crude methods of firing led to pre-ignition, even with low compression.

The relation between economy and compression has been fully dealt with in many Papers and in discussions, and the result may be summed up in Table I, which gives the thermal efficiency for theoretical and practical gas-engines for various ratios of

TABLE I.

Gas-Engines: Theoretical Thermal Efficiencies.

Compression Ratio.	Air Standard.	Gas Standard.	Actual Thermal Efficiencies obtained.
2	0·242	0·200	0·12
3	0·356	0·275	0·20
4	0·426	0·335	0·27
5	0·475	0·384	0·33
6	0·512	0·417	0·38
7	0·541	0·445	0·40
8	0·565	0·470	—
9	0·585	0·490	—
10	0·602	0·508	—

compression, as well as the thermal efficiency of the "air-standard." A matter which is frequently misunderstood is that the size of a gas-engine cylinder to develop a given horse-power depends only to a small extent on the calorific value of the gas. The reason is the simple one, that the higher the calorific value, the greater amount of air is required for combustion, thus introducing a proportionately larger amount of nitrogen from the air and consequently the calorific value per cubic foot of the explosive mixture is nearly constant whatever the gas may be, and is of the order of 45 to 50 B.Th.U. per cubic foot to obtain the maximum economical results.

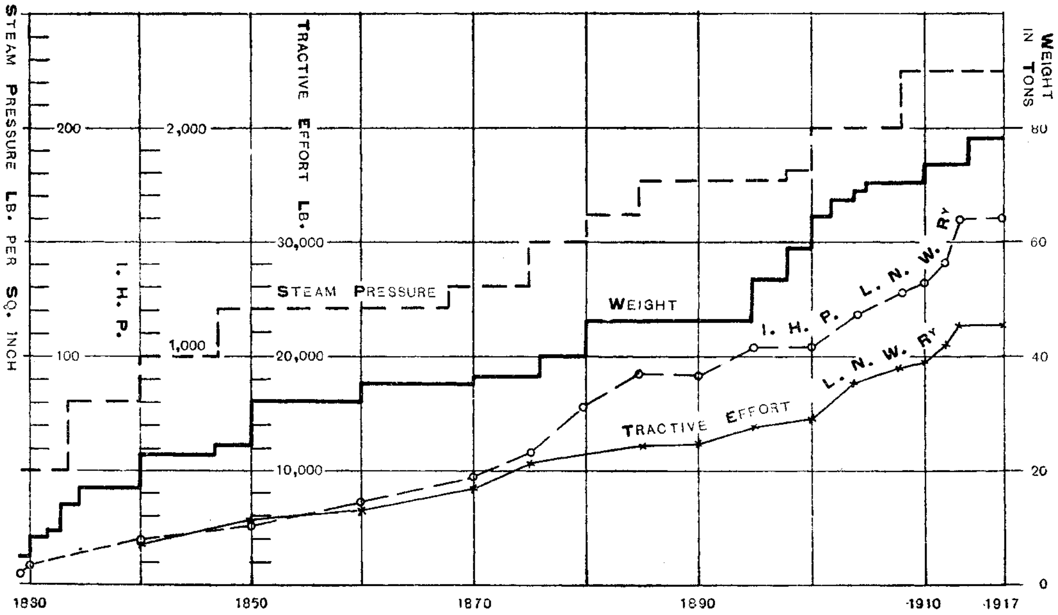
To avoid misconception, it is necessary to state that for the purposes of this Lecture two meanings are attached to the expression "the power of a single engine." The first applies only to steam-engines, and, in the case of reciprocating engines, is the power of an engine obtained by the expansion of a single flow of steam, working in one or in succession in two or more cylinders, or in that of steam-turbines in one or in succession in two casings.

The second applies principally to internal combustion-engines but also to some steam-engines, and is the power of an engine obtained from one or more separate and independent cylinders working on the same crankshaft.

The various diagrams that have been prepared will now be considered.

British Locomotives.—In Fig. 1 the size of British passenger locomotives is indicated by their weight in working order, but excluding the weight of the tender. A stepped diagram has been adopted in this case because, by means of information kindly sent to me by several locomotive superintendents and locomotive engine-builders, I have been able to ascertain with a fair amount of accuracy the weight of the largest engine running during any period. The diagram begins in 1829 with the "Rocket," weighing 4½ tons. The increase in weight was fairly rapid up to 1850, after which there were several pauses up to 1876, when the weight had reached 40 tons. In 1880 there was an increase in speed and in

FIG. 1.—*Heaviest Passenger Locomotives running in Great Britain.*



weight of trains, and the effect is noticeable on the diagram. There was a further long pause up to 1895, after which the increase was rapid up to the present time. During the period from 1876 to 1914 the weight has been doubled, namely, to very nearly 80 tons, and this appears to be the maximum size possible for passenger locomotives (with tenders) in Great Britain owing to the permissible axle-loads and the loading gauge. In this Country, goods and tank locomotives considerably heavier than the passenger locomotives shown are used, and, moreover, much heavier locomotives of all types are built for use abroad and in the Colonies.

It does not seem improbable that more powerful and, therefore, heavier locomotives will eventually be required in Great Britain, and if so it would appear that apart from electric locomotives a new type will be needed, and I venture to think that the Garratt may be the one to follow, Fig. 2, Plate 11. One of the difficulties of the present design is due to the fact that the size of the boiler and of the fire-grate is limited by the distance apart of the wheels. In the Garratt type the boiler and the grate are quite free from the wheels, so that a much greater width of grate can be adopted and, incidentally, the consumption of coal per square foot of grate area can be diminished, which, as is well known, improves the boiler or rather the furnace efficiency.

The upper "stepped" line on the diagram shows the boiler steam-pressure at different periods. The maximum pressure shown is 225 lb. per square inch, which is that used on the Great Western Railway from 1908 up to the present time. On the London and North Western, however, it increased up to 200 lb. per square inch in 1900 with compound engines, but the pressure has since been diminished to 175 lb. per square inch for superheater engines. Incidentally it should be observed that the temperature of the steam on the Great Western is 557° F., which is less than that used on the London and North Western Railway, namely, 650° F. Thermodynamically there is nothing to choose between these two alternatives, and the question is whether the greater temperature or the greater pressure causes greater wear and tear, a matter which I presume only experience will solve.

The two lower lines show the i.h.p. and the tractive effort respectively, and have been plotted from data kindly supplied to me by Mr. C. J. B. Cooke, the Locomotive Superintendent of the London and North Western Railway. The maximum i.h.p. shown is 1600 which may be compared with 2,200 i.h.p. obtained in France with the "Baltic" locomotives on the Northern Railway and with 3,000 h.p. with electric locomotives. I have not attempted to show any coal-consumption line, owing to the difficulties I have found in obtaining reliable data which I could use for comparison with other heat-engines. For railway purposes the coal consumption is reckoned as so many pounds per train-mile or per ton-mile, and there is no factor of conversion to ascertain the pounds of coal per i.h.p.-hour. Isolated tests appear to show that in 1884 the coal per b.h.p. was about 3·6 lb. per hour and that to-day, with superheated-engines, it is under 2 lb.

Attempts to improve the coal consumption by expanding the steam in two cylinders in succession was suggested as early as 1847, and various attempts were made at intervals up to 1876, when Anatole Mallet began his well-known researches on the Bayonne and Bearne Railway. In 1878 Mr. Webb took the matter up in this country and was followed by Worsdell and others. Locomotive engineers in all countries have vied with each other to produce the best compound locomotives. Nevertheless, diverging views have been and are still expressed as to the balance of advantages obtained by compounding. As a contrast the unanimous opinion as to the economical advantages of using superheated steam is very remarkable, although it is only comparatively recently that practical effect was given to the suggestion; for instance, the first superheater locomotive on the Lancashire and Yorkshire Railway was tried in 1906, and on the Great Western Railway and the London and North Western Railway superheater engines were first adopted in 1910. To-day new large locomotives are all being fitted with superheaters, and old locomotives are being converted in large numbers.

In general, it would appear that compounding has been more successful abroad than in this country, and I offer as a suggestion that this may be due to the fact that abroad outside cylinders are in general use, leading to greater initial condensing than with inside cylinders, which are kept warm; the gain by compounding would, therefore, be accentuated. In a locomotive cylinder the range of temperature is about one-half that in a condensing engine cylinder having the same initial steam-pressure, so that the gain cannot in any case be large.

Quite recently a further coal economy has been realized by heating the feed-water, as was done with success by Trevithick in 1912, and the system has also been adopted in the U.S.A., with the larger "Mallet" engines, which are also fitted with an economiser, but there probably would be difficulties in applying either or both of these improvements in this country, owing to the added weight.

American Locomotives.—Three lines are shown in Fig. 3 for American locomotives, corresponding to the weight of the largest passenger, freight, and "Mallets" respectively, and for comparison the largest British passenger locomotives are also shown, taken from the previous diagram. Up to 1895 British and American passenger locomotives were nearly of the same weight, but after that time the latter increased more rapidly and they are now double the weight. The increase in freight locomotives since 1912 is noticeable and is due to the practice of running very long and heavy freight trains.

"Mallet" articulated locomotives, weighing 152 tons, were introduced in 1903 for "pusher" service, because in certain districts of the Rocky Mountains trains were so long and heavy that they required in some cases as much as five of the then freight locomotives. They were, however, regarded as "monstrous" locomotives; nevertheless, since then, as shown on the diagram, a great increase in their weight has taken place. The largest "Mallet" weighs 410 tons, and has a tractive effort of 160,000 lb. and can draw 251 freight cars, the total weight of the train being 17,912 tons at a speed of 14 miles per hour.* According to a discussion before the American Society of Mechanical Engineers,

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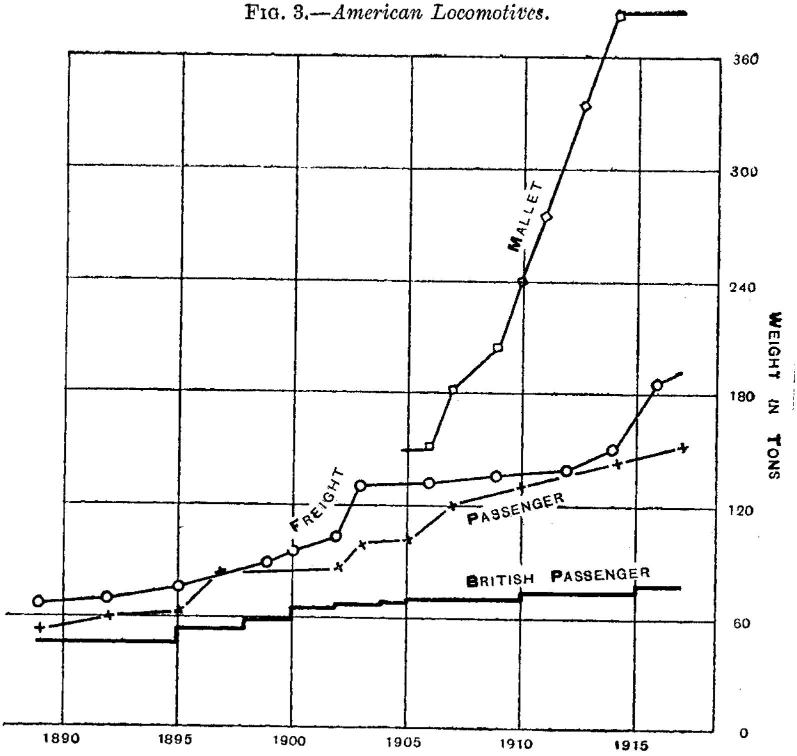
* Report of the Sub-Committee on Railroads. Trans. A.S.M.E.

it may be possible to increase further the power of such engines and obtain a tractive effort of 300,000 lb., which is nine times greater than the tractive effort of the most powerful existing Great Western Railway goods locomotive.

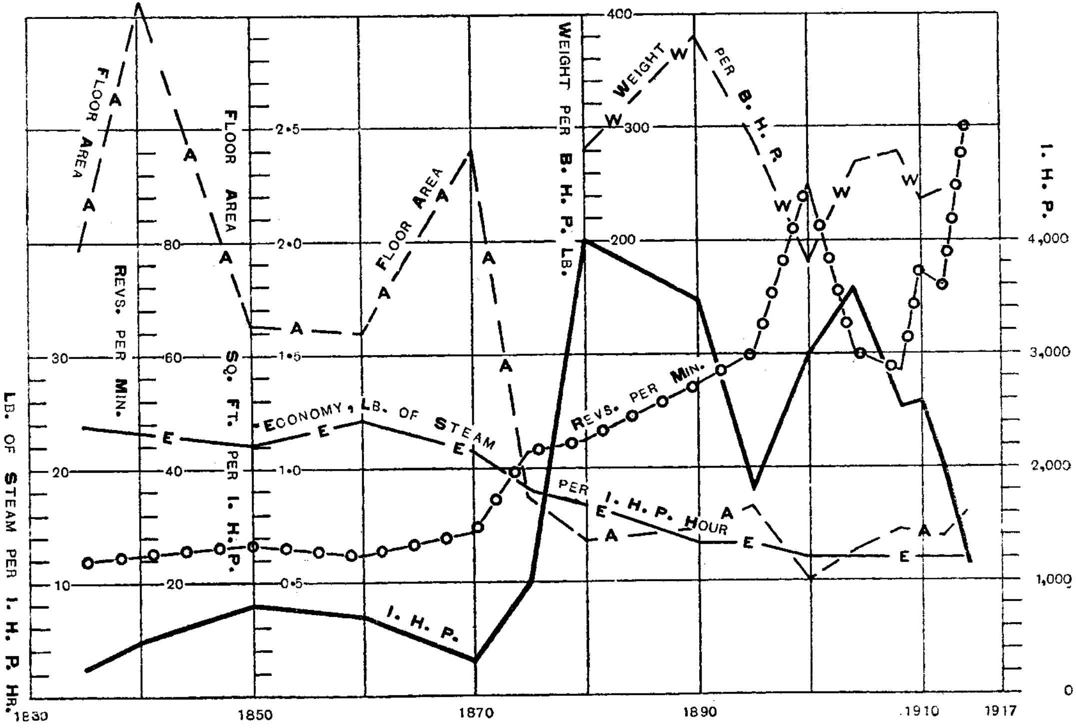
Fig. 3.—*American Locomotives.*



As a contrast, it may be stated that the first "Mallet" articulated locomotive was built in France by Anatole Mallet in 1887 for negotiating the sharp curves on a Decauville 60 centimeter gauge and weighed about three tons.

The "Stourbridge Lion," Fig. 4, Plate 11, belonging to the Delaware and Hudson Canal Company, was the first locomotive placed on rails in America and started in 1829. In 1827 the

Fig. 5.—*Textile Mill Steam-Engines.* (Messrs. Hick, Hargreaves and Co.)



Company decided to have three locomotives built in England, and in 1828 John B. Jervis arrived in England and ordered the "Stourbridge Lion" from Foster Rastrick. Two other locomotives were ordered at the same time from Robert Stephenson and Company and were identical with the "Rocket," and if they had been ready by the time promised they would have anticipated the performance of the "Rocket" in England.

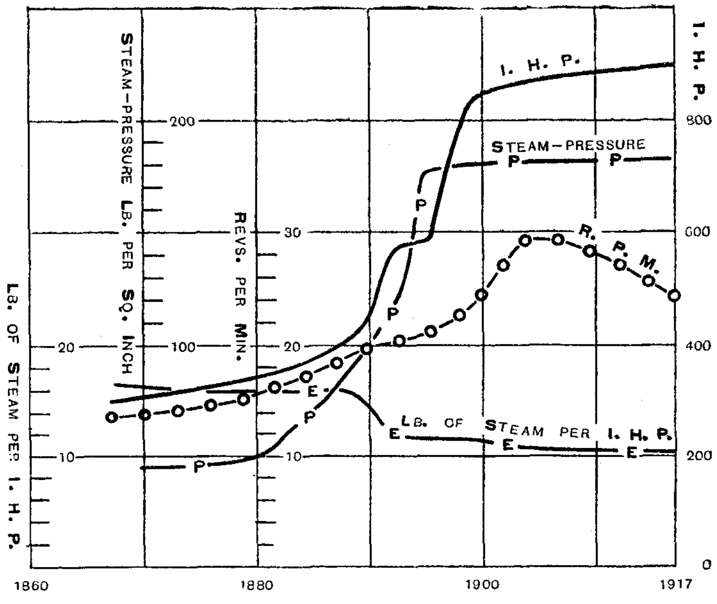
Textile Mills.—The data for this diagram, Fig. 5, were kindly supplied to me by Mr. Richardson of Messrs. Hick, Hargreaves and Co., and give the largest mill-engines built by that firm at the dates plotted. Up to 1860 the record refers to beam-engines, which accounts for the low speed and the large floor-space occupied. The weight of these beam-engines was not stated, but undoubtedly it would be much more than that shown for later years for the vertical or horizontal Corliss engines then built. Up to 1875 there was not much change in the size of the engines and then a rapid growth took place, which stopped for a few years, but since 1906 there has been a rapid diminution in size; I have not been able to ascertain the reason.

Pumping Engines.—Pumping engines were dealt with in some detail by Mr. Bryan in the Third Thomas Hawksley Lecture, and it will, therefore, only be necessary to make a few remarks with the object of comparing these engines with the other heat engines described.

The earliest use of steam-engines was for pumping—for example, Savery's engine of 1698 and later the Newcomen engine of 1705. Pumping engines have always been most economical, in a large measure due to good vacuum and to the use of the Cornish cycle. They are also characterized, when direct-connected to the pump, by very low speeds, and consequently they have a long stroke, and large cylinders; even so far back as 1820, 90-inch cylinders were frequently used. The earlier engines for waterworks were of the beam type, but recent engines, such as those built by the Allis Chalmers Company, are either direct or rotary and of the vertical inverted type.

The diagram, Fig. 6, for pumping engines begins in 1868, because I have been unable to obtain reliable data for either power or steam pressures previous to that date, and it will be seen that in point of power they have always been small, and even to-day do not generally reach more than 900 i.h.p., the most usual size being from 500 to 600 i.h.p. Up to 1890 the growth in i.h.p. was fairly uniform but slow. After that date it was rapid until 1900 when it became stationary. Probably the largest pumping plant in existence was designed by Mr. Henry Davey for the Müke Mine, Japan, and consists of four horizontal tandem compound engines working on the same shaft. This plant lifts 9,000 gallons of water per minute against a static head of 900 feet and indicates 2,500 h.p.

FIG. 6.—*Pumping Steam-Engines. Slow-Speed.*



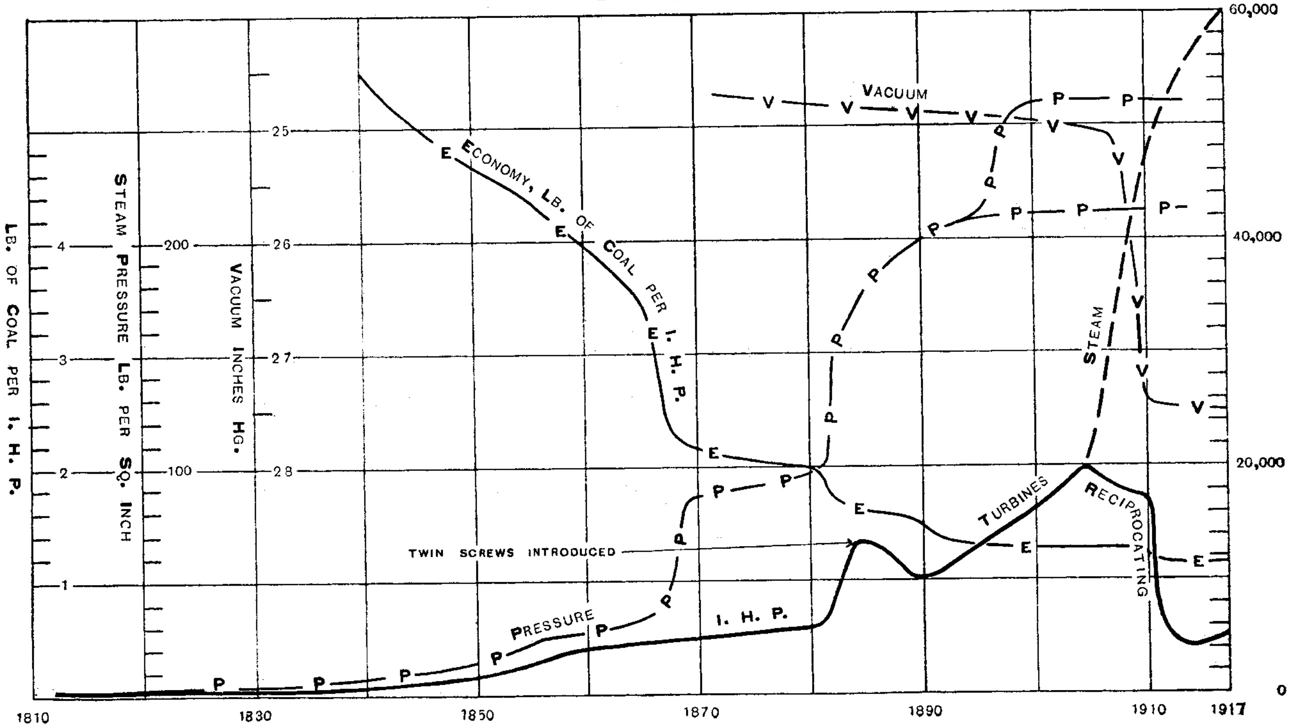
In point of dimensions and weight, however, they are very large. As a comparison the low-pressure cylinder of a modern pumping engine, indicating 800 i.h.p., would be 92 inches in diameter, which would be suitable for the l.p. cylinder of a 14,000 i.h.p. marine engine (warships).

The steam-pressure at the beginning of the nineteenth century was only a few lb. per square inch, and even atmospheric, and it was below 50 lb. per square inch up to 1880 when a rapid increase took place following the practice with other steam-engines. For some time after, however, many important waterworks engines were designed for low pressures. The effect of this increase, required by the use of triple-expansion engines, shows itself in the improved steam consumption which took place at the same date. As regards economy, the diagram shows that in 1868 17 lb. of steam were required per i.h.p., but in 1895 it was 12 lb., showing a great improvement. Between 1865 and 1884 there was very little improvement; then compounding and tripling had a great effect, and recently a further improvement has taken place due to the use of superheated steam.

The Louisville Leavitt pumping engine, erected in 1890, attracted attention at that time, not only because it was the most economical pumping engine, but also because a very complete trial of this engine was made. The data were used in the introductory note to the report of the Thermal Efficiency Committee of the Institution of Civil Engineers to construct a diagram showing the heat flow in a steam plant.

Marine Reciprocating Engines.—This diagram, Fig. 7 (page 720), begins in 1812 with the engines of "Fulton I," which was the first war vessel fitted with a steam-engine. The increase of power of marine engines was slow for many years, but from 1850 to 1860 it was more rapid. A compound engine was put into the "Brandon" in 1854, but, owing to the insufficient steam-pressure available at that time, no economical advantage was obtained, and it was only after 1868 that compounding really came into general use owing to the greater boiler pressure then possible, because

Fig. 7.—*Marine Reciprocating Steam-Engines.*



old prejudices were given up and better means of manufacture were available.

In 1881, when triple engines were first built, a sudden increase in size took place, culminating in 1884 in an engine of 14,000 i.h.p., which is the largest engine put into a single-screw ship. After that date twin screws, originally suggested by Sir Wm. White in 1877, were introduced and consequently for a short time the individual engine units built were smaller, as is indicated by the hump on the curve. The total h.p. in the ship was, however, greater than previously, namely, double that shown.

In 1890 a comparatively rapid increase took place, reaching in 1904 to a size of 20,000 i.h.p. per single engine or 40,000 h.p. in a ship with twin screws, but at this time steam-turbines for ship propulsion had reached the same power, and further increases in reciprocating engines ceased and a diminution began; and to-day the largest engine of that type built for marine work is about 4,000 i.h.p., a size which is likely to diminish further owing to the introduction of geared steam-turbines, which are now being used even for cargo boats.

As regards economy, it has been difficult to obtain information prior to 1840, when the best record was about 5½ lb. of coal per i.h.p., and the coal consumption then improved slowly until 1868, when a sudden improvement took place owing to the introduction of compounding, and there were further sudden improvements in 1881 due to the use of triple engines, in 1890 due to quadruple engines, and in 1910 to increase in vacuum. This last improvement in economy is of great interest and was due to the discovery by Mr. D. B. Morison that the feed could be heated by means of the steam exhausted from the auxiliaries and especially from the evaporator, as described by him in a Paper read before the North East Coast Institution of Engineers and Shipbuilders in 1910. Up to that time the vacuum was kept at 25 inches, because, with a lower vacuum in the condenser, the feed-water was cold and the coal consumption was thereby increased.

The coal consumptions given are the best recorded for merchant steamers, and these engines could be designed for a definite horse-power so that the ratio of cylinders could be adjusted to get the best economical result. In the case of engines for warships, however, a wide range of power has to be allowed for varying from that required for cruising to the maximum needed for full speed, and under these conditions the same economy cannot be expected; and as a fact it is from 25 per cent. to 40 per cent. worse than that for merchant vessels.

The steam-pressure from 1812 to 1830 was about 3 lb. per square inch, and even up to 1850 it only reached 15 lb. for condensing engines, although at that time from 30 to 40 lb. was used for non-condensing marine engines. It is curious to note that Crampton, of locomotive fame, in a discussion before this Institution in 1872, said that the 80–100 lb. per square inch steam-pressure then in use would be found unnecessary, and that they would go back to 40 lb. owing to the difficulty in making sufficiently thick boiler plates.

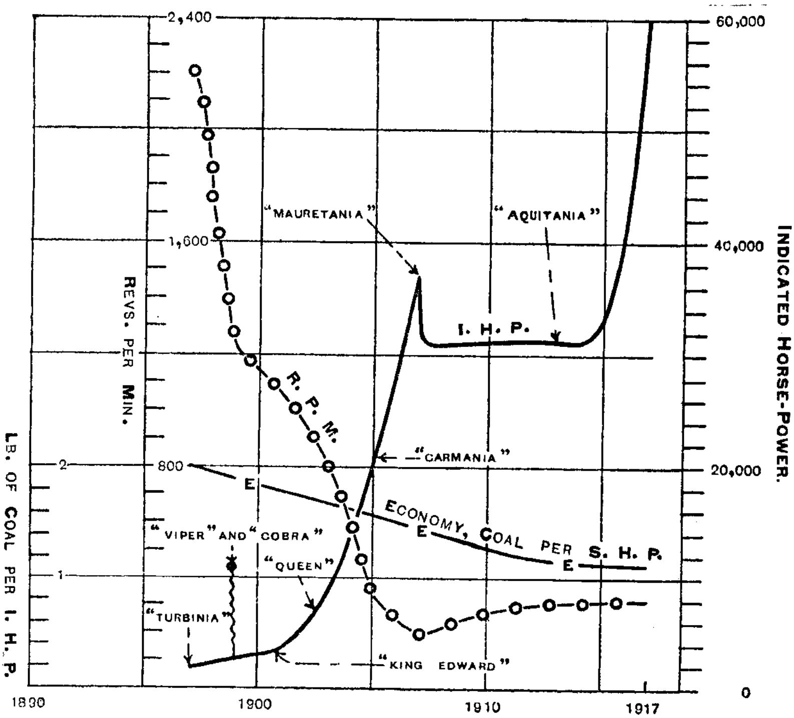
Subsequently to 1867 the steam-pressure line shows sudden and gradual increases. The sudden increases coincide with the introduction of compounding, tripling, and quadrupling respectively. At present the usual pressure is from 180 to 200 lb. per square inch, but in many ships fitted with water-tube boilers higher pressures are used up to 260 lb. and even more.

Marine Steam-Turbines.—The application of the steam-turbine to marine propulsion began in 1897 with the "Turbinia," Fig. 8, with which various combinations of engines and propellers were tried, resulting finally in a turbine of 2,300 i.h.p. which gave a speed of 34½ knots when running at 2,800 r.p.m. At that time the largest land turbine was 1,100 i.h.p. running at 2,500 r.p.m.

In 1898 the torpedo destroyers "Viper" and "Cobra" were fitted with turbines of 11,000 i.h.p.; they are shown on the diagram. The "King Edward," with 3,500 i.h.p., was the first commercial ship fitted with turbines, and is shown in 1901, followed by the "Queen" in 1903. After this the growth was very rapid, culminating in the "Mauretania" and "Lusitania," with 35,000 i.h.p. per unit or 70,000 in the ship.

The "Turbinia's" propeller speed of 2,800 r.p.m. and that of the "Viper" of 1,200 r.p.m. caused great difficulty due to "cavitation," which led to extensive trials to determine the cause of this action and the best means of remedying it. Cavitation produces a great reduction of propeller efficiency and also corrosion of propeller blades, due to the evolution of oxygen in the vacuum produced by cavitation. In consequence the speed was reduced in succeeding ships, such as the "Amethyst," to 600 r.p.m.

Fig. 8.—*Marine Steam Turbines.*



Although the corrosive effect of cavitation was thus practically annulled, the propeller efficiency was still low, and in consequence in designing the turbines of the "Mauretania." and of the

"Lusitania," the speed was kept down to 187 r.p.m. This necessitated enormous turbines, and the speed was also too low to get the best economical results from the turbine, because the blade speed was too low in respect to the steam speed. This difficulty of propeller speed was solved in connexion with the "Olympic" and "Teutonic" by first passing the steam through two reciprocating engines of the ordinary marine type, each working a propeller and exhausting at atmospheric pressure into one l.p. turbine working a third screw. A moderate r.p.m. could be adopted for this turbine, and good economical results were obtained because the "efficiency ratio"* of the reciprocating engines was greater than that of the corresponding h.p. turbines, which would have had to run at too low a speed.

The obvious best arrangement is to run the turbines at a high speed, and by applying speed-reduction gear run the propeller at its appropriate low speed. For many years the Laval steam-turbine used helical gearing, and for instance reduced a rotor speed of say 10,000 r.p.m. down to 1,000 r.p.m. for the dynamo, but it was only when this form of gearing was improved by Parsons and also by McAlpine in 1911 that it could be used for marine turbines, and it was applied in the first instance by the former to the cross-channel steamer "Hantonia." In this case the turbines ran at 2,000 and 1,400 r.p.m., and the propellers at 310 r.p.m. Both the turbine and the propeller were, therefore, more efficient, resulting in considerable improvement in coal consumption. This system is now being generally adopted, and there are indications that in the future it will become the standard arrangement, using probably a double reduction-gearing instead of a single. In a Paper read before the Institution of Engineers and Shipbuilders in Scotland a few weeks ago, Mr. Alex. Cleghorn stated in effect that the introduction of high superheats and double reduction-gearing

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* The "efficiency ratio" is defined as

$$\frac{\text{Steam consumption of Rankine (ideal) engine.}}{\text{Steam consumption of actual engine,}}$$

$$\text{or } \frac{\text{Thermal efficiency of Rankine engine.}}{\text{Thermal efficiency of actual engine.}}$$

marks an epoch of advance without equal in modern engineering history.

There are other forms of speed reducing gear. One of these is the "Fottinger" hydraulic gear, which, so far as I know, has not been practically applied in this country, but which was fitted to the German pleasure steamer "Princess Louise," a ship notorious by the fact that she was employed to lay mines in the North Sea just before the declaration of war, but was sunk a few days afterwards. There is also the Ljüngstrom electro-mechanical gear, and the electric reduction-gear known as the "Paragon."

Electric Power Reciprocating Engines—Slow Speed.—The diagram, Fig. 9 (page 726), begins in 1890, although previously to that date slow-speed engines of comparatively small size had been largely used for electric lighting. It will be seen that the size, as represented by kilowatt output of the generator, increased rapidly, but this increase took place principally in Germany and in the U.S.A., where the high-speed type of engine did not become popular.

From 1893 to 1903 a lull appears to have occurred according to the data I have been able to obtain, after which the increase became rapid again, reaching a maximum in 1910 in some engines installed at the 74th Street Station of the New York Edison Company.* A rapid diminution in size then took place to about 1,000 kw. owing to the competition of the steam-turbine, and now large slow-speed reciprocating-engines for electric power purposes are practically defunct. The small sizes can still compete with the steam-turbine because the latter is not very economical in small sizes, and the very high speed at which such turbines have to be run is not suitable for direct dynamo driving. The geared turbine will, however, modify this, and it may be anticipated that the size of slow-speed engines for electric power will still further be reduced. The r.p.m. naturally diminishes as the size is increased, but, owing to the substitution of drop-valves for Corliss

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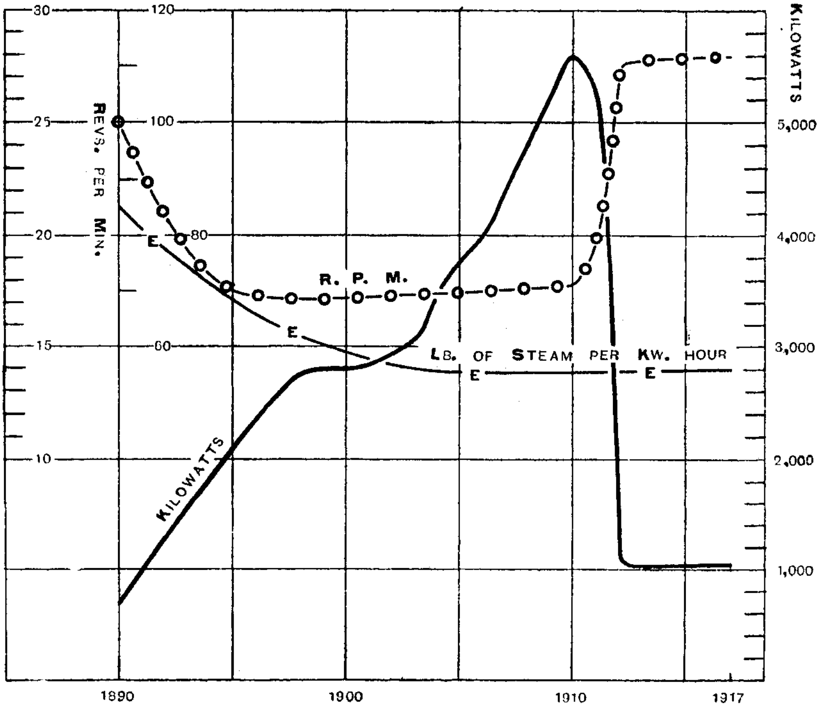
* In Fig. 9 the size of engine shown for 1910 is somewhat too large.

valves, the revolutions for the same i.h.p. is greater now than it was about 10 years ago. The improvement in economy (expressed in terms of "equivalent feed") from 1890 to 1905 is principally due to the use of superheated steam.

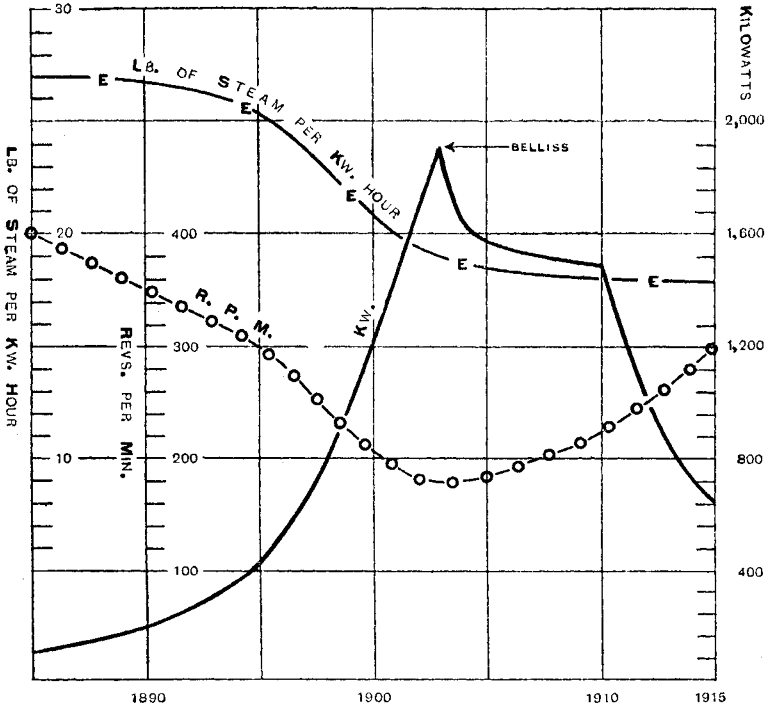
FIG. 9.—*Electric Power. Reciprocating Steam-Engines. Slow Speed.*



Electric Power Reciprocating-Engines—High Speed.—Apart from small installations the high-speed reciprocating-engines for driving dynamos may be said to have made their appearance in 1885 with the Willans central valve-engine, with an output of 80 kw., Fig. 10. At first the growth in size was not rapid, and I remember the late Mr. Thomas Parker saying to me in 1890 that the 200 i.h.p.

Willans engines were splendid, but would it be possible to build them up to 500 i.h.p. That size was reached towards the end of 1892 for electric light, although two Willans engines of nearly 900 i.h.p. had been built and were running early in 1892, just previous to Mr. Willans' death. After this the increase became rapid, reaching a maximum in 1901, when a Willans central valve-engine of 2,500 i.h.p. (1,500 kw. generator output) was exhibited at Paris, and ran every night during the Exposition without a hitch, which is more than can be said of the much larger slow-speed engines, principally of German make.

Fig. 10.—*Electric Power. Reciprocating Steam-Engines. High Speed.*



The Willans engine thus held the field for a long time for direct dynamo driving until, in fact, the double-acting forced lubrication-engine was perfected. It is true that certain double-acting marine-engines for destroyers and cross-channel steamers, and more particularly for locomotives, were able to run at high revolutions per minute, but they only did so for a comparatively short time and the brasses had to be frequently taken up. Such a process would be inadmissible for engines driving dynamos direct at power stations. This difficulty was, however, got over by the introduction of forced lubrication by Messrs. Belliss in 1893, and enabled such engines to run faster than the Willans engine as designed, but this advantage could not at first be made use of, because dynamo-makers were unable at that time to construct the continuous current-machines then in vogue to run at a sufficient speed for the large sizes, and it was even necessary to design a slow-speed Willans engine. The dynamo-makers soon overcame this difficulty, and moreover alternating-current generators began to be required, and thus the double-acting forced-lubrication engine was able to make use of its capability of being able to run faster, and was then built in sizes closely following the Willans engine.

As regards economy, the Willans engine, owing to perfect cylinder drainage, was superior to other high-speed engines so long as saturated steam was used; but the advent of superheat removed this advantage, and finally the Willans engine was discontinued about 1910 after a very good innings.

I would here recall a prophecy I made in 1893, when replying to the discussion on Willans' second Paper on Steam-Engine Trials, read after his death, before the Institution of Civil Engineers.

The following is an abstract from the Proceedings of that Institution (Vol. CXIX):—

> "He (Captain Sankey) believed that Willans' name would remain with them not principally as the designer of the Willans engine, but as the Author of this and other Papers of deep scientific interest, and, he would venture to add, as the discoverer of what he felt would henceforth be known as the 'Willans Law.'"

This prophecy has certainly come true.

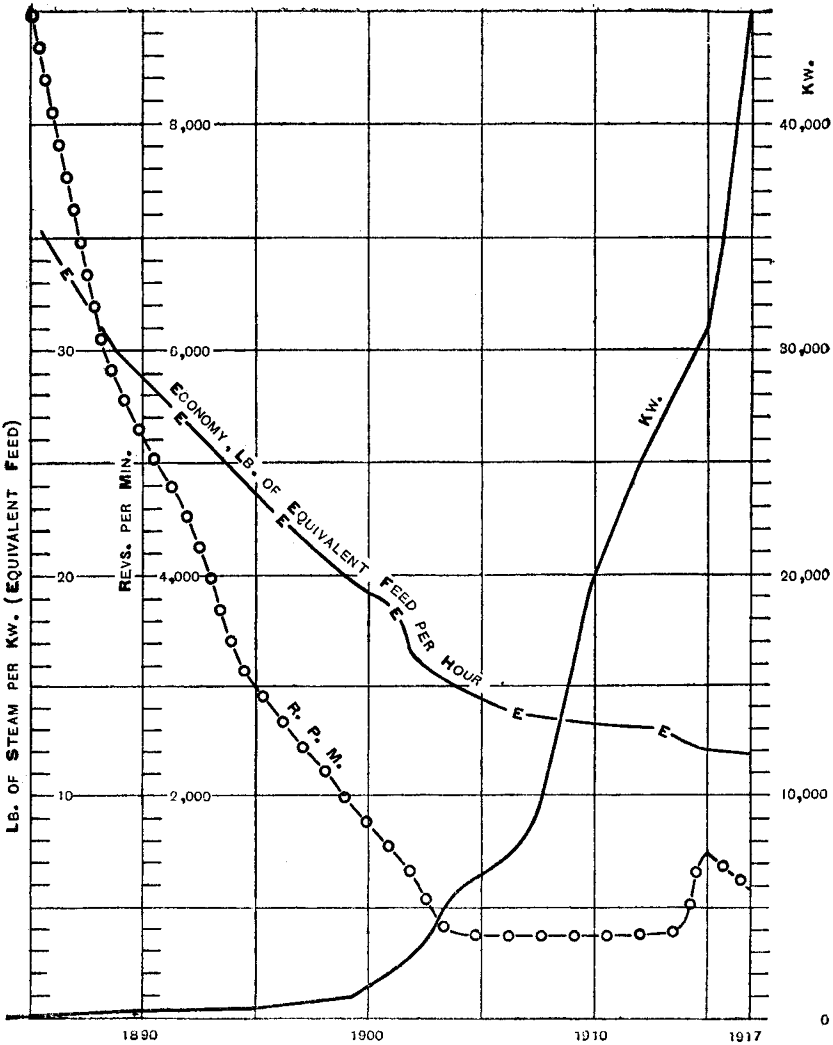
Electric Steam-Turbines.—The Parsons steam-turbine was first introduced in 1884 by a small turbine of 6 kw. running at a speed of 18,000 r.p.m., and its manufacture was begun systematically in 1885. It will be noticed from Fig. 11 (page 730) that the size increased very slowly up to 1898, the reason being that such small turbines were handicapped in the matter of economy as compared with the high-speed and slow-speed engines then in use. During that period, however, the steam consumption was very much reduced, so that in 1898 it had nearly reached that of other engines; moreover, it was then found possible to run the turbines at a much lower speed, and improvements in dynamo design, by the addition of interpoles, and also the introduction of alternating current for electric distribution, allowed of higher speeds for dynamos, so that the speed difficulty disappeared. From that date the increase in size became rapid and continuous, and practically without a pause it has now reached 45,000 kw. in one unit, and it is understood that 75,000, and even 100,000 kw., are being talked of in the United States.

It was early realized that the steam-turbine could make better use of vacuum than a reciprocating engine, but the art of building high-vacuum condensing plant had not developed sufficiently to enable the turbine in the early years to take advantage of this fact until Parsons introduced his Augmentor in 1904. As is well known, the ordinary air-pump is incapable of dealing satisfactorily with vacua over 27½ inches, and the Augmentor enabled an ordinary air-pump to deal with 28 to 29 inches of vacuum, depending on the temperature of the cooling water.

The best steam economy reached in 1900 was 19 lb. of steam per kw.-hour, when the largest unit was 1,250 kw. The effect of the Augmentor was to improve this figure to 16½ lb. per kw.-hour. Since then it has been further improved by the introduction of superheat and by the increase in size of unit to 12 lb. per kw.-hour, "equivalent feed."

The change of turbine speed is interesting. At first it was very high indeed—that is, 18,000 for the early Parsons turbine and Laval turbines. In the latter, the actual turbine speed was reduced by helical gearing to a reasonable speed for driving dynamos. The

FIG. 11.—*Electric Power. Steam-Turbines.*



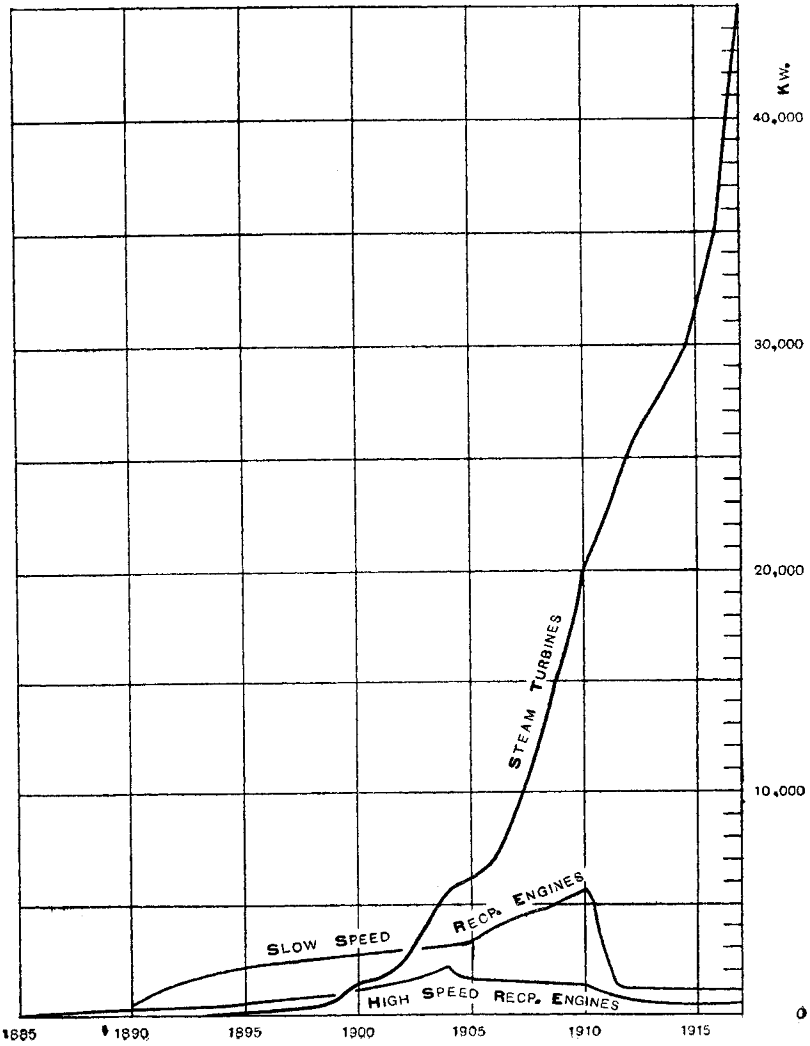
speed-curve shows that the speed in 1885 was 9,200 r.p.m., and that it diminished rapidly up to 1904, when, for the then large units of 5,000 kw., it was as low as 750 r.p.m.—a speed which was necessary, because dynamos could not be built to run at a higher speed for such sizes. The turbine, therefore, had to run at too low a speed for economy. To-day, higher speeds are used for the largest units —in fact, the latest 45,000 kw. units are running at 1,200 revolutions and 35,000 kw. machines at 1,500 revolutions, as shown on Fig. 11, and the speed of 5,000 kw. turbines is often 3,000 r.p.m.

It is to be observed that, when driving alternators, certain speeds are necessary in order to conform to the frequency of the alternations. These speeds are 750, 1,000, 1,500, and 3,000 for a frequency of 50 cycles per second, and 600, 800, 1,200, and 2,400 for 40 cycles.

A Comparison of High-Speed and Slow-Speed Reciprocating Engines with Steam-Turbines.—This diagram, Fig. 12 (page 732), compares the growth of power of the three important types of steam prime-movers used for electric power. It will be seen that the slow-speed engines were at all times of greater power than the high-speed engines. It will also be noticed that the steam-turbine was smaller than either up to 1899 when it crossed the high-speed line, and in 1903, when it crossed the slow-speed line. The steam-turbines then grew at a very rapid rate, whereas of recent years both the high-speed and the slow-speed engines have materially diminished in size.

Blowing Engines.—Reciprocating steam-engines are largely used in connexion with blast-furnaces for compressing air to 5 or 6 lb. per square inch pressure. Frequently, if not generally, they are simple non-condensing vertical inverted steam-engines and of a very uneconomical type, but of late years use has been made of the exhaust steam, which is at atmospheric pressure, to run what is known as an exhaust turbine. This system was introduced by Rateau in 1903, and has had a marked economical success. Owing to the intermittent work of the blowing engines, the steam has to be accumulated in various ways, either by heating water in a species of boiler, as was done by Rateau or more recently by

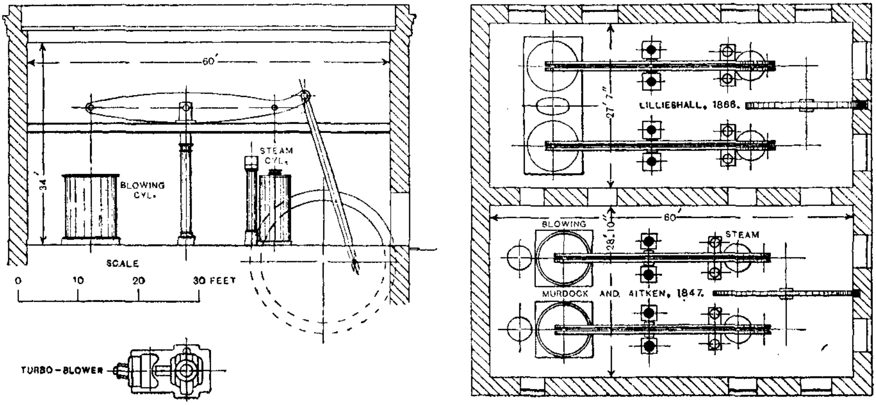
Fig. 12.—*Electric Power Engines. Comparison of High-Speed and Slow-Speed Reciprocating Steam-Engines and Steam-Turbines.*



storing it in a vessel acting on the same principle as a gasometer. The steam-turbines are also used connected direct to a turbine blowing engine, and gas-engines are also used for the same purpose.

An interesting comparison of an old beam engine and a steam-turbine is shown in Fig. 13, which gives the relative floor space occupied. Two of the old beam engines were built in 1847 by Murdock and Aitken, and the other two in 1866 by the Lilleshall Engineering Company, and are a very fine piece of work. Each engine has a capacity of 13,000 cubic feet of free air and compresses up to 4½ lb. per square inch when running at 13 r.p.m. The steam-pressure is 40 lb. per square inch and the boilers are fired by blast-furnace gas (in the old days they were fired with coal). The i.h.p. developed in each cylinder is about 400. The turbo-generator, which will replace these old engines, and is now being erected, has a capacity of 25,000 cubic feet of free air when running at 3,350 r.p.m., compresses up to 6 lb. per square inch and requires 880 h.p. to drive it. The power is obtained by a direct connected

Fig. 13.—*Space occupied by Beam Engine and Turbo-Blower.*



Capacity of Turbo-Blower
6 lb. pressure, 26,000 cub. ft. free air.

Capacity of each of these Four Engines
5 lb. pressure, 12,000 cub. ft. free air.

Rateau turbine, taking steam at a pressure of 150 lb. per square inch obtained from Babcock and Wilcox boilers, fired by blast-furnace gas. This new blower will effect a considerable saving in blast-furnace gas, so that it will be possible to run in addition a 750 kw. steam-generator for supplying electricity to the works and for War Office purposes.

An important field for the steam-turbine is the direct-driving of turbo-compressors, and they are very suitable for this purpose because the turbo-compressor has to be run at a high speed. The largest turbo-compressor in this country, built by Messrs. Fraser and Chalmers, requires 2,290 b.h.p. and it runs at 4,400 r.p.m. Its capacity is 10,000 cubic feet of free air, compressed up to 110 lb. per square inch. Larger sets have, however, been installed at Johannesburg by the A.E.G. Each unit has a capacity of 21,000 cubic feet of free air at 12 lb. absolute pressure (Johannesburg is 5,000 feet above sea-level), compressed up to 107 lb. per square inch gauge and requires 4,000 b.h.p. to drive it.

Rolling-Mill Engines.—I had hoped to make a diagram showing the early growth of power of rolling mill engines, but I was unable to obtain sufficient data. In this type of engine, economy is of secondary consideration, and they are frequently of the three-throw horizontal type simple non-condensing engines without fly-wheels. They work spasmodically just when a section is going through the rolls. The exhaust steam is frequently utilized by means of an exhaust turbine.

Recently some very large rolling-mill engines have been built, as is shown by the following list, and it will be seen that in point of power the last on the list exceeds all other reciprocating steam-engines.

Modern Vertical Rolling-Mill Engines.

Year.		I.H.P.		R.P.M.
1904	..	15,000	..	80
1912	..	20,000	..	,,
1913	..	25,000	..	,,

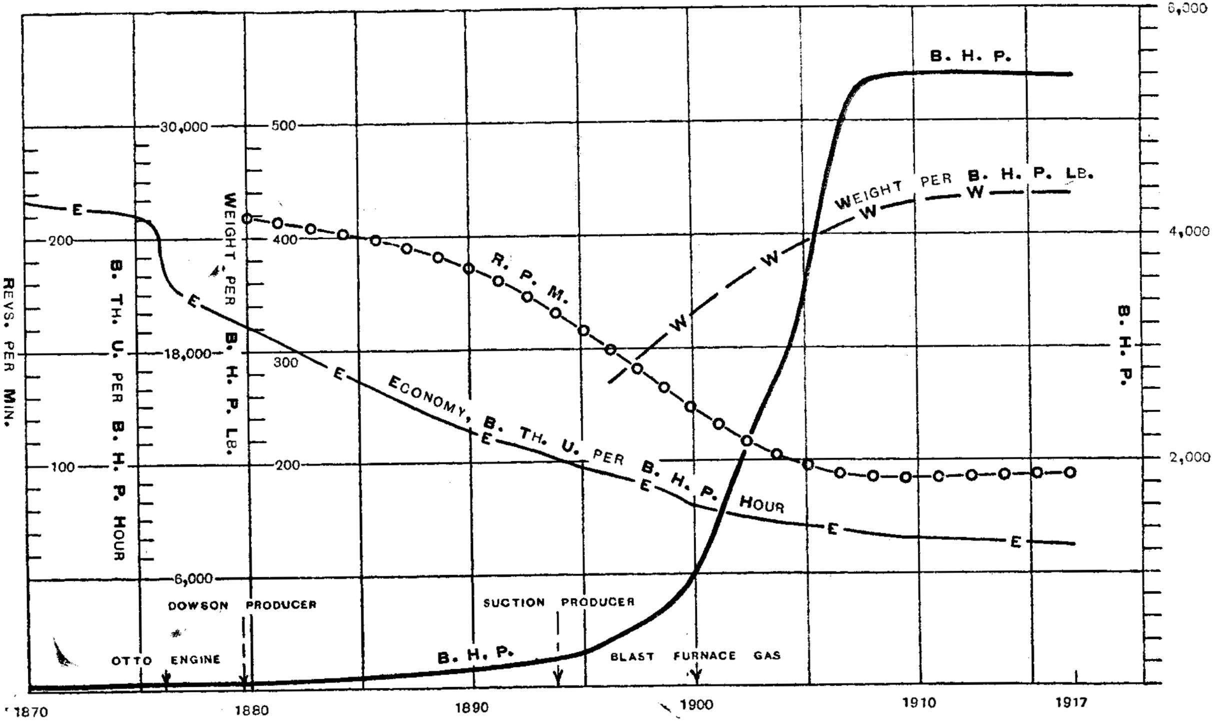
Gas-Engines.—The diagram, Fig. 14 (page 736), begins in 1870, although gas-engines had been in use for some years previously. At this time the largest gas-engine developed merely a few b.h.p. It need only be recalled that the Lenoir gas-engine, using about 100 cubic feet of town-gas per b.h.p., made its appearance in 1860, followed by the engine devised and patented by Dr. Otto in 1876, which worked on a cycle, which was subsequently discovered to be the Beau de Rochas cycle, patented in 1862.

The first engine of the Beau de Rochas type developed only 3 b.h.p., but it must be regarded as epoch making. The development of size was, however, slow, and in 1881 the largest engine developed only 20 b.h.p., and was known as the "King of Gas Engines."

In 1882 a great impetus, especially in the matter of size, was given by the introduction of producer-gas, as up to that date only town-gas had been used. During the period from 1870 to 1897 the gas consumption was much improved, as is seen by the diagram, partly owing to increase in compression and partly owing to the introduction of scavenging in 1881 by Sir Dugald Clerk. The Otto engine caused a notable improvement in economy in 1876, as is clearly indicated on the diagram.

It will be noticed that on the diagram the economy is shown as B.Th.U. per b.h.p.-hour. In 1905 the best economy recorded for a 50 b.h.p. gas-engine (the X engine, tested by the Committee of the Institution of Civil Engineers on Internal-Combustion Engines) was 14·9 cubic feet of town-gas per b.h.p., having a lower calorific value of 561 B.Th.U., corresponding to a heat consumption of 8,500 B.Th.U. per b.h.p.-hour. Not long after, namely, in 1907, an engine using producer-gas was tested by Professor Burstall and, when the ratio of compression was the same as for the X engine, required 50 cubic feet of producer-gas per b.h.p., having a lower calorific value of 170 B.Th.U. per cubic foot corresponding to 8,500 B.Th.U. per b.h.p.-hour. In point of economy, therefore, there is nothing to choose between the two kinds of gas. The rapid improvement in economy, which took place up to 1897, has already been noted, but after that year the improvement continued

Fig. 14.—*Gas-Engines. Slow-Speed.*



slowly, being due to increase in compression and to the general effect of better knowledge in the design of gas-engines.

The first attempt to utilize the suction of the outward charging stroke of the gas-engine to obtain the draught through the producer was made by Bennier in France in 1894, but it was only some years later, in 1903, that the numerous difficulties attending this form of producer were practically overcome. The suction producer has not been instrumental in increasing the size of gas-engines, but it has led to the extended use of gas-engines in various directions in small sizes.

In 1895 Thwaite advocated the use of blast-furnace gas, but the matter was not then taken up seriously in this country, and it was left for the Société Cockerill of Liége to open up this new field, and a very large number of such engines and of large h.p. have been made. Their first engine of 215 b.h.p. was built in 1898, and they exhibited a 600 b.h.p. at the Paris Exhibition in 1901.

Unfortunately many engineers were at that time led to conclude that large gas-engines were a practical possibility, not realizing the difference between blast-furnace and producer-gas. The difficulties due to the high temperature of the explosion and the presence of tar in producer-gas were also not appreciated, and the result was that many manufacturers who undertook the construction of large gas-engines, after losing much money, desisted. Nevertheless, some makers overcame all these difficulties, and a rapid development in size took place, principally in Germany and in America, and in 1907, engines of 5,000 h.p. were built for driving dynamos, and blast-furnace blowing-engines.

It was anticipated at that time that much larger sizes would be built, notwithstanding the enormous cost of such engines, and the large space occupied by them, because of the great economy in fuel, but a check was received through the competition of the steam turbine, which, as already seen from Fig. 11 (page 730), had then reached an output of 8,500 kw. or 12,000 b.h.p., a size which has now been far exceeded.

I have been unable to get reliable information as to the largest gas-engine now being built, but I think probably it does not exceed

5,000 b.h.p. There is, however, a statement in a Paper by Professor H. Hubert, of Liége, in 1915, that an 8,000 b.h.p. gas-engine was in process of construction by the Cockerill Company, of Liége, just prior to the outbreak of war, and that the main shaft of this engine was exhibited at Ghent in 1913.

The diagram refers only to slow-speed gas-engines of the horizontal type, but it should be mentioned that in this country engines of considerable power, namely, 1,000–1,500 b.h.p., and running at 200 r.p.m., have been built, both by the National Company and by the British Westinghouse Company, and give, I understand, satisfactory results.

Oil-Engines.—The different kinds of oil-engines are very numerous, depending on the specific gravity of the oil used, on the degree of compression applied to the explosive mixture, and on the method of ignition. It is notorious that the nomenclature is confused and is badly in want of revision, and it is hoped that the matter will be considered by a Committee of the Institution of Civil Engineers after the war.

In 1912 I prepared a classification of oil-engines for a Lecture I gave at the Royal Society of Arts, and this is reproduced in Table 2 with some modifications. It will be seen that oil-engines may be divided into three groups, namely, light, medium, and high compression, which, owing to the fact that economy improves as the compression is increased, is also a grouping in respect of fuel economy.

The earliest commercial oil-engines, namely, those of Priestman and Hornsby-Ackroyd, introduced in 1888 and 1892, belong to the light compression group. They have been made in large quantities but have never reached large powers, because of the want of fuel economy. The Petter, Robey, and other oil-engines were placed on the market comparatively recently (1910), but have not yet reached large sizes, and they belong to the medium compression group. In my opinion, however, when the present difficulties with hot bulbs have been overcome, this type will be a serious rival to the Diesel engine, which belongs to the third group.

TABLE 2.—*Oil-Engines.*

<table>
<tr><th colspan="4">HEAT ADMISSION AT</th></tr>
<tr><th colspan="2">CONSTANT VOLUME.</th><th>CONSTANT PRESSURE.</th><th>PARTLY CONSTANT VOLUME AND CONSTANT PRESSURE.</th></tr>
<tr><td colspan="2">Explosive mixture is produced by vaporization of the oil either at atmospheric temperature (light oils) or at a higher temperature (heavy oils). Compressed in the cylinder prior to explosion.</td><td colspan="2">Pure air is compressed in the cylinder, and the oil is introduced just before the turn of the stroke, and there is no explosive mixture.</td></tr>
<tr><td colspan="2">Ignition is caused by a hot tube or bulb, or by an electric spark.</td><td>Ignition is caused solely by the temperature of the compressed air.</td><td>Ignition is caused partly by the temperature of compression and partly by the oil striking against a hot surface, or by an electric spark.</td></tr>
<tr><td colspan="2">Compression must be less than the amount at which pre-ignition takes place.</td><td>Compression must be greater (to ensure ignition) than the amount at which the temperature is sufficient to produce ignition.</td><td>Compression unlimited over a considerable range.</td></tr>
<tr><td colspan="2">LOW COMPRESSION.
80 lb. per square inch.</td><td>HIGH COMPRESSION.
500 lb.
per square inch.
Sp. Gr. up to 1·2.</td><td>MEDIUM COMPRESSION.
150 to 250 lb.
per square inch.
Sp. Gr. up to 0·9.</td></tr>
<tr><td>Specific Gravity,
0·68 to 0·72</td><td>0·82</td><td></td><td></td></tr>
<tr><td>< LIGHT OIL ENGINES ></td><td colspan="3">< HEAVY OIL ENGINES. ></td></tr>
</table>

Petrol-Engines.—This is too large a subject to deal with except to refer to one type, which is of exceptional interest at the present moment—aeroplane-engines.

The first aeroplane-engine was driven by steam and the weight was not less than 11 lb. per b.h.p.; it was built by Maxim in 1893. An attempt was made in 1898 in America to build an aeroplane petrol-engine of 12 h.p. to weigh not more than 100 lb., but it gave only 4 b.h.p. After many efforts a five-cylinder rotary-engine was produced in 1901 for the Langley aeroplane, running at

950 r.p.m., giving 52·4 b.h.p. and weighing 2·37 lb. per b.h.p. (based on the "stripped" weight).

No further great progress was made until 1907, but then a rapid increase took place, and now there are many types of petrol aeroplane-engines of from 300 to 500 b.h.p., both with fixed cylinders, vertical and inclined, and also with rotating cylinders.

The following are particulars of a recent engine:—

18 cylinders; b.h.p., 410; weight, including propeller boss, 1·95 lb. per b.h.p.

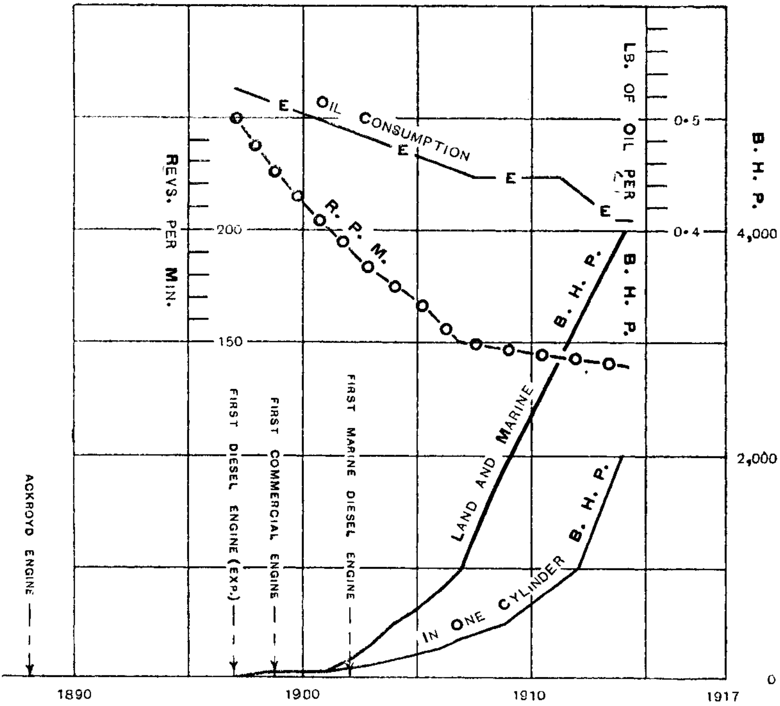
Owing to war restrictions, it is not possible to give any further detailed particulars.

Diesel Engines.—Fig. 15 shows the increase in power of Diesel engines in b.h.p. dating from 1897 up to 1914, both for land and marine purposes as given to me by Messrs. Sulzer Bros. Beyond this date I have not been able to obtain reliable information. The lower line gives the b.h.p. for one cylinder, and it will be noticed that in 1914 as much as 2,000 b.h.p. was thus obtained. The cylinder of this experimental engine had a diameter of 40 inches. If four such cylinders were placed on one crankshaft, 8,000 b.h.p. would be developed by one engine in accordance with the definition given at the beginning; so far this has not been done. This particular cylinder was that of an experimental engine of which Fig. 16, Plate 11, is a photograph. It is usual in all engines for the total pressure on the cylinder-head to be transmitted to the crankshaft-bearings through the cylinder walls and the engine framing, but in this case the total pressure was so great, namely 300 tons, that a special construction was adopted and the cylinder-head was directly connected to the bearing seatings by means of four through bolts. The inset, Fig. 16, shows this construction diagrammatically.

The revolutions per minute naturally became less as the power per unit increased, as shown in Fig. 15. The consumption has improved slightly owing to increase in size and to the better arrangement for atomizing the fuel.

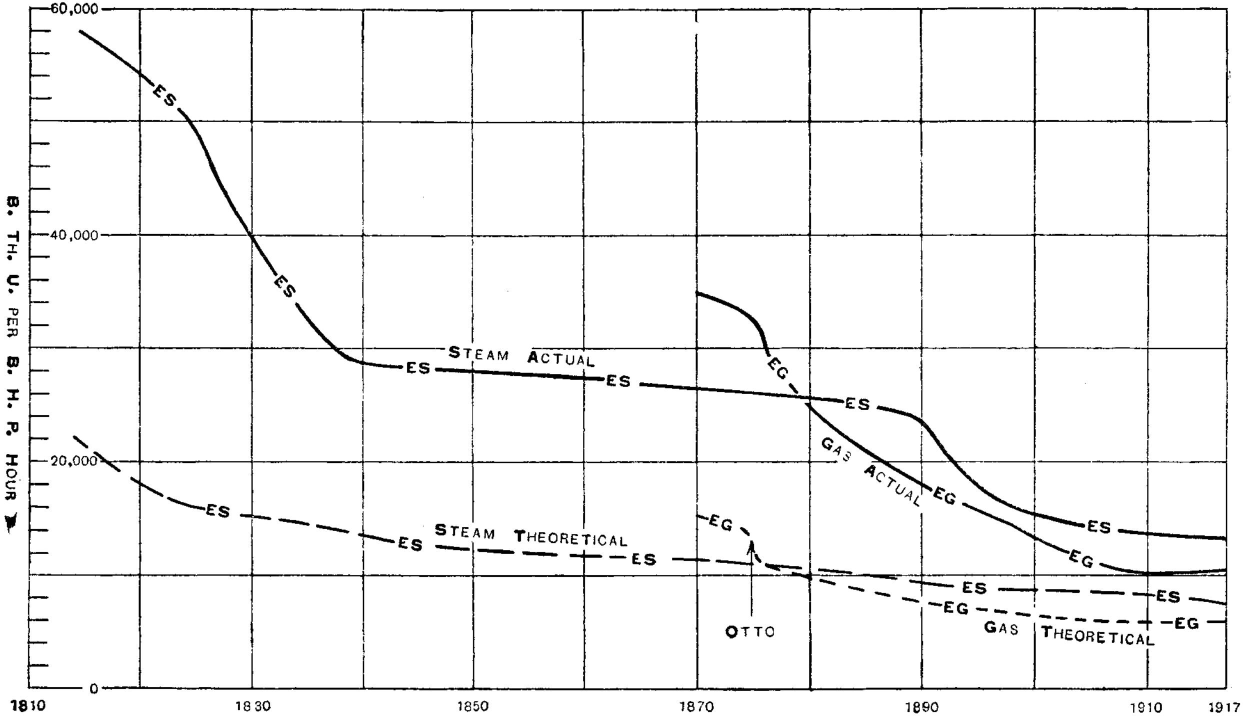
Dr. Diesel took out his patent in 1892, but the first successful experimental Diesel engine was only built in 1897, and in 1898 the M.A.N. sold a 68 b.h.p. engine, which it is believed is still working satisfactorily. Until 1907 the development was slow, but then the increase in size was rapid, reaching 4,000 b.h.p. in 1914. The first reversing marine engine was built by Messrs. Sulzer in 1905 for a boat on the Lake of Geneva, and since then the marine Diesel engine has made rapid strides. For this purpose they are of two types, namely, the heavy engines weighing 450 lb. per b.h.p., and the light type for destroyers and submarines, in some cases weighing not more than 32 lb. per b.h.p.

FIG. 15.—*Diesel Engines. Slow-Speed.*



B.Th.U. per b.h.p.-hour for Steam- and Gas-engines.—The heat consumption per b.h.p.-hour for the best recorded results are given

FIG. 17.—*Economy. B.Th.U. per B.H.P.-Hour. Steam- and Gas-Engines.*

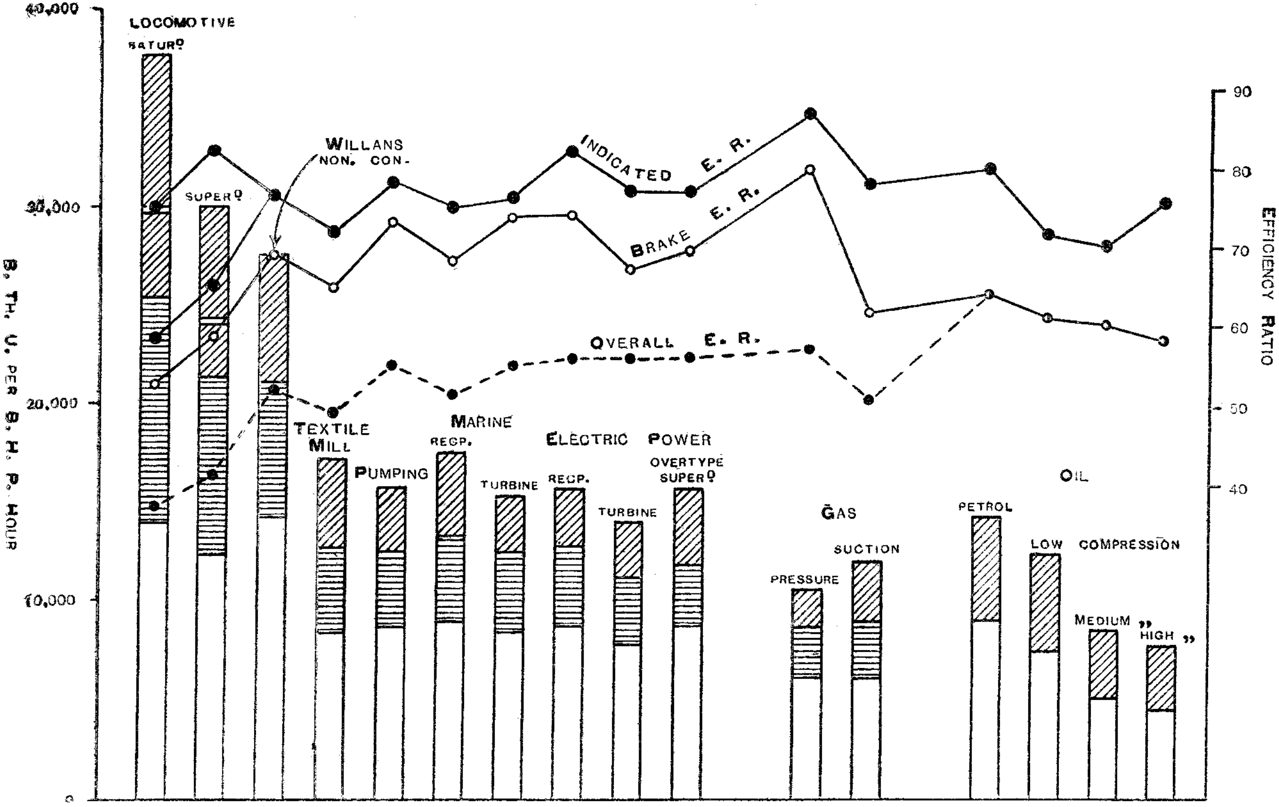


in Fig. 17 for steam-engines from 1815 onwards. In all cases allowance has been made for loss of heat due to the steam generator. It will be seen that rapid improvement took place up to 1840, after which it became slow up to 1890. A rapid increase then took place owing to the introduction of superheat, better vacuum and larger units, especially in the case of steam-turbines. Another line is shown giving the theoretical heat consumption for the Rankine or ideal engine working under the same conditions as the corresponding steam-engine. In the Rankine engine there are no losses either of the engine proper or of the steam-generator. By a comparison of these two lines, it will be seen that part of the improvement in heat consumption of the actual engine is due to the improvement of the steam conditions which has taken place, but the principal improvement is due to better knowledge of the art, both as regards the steam-engine and the steam-generator. Similar curves are shown for gas-engines, starting in 1870, because earlier records are somewhat uncertain. A great improvement took place in 1876, due to the introduction of the Beau de Rochas cycle by Otto. Up to 1879 the heat consumption, both for actual and theoretical steam-engines, was better than for gas-engines, but now gas-engines are considerably better.

Comparison of Heat Consumption for various Types of Engines.—A comparison of the economy of various types of heat-engines, expressed as B.Th.U. per b.h.p.-hour, is given in Fig. 18, and the total height of each rectangle represents the B.Th.U. per b.h.p.-hour required for each engine. The lower plain part of each rectangle represents the heat required for the corresponding Rankine engine or standard of comparison, that is, the most perfect heat-engine possible working under the given conditions, and the remaining part of the rectangle represents the losses; further, the inclined ruled part is the loss due to the engine proper, and the horizontally ruled part that due either to the steam or to the gas generator. It is to be observed that oil-engines have not got the latter loss.

The heat consumptions given are substantially the best recorded at the present time with large units, and it is to be noted that in

Fig. 18.—*Comparison of Heat Consumption and Efficiency Ratio of Various Heat Engines, best recorded results.*



the case of oil-engines the consumption of small or inferior engines should not be 10 per cent. more, and in the case of gas-engines, say 15 per cent. more than those given respectively. With steam-engines, however, far greater heat consumptions may be expected, especially in the case of small units and when working under less favourable steam conditions.

The data for locomotives represent approximately the best performances of British locomotives, and it is to be observed that the inclined ruled part of the rectangle has been divided into two; the lower part represents the loss in the cylinders due to the fact that the exhaust must be about 7 lb. higher than atmospheric pressure in order to obtain the blast. There is a possibility of reducing the loss due to blast by the adoption of finely powdered coal. Extensive tests have been made in America recently with promising results, and, incidentally, this method enables one fireman to handle an engine developing 2,000 h.p.

The ratio of the actual to the theoretical heat consumption is also given, first as an overall "efficiency ratio," that is, including the steam or gas generator, and secondly as a b.h.p. "efficiency ratio." It will be noticed that for steam-engines this latter does not vary very much, and is less in the case of non-condensing engines than in the case of condensing engines. Owing to the inferior brake efficiency of gas (suction producers) and oil-engines, their b.h.p. efficiency ratio is less than that of steam-engines. The efficiency ratio referred to the i.h.p. is also shown, and it is generally greater for internal combustion-engines than it is for steam-engines; in fact for the former there is very little loss to recover, and this shows incidentally that unless some new cycle can be developed for internal combustion-engines there is no hope of any great increase in their practical heat economy. In the case of locomotives, two points are shown for the indicated efficiency ratio. The upper point assumes that the exhaust-pressure of the Rankine engine is 7 lb above atmosphere, and the lower that it is at atmospheric pressure. The data for the over-type superheated steam-engine were obtained from a test made with a 50 b.h.p.-engine, and a remarkable economy for such a small engine is shown.

Floor Space.—The floor space occupied by a heat-engine is of considerable importance, inasmuch as the cost of the engine-house is greatly affected thereby. In the case of steam-engines, the floor space occupied by the steam generator should be included, and in the case of gas-engines using producer-gas that occupied by the gas-producer. In all cases the working room around the plant should be allowed for. The mean pressure in the cylinders, the revolutions per minute, whether the engine is of the vertical or of the horizontal type, are the main factors which affect the floor space occupied by any heat engine and, as regards boilers, whether they are of the horizontal (Lancashire type) or of the water-tube type, and also whether superheaters and economizers are provided.

TABLE 3.—*Floor Space.*

SQUARE FEET PER B.H.P.

———	From	To
Textile Mills—Vertical Engines	0·5	1·0
Pumping—Vertical Engines	1·0	..
Electric Power Reciprocating Engines { slow speed }	1·6	3·7
,, ,, ,, ,, { high speed }	0·7	0·1
,, ,, ,, ,, { Steam-Turbines }	0·017	0·033
Gas-Engines—horizontal	0·7	1·0
,, ,, vertical	0·3	..
Diesel Engines—heavy	0·48	1·2

The conditions are so various that it would be misleading, even if it were possible, to give any exact figures, but in Table 3 the floor-space for some types of heat engines may be of interest. In this Table, only the actual floor-space taken up by the engine is considered.

In long-established works, cases arise in which the engine and boilers are old and uneconomical as regards fuel consumption. They have, or ought to have, been written down to scrap value, and the cost of replacing them by modern plant might produce an annual cost by way of interest and depreciation on the actual new expenditure which would be substantially equal to the saving in cost of fuel. The floor-space occupied should, however, be taken into consideration, and if the old engine and boilers were replaced by electric motors supplied with current from a central station, the floor-space thus freed might be of extreme value for extensions to the works. For example, if the old engine were of the beam type and indicated 200 h.p., the floor-space that would be released would be about 1,000 square feet.

Other Heat Engines.—Time does not permit to describe many other heat engines, such as the uniflow, overtype-superheated, and motor-car engines.

Future Developments.—A study of some of the diagrams will assist in considering the future development of electric power distribution in this country. The economy lines for steam-, gas- and oil-engines show that very little improvement has been made of late years; in other words, it appears that a practical limit has now been reached with the present methods of converting heat into work, and a knowledge of the laws of thermodynamics enables one to say that with these methods little, if any, further improvement is possible. The best results, as shown in Fig. 18 (page 744), are as follows:—

Steam-Turbines . . .	14,000	B.Th.U.	per B.H.P.	hour.
Gas-Engines	10,600	,,	,,	,,
Diesel Engines . . .	7,700	,,	,,	,,

From the power lines it would seem that both gas- and oil-engines have reached a practical limit as to size, but the steam-turbine can, it appears, be built in larger units than any yet attempted—a view which is confirmed by considerations of initial cost, space occupied, and facilities of manufacture, erection, maintenance, and running. It will also be observed that even now the power developed by the largest steam-turbine is over twelve times greater than that of the largest internal-combustion engine. Notwithstanding, therefore, the considerably higher heat economy of gas- and oil-engines as compared with steam-turbines, the last will hold the field for the large units used for electrical power distribution until a satisfactory gas-turbine has been evolved.

There has been much theorizing on the subject of gas-turbines during the last 15 years, and a few small experimental turbines have been built, but so far there has been no real progress. The main difficulty is to obtain a material for the blading that will withstand the very high temperatures of the impinging gas. There is also the loss due to compressing the combustible mixture of gas and air, which loss greatly reduces the intrinsic higher thermal efficiency of the internal-combustion engine, so that, under the best conditions, it is not likely that the brake thermal efficiency of a gas-turbine will much exceed that of the present steam-turbine. For reasons which would take too long to explain, an experimental gas-turbine must be of very large size, hence the experiments would entail heavy expenditure, and it is hardly to be expected that private enterprise would be justified in risking the great expenditure involved.

The real aim is the utilization of the world's fuel supplies of coal, oil, and peat to the best all-round advantage, and with this object in view, increasing attention is being paid to devise means whereby fuel shall not be burnt to obtain heat until the so-called by-products have been separated.

The recovery of by-products can only be economically affected in very large plants, and the same may be said as regards producing electrical power, that it must be carried out in large stations for general distribution. Consequently, we may expect in the future that coal and peat will be gasified in producers of a character to recover the maximum amount of by-products, the remaining gas being utilized for producing electric power. As a rule, the monetary value of the by-products is greater than that of the heat-producing element of the fuel, hence, when they have been separated, it may be said that it is the gas which is the by-product. It follows that the small percentage economical gain of a gas-turbine (could it be built) is greatly reduced in value.

We are justified, therefore, in coming to the conclusion that the gas resulting, after the separation of the by-products, will be used under boilers for producing steam to drive very large steam-turbo electric generators. Inasmuch as high vacuum is essential for economy with steam-turbines, the principal requirement of the site of the power-station is to be quite close to an ample supply of water for condensing. As a secondary consideration, it should be as near as possible to a coal-field or to a peat moor and to the centre of the load.

I wish to thank numerous friends who have supplied me with information.

The Lecture was illustrated by 43 lantern slides, of which 18 Figs. and 3 Tables are incorporated in the Proceedings.

The attendance was 90 Members and 63 Visitors.

The LECTURE was repeated by Captain SANKEY in Birmingham and Manchester:—

At BIRMINGHAM, in the Medical Lecture Hall, Edmund Street, on Thursday, 6th December. Mr. E. C. R. Marks, *Member*, presided, and the attendance exceeded a hundred.

At MANCHESTER, in the Examination Hall, School of Technology, on Friday, 7th December. Mr. J. P. BEDSON, *Member* (President of the Manchester Association of Engineers) was in the Chair, and about 200 were present.

Fig. 2. *Heavy Modern Locomotive (Garratt).*

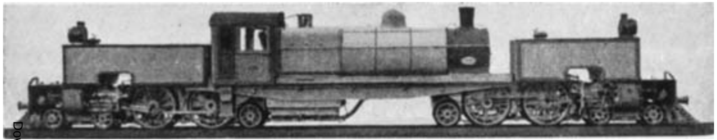


Fig. 4. *"Stourbridge Lion," 1829. First Locomotive runniug in U.S.*

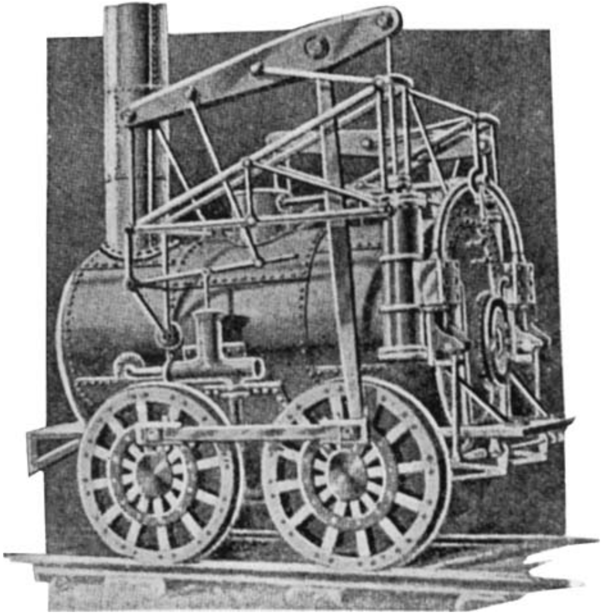


Fig. 16. *Experimental Diesel Engine. 2,000 H.P. in one cylinder. (Sulzer).*