COMMERCIAL TESTS OF INTERNAL-COMBUSTION ENGINES.

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The circumstances under which gas- and oil-engines are operated, when installed in factories, usually preclude an engineer from carrying out any desired tests upon the exact lines which have been suggested by committees of Engineering Institutions in England, Germany, and America, and which have been formulated with the object of effecting a standardization of results by means of which proper comparisons can be made. In the laboratories of technical colleges, tests can be conducted according to schedule, and on makers' test-beds—very occasionally—records of desirable observations are sometimes heard of as being more or less complete in connexion with engines of novel characteristics. But the conditions applying in the case of industrial works, in which gas- or oil-engines have been installed for driving the machinery, are usually not such as will allow the application of any form of dynamometer. No direct measurements can be taken of the quantity of heat absorbed by the cooling water or rejected in the exhaust. No direct measurement of the air admitted into the cylinder is practicable. In fact, it is rarely possible to do more than to measure the gas consumed or to weigh the liquid fuel, and to indicate the engine with due care. From these two operations all information must necessarily be obtained.

[THE I.MECH.E.]

During the past few years the author has been called upon to make tests of over 700 gas-engines, of various sizes and types, working with town gas, within the London area, and the present Paper describes the method adopted by him to enable reliable comparisons to be made respecting the performances of these widely differing engines. An extensive series of tests was undertaken on behalf of the Gas Light and Coke Co. and also, and in greater numbers, for the South Metropolitan Gas Co. The objects in view were to note the performances of the engines in their condition "as found," to improve such performances when it was possible to do so by adjustments of mechanical details, and to report whether still further improvements could be expected, if proper attention were paid to necessary repairs or renewals of worn parts.

The two London gas companies concerned realized the fact that many of the thousands of engines used by their consumers were expected to work year in and year out with the very minimum of attention beyond starting, stopping, and lubricating, and, therefore, it was to their interests, although indirectly, to ensure that the utmost work could be obtained from the least volume of gas. The whole cost of the survey was borne by them, and that the consumers have benefited very considerably will be evident from the following statement.

Up to the present time—October 1913—the number of engines inspected and reported upon is 763. A considerable proportion were found to be well looked after and maintained in such good order that very little improvement was possible. On the other hand, some had been so neglected that no improvement could be effected without previous overhauling, more or less extensive. Quite a number of old type, slide-valve engines are still doing good work with such moderate gas consumption that, for the amount of horse-power-hours developed, the savings in the cost of gas obtainable by utilizing modern gas-engines, despite the greater efficiency of the latter, would be insufficient to recoup the interest on capital outlay involved in their replacement. Examples of gas-engines have been met with, the mechanical details of which necessitated reference to early editions of standard gas-engine

books, especially in the case of two-cycle engines with displacer cylinders, six-cycle double-acting engines, and others working upon the four-stroke cycle but with complicated valve-gear that demanded some little study before one could appreciate their peculiarities.

It was found to be possible to improve the working of 66 per cent. of all the engines tested, merely by adjustment to gas or air regulation or by correction of ignition-timing and valve-setting. A greater proportion could have been improved had new parts been fitted and had attention been given to matters which would involve stoppage for periods varying from a few hours to a few days. In all cases where renewals or overhauling appeared to be imperative, recommendations were made to the user to call in the makers or a firm of expert gas-engine repairers to put matters right. In some instances such improvements as could be made at the time increased the power developed per impulse as well as reduced the consumption of gas; in others either the output or the efficiency, but not both, was increased. The average improvement as regards increase of power per impulse was 27 per cent. For example, an engine found to be giving a mean pressure of, say, 60 lb. per square inch would be left giving 76 lb. with the same, or even decreased, gas consumption, under the same load and speed. The average reduction in gas consumption was 13.3 per cent. on the i.h.p.-hour basis.

It was essential that all tests should be conducted in such a manner that no stoppage of the work of the factory in which the engine was fixed was involved, and further, that the adjustments made should be such as would bring about improvements in working, not so much under "light" or "maximum" loads, but that which accorded with the average output in daily work. Following upon a preliminary inspection at which was noted the size, type, and make of engine, arrangements were made to fit up the indicating gear and to check over the valve-settings—which gave opportunities for close examination of all mechanical details—during the midday meal hour. As may be imagined, sometimes considerable difficulty was experienced in noting all the necessary observations as well as in fitting up the reducing gear within the space of one hour. The

different provisions for indicating by various makers made it necessary to be equipped with a considerable number of adaptors to suit different sizes of Whitworth and gas-threads for the erection of a pillar or standard on the cylinder or engine frame, and also for the link to connect the piston with the ordinary pendulum reducing gear which was mainly used. The great range of cylinder sizes and strokes for which the reducing gear had to be equally suitable, and the peculiar position of indicator plugs, called for considerable ingenuity in obtaining reliable diagrams.

While the indicator gear was being fixed and the valve-settings were being checked, the opportunity was taken of noting whether the gas-meter index remained stationary while the gas-bag was kept fully distended and with the ignition-tube burner turned "off." Any variation noted in the interval gave the rate of leakage, if any, in the supply pipes.

After the indicator gear had been properly fitted and the valve-settings taken, the engine was started up, and very shortly after, as soon as a trial card had been taken and examined, other diagrams were obtained and, at the same time, the impulses per minute, and number of revolutions per minute, were counted, and the gas consumption per minute was noted while the engine was running without any load except that due to the main driving-belt running on the loose pulley. This trial was known as "light, as found." The shop load having been put on, a similar series of observations were taken and noted as "load, as found." The diagrams referring to the latter were then worked out on the spot and calculations were made, as explained later, to note the mean pressure obtained with respect to the mixture strength.

From the previous checking of the valve-settings and the information afforded by the "load, as found" cards, together with an examination of the curves recorded upon a diagram taken with a light spring, it was then possible to decide which, if any, adjustments should be made to bring about improved performances. Several diagrams were thereupon taken under different conditions until it was determined, by means of temporary

adjustments, exactly how to achieve the desired result. Occasionally the improvement could be effected within a short space of time, but frequently several hours were spent, according to the condition of the engine, before a satisfactory result could be obtained.

TABLE 1.

TEST No. 595A. Date: 13 Feb. 1913.
 Name: S. & Co. 2 Meters: 300 lt. No. 906089.
 Address: Bermondsey, S.E. 300 lt. No. 37388.

Assistant's Initials: A. R. P.
 Machinery driven: Dynamo and Cocoa-grinding plant.

24" × 30" (——) GAS ENGINE No. 10841.

R.p.m. { Light: 155.
 Load: 154.

Specific Piston displacement $\left(\frac{A. \times S.}{1728}\right) = 7.854$ cubic feet per stroke.
 Governor: Hit-and-miss.
 I.h.p. constant $\left(\frac{A. \times S.}{396,000}\right) = 0.03427$.
 Ignition: Two magnetos (low tension).
 Piston positions from edge of liner—in-centre: 23.375" in; out-centre: 6.625" out = 30" stroke.

Exhaust valve setting	{ Open; piston 1" out; crank $\odot$: lead 5.625". Close; " 14.5" in; " $\odot$: lag 8.875".	
Mixture " "	{ Open; " 22.75" in; " $\odot$: lead 0.625". Close; " 3.875" out; " $\odot$: lag 2.75".	
Gas " "	{ Open; " 20.5" in; " $\odot$: lag 2.875". Close; " 6.25" out; " $\odot$: early 0.375".	

Compression pressure: 120 lb.
 Compression pressure ratio $\left(\frac{C.P. + 15}{15}\right) = 9.0$.
 Volumetric efficiency: 0.876.
 Effective piston displacement: (Spec. P.D. × V.E.) = 6.88.
 Clearance volume ratio $\left(\sqrt[13]{C.P. \text{ ratio}}\right) = 5.4$.
 Clearance volume $\left(\frac{E.P.D.}{C.V.R. - 1}\right) = 1.563$ cu. ft.
 Charge volume: 8.443 cu. ft.

Improvements obtained: power per impulse, 9 per cent.; consumption, 10 per cent.

(Continued overleaf.)

TABLE 1 (*continued*).

Load.	Impulses per min.	Gas, cu. ft. per min.	Impulses per cu. ft.	Charge Volume per cu. ft. of Gas.	Mixture Strength B.Th. U. per cu. ft.	Mean Pressure lb. per sq. in.	Factor : M.P. M.S.	I.h.p.	Cu. ft. per I.h.p. hour.
Load, as found	67.5	46.2	1.46	12.32	40.55	87.5	2.158	202.4	13.7
Load, as left .	64.7	43.6	1.48	12.49	40.0	95.5	2.388	211.8	12.36

Observations.—Diagrams “Load, as found” showed late firing, which was corrected by advancing ignition of both magnetos, one by one notch and the other by two notches. Anti-pulsator valves in both gas-bags were not working freely, and diaphragms were flabby. The exhaust valve was opening early and closing very late. Instructions were left with attendant to correct this.

The desired goal having been more or less nearly approached, the inspection was concluded with a final consumption test under normal shop-load, and the comparisons then made of the initial and final (“as found” and “as left”) results showed exactly what improvement had been effected. A record or test-sheet was then made out in the form shown in Table 1, and from this a report was drawn up and sent to the gas company for the information of the consumer. Such report was not so detailed as was the test-sheet, as the engine proprietor could not be expected to appreciate the value of all the figures upon the latter. The report therefore merely gave the comparative “as found” and “as left” figures, with a brief statement of the condition of the engine, with suggestions as to repairs, etc., required to obtain still further improvements.

To engineers, much of the information recorded on the test-sheet, Table 1, will be self-explanatory, but in order to show clearly the method by which proper comparison between the performances of each of the engines was made possible, some explanation is necessary. The author's experience with internal-combustion engines has indicated that, while the strength of

mixture taking part in combustion has rarely, if ever, been taken into account in authoritative trials, yet this is one of the most important matters which should be determined in all tests. In *Engineering* of 15th October 1909, the author contributed to the correspondence columns of that journal a lengthy analysis of the figures given in the Third Report* of the Gas-Engine Research Committee of this Institution, which analysis showed that the influence of mixture strength upon the thermal efficiency of internal-combustion engines was of at least equal importance as was the compression ratio. In that contribution he described how the mixture strength could be computed, and from the comparisons then possible gave the following conclusions:—

- (1) Equal thermal efficiencies can be obtained throughout a wide range of compression pressures.
- (2) Equal thermal efficiencies can be obtained from varying mixture strengths, provided that ignition is properly correlated.
- (3) By increasing the mixture strength and delaying the firing point, higher mean pressures can be obtained with little, if any, loss of efficiency, within certain limits.

Since the date of that contribution (1909), the author has had many opportunities of putting the above conclusions to the test of practical work, and is more than ever convinced of their soundness. Throughout the extensive series of commercial tests alluded to in this Paper, the mixture strength of the charges taken in by the various engines has been computed in terms of total cylinder contents, that is to say, gas, air and residuals, and then compared with the mean pressure (positive loop) calculated from indicator diagrams. The factor— $\frac{\text{mean pressure}}{\text{mixture strength}}$ —thus obtained has been an invaluable aid in deciding what steps to take in order to obtain better performances from all the engines inspected.

* Proceedings, I.Mech.E., 1908, pages 34-5.

In order to express the mixture strength in terms of total cylinder volume, however, it is necessary to know the clearance volume as well as the piston displacement. The latter can be calculated at once from the cylinder dimensions of an engine, but the former, in commercial tests, cannot be definitely measured. A close approximation can nevertheless be obtained by observing the compression pressure attained and also by noting the volumetric efficiency of the engine.

Fig. 1, Plate 1, shows a light spring card taken from the engine referred to in Table 1, and the method of determining the volumetric efficiency is there indicated. It will be seen that the point along the atmospheric line at which the compression curve crosses the latter is alone taken into account, for, at this point, it is clear that the whole of the cylinder is filled with a mixture of gas, air and residuals at atmospheric pressure and at some indeterminate temperature. In this engine the specific piston displacement was 7.85 cubic feet, and the effective piston displacement was therefore $7.85 \times 0.876 = 6.88$ cubic feet. The compression pressure attained was 120 lb. above atmosphere, or in round figures 135 lb. absolute. Taking the atmospheric pressure as 15 lb. per square inch, the compression pressure ratio was 9.0, and assuming the exponent of the compression curve to be 1.30, the total cylinder volume must have been 5.4 times that of the compression volume. Therefore it can be computed that the effective piston displacement 6.88 divided by $5.4 - 1.0$, or 4.4, will give the content of the clearance space with fairly close approximation to accuracy. Thus the figure 1.56 cubic foot is arrived at for the clearance space and that of 8.44 cubic feet for the effective cylinder volume.

The number of impulses being noted for the various tests, as also the amount of gas registered by the meter in cubic feet, both expressed on a similar time basis, the division of the latter into the former will give the number of impulses obtained per cubic foot of gas. In Table 1 (page 10) for the "load, as found" count it will be seen that the figure 1.46 is thus obtained. Therefore 1.46 multiplied by the effective cylinder volume, 8.44, gives the number of cubic feet of stuff with which 1 cubic foot of gas is mixed, namely, 12.32. If

then the calorific value of the gas be known—in this case 500 B.Th.U. per cubic foot*—it can be computed that the calorific value of 1 cubic foot of stuff in the effective cylinder volume is $\frac{500}{12.32} = 40.55$ B.Th.U. The diagram, Fig. 2, Plate 1, shows that, upon ignition, this strength of mixture gave a mean pressure of 87.5 lb. per square inch, or 2.158 lb. for each B.Th.U. in 1 cubic foot of the mixture. To one who is in the habit of checking the performances of internal-combustion engines in this way, the value obtained for the factor— $\frac{\text{mean pressure}}{\text{mixture strength}}$ —at once indicates that the engine was doing well in respect of economy, and that, usually, no betterment can be expected under ordinary working conditions by adjustment.

From the diagram, Fig. 2, however, it will be seen that the ignition was somewhat late. An attempt was made to correct this by accelerating the low tension spark from both magnetos with which the cylinder was equipped, each lever being moved one notch forward. The result is shown in Fig. 3. Even with this acceleration, while improved, the ignition was still somewhat late, and consequently, that magneto which was situated at the back end of the combustion chamber was further adjusted by moving the control lever one notch further in advance. The diagram then obtained, Fig. 4, was satisfactory, the slight variations in successive cycles noticeable at the top of the card being attributable to the irregular movements of the anti-pulsator valves in the two gas-bags provided.

The next step was to determine what effect these ignition adjustments had upon the gas consumption. The “load, as left” count was therefore taken, with the result shown by the series of figures in the lower line of Table 1 (page 10). The “factor”— $\frac{\text{mean pressure}}{\text{mixture strength}}$ —is there found to be 2.388—a most satisfactory value.

* The average calorific value of gas distributed by the “ring” mains of the South Metropolitan Gas Co., into which all their stations feed, is approximately 500 B.Th.U. per cubic foot, and practically constant at that figure.

Naturally, the assumptions necessary for obtaining this factor in commercial tests will not permit acceptance of the figures as being absolutely accurate, but, being recognized as but an approximate standard of comparison, the "factor" will, for test-bed work and for general purposes, be found particularly useful. It shows very clearly whether any engine is or is not doing well, whether the mixture employed is too strong, and also what influence ignition-timing, prevailing skin-temperature of the cylinder walls, and deliberate adjustments have upon the performance of any engine under observation.

In many cases published results of tests have not hitherto included volumetric efficiency of the engines, nor has any standard been authoritatively approved of the measurement of volumetric efficiency. Usually, however, the latter has been determined by referring the length of atmospheric line between the two points where the suction and compression lines cross the atmospheric, as a percentage of the total length of the indicator diagram. This is incorrect for the purpose of computing clearance volume and mixture strength on the lines indicated in the present Paper. The importance of taking volumetric efficiency into account is very marked, and particularly in connexion with engines governed by throttling the mixture, as, with the same clearance volume, lower compression pressures are then attained.

In one test made by the author, a vertical gas-engine, which was designed to work at 100 lb. (say 115 lb. abs.) compression pressure, attained at maximum, normal full load, three-quarter load, and half load, 96, 92, 78 and 73 lb. per square inch respectively. The volumetric efficiencies at each compression pressure were respectively 88.2, 83, 80, and 76.5 per cent. Assuming the exponent η in $\frac{P}{p} = \left(\frac{V}{v}\right)^\eta$ was 1.30, the clearance volume at 100 per cent. volumetric efficiency for a piston displacement of 0.55 cubic foot (cylinder 11 inches diameter by 10 inches stroke) would be 0.145 cubic foot; and the total cylinder volume 0.695; the clearance ratio—total cylinder volume (piston displacement plus clearance) divided by clearance volume—being 4.8. At 96, 92, 78, and 73 lb. compression

pressure, the clearance ratios would be respectively, 4·7, 4·5, 4·05, and 3·9 ($\eta = 1\cdot30$), and with the clearance volume common to all at 0·145 cubic foot as before, the effective piston displacements for each ratio would be 0·535, 0·5065, 0·4410, and 0·4193—each of which are equivalent, in respect of the specific piston displacement of 0·55 cubic foot, to the volumetric efficiencies determined by the indicator. For the purpose of computing total cylinder capacities, therefore, as long as the compression pressure and volumetric efficiency are known, the compression ratio can be determined and the clearance volume ascertained therefrom, with reasonable accuracy for commercial testing, as exemplified in connexion with Table 1.

The compression curve exponent 1·30 appears to hold good for engines widely varying in design, within close limits. For instance, in Mr. H. Ade Clark's Paper* on the Diesel Engine, read before this Institution in 1903, it was mentioned that the compression pressure ratio was 35 for a Diesel engine having 41·1 mm. clearance volume and 600 mm. stroke volume—that is to say, a clearance volume ratio of 15·6 ($641\cdot1 \div 41\cdot1$). From these figures it is evident that the exponent would be 1·294. Again, as already stated, the 11-inch by 10-inch gas-engine, respecting which figures for volumetric efficiency at various compression pressures due to throttling have been given, gave the exponent as 1·30, while in Professor Burstall's tests† for the Gas-Engine Research Committee, assuming 100 per cent. volumetric efficiency, the terminal compression pressures attained for various clearance ratios gave a value for the exponent varying from 1·24 to 1·35 with an average of 1·30 (Professor Burstall's remarks upon the determination of the compression curve exponents in these tests should, however, be referred to).

Other instances could be cited confirming the exponent 1·30 being in accord with compression pressures obtained with known clearance volume ratios for many different types of gas-, petrol-,

* Proceedings, I.Mech.E., 1903, page 395.

† *Ibid*, 1908, page 5.

and oil-engines, and, as the Diesel engine tested by Mr. H. Ade Clark running at 160 revolutions per minute, the Premier engine used by Professor Burstall running at 170 revolutions per minute, and the Browett-Lindley vertical gas-engine tested by the author running at 450 revolutions per minute, may be accepted as widely varying examples, it does seem probable that computations upon the exponent of 1.30 will give sufficiently accurate data for ordinary commercial testing purposes.

The author has frequently been impressed by the fact that, in the majority of scientific investigations reported to engineering societies, all references to mixture strength have been omitted. In saying this he is, of course, aware that some exceedingly ingenious methods have, on rare occasions, been adopted to determine the volume or weight both of air and of gas, or air and petrol, etc., that have been drawn into engine cylinders, in order to state the ratio of one ingredient to the other. But, in practice, the combustible forms part of a mixture of air, gas, and residuals, and it is probably because of the difficulty in measuring the latter that the hitherto existing lack of information is due.

Dr. Dugald Clerk, in his book "The Gas, Petrol and Oil Engine," Part 1, 1909, refers to this in connexion with Dr. Slaby's well-known experiments, and suggests that the inclusion of hot residuals makes the actual weight of mixture practically indeterminate. Yet the internal-combustion engineer, for commercial purposes, does not need to know the weight of the mixture. It will suffice if he can obtain information as to the relative mixture strength in B.Th.U. per cubic foot of effective cylinder volume. Knowing this, he can, by taking into account the mean effective pressure obtained, get all the information that is of practical use to him, for with this common basis of comparison experience will soon teach him how to apply such knowledge to the best advantage. In the absence of knowledge as to the mixture strength used, he is absolutely in the dark, and is daily confused, in that, with one engine of a certain size coming on to the test-bed, the rated power—or consumption—may be readily obtained, while with perhaps another engine of the same or a

TABLE 2.

5" x 12" GAS ENGINE No. 53610.

R.p.m. { Light: 273.
Load: 267.

Specific piston displacement = 0.1365 cubic foot.

Governor: Hit-and-miss.

I.h.p. constant = 0.000596.

Ignition: Low-tension magneto.

Compression pressure: 110 lb.

Volumetric efficiency: 0.92.

Effective piston displacement: 0.1255 cubic foot.

Clearance volume ratio: 5.1.

Charge volume: 0.1562 cubic foot.

Load.	Impulses per min.	Gas, cu. ft. per min.	Impulses per cu. ft.	Charge Volume per cu. ft. of Gas.	Mixture Strength B.Th.U. per cu. ft.	Mean Pressure lb. per sq. in.	M.P. Factor: M.S.	I.h.p.	Cu. ft. per I.h.p. hour.
Light, as found	47.6	0.718	66.4	10.26	48.25	103	2.133	2.92	14.75
Load, as found	95.7	1.5	63.4	9.90	50.25	92	1.83	5.25	17.15
Load, as left .	111.8	1.31	85.4	13.25	37.75	91	2.41	6.05	13.0

Observations.—Engine had been recently overhauled. "As found," the mixture was too rich, involving heavy bumping on ignition. The exhaust valve was opening very early and closing after gas-valve opened. The ignition had too much lead and was retarded.

different batch he finds it extremely difficult to obtain the "list" figures for output or for efficiency. Without a knowledge of the mixture strength with which the engine is working—and also the mixture strength at which the engine works best—he cannot even be certain that the test-bed adjustments are final; for if, for example, when the engine is put into regular operation, an undue increase of cylinder-wall temperature occurs, the performance of

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the engine will be likely to cause trouble, and especially so should richer mixtures be admitted than those for which the ignition timing has been "set."

The large number of tests systematically made during the survey already referred to provides much valuable data which cannot be presented in a complete form in the present Paper, but a selection of test results, taken almost at random from a number of engines of varying cylinder dimensions and compression ratios, may be presented and discussed.

Table 2 reproduces a portion of the test sheet of a small gas-engine. Here it was found that for "load, as found" the factor, $\frac{\text{mean pressure}}{\text{mixture strength}}$, was 1.83. The diagrams, Fig. 5, Plate 1, showed that "as found" ignitions were extremely rapid. The effective cylinder volume per cubic foot of gas was somewhat low, namely, 9.90 cubic feet. Therefore the adjustments made were to retard the lead of the magneto ignition and to diminish the gas supply. Another point that the light spring cards drew attention to was the ill-effect caused by the exhaust-valve opening too early and closing too late: adjustment was therefore made to curtail the exhaust period. The effect of these slight alterations is shown in the "as left" diagram, Fig. 6, and in the "load, as left" line of Table 2. It will be seen that 1 cubic foot of gas then sufficed for 13.25 cubic feet of effective cylinder volume, and the factor, $\frac{\text{mean pressure}}{\text{mixture strength}}$, rose to 2.41. So that, in this small engine of 0.1365 cubic foot specific piston displacement per stroke, almost equivalent efficiency was obtained as in the larger engine, Table 1 (page 10) of nearly sixty times the cylinder capacity. It is interesting to notice the relative figures in this test when the engine was running "light, as found." With no variation due to deliberate adjustments, but consequent merely upon additional load and less frequent internal cooling by means of consecutive idle strokes or scavenging cycles, the factor of 2.133 was reduced to 1.83. It will be noticed also that, although the mean pressure was higher at "light, as found," yet this was obtained by a somewhat weaker mixture than "load, as found." That still

TABLE 3.

11½" × 18" GAS ENGINE No. 36553.

Specific piston displacement = 1·08 cubic foot.

Governor: Hit-and-miss.

I.h.p. constant = 0·00471.

Ignition: Low-tension magneto.

Compression pressure: 160 lb.

Volumetric efficiency: 0·935.

Effective piston displacement: 1·01 cubic foot.

Clearance volume ratio: 6·6.

Charge volume: 1·19 cubic foot.

Load.	Impulses per min.	Gas, cu. ft. per min.	Impulses per cu. ft.	Charge Volume per cu. ft. of Gas.	Mixture Strength B.Th.U. per cu. ft.	Mean Pressure lb. per sq. in.	M.P. Factor: M.S.	I.h.p.	Cu. ft. per I.h.p. hour.
As found . .	45·14	4·45	10·15	12·08	41·4	100·5	2·43	21·4	12·5

Observations.—Engine practically new. Temporary adjustments to mixture regulation and ignition timing resulted in no improvement, and engine was left "as found."

further reduction of mixture strength was advisable to obtain higher efficiencies under the prevailing conditions is clearly shown from the "as left" factor. Incidentally, it may here be pointed out that the factor as used by the author enables an experimenter to observe, with great practical benefit, the actual variations of mixture strength consequent upon normal variations of conditions peculiar to all internal-combustion engines, and their effect upon efficiency, etc.

Table 3 is an abstract from the test-sheet relating to a gas-engine of about the average size in general use in London factories. In this instance it was found that the engine was working so well

that no improvements could be effected. It is interesting to note that the value of the factor— $\frac{\text{mean pressure}}{\text{mixture strength}}$ —is slightly higher than that noted in Table 1 (page 10), although the cylinder dimensions of the latter were more than seven times as great. Similarly, the factor is comparable also with the small engine in Table 2, although the latter was but one-eighth the size in terms of cylinder capacity.

Very efficient cooling and careful adjustment of ignition-timing devices are required when engines are called upon to deal with loads necessitating a continuity of explosions producing mean pressures of the order of 90 lb. per square inch. As will be sufficiently clear from the examples already referred to, such high pressures are not at all uncommon in everyday work (the author has obtained as much as 118 lb. per square inch from an engine lightly loaded and taking a scavenging charge after each power cycle), and there is little doubt that gas-engines, rated by the makers upon the basis of 80 lb. per square inch for continuous work, actually possess a considerable reserve of power; but, unfortunately, the manner in which engines can be run at such overloads is very rarely understood by men in whose charge they are placed, while, until recent years, no facilities were provided by means of which the necessary adjustments could be made to achieve this much-to-be-desired end.

The only limit to an engine's capacity for overload within the range above mentioned is the liability of pre-ignition of the charge during the final portion of the compression stroke. The more nearly the temperature reaches a certain critical point either by heat generated during compression, or by cylinder wall radiation, practice seems to promise higher efficiencies. The output of power depends upon the mixture strength—the richer the mixture the more powerful the impulse, in terms of mean pressure. But if the load demands a mixture so rich that the combustion, when once started, proceeds with extreme rapidity under the temperature due to compression and wall radiation, then pre-ignitions are set up spontaneously, which announce their existence by violent bumping and quickly bring the engine to a standstill if allowed to continue.

It is for this reason that engines governed on the "hit-and-miss" system can work continuously at high mean pressures without giving trouble. Even if but one miss occurs at intervals of, say, twenty cycles, the engine will work quite satisfactorily under such conditions, probably due to the fact that the air, admitted during the "governing cycle" or "miss" in a state of turbulence, very effectively cools the skin of the internal wall below the critical temperature, which water-circulation alone is not able to reduce.

Pre-ignitions are much more likely to give trouble when engines are throttle governed, for, under heavy loads, the compression pressures and temperatures are higher and more heat is given to the walls; but, even then, with copious water-circulation and with properly retarded ignition suitable to the load, overloads requiring upwards of 90 to 95 lb. mean pressure can be carried for quite considerable periods.

The author is of opinion that, judging by his own experience, internal-combustion engine makers will find that the factor value suggested in this Paper will be most useful to them in tuning up their engines. Tables can be prepared for the use of the test-bed staff, which will give definite figures without calculation for effective cylinder volumes corresponding with actual volumetric efficiencies. Then, with diagrams obtained by means of correctly set reducing gear and with instruments of fair accuracy, the factor value can be calculated from the following formulæ:—

$$(1) H \times F \div I \times V = S.$$

$$(2) P \div S = \text{Factor};$$

in which—

H = Average calorific value of fuel per lb. or cubic foot.

F = Lb. or cubic feet of fuel consumed per minute.

I = Impulses per minute.

V = Effective volume of cylinder in cubic feet.

P = Mean pressure lb. per square inch.

S = Mixture strength in B.Th.U. per cubic foot.

The term S will be a direct guide to the relative mixture strengths admitted to every engine, and, this being known, many phenomena hitherto held to be inexplicable will be made clear to

those engaged on the test-bed. With a certain setting of the gas-regulating valve or its equivalent, the standard mixture strength for which the rated powers apply can be readily obtained, and the air-adjustment can then be regulated so that proper combustion ensues. With a mixture strength of, say, 40 B.Th.U. per cubic foot, mean pressures of 80 lb. per square inch can be definitely relied upon; and, given sufficiently close adjustment of ignition timing, even 90 lb. or more can be secured without risk of pre-ignition, provided that the compression pressure is not too high and the internal cylinder walls, etc., are efficiently cooled.

When it is realized, as various test-sheets in the author's possession show, that mixture strengths of 50 and 55 B.Th.U. per cubic foot of effective cylinder volume can be efficiently burnt in gas-engine cylinders, which will give proportionately greater power without loss of efficiency, it will be recognized that gas-engines rated on 80 lb. m.e.p. possess a capacity for overload far greater than has usually been conceded to them. To obtain this overload capacity, however, it is essential that means of control of ignition and combustion of mixture should be provided by makers. Ignition-tubes with timing-valves must be abandoned in favour of some form of electric ignition device that shall be adjustable. When utmost efficiency must be maintained, gas-engine drivers should be encouraged to take indicator diagrams from time to time when noting the consumption of gas, and thus to obtain the factor value. For this purpose the supply of gas to each and every engine, whether town- or producer-gas, should be passed through meters. The arithmetical problems are of the simplest description and can be done expeditiously.

The Paper is illustrated by Plate 1.

Discussion.

The PRESIDENT, in proposing a hearty vote of thanks to the author, said the Institution was to be congratulated on the receipt of a Paper which was evidently so full of matter, and which had been prepared and handled in so excellent a way that all the results were consistent in the experiments and in the work which had been undertaken; consequently the Paper became even more valuable than many which had been submitted to the Institution. He had very little doubt that the discussion which would arise would add to the value of the Paper, and he therefore asked the members, not only on account of the value of the Paper itself but of the collateral value of the discussion which would arise, to accord the author a very hearty vote of thanks.

The vote of thanks was passed with acclamation.

Mr. W. A. TOOKEY said he desired, before the discussion on his Paper commenced, to explain a chart, Fig. 7 (page 24), he had prepared showing four different curves. He thought it was worth explaining because it presented some interesting points in relation to mixture strength which had not, as far as he knew, been previously brought out. The horizontal lines 2, 4, 6, 8, 10, and 15, referred to the compression volume ratios; the vertical lines were percentages of thermal efficiency, and the chart actually showed the efficiencies that various authorities said could be expected from any internal-combustion engines in terms of compression pressure, or compression pressure ratio, which was the same thing. The curve Y graphically reproduced the thermal efficiencies referred to by the Committee of the Institution of Civil Engineers, appointed to report upon the Standards of Efficiency of Internal-Combustion Engines, in their Report in 1905 for the air standard engine on the basis of Constant Specific Heat, when it was stated that, as the compression pressure went up, higher thermal efficiencies could be obtained. It was

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FIG. 7.

- Z Increasing efficiency with increasing compression pressure due, by reason of reduction in clearance volume, to lesser total quantity of heat required to maintain equivalent mixture-strength.
- Y Air Standard Efficiencies on basis of constant specific heat. (Inst. C.E. Committee, 1905)
- X Clerk's corrected efficiencies on basis of varying specific heat. (Junior Inst. E. Connet Lecture, 1913).
- T Tookey's curve of practical efficiencies ($Z \times X = T$)

The circles, and dotted continuation of curve T, show the actual efficiencies obtained by various experimenters during thirty years (1881 to 1911) as accompanying table and their close agreement with Tookey's curve.

Reference letter	Test by:-	Maker of engine.	Date	Size of engine.
A	Slaby.	Otto.	1881	4.5 B.h.p.
B	Humphrey.	Crossley.	1900	360 B.h.p.
C	Inst. C.E.	National.	1905	L, R, & X engines
D	Stead.	do.	1911	750 B.h.p.
E	Clerk.	Crossley.	1894	12 B.h.p.
F	Burstall.	do.	1904	50 B.h.p.
G	Atkinson.	do.	1905	40 B.h.p.
H	Hopkinson.	do.	1908	40 B.h.p.
K	Longridge.	Diesel.	1905	500 B.h.p.
L	do.	do.	1905	60 B.h.p.
M	Robinson.	Ruston.	1910	50 B.h.p.

within the knowledge of most present that practice did not quite bear out that theory, and Dr. Dugald Clerk, amongst others, set to work to ascertain why this was so. The curve X was taken from Dr. Dugald Clerk's figures, in which allowance had been made for the variation in the specific heat of the actual working fluid of the internal-combustion engine. It would be seen that curve X was much nearer the Y curve at the ratio of 2 than it was at the ratio of 7, which showed that as the ratio increased so the actual engine tended to become less efficient, because of the varying specific heat of the working fluid. In the chart he (the speaker) had shown another curve marked T, along which from $2\frac{1}{2}$ right up to 15 there were some circles plotted which closely followed the line of the curve. The lower part of the curve, where it was in full lines, had been calculated in a way that he was about to explain. The upper dotted part had been extended so as to make it agree with the circles which represented the actual efficiencies that had been obtained during the last thirty years by different experimenters with internal-combustion engines of varying compression pressure (or clearance volume) ratios. Before showing how the curve T had been calculated it was necessary, however, to explain how the curve Z had been computed. For the purposes of such explanation he wished to remind the members that in the early days of the gas-engine, when the old slide-valve engine was first introduced, this type of engine had a fairly considerable clearance volume. At a later period in the history of the gas-engine the higher compression pressure required a less clearance volume; again, for the new crude oil-engines that were now being introduced, a very much less clearance volume was needed; and for the Diesel engine a still less clearance volume was required. So that one might reasonably say, for purposes of argument, that infinity could be reached with an engine that was all piston displacement with no clearance volume whatever. That was what he had assumed when plotting the curve Z on the chart exhibited. With such an engine the curve Z would be continued so much above the ratio 15 on the chart as would allow the top of the curve Z to reach 100 per cent. thermal efficiency. From this reasoning it could be stated

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that as the clearance volume ratio decreased, so the thermal efficiency would be reduced proportionately. The curve Z was plotted on such an assumption, which the speaker held to be an entirely reasonable one; for if, for example, it was desired to charge the whole cylinder volume of any engine with such a quantity of combustible that would give a strength of, say, 40 B.Th.U. per cubic foot, it was necessary not only to put in the amount of gas which would bring the contents of the piston displacement to this figure but as much more as was necessary to vivify, so to speak, the stuff in the clearance space also, and thus to bring the whole of the working fluid up to the equivalent mixture strength of the imaginary engine which, as before stated, would give infinity of compression ratio and 100 per cent. thermal efficiency. Taking the values of the curve Z computed in that manner, and multiplying them by Dr. Dugald Clerk's figures, or rather, by the mean of Dr. Dugald Clerk's figures for the variation of specific heat as in curve X, he obtained curve T. He thought the members would agree that the latter curve showed a striking correspondence with the actual thermal efficiencies obtained in the tests of those engines of which particulars were given in the accompanying Table, and he submitted that, by such computation, it was possible to determine the probable "practical" thermal efficiency of any internal-combustion engine of which the clearance volume ratio was known.

Mr. LEONARD MURPHY considered that the Paper was a record of a very valuable piece of work, particularly because of the extremely practical nature of the tests. The tests were made under working conditions, and while therefore the results could not compare in accuracy with figures from laboratory tests, one might look upon them as giving a reliable statement of the behaviour of the engines when used under everyday conditions. The only difference between a test of this kind and one carried out under laboratory conditions would be found in the neglect of some comparatively unimportant sources of errors, and proper discrimination had been employed to ensure that the results were

of scientific accuracy within the limitations imposed by the conditions under which they were obtained. It was, however, rather a pity that the author should, in some cases, have expressed his results in a manner which might lead one to think that a much higher degree of accuracy had been obtained than was really possible under the circumstances. Referring, for example, to the performance factor, it would seem from the various Tables that the author was able generally to express this to an accuracy which involved four significant figures, that is, the error was probably between one-tenth and one-hundredth part of 1 per cent. This factor, however, contained some quantities which could not be measured with anything approaching such precision, even in the most careful tests. When calculating the mean pressure from a gas-engine indicator diagram, and after allowing for errors introduced by the instrument itself, one would not generally be dogmatic about the result to a greater degree of accuracy than, say, 3, or even 5 per cent. Then there arose the question of the calorific value of the gas, which surely would vary at least several per cent., so that in the calculation of the factor it would seem difficult to uphold an accuracy much better than 7 to 10 per cent.

Referring to the conclusions stated on page 11, it was not altogether clear as to whether the author referred to the final limitations of gas-engine design, or only to the results one might expect by varying one point in a given design and then adjusting the various others in order to produce the best results under the particular working conditions considered. To take a specific case, it might be deduced from conclusion (1), that the author would not expect a throttle-governed engine to have an appreciably less thermal efficiency when running light than when fully loaded, whereas this was generally admitted to be the case, and was, in fact, one of the chief reasons why "hit-and-miss" governing was employed wherever the load conditions would permit. Similar observations might be applied to the third conclusion, which apparently negated the generally-accepted axiom that the highest efficiency and greatest power per impulse were only obtainable with a certain mixture, provided that in all comparisons due care had been taken to work

(Mr. Leonard Murphy.)

the engine under the best conditions in all other respects for that particular load. In his (the speaker's) opinion, an ideal engine would necessarily work at all times with the highest compression pressure permitted by considerations of pre-ignition and with a certain mixture strength, whose composition could be determined from a knowledge of the calorific value and chemical constituents of the gas employed. If the author's experience had led him to differ from this opinion, as seemed to be indicated by the conclusions enumerated on page 11, would he kindly amplify these conclusions in his reply.

This point led up to the question as to whether an engine could

FIG. 8.—*Automatic Variable Compression Device.*

be designed to work at the correct compression pressure and mixture at all loads, and, in this connexion, he thought it might be desirable to put before the members a scheme for obtaining this result. It was, of course, well known that previous attempts had been made to achieve this result, but generally speaking, the mechanical complications involved had proved too great. The "hit-and-miss" method of governing partially accomplished it, but introduced considerable speed variation and reduced mechanical efficiency, and was, in fact, intolerable on these accounts for certain classes of work. The scheme he was describing abandoned "hit-and-miss" governing straight away, and relied entirely on varying the supply of a constant mixture by a throttle governor. The object was to obtain a compression volume which depended on the amount of charge in the cylinder, Fig. 8.

In the figure was shown a diagrammatic section of the proposed arrangement, from which had been omitted all the usual mechanical details such as valves and water-jacket. These would be very similar to those found in any standard design, and were not therefore of special interest. It would be noticed that into the cylinder head a gas-tight diaphragm or floating piston was shown fitted, and the scheme provided means for maintaining a pressure at the rear of this diaphragm, approximately equal to the desired compression pressure. The space at the rear of the diaphragm was sufficiently large to permit of appreciable movement of the diaphragm without thereby greatly varying the pressure behind it, and, in action, the diaphragm would move away from the piston during the compression stroke to a greater or less extent according to the quantity of charge being compressed. Thus the compression pressure would remain approximately constant whether the engine was working on a heavy or light load. Other incidental advantages of the scheme were the facts that practically the whole of the burnt gases were expelled on the exhaust-stroke and that a certain cushioning effect was obtained at the moment of explosion. The diaphragm would obviously be driven still further back under the explosion pressure, but the gas at the back of it would recover its greatest permitted volume before the piston had reached the end of its outward stroke, and would thus return the energy absorbed to the piston. The result of this action would be to maintain a considerably more even driving torque during the explosion stroke, with a probable increase in the mechanical efficiency.

The small channel and non-return valve shown in the lower part of the diagram were merely one method of keeping up the pressure within the space at the rear of the diaphragm, as a small leakage was bound to occur during the suction and exhaust periods. The channel entered the working portion of the cylinder at some suitable point, and, on account of the non-return valve, the space at the rear of the diaphragm was charged up in a few strokes to a value equal to that which occurred in the working portion of the cylinder on the explosion stroke when the piston reached the point of entry of the channel.

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A further point which apparently needed some proof was the author's opinion stated on page 21, that the air admitted during a "miss" was particularly effective in cooling the cylinder walls, and was therefore responsible for the ability of engines, governed on this plan, to work continuously at high mean pressures, so long as governing cycles continued to occur occasionally. Had the author considered the extremely small quantity of heat which it was possible for a charge of air to take up in this way, and was it not more probable that the explanation of the behaviour referred to, was to be found in the large proportion of residuals which would accompany every working stroke as soon as the governing cycle was entirely omitted? This view of the matter was borne out to some considerable extent by the ability of petrol engines to work continuously at what would ordinarily be regarded as heavy overload, provided that a clear exhaust was used—a state of affairs which occurred in motor-car racing. If this were the correct explanation, the variable compression device which had been described should be particularly effective for working continuously at full load.

In conclusion, he would like to say that he felt one of the most valuable features of the Paper was the incentive it undoubtedly contained to manufacturers to produce engines of higher efficiency. The competition between various forms of motive power was becoming increasingly important, and the times demanded gas-engines of higher efficiency if they were going to hold their position in the field of industrial power supply.

Mr. F. E. RAINEY said the difficulties described by the author in carrying out tests on over 700 gas-engines running under commercial conditions (which after all were the conditions that all gas-engines had to deal with in everyday use), and which represented their value, should prove of great use to those called upon to make similar tests. With electricity on the doorstep of nearly every gas corporation, and the facilities it afforded of obtaining records of the power at any moment and for any load, and the simplicity and rapidity with which it could be started up

and shut down, made it a serious rival to gas for power purposes. The broad policy of the Gas Light and Coke Co. and the South Metropolitan Gas Co. in having the tests carried out for them should stimulate other gas corporations to show similar enterprise. From a user's point of view he should know, not only the number of cubic feet of gas passing through his engine for any fixed period, but the "horse-power" he obtained from it. To do that it was necessary to have suitable instruments for measuring and recording what was taking place in the engine, and that they should, with the engine, be periodically tested.

A great number of gas-engines were installed all over the country, the users of which knew nothing of gas and very little of anything else except what they had to get out of the engine. If other gentlemen like the author would apply tests by which practical results could be obtained, it would be satisfactory to gas-engine users and a great benefit to the industry, not only from the gas-producer's point of view but also from the gas-engine builder's point of view. By adopting such a course, some of the difficulties referred to by the author could be minimized, if not completely eliminated. The maximum power developed with a minimum weight of gas depended on the explosive mixture of air and gas being so proportioned that the maximum pressure obtainable was reached. It was simply a chemical combination, and if the gas and air were not mixed in the right proportion for that chemical combination, no amount of coaxing of the spark by advancing or retarding would get the best results, which could only be obtained if the mixtures were absolutely right. That depended on the exact weight of oxygen being present in the charge of air to effect complete combustion, but, as the weight of oxygen present in each cubic foot of air must vary proportionally with the density of the air, and as the density of the air varied daily and hourly it was difficult to understand how the best results could be expected, if the charge of air was measured in cubic feet without any record of the oxygen value in it. The density of the air varied with the thermometer, barometer, and humidity. By the more general use of the wet and dry bulb thermometer,

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together with the mercury barometer, the weight of oxygen present in the air per cubic foot could be obtained as well as that of the moisture; and with a suitably-constructed chart, any attendant would be able to adjust the air to the atmospheric conditions, without having to call in technical assistance.

With regard to the author's remarks on the subject of waste heat in cooling water, he ventured to suggest that it could be measured by means of thermometers, with recording charts fitted to the inlet and outlet pipes, and by metering the water, provision for which could be made in the piping for fixing temporarily or permanently a suitable water-meter. The waste heat in the exhaust could also be measured more or less correctly by similar thermometers. The author admitted that the methods used by him in ascertaining the percentage of the heat units passing through the engine which had been converted into work had been, (*a*) to measure the fuel and presumably check the calorific value, and (*b*) to indicate the engines. The commercial running conditions of all prime movers, steam or gas, extended generally over several hours, while with the present types of indicators it was not possible to obtain separate records of each stroke, revolution, or cycle for more than a few minutes at a time. Any power calculation for long periods of running based on records obtained during short intervals of running, even though they might have been repeated frequently, must be more or less approximate, and dependent on the percentage of the total time the engine ran which they represented.

With internal-combustion engines it was also known that considerable variation occurred at every stroke in the compression pressure and expansion, even when running under constant loads. Under commercial conditions, with the engine on a governor, the load was subject to momentary variations representing wide fluctuations in power, often within a few seconds, and it was therefore necessary if an exact power record was to be obtained, that a measure of pressures for every revolution or cycle made by the engine during the whole time of running should be obtained. This had been made possible by a well-known German firm which had built special indicators for Diesel and other engines. They

had perfected an instrument, which could be fitted to a series of indicators, and which automatically integrated the cylinder pressures during every revolution or cycle. The action was not limited by any period of time; its results might be checked at intervals on single cards or continuous rolls, if desired, without in any way interfering with the action of the power-counter. By this means valve adjustments could be checked and sparks adjusted without interfering with the power record or its continuity. By taking readings on the counter at the start and finish of the run and at the same time those on the revolution counter, the "mean effective pressure" could be obtained within a few minutes, by means of a simple formula, even though the period of running might have been several hours. Its accuracy was guaranteed within 1 per cent. for speeds up to 400 revolutions, provided the instructions were followed. Those figures were taken not from the manufacturer but from the user. This instrument, in addition to giving a record of the power for long periods of running (hitherto not possible to obtain), effected a considerable saving in time and money with greater accuracy. An engine running at 200 revolutions for a period of ten minutes would require a roll of paper 34 feet long to record the 2,000 diagrams. Allowing ten minutes to work out each diagram, the time occupied in doing so would be 333 hours, or over a month working ten hours a day, and would cost at £2 per week nearly £10, while the counter (the cost of which was under that figure), would have the answer ready in less than ten minutes, and being mechanical in its action was free from the inaccuracies inherent in humanity and its labours. The instrument in question had been before the public for several months, and probably it would be of great assistance to many people.

Captain H. RIAL SANKEY, R.E. (ret.) (Member of Council), said that, amongst the many matters considered in the Paper, the principal one was the factor obtained by dividing the mean pressure by the mixture strength, and he thought perhaps it might be interesting to the Meeting to see how that factor was related to thermal efficiency and the compression ratio. The mean effective

F

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pressure in any engine producing an indicator diagram could be obtained from the following expression :—

$$5.4 \frac{\text{B.Th.U. per lb. of substance} \times \text{thermal efficiency}}{\text{Volume swept by piston per lb.}}$$

Either the mean pressure of the ideal cycle or the actual mean pressure was found according as the thermal efficiency of the ideal cycle or the actual thermal efficiency was inserted in this expression.

FIG. 9.

Dealing now with a gas-engine, the volume swept by the piston per pound of substance was equal to: $v \times \frac{\theta_c}{288} \times \frac{r-1}{r}$, where v was the specific volume of the explosive mixture at 15°C . and at atmospheric pressure, θ_c the absolute charge temperature in degrees Centigrade, and r the ratio of compression. Again, it could be shown that the mixture strength as used by Mr. Tookey was the B.Th.U. per pound of the explosive mixture divided by its specific volume per pound. Combining the above it would be found that the factor was $1,555 \left(\frac{\text{thermal efficiency}}{\theta_c} \right) \times \frac{r}{r-1}$.

Based on that formula and calculating the thermal efficiency of the Beau de Rochas cycle by means of the $\theta\phi$ chart, using the latest values for the increase of specific heat with temperature, he had worked out the diagram on the preceding page, Fig. 9.

The ratio of compression had a wide range from 3 to 10. Two mixture strengths had been considered, and the full lines referred to a mixture strength of 40 B.Th.U. per cubic foot, and the dotted lines to a mixture strength of 64. The two top curves referred to a charge temperature of 27° C.; the two middle curves to a charge temperature of 127° C.; and the lower curves to a charge temperature of 227° C. It would be observed that the factor increased slightly with the ratio of compression, and that there was not very much variation depending on mixture strength, but there was a great deal of variation depending on the charge temperature. The two factors given in Table 1 (page 10) were shown. The point marked 2.158 referred to the engine "as found," and the point marked 2.388, and also *b*, to the engine "as left." There was no information as to the temperature of charge, but if it had been in the neighbourhood of 27° C. then the ratio $\frac{bc}{ac} = 0.89$

obtained from the diagram was the ratio between the performance of the actual engine and that of the corresponding ideal Beau de Rochas cycle engine. It would, in other words, be the "efficiency ratio" of the engine. The cross represented the factor for one of Professor Coker's experiments referred to in a Paper read at the Institution of Civil Engineers in December last. In that case the charge temperature was 210° C., and the mixture strength was 67, and, by calculation from the formula given above, the point *d* was obtained for the position of the ideal factor for that engine, and the efficiency ratio worked out to 0.85.

Denoting by *F*, the ratio of mean pressure to mixture strength, the formula given above became $\theta_c = 1,555 \frac{\text{thermal efficiency}}{F} \times \frac{r}{r-1}$.

The thermal efficiency could be calculated, and ratio of compression obtained in the usual way and the factor *F* as shown by Mr. Tookey. Hence the charge temperature could be obtained, a matter which

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had been very difficult to deal with hitherto. In order to verify this deduction, he had compared the formula with some of the results given by Professor Coker in the Paper to which he had just referred. Professor Coker had measured the charge temperature by means of a thermo-electric couple and the results of the comparison were given in the following Table:—

Test.	Charge Temperatures.	
	Calculated.	Observed by Professor Coker.
	°C.	°C.
G ₁	230	210
G ₂	242	210
G ₃	267	250
G ₄	213	260
G ₅	277	320

It would be seen that there was some disparity between the calculated and observed temperatures, but in view of all the difficulties that existed in such measurements, he thought the deduction he had made was fairly confirmed and that the formula could be used for finding the charge temperature in the case of a gas-engine.

Referring again to the diagram, in actual engines the ratio of compression varied from 5 to 7, and further, if working properly, the charge temperature would be low. Hence the part of the diagram which was of practical interest was that indicated by shading, and it could thus be seen that the author's statement that about 2·3 was the factor to aim at to see whether an engine was working properly, was confirmed on theoretical grounds. He therefore considered this contribution of the author's to be of great value, and suggested that this factor should be called Tookey's Factor.

Mr. E. J. DAVIS said he noticed the author stated on page 11 that "The strength of mixture taking part in combustion has rarely, if ever, been taken into account in authoritative trials." Five years ago Professor Bertram Hopkinson read a Paper at the Institution on the Effect of Mixture Strength and Scavenging,* and thoroughly thrashed out the effect of various mixtures. He then showed that, with an 8.5 per cent. of gas to the total contents of charge and exhaust, he obtained 12 per cent. more power out of a cubic foot of gas than when working with an 11 per cent. mixture, showing that there was a thermal advantage in working with a weak mixture. He (Mr. Davis) proved the same point in 1895 in an article in the *Mechanical World*, where he gave a series of diagrams showing the different effects on an engine running with various mixtures. In the same series of articles twenty years ago, in 1894, he gave a simple formula by which the greatest advantage could be obtained out of a gas-engine as far as the amount of gas necessary for running it was concerned. He also gave the formula five years ago in a discussion at this Institution,† but he would give it again, as he was sure it was very useful, and one that he had used for twenty years. In the formula he only took into account the air taken in by the piston, and it was assumed that the engine was properly tested. If an engine was properly tested up to about 25 b.h.p. a suction of about 1 lb. was allowed; up to 50 h.p. about 2 lb. were allowed, and for 100 h.p. a little more than 2 lb., but not much more. He found at 60 lb. compression the best mixture was obtained with 1 of gas to 8 of air, taking the volume swept by the piston only, and taking no account whatever of the combustion space. With an 8 to 1 mixture the formula worked out at 15,552 over the volume swept by the piston at 60 lb. compression. So that for any engine working at 60 lb. compression, all that it was needful to know was the diameter and stroke; and after getting the cubic inches of the diameter and stroke, that is, the volume swept by the piston, and dividing it into 15,552, it gave the number of explosions

* Proceedings, I.Mech.E., 1908, page 417.

† *Ibid*, page 46.

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per cubic foot that that engine would run with most economically. With 110 lb. compression pressure the formula was $\frac{20,543}{\sqrt{V}}$, and with 160 lb. pressure it was $\frac{21,600}{\sqrt{V}}$. It was a very simple formula because there was no unknown quantity in it, and the engineer had not to calculate the expansion curve for the index.

He had tested many engines and adjusted them to the foregoing formula, with very satisfactory results. With a piece of squared paper it was possible to work out the proper mixture for any compression. If the figure had to be worked out for an engine of which they did not know the compression—for instance, an old type of engine—it would be taken probably at 60, and a new type of engine probably at 110. If the figures were taken out in that way, it was easy to ascertain afterwards whether they were right or not. He desired to compare that with the figures the author had given in his formula. Taking Table 1 (page 10), if the explosions per cubic foot were worked out according to his formula they came to 1.51 against the author's 1.48 for 120 lb. compression, which meant that the engine was working with a slightly weaker mixture. In case 2 at 110 lb. compression, his formula worked out at 87 and the author's at 85.4. In the third case at 160 lb. compression, his formula worked out at 11.5 and the author's at 10.15. It would be seen therefore that there was very little difference, and he thought it would be found that, if anything, his were the most economical figures.

With regard to the question of testing, at which he had practised for some years, when he first studied the author's figures he thought that the measurements of the stroke of the piston were taken in thousandths of an inch. He had never known a tester to take the stroke of an engine in thousandths of an inch. On studying the figures for a little time he thought they seemed familiar, and after making a short mental calculation he found that 0.625 inch meant $\frac{5}{8}$ inch; that 0.875 was $\frac{7}{8}$, and 0.375 inch meant $\frac{3}{8}$ inch. It would have been very much better, in his opinion, if the fractions had been inserted instead of the decimals because they were accurate as far as the engine was concerned, whereas the

decimals were not accurate for the reason that it was impossible to run a gas-engine without a little lost motion. If one tried to do so, there would be a seized bearing, so that it was impossible to have the engines running with the figures given in the Paper. If $\frac{7}{8}$ inch were put down, they knew it might not be right within $\frac{1}{1000}$ inch, and he was sure the engine could not have been run within $\frac{1}{1000}$ inch of its list stroke, because it must have that clearance in the two bearings to allow it to run at all.

He also wished to say that he thought the indicator was not a very necessary thing for showing when an engine was working properly. The author used an indicator to find out what was the matter with the engine. He (Mr. Davis) assured them that in the last twenty years he did not suppose he had used an indicator twenty times to find out what was wrong with an engine. To state that a gas-engine driver should have indicators to work with would, he was afraid, simply be a loss of money to the employer, and the indicator would very soon be scrapped.

The author stated (page 7) that 66 per cent. of the engines working could be improved; this seemed a very debatable point. Over what period of time was the improvement noted? Gas-engines were frequently run in a haphazard way; the gas was frequently not adjusted by a check plate but by the gas-cock, and this might not be in the same position for two consecutive days. He (Mr. Davis) assumed that the engine was first tested with the gas-cock in the position as given by the driver, which was a very casual approximation; again, the gas-pressure might vary, due to varying consumption from the same main; also, improvements shown by short test figures did not always materialize in actual working. For instance, in one of the tests undertaken by the Gas Light and Coke Co., a report was sent in to the owners that a 15 per cent. economy in gas-consumption had been effected in one engine and 5 per cent. in another. This report was forwarded on to him (Mr. Davis). He found the 15 per cent. engine was left running with a strong charge; its foundation had previously been giving much trouble, and the engine was rocking on its bed at each explosion. He explained the effect of this, and asked the

(Mr. E. J. Davis.)

owner to let the engine be run so that the actual gas-consumption could be checked. This was found to be at the rate of 10,000 cubic feet more gas per month than it had been previous to the alteration. If to this were added the trouble that would have ensued had the engine been left running under altered conditions, one would obtain a fair idea of what was meant by economy in this case.

In the formula $\frac{H \times F}{I \times V} = S$ (page 21), the gas pressure, temperature of charge, back pressure at the end of the exhausting stroke, and leakage past piston, were all unknown quantities. Where there was any serious leakage of the charge the index 1.3 became useless, for it was obvious that the leakage past the piston would lower the compression pressure so that the calculated clearance space would be artificially increased, and the percentage of gas would actually be higher than the calculated; with his (Mr. Davis's) formula this was not so. With liquid fuel the exact charge could only be found by experiment; the size of a drop was variable, the dimensions of the pump were of course calculated, but the final adjustments could only be found by experiment.

Mr. WILLIAM H. PATCHELL (Member of Council) said that Captain Sankey had just given a series of figures calculated on Professor Coker's tests and also the actual measure figures. He thought it might be of interest if he stated that the sum of the calculated figures was 1,229, and the sum of the measured figures was 1,250, a difference of only 1.68 per cent.

Mr. CHARLES HAWKSLEY (Member of Council) inquired why the nights, as well as the afternoons of Saturdays and also Sundays, if needful, should not have been utilized for doing what was necessary to the engines, instead of confining the time employed to the meal-hours.

Mr. JOHN CHAMBERLAIN said that the author referred (page 7) to the difficulty of rigging up the reducing gear for the engine

during the dinner-hour. Having regard to the limited time available for this and the great variety of sizes of engines tested, he would like to ask whether, in place of the ordinary reducing gear, he had ever tried the reducing wheel by which the movement of the engine could be transferred to the indicator. It was a very simple arrangement, and was connected to the indicator at the place where it was fixed, without a special attachment, and could be adapted to engines with strokes of from 1 foot to 6 feet. It was put to work by attaching its cord to a convenient reciprocating part of the engine, and if used, it would obviate the difficulty and save time.

The author also referred (page 11) to the question of total cylinder contents and clearance volume. It was important that the clearance volume should be known, of course, and its proportion to the volume of the cylinder proper was very instructive if accurately known. He would like to ask if the cubic contents of the clearance space or combustion chamber had been accurately determined by direct measurement, on, for instance, an experimental engine, or whether it had been arrived at only by calculation.

Mr. W. A. TOOKEY, in reply, thought it would be of greater interest if he replied to Mr. Davis first, seeing that that gentleman mentioned so many important points in such an interesting way. There was no doubt that mixture strength had been referred to before in the Proceedings of the Institution; that was well known to every member, and to every engineer who did not happen to be a member, because the Institution Proceedings were so well reported in the technical press. The point he wished to make, and which he thought he had made in the Paper, was that mixture strength "in terms of total cylinder contents" had not been dealt with so far as he was aware. Mr. Davis, he believed, took part in the discussions on Dr. Hopkinson's and also on Professor Burstall's Papers, and on each occasion had said that, in his experience, as the compression pressure went up so it was necessary to reduce the amount of gas going in. That was a well-known interesting fact, but he (the author) did not think it had ever been plainly

(Mr. W. A. Tookey.)

stated that the mixture strength was calculable in terms of total cylinder volume, and, that to obtain an equivalent mixture strength, less gas was required in proportion to the diminution of clearance volume.

The formula Mr. Davis had given that evening was new to him. Mr. Davis had stated that the formula he gave referred only to "hit-and-miss" governed engines; and, as far as the speaker could see, it did not make allowance for any variation of calorific value of the gas; it merely gave the number of explosions that could be obtained from 1 cubic foot of gas when the engine was working most efficiently, but at some particular calorific value which might or might not apply in particular instances. Therefore he (the author) thought Mr. Davis's formula, simple though it might be, was likely to be misleading. The "factor" which he had put before the members in the Paper not only related to gas-engines, but was also applicable to petrol engines, and liquid fuel engines of all kinds. What help was it to an engineer who was interested in petrol engines or semi-Diesel engines or Diesel engines to know that a particular gas-engine consumed so many cubic feet of gas of undetermined calorific value? By giving a "factor" which expressed the mixture strength of the whole cylinder contents in terms of B.Th.U., he had endeavoured to give a standard which could be universally applied to all types of internal-combustion engines. He noted that Mr. Davis did not approve of the decimal system when used in connexion with gas-engine measurements, but he did not think he need say any more on that point, seeing that it was obvious that the figures of dimensions given in the Paper were nominal rather than actual.

He entirely agreed with Mr. Davis that it would be the height of luxury to put an indicator into the hands of an ordinary gas-engine driver, but it would be noticed that he had said in the final paragraph of the Paper that the indicator should be used when the utmost efficiency must be maintained. To obtain the utmost efficiency it was necessary to have a high-class man, not an engine-driver who was merely an engine-driver, but an engineer who was competent to handle an indicator properly. He did not intend for

a moment that any remarks of his in the Paper should convey the impression that he advocated an indicator being put into the hands of any and every driver, but only of engine-drivers in power-houses, such as central stations, where it was necessary to get the best results out of the particular combustible used.

He desired to thank Captain Sankey for his very valuable contribution to the discussion. Captain Sankey had shown that the factor he (the author) had put forward in the Paper had also a scientific application, and for members to realize from Captain Sankey's remarks that the factor could be used in finding out what had always been a difficult thing to ascertain, that is, the temperature of the charge, made the discussion that evening a very valuable one.

Mr. Hawksley had asked why the work could not be carried out at nights and week-ends. Seven hundred week-ends would of course mean a very considerable period of one's existence, but he thought Mr. Hawksley had misunderstood what had been said with regard to indicating gear. What he meant to convey was that it was imperative for the engine to be stopped and the indicator gear fitted to it at a time when the proprietor would not be prejudicially affected. As the engines were never working throughout the midday meal-hour, that opportunity therefore was taken for the making of the close examination of the valve mechanism, etc., and for the fitting up of the gear. All tests were made under actual conditions of work during the afternoon working hours.

Mr. Chamberlain had suggested that, as some difficulty was experienced with the ordinary pendulum reducing gear, the use of a reducing wheel might have overcome such difficulties. The ordinary reducing wheel mechanism had never recommended itself to him, for many reasons. Lately he had been using a special type of reducing gear with a system of pulleys, but it was rather outside the scope of the Paper to give its exact details. As a matter of fact the pendulum gear was used throughout the tests in an attempt to get really reliable results from indicating tackle, and the author considered it more suitable for his purpose than the ordinary reducing wheel referred to by Mr. Chamberlain.

(Mr. W. A. Tookey.)

Mr. Murphy's remarks led him to suggest that the computation throughout the Paper had been intended mainly for illustrative purposes. He had deliberately used figures which were only approximate figures. He quite appreciated Mr. Murphy's point about working to three or four places of decimals in a Paper dealing with the commercial side of the subject; but one got into the habit of using a slide-rule and putting down all the figures which could be read or inferred from it. That must be his excuse for the figures which might suggest unwarranted meticulous accuracy. With regard to the question of maximum efficiency, that of course must vary with every engine, and was quite easily obtained from experiment; but it might be interesting to mention the "factor" value obtainable varied with the different engines, and with different compression ratios. Taking, for example, a gas-engine of the modern type working with throttle-governing, the factor value at the top load would be, as had been said, somewhere between 2.1 and 2.3, or probably in exceptional cases 2.4; but as the governor came into operation it reduced not only the amount of gas, but the amount of air admitted, and thus varied the mixture-strength even in those engines which were supposed to work with a practically constant mixture. The mixture strength was never constant in quantity-governed engines, but varied with every depression of the inlet valve, as the author's formula showed. But the "factor" value dropped also as the compression ratio decreased, and he therefore thought that the use of the "factor" value by future experimenters, who had every facility at their command for measuring temperatures and other things with great refinement, would be able to help practical men very considerably in ascertaining the maximum efficiency that could be expected under different temperature conditions, and in determining the system of governing which might prove to be the most efficient, taking everything into consideration. He desired to thank the Members for the attention with which they had listened to the Paper, and for the kindly way in which they had received it.

Communications.

Mr. ALAN E. L. CHORLTON wrote that there were two points in the Paper which he would like to discuss, namely (a) mixture strength, and (b) volumetric efficiency of the cylinder. With regard to the mixture strength, while recognizing the factor put forward by the author as a useful one, he was disappointed that it had not been applied to ordinary work, that is, to larger engines running on different gases, such as blast-furnace gas, producer gas, coke-oven gas, etc. He would be glad, therefore, if the author, in his reply, would state what he considered the best values for the factor under the above conditions; furthermore, if for gas consumption, how it affected the b.h.p. of the engine considered commercially.

With regard to the volumetric efficiency of the cylinder, the author, he thought, did not mention fully how this was governed, and, if low, how it could be most advantageously remedied. If the prime governing factors were: (1) area of valves and fluid friction, (2) setting of valves, and (3) length of induction and eduction pipes, it would be useful if the author would state his experience on the effects on these three or other factors, and the remedies he recommended. In two-cycle engines the length of the exhaust pipe with its capacities was the most important factor. Could the author give any records of fluid vibration in exhaust and inlet pipes?

The writer had made many tests, using pipes of varying diameters and lengths, with combinations of silencing boxes, exhaust boilers, etc., to determine if possible the governing factors of the vibration waves occurring therein, with their reactive effect in the engine cylinder. Many interesting results were obtained; but it was found to be extremely difficult to determine a formula which would meet the usual conditions of engine installations. A method was arrived at, however, for damping down an oscillation, and at the same time, practically increasing its period in order to fit in accurately with what was required in the main cylinder of the engine. As was well known, by a suitable length of exhaust pipe, scavenging could be induced in the cylinder, and on the other hand,

(Mr. Alan E. L. Chorlton.)

supercharging could be effected, that is, over 100 per cent. volumetric efficiency. This involved (as was tried by Mr. Atkinson with the Crossley engine) a very long exhaust pipe. Where the vibration difficulty was perhaps commercially more apparent, was in the multi-cylinder engine. Here the effect was to prevent full charging of all the cylinders, consequently the power given off was not equal to the number of cylinders times the unit cylinder output. It would have been noticed, however, that in racing multi-cylinder motor-cars, a special form of induction pipe to overcome this difficulty had given improved results.

Another method was to adopt the principle of "evening" out the vibrations by some compensating device, and the writer had had under trial an apparatus of this description which had so far given improved results over the plain pipe itself. The whole question of the vibration in the inlet and exhaust pipes of internal-combustion engines was most important, in fact, it was one of the governing factors of the engine itself; and it would be greatly to the advantage of the trade in general if some public work could be undertaken on this subject, either by a Research Committee or by one of the Universities or Technical Colleges.

Mr. R. A. COWELL wrote that the Paper apparently treated of the "tuning up" of small engines on town's gas only, as the author made no reference at all to results obtained on any other gas, either Mond (bituminous) plant, coke-oven, or blast-furnace gas, and it seemed to be wholly confined to illuminating gas. He thought it would have been appreciated if the author had given data from some of the other gases mentioned in commercial service, as of course, with even a moderate size of plant, town's gas was out of the question on account of price, excepting possibly in very special areas, such as Sheffield or Widnes, where town's gas was only about one-half the price it was anywhere else, which was certainly not the case round London. Further, the largest size of engine dealt with appeared to be about 220 i.h.p., and he concluded that a considerable number of these were of quite an obsolete pattern, so that the requisite adjustments might apply in some particular cases, and most probably would not in the

case of more modern plant, where there would be a dissimilarity in form of design, arrangement, and shape of combustion head, relative clearance to stroke, volume, etc.

Taking the consumption figures given in some of the test reports, the author assumed the lower calorific value of the gas to be 500 B.Th.U. per cubic foot, and not to vary. Personally, he questioned this, because, in the course of ten years' continuous practical testing of internal-combustion engines, he had not found the gas value sufficiently steady for accurate tests as not to require calorific tests being taken at regular intervals, particularly in the case where relative mixture strengths were being considered, and he thought one could easily be misled in this data due to this cause. He had found town's gas vary as much as 40 B.Th.U. in so short an interval as five minutes, particularly where there were one or more sources of supply going into the same ring of mains, such as would be the case with the South Metropolitan Gas Co. Probably the author would enlighten them a little further on this point, as, granted the mixture-strength was a most important factor, particularly with town's gas, but of somewhat less importance with the lower value gases, the tendency in the past with most gas companies (particularly before the advent of the incandescent burner) had been to go solely on candle power, and to neglect calorific value. The gas had been watered down as much as possible to make the most of it at the expense of the B.Th.U.; now that the incandescent lighting was practically universal the heat value was receiving a little more attention.

With reference to the consumption figures quoted, the author mentioned one of 12.6 cubic feet per i.h.p. hour on a 220 i.h.p. engine. Was this arrived at from the indicator diagram in the ordinary way, as he thought results such as these were too good? It made one question the accuracy of the diagrams, as 12.6 cubic feet with gas at 500 B.Th.U. lower value was equivalent to 6,300 B.Th.U. per i.h.p. hour; and allowing a mechanical efficiency even as low as 83 per cent. would only be 7,600 B.Th.U. per b.h.p. hour, which, he thought, would be admitted somewhat low, particularly in the case of a small plant under commercial operation.

(Mr. R. A. Cowell.)

If the gas value went below 500 B.Th.U. per cubic feet which, was quite probable, it would make it lower still. While quite appreciating the difficulties which the author had had to contend with, and the short time at his disposal for necessary adjustments, etc., it would be most interesting to know if he could corroborate such figures by an accurate brake-test, and absolutely eliminate indicator diagrams, as it was well known, particularly on high-speed steam-engine work, these were not reliable.

In the latter part of his Paper, the author said, with reference to the output of power being dependent upon the mixture strength, the richer the mixture the more powerful the impulse in terms of mean pressure. He (the writer) thought this was not so in every case, and it would be most interesting to know the views of other engineers on this matter. Did this statement apply to one particular type of engine or speaking generally? In any case it would be interesting to know on what type and size of engine these experiments were carried out.

Mr. KENNETH R. W. Cox wrote that the author's tests were apparently all taken from comparatively small engines working on town's gas, and in the case of these small installations it was usually considered sufficient to assume the actual output from the indicator diagram. In the case of large engines, say 200 b.h.p. and upwards, more accurate tests were demanded to demonstrate the output of the engine and its ability to meet its guaranteed conditions. Where there was any difficulty in measuring the exact output on site, such as an engine driving a mill, a test was usually carried out at the maker's works, and the output was carefully measured by means of a water dynamometer or by coupling the engine directly to an electric generator. The gas quantity was measured by means of a meter, and this amount corrected to the guaranteed conditions of temperature, pressure, and calorific value. The calorific value was also taken simultaneously with the gas-meter readings, and, as these readings were usually taken at stated periods over several hours, a very accurate measurement of the thermal units used to develop a given horse-power was obtained.

Diagrams were also taken—but these were taken during the

"tuning-up" period previous to the official tests—and the object of these diagrams was not so much to obtain the indicated horse-power as to ascertain that the compression was correct, the ignition taking place at the correct point, and also in the case of multi-cylinder engines, to balance up the power in each cylinder so that the load was equally distributed between them. Light spring cards would also be of considerable use to check the valve-setting, and to make sure that there was no back-pressure in the exhaust. For calculating the power developed from the indicator cards, a very accurate and rigid gear was absolutely necessary in order to obtain correct indicator cards, and any temporary rig, which, as the author suggested, could be fixed up in the meal-hour, was liable to lead one astray by giving distorted diagrams. Again, owing to the very heavy spring rate necessary for gas-engine indicating, a very slight distortion would make a great difference to the indicated horse-power.

Some of the figures obtained by the author were remarkable, as they showed a thermal efficiency very much higher than was usually obtained in practice. In Table 1 (page 10) a consumption of 12.36 cubic feet of gas of 500 B.Th.U. was obtained. This gave a thermal efficiency of 0.412, practically equal to the highest result mentioned by Professor Burstall in his Third Report to the Gas-Engine Research Committee.* Professor Burstall's figure was obtained on a specially constructed engine having a cylinder designed to give the maximum efficiency, and also provided with scavenging, so that the result obtained by Mr. Tookey rather led one to suggest that either the mean pressure shown on the diagram was higher than that actually obtained or that the gas-value was higher than 500 B.Th.U. per cubic foot.

Throughout the tests the author had assumed the value of the exponent η to be 1.3 (page 14) and stated that this was near enough for commercial practice. This figure, however, varied so very widely that the assumption was hardly good enough to get even an approximate idea of the clearance volume. As Professor

* Proceedings, I.Mech.E., 1908, page 5.

(Mr. Kenneth R. W. Cox.)

Burstall showed, this might vary between 1.24 and 1.35 on an engine having a purely cylindrical clearance space, but with a vertical engine having a large surface in the combustion space in relation to its volume—such as would be found on a petrol engine having valves on either side of the cylinder—this exponent would vary still further.

Mr. FREDERICK G. HATCH (Manchester) wrote that the author had dealt only with the testing of engines on town's gas, but he (Mr. Hatch) felt sure that the application of this method would be universally applied to all tests on internal-combustion engines, as it seemed to give a standard method of comparison of efficiency for engines working on any fuel. If he might do so, he would like to give to the factor which the author had expounded the name of the "Tookey" factor.

When making tests of the engines referred to in Tables 1, 2 and 3, he would like to ask if any reference were made to the actual load carried by the engines in relation to their rated load, and if so, what relation the load factor had to the "Tookey" factor obtained. In referring to the test given in Table 3 (page 19), the high factor of 2.43 was obtained. This appeared to the writer to be higher than that which could usually be obtained in any gas-engine working commercially, and corresponded to a heat consumption of 6,250 B.Th.U. per i.h.p. From the particulars given in the Table he would imagine that the rated power of an engine of the dimensions given would be about 45 i.h.p., and therefore at the time of the test this engine would be running at about half load. Governing as it did—on the hit-and-miss principle—one explosion would be followed by a cut-out, which would scavenge the cylinder and probably lead to more efficient combustion, and a higher resulting "Tookey" factor than would be obtained working at full load. Did the author attribute the high "Tookey" factor obtained in this instance to this condition of working, rather than to the possibility of the gas having a higher value than the average, to which he would refer later? It was interesting to compare Table 3 with Table 1. From the sizes given, apparently the 24-inch by 30-inch engine was working at nearly full load, yet the "Tookey"

factor, "as found," was 2.158 at full load compared with 2.43 for the smaller engine at half load.

For the purposes of these tests, the author had assumed that the calorific value of the gas was constant at 500 B.Th.U. per cubic foot, and for the object of the tests which he mentioned this assumption was probably quite correct enough for the ends in view. In test-plate work, however, it was necessary to be a little more accurate, and on the tests of the Browett-Lindley engine mentioned, gas calorimeter tests were taken of the value of town's gas throughout the day, and the calorific value was found to vary from 470 B.Th.U. per cubic foot in the morning up to 524 B.Th.U. per cubic foot in the afternoon. If the gas used at the time of the test given in Table 3 had a calorific value above the average for a short period, would it not show a higher factor than that actually obtained, and would this be the reason for the high factor of 2.43 obtained rather than the fact of the engine working at half load?

The adoption of the "Tookey" factor method of comparison would necessitate more care being taken in ascertaining calorific values of fuel gas used, more particularly when applied to engines using fuel gas, and would also necessitate the measuring of the gas supplied to the engine. At the present time there did not appear to be any agreement on a standard method of ascertaining calorific values. Some engineers found the heat value of the gas by analysing samples and computing the heat value from the various constituents. This did not appear to be satisfactory, especially when samples were taken during lengthy periods, as these only gave an average calorific value, whereas what was required was the actual calorific value of the gas at the moment the light spring diagram, from which the volumetric efficiency was calculated, was taken. Neither the analytical nor the Junker's type calorimeter would meet this condition, and it appeared to the writer, therefore, that the recording calorimeter must be used.

It would have been interesting if the author had given some results from engines governed by throttling the amount of gas or amount of mixture, as, for the larger engines, one of these methods was now becoming universally adopted. All the engines mentioned

(Mr. Frederick G. Hatch.)

in the Paper, of which he had given the "Tookey" factor, had been governed on the hit-and-miss principle, and any alteration in the load would not affect appreciably the mixture strength of the charge when entering the cylinder, the only alteration being the amount of residual left to mix with the incoming charge. With engines governed by throttling the amount of gas only, any variation in the load would alter the mixture strength of charge in the cylinder, and it was conceivable under these conditions that the efficiency of combustions might change as the load varied, giving a change in the "Tookey" factor obtained.

Mr. A. E. MALPAS wrote that the problem of cheap power was one of the most important with which engineers had to deal, and was one which had engaged the attention of the writer now for many years. The enterprise of the London gas companies in undertaking the series of tests which formed the basis of the present Paper was highly to be commended, as tending to maintain their consumers' plants in the most efficient state, which it was necessary to do in order to meet the competition of the electric motor.

With large industrial plants using large quantities of gas, and other gases beside power-gas, one had not always the advantage even of being able to measure the quantity, since large gas-meters were in general too costly. In the case of a large installation of six gas-engines, each of 2,000 h.p., with which the writer had had some experience, the only control possible was through the coal used and the gas analysis. The author was therefore happy in that he had, in general, to deal with small installations fitted with a gas-meter. In connexion with the measurement of gas volumes, the writer was at present experimenting with a method which gave practically accurate results, when dealing with large quantities of gas, for quite a small capital outlay. The apparatus was at present being employed in connexion with a nitrogen plant liquefying 100 tons of air per day. Although such plants could hardly be classed as internal-combustion engines, yet cases of explosion had been known to occur with them through the accumulation of solid acetylene in the liquid oxygen receivers. It was interesting to

note, that under the conditions under which engines of the class considered were usually worked, that the exponent to the compression curve came out about 1.3. Working on a reversible cycle such as the Carnot cycle, this exponent should be equal to the ratio of the specific heats of the mixture at constant pressure and at constant volume. If the cylinder walls cooled the mixture, then the terminal pressure would be less, and the exponent would be less than the ratio of the specific heats.

Some twelve years ago the writer was concerned with the operation of two gas-engines of 250 b.h.p., for that day rather large. The conditions of working were somewhat unusual. In fact, it was the first case of its kind in England. The gas used was supplied from a battery of coke-ovens, and was not altogether constant in quality. The load was a continuous one, and consisted of electric furnaces for the manufacture of calcium carbide, which at that time commanded a higher price in the English markets than it did now. The load factor was therefore 100 per cent., and the number of working hours per week 168. This state of affairs led to trouble, as might be expected, and the writer, who at that time knew nothing about the constant of 1.3, had to adopt other measures. In default of a better method of determining the clearance, an engine was put on to a dead-centre and filled with water. The result gave the clearance volume as 1.56 cubic feet, the piston displacement being 5.46 cubic feet. The compression pressure was 83 lb. per square inch. Calculated according to the method given in the Paper the clearance volume would be 1.545 cubic feet, a sufficiently close agreement. However, at that time the particular difficulty seemed to have been to determine the temperature at the end of the suction stroke as a starting point in the construction of the entropy diagram. To solve it, a hole was drilled in the exhaust pipe just below one of the valves, into which a bolt pyrometer was inserted. The result gave the exhaust temperature as 500° C. The more expensive instruments used now might possibly be somewhat more accurate. The same hole was used to take samples of the exhaust gases, which enabled the ratio of air to gas to be determined. The engine running at 145 revolutions per minute,

(Mr. A. E. Malpas.)

governing on hit-and-miss, was doing 90 per cent. full load, when a simultaneous sample of the gas supplied and of the exhaust gases were taken. The gas analysed as follows :—

H	.	.	.	59.8	percentage by volume.			
CH ₄	.	.	.	26.2		"	"	"
C ₃ H ₈	.	.	.	2.4		"	"	"
CO ₂	.	.	.	3.2		"	"	"
CO	.	.	.	6.7		"	"	"
O	.	.	.	0.1		"	"	"
N	.	.	.	1.6		"	"	"
				100.0				

Calorific value by Junker's calorimeter 468 B.Th.U. lower,

520 " higher.

The exhaust gas was :—

CO ₂	.	.	.	5.5	per cent.			
O	.	.	.	10.0		"	"	
N	.	.	.	84.5		"	"	
				100.0				

Corrected for the 10 per cent. air-shots the CO₂ would be 6.2 per cent. It could be calculated from these figures, which were sufficient for the purpose, that the ratio of air to gas was 7.45 to 1. The temperature at the end of the suction stroke was 63° C. assuming no heating from the cylinder walls.

The composition of the mixture on the suction stroke was :

Air	.	.	.	79.3	percentage by volume.			
Gas	.	.	.	10.3		"	"	"
Residuals	.	.	.	10.4		"	"	"
				100.0				

And that the ratio of the specific heats was

$$\frac{C_p}{C_v} = 1.39.$$

That this figure was higher than that reported as exponent to be adopted for the compression curve could only be attributed to the cooling action of the cylinder walls; and this was really the crux of the whole question. If the cylinder walls did not cool sufficiently then trouble must ensue.

Taking the three cases quoted by the author, the heat efficiency taken on the i.h.p. came out as follows:—

Table 1	.	.	.	41.4	per cent.
Table 2	.	.	.	39.2	„ „
Table 3	.	.	.	40.5	„ „
				<hr/>	
				100.0	

which were certainly very excellent results if they were true.

It was not clear, however, whether the 500 B.Th.U. per cubic foot mentioned was higher or lower value. In the case of the engine to which he had referred, the efficiencies were 31.5 per cent. on higher value and 29.3 per cent. on lower value. In this case the

mixture strength was 40.5 B.Th.U. per cubic foot at the suction temperature, and the factor $\frac{MP}{MS}$ was 1.84. This figure was low, owing probably to the low compression pressure. On account of the high percentage of hydrogen in the waste coke-oven gases to be used, it was considered desirable by Mr. E. J. Duff, in designing the plant, to sacrifice somewhat in the economy in order to reduce the tendency to pre-ignitions. The diagram, Fig. 10, showed also that the firing was a little late, but it was found under the actual working conditions that pre-ignitions were likely to occur if the firing was advanced too far.

In conclusion, he wished to congratulate the author on having evolved what appeared to be a quick and practical way of judging the performance of an engine, and agreed with him that a gas-

(Mr. A. E. Malpas.)

meter or equivalent apparatus for measuring the quantity should be installed wherever gas of any sort was being used for any purpose.

Mr. W. A. TOOKEY wrote that several members had commented upon the possibility of wide variations occurring in the calorific value of the gas used from time to time, which would affect the accuracy of the figures given in the three tests which the author used as examples in his Paper in order to show the application of his "factor." He would therefore like to emphasize the fact that the examples mentioned must not be taken otherwise than as demonstrations of the method of comparison. Certainly he had endeavoured to use figures and values as nearly accurate as had been possible under the circumstances of each test, but for obvious reasons, it was impossible to set up calorimeters and other instruments, for each test had to be taken in hand at short notice, and neither facilities nor opportunities were provided for doing more than indicating the engine with due care and reading the gas-meter over short periods.

Nevertheless, from the weekly reports issued by the London County Council, the value taken by the author agreed very closely with the average figures obtained from the observations of inspectors in the testing stations throughout the area supplied by the South Metropolitan Gas Co. In this connexion it appeared desirable to give two abstracts from Tables contained in *The Journal of Gas Lighting* (20th January 1914) in which figures were given, compiled from the official reports, showing the variations of calorific value for the last quarter of 1913 and also for the whole year. From Tables 4 and 5 the following figures were taken.

The computations of mixture strengths and factor values could be taken as approximate only in the examples given in the body of the Paper, for although the average calorific value was practically that upon which all calculations were based ($128 \text{ calories} \times 3.968 = 508 \text{ B.Th.U.}$) yet the maximum recorded was 12 per cent. above and the minimum was 7 per cent. below.

TABLE 4.

Summary of Testings of Calorific Power (Gross and Net) for the Fourth Quarter of the Year (Calories per cubic foot).

(South Metropolitan Gas Co.)

	Average.			Maximum.			Minimum.		
	1911	1912	1913	1911	1912	1913	1911	1912	1913
Gross . .	144.2	144.3	144.2	156.4	163.4	160.2	134.9	133.2	133.9
Net . . .	128.5	128.5	128.3	140.6	145.8	143.4	119.7	118.4	118.8

TABLE 5.

Summary of Testings of Calorific Power (Gross and Net) for the Whole Year (Calories per cubic foot).

(South Metropolitan Gas Co.)

	Average.			Maximum.			Minimum.		
	1911	1912	1913	1911	1912	1913	1911	1912	1913
Gross . .	144.6	143.4	143.9	160.3	163.4	160.2	133.5	131.7	133.9
Net . . .	128.9	127.7	128.1	144.5	145.5	143.4	119.0	116.6	118.8

As Mr. Hatch pointed out (page 50), there could be no question that gas-engine makers would find it a decided advantage to install a recording calorimeter as an indispensable item in their test-plate equipment. The author believed that in Messrs. Browett Lindley's works, Mr. Hatch had appreciated the value of such a piece of apparatus on many occasions and particularly when gas-engines, under test after erection for tuning-up purposes, were found to be affected by variations in quality of gas coming forward from the gas-producer plant, for, under these circumstances,

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it was a difficult matter to keep the gas uniform, fluctuations of load and stoppages for adjustment of mechanical details causing considerable differences in the quality produced with consequent effect upon the engine performances.

TABLE 6.

*11½ by 21 inches Crossley Gas-Engine.**Tested by Professor Bertram Hopkinson.*

Actual Piston Displacement		1.2623 cubic feet.
Actual Clearance Volume		0.2355 „
Actual Total Cylinder Volume.		1.4978 „
Effective Piston Displacement (Volumetric		
Efficiency, say, 0.965)		1.22 „
Effective Cylinder Volume		1.4555 „
Calorific Value of Gas		600 B.Th.U. per cubic foot.

Test No.	Gas. Cubic feet per impulse.	B.Th.U. per impulse.	Mixture Strength. B.Th.U. per cubic foot Effective Cylinder Volume.	Mean Pressure.	Factor.	Thermal Efficiency.
						Per cent.
1	0.1275	76.5	52.6	102.2	1.942	32.5
3	0.1147	68.85	47.3	98.4	2.08	34.7
5	0.1005	60.3	41.45	90.2	2.175	36.5
2	0.1275	76.5	52.6	108.4	2.06	34.5
4	0.1140	68.4	47.0	101.6	2.16	36.1

With regard to the variation of the "factor" value in connexion with throttle-governed engines, and to the statements made respecting the generally accepted dictum that highest efficiencies could only be

achieved with an engine working at the maximum compression pressure for which it has been designed and with one certain strength of mixture, the author thought it advisable to include in this reply two Tables that were given in the original draft of his Paper but afterwards omitted, partly from a desire to keep the length within due bounds, and partly owing to the fact that it was necessary to assume a figure for "volumetric efficiency" seeing that no "light spring" diagrams were available for the tests concerned.

FIG. 11.—Prepared from the Third Report of the Gas-Engine Research Committee.
Proc. I.Mech.E., 1908, pages 34-5. ;

*B.Th.U. contained in each Cubic Foot of Total Cylinder Volume.
(Piston Displacement plus Clearance.)*

Table 6 referred to Professor Hopkinson's five tests reported to the Institution in 1908 (Proceedings, page 417).

The actual clearance volume was determined by experiment, so that no computation based upon the index 1.3 for the compression curve was necessary. In his Paper Professor Hopkinson stated that all the tests were completed within two or three hours. He did not state the order in which they were made, but presumably having adjusted his apparatus for one mixture strength, full load and light load figures were taken one after the other, and afterwards,

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TABLE 7.

Results of Tests by Professor Burstall.

(Third Report of the I.Mech.E. Gas-Engine Research Committee, 1908.)

Test No.	Compression Pressure. Lb. per square inch.	Mixture Strength. B.Th.U. per cubic foot.	Mean Pressure. Lb. per square inch.	Factor. M.P. M.S.	Ignition Lead (Seconds).	Actual Thermal Efficiency on i.h.p.
						Per cent.
A 1	212	32·79	80	2·44	0·062	39·58
2	222	35·37	86	2·44	0·053	39·24
B 2	201	35·0	87	2·485	0·065	40·01
3	191	33·44	82	2·45	0·067	39·55
C 1	172	33·29	90	2·7	0·069	42·91
2	175	36·9	92	2·49	0·047	39·87
3	168	33·75	87	2·58	0·053	41·14
4	175	37·79	99	2·62	0·045	41·94
D 2	159	41·09	106	2·58	0·051	40·42
3	166	43·3	110	2·54	0·053	39·78
4	154	32·86	82	2·5	0·064	39·56
5	158	35·15	93	2·645	0·057	41·66
F 1	137	36·79	93	2·53	0·066	39·24
2	129	54·49	114	2·09	0·038	32·46
4	132	34·24	86	2·51	0·056	39·03
5	129	53·32	113	2·125	0·034	32·81
J 1	124	35·3	82	2·325	0·056	34·79
2	132	47·45	106	2·235	0·036	33·85
3	124	39·44	94	2·385	0·036	35·91
Q 1	88	50·14	100	2·0	0·049	28·24
2	87	33·95	72	2·12	0·071	30·07
3	87	39·95	88	2·2	0·053	31·47

the mixture strength being changed, similar tests were repeated. From the figures given in the Table for thermal efficiency it would be seen that there was little difference between tests 2 and 3 and between tests 4 and 5, notwithstanding the difference in mixture strengths.

From Table 7, and especially from Fig. 11 (page 59), which had been prepared from the figures given by Professor Burstall in his Third Report of the Research Committee as referred to in the Paper (page 11), it would be evident that over a wide range of mixture strength, equivalent thermal efficiencies were obtained and that the mean pressures increased with mixture strength irrespective of compression pressure and thermal efficiency. A further lesson taught by Professor Burstall's results, when compared on the basis suggested by the author, was that undoubtedly ignition timing had to be correlated to the strength of mixture.

Comparatively few opportunities had yet presented themselves to the author for recording and comparing the "factor" values in relation to throttle-governed engines but, as far as the information yet available permitted conclusions to be formed, he saw nothing that pointed to the desirability of qualifying any of the statements made on page 11, to which references had been made in the written contributions to the discussion. Within the last few weeks the author had had an opportunity of testing one of the most modern types of gas-engine, governed by variable lift of the inlet-valves, the gas and air valves being arranged on a common spindle with the former spring held so that it left and regained its seat, respectively later and earlier than the air-valve. Tests were made at three different loads, and the engine being direct-coupled to a dynamo in connexion with an electric lighting installation, close readings were obtainable while the load remained uniform. At light load, 11 i.h.p. was developed as computed from the diagrams taken, the consumption of gas being at the rate of 17 cubic feet per i.h.p.-hour. At 20 i.h.p., 16.75 cubic feet; and at 25.5 i.h.p. (full load), 15.7 cubic feet. From these figures it was evident that a reduction of load to 40 per cent. of full output on the i.h.p. (equivalent to 20 per cent. on b.h.p. in the particular circumstances)

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only involved a decrease in thermal efficiency of the order of 8 per cent., and this without any attempt being made to lessen the rate of consumption at the lighter loads, such as by varying the timing of the ignition spark to suit better the weaker and less dense mixtures then admitted. Computing the mixture strength in accordance with the author's suggestion, the figures were 26.3 to 43.1 B.Th.U. per cubic foot, light and full load respectively. The compression pressures ranged from 60 to 120 lb. The light loads were taken first so that the engine was "warmed up" at the heavier loads while "cold" when the lower thermal efficiencies were noted. From this consideration alone, it might be safely conjectured that

FIG. 12.

Full-load Test-run showing Influence of Cylinder-temperature on "Factor-value."

under similar cylinder-jacket temperature conditions the difference of 8 per cent. would have certainly been reduced.

To show that cylinder temperature did affect the thermal efficiency of an engine from first starting up, the author gave a chart, Fig. 12, which depicted graphically the change in the "factor value" during the first three hours of a full-load test-run of a 4-cylinder vertical engine supplied with producer-gas under pressure, the calorific value of which was automatically recorded throughout the whole run of twenty hours. The quantity of gas was measured through a meter. The factor was calculated from indicator diagrams taken at regular intervals throughout, from each of the four cylinders.

The question had been raised by Mr. Chorlton (page 45) whether the factor had yet been applied to engines working

with blast-furnace or coke-oven gas. The author had recalculated test figures given by various experimenters in this country and on the Continent when the published figures had included references to compression pressures, but as Mr. Chorlton knew, the number of tests made upon large engines when the gas was actually measured

TABLE 8.

Willans-Diesel Engine, 4-cylinder.

Computed piston displacement	.	.	1.19 cubic ft. per cylinder.
„ clearance volume	.	.	0.08 „ „
„ total cylinder volume	.	.	1.27 „ „
„ calorific value	.	.	18,000 B.Th.U. per lb.

Load.	Impulses per min.	Oil. lb. per min.	Impulses per lb.	Charge volume (cu. ft.) per lb.	Mixture Strength. B.Th.U. per cu. ft.	Mean Pressure. lb. per sq. inch.	Factor M.P. ÷ M.S.	I.H.P.	Lb. per i.h.p. hour.
10% overload .	440	1.375	320	402	44.9	105.1	2.34	239.9	0.344
Full load . .	440	1.265	348	442.5	40.65	96.75	2.38	222.2	0.341
$\frac{3}{4}$ load . . .	448	1.015	441	561	32.1	75.4	2.35	175.0	0.348
$\frac{1}{2}$ load . . .	452	0.813	556	707	25.45	59.4	2.33	139.8	0.349
$\frac{1}{4}$ load . . .	456	0.533	855	1087	16.55	39.15	2.365	92.6	0.346

NOTE.—The above “factors” are based upon 100 per cent. volumetric efficiency.

were very few indeed, owing to the lack of facilities for dealing with large volumes of power-gas. From such tests as had been made, it could be taken that the factor value was approximately that mentioned in the Paper, namely, 2.0 to 2.3 lb. of m.e.p. per B.Th.U. per cubic foot of mixture, or thereabouts. It was this common agreement in the factor for all types of internal-combustion engines that had prompted the author to submit his method of comparison to the members of the Institution.

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In support of this universality of factor value, Table 8 (page 63) was interesting, referring as it did to a Willans-Diesel engine running at various loads, and reported to the Rugby Engineering Society by Mr. Pfeiderer about a year ago. Here again it would be seen that mixture strength varied, but the thermal efficiency remained uniform throughout the load range. This was no doubt owing to the fact that in this type of engine the correlation of the ignition timing to the strength of mixture was unnecessary.

As to the steps to be taken in respect of improving low volumetric efficiencies, as a result of his experience with engines having very varying charge velocities, valve areas, length of exhaust and inlet connexions, etc., the author had formed the opinion that one of the main, if not the only consideration in this respect was to give the inlet-valve plenty of lag, so as to obtain full benefit from the inertia of the mixture flowing to the cylinder. While the area of the connexions should be ample, it was very desirable to create a local restriction, by means of a baffle-plate or other device near to the inlet-valve, to increase the velocity of admission coincident with the establishment of suction pressures of the order of one or two pounds per square inch below atmosphere. The admission curve on the light spring indicator diagram should show a decided rounding up while the outer dead-centre of the crank was being passed. The author had no records of exhaust-pipe pressure fluctuations that he cared to reproduce. He had taken such records on a clockwork-driven drum attached to a gas-engine indicator, but the few cases in which he had been able to do this had afforded no results of practical value. He agreed with Mr. Chorlton that, especially with two-cycle engines, the length and capacity of the exhaust pipe was a very important factor.

The author had noticed that in the printed report of the discussion some further criticisms had been made by Mr. Davis. These called for little comment. He could not accept Mr. Davis's remarks to the effect that an improvement of 15 per cent. in the gas consumption involved an increase of 10,000 cubic feet per

month, nor that any of the hundreds of engines tested had been left by the author or his assistants in an unsafe condition. As to the effect of gas-pressure variations, it was well known that an engine would work as well, that was to say with practically the same volumetric efficiency, when served from a suction-gas producer as from a gas-bag supplied at pressure. As long as, in the latter case, the pressure of supply was sufficient to keep the gas-bag distended, the actual pressure of supply as far as the engine was concerned was a matter of little moment. Indeed, this was self-evident when it was realized that the admission pressure of the charge being from one to two pounds per square inch below atmosphere—say from 28 to 56 inches of water—an inch or so of pressure variation above or below these figures could not make any appreciable difference. As to piston leakage affecting the compression pressure realized to an extent that would seriously vary the index of 1.3, this could easily be detected, and common sense was always supposed to be an attribute of anyone engaged in gas-engine testing.

Figs. 1 to 4. Refer to Test as Table 1.

Fig. 1.
Determination
of
Volumetric
Efficiency.

Fig. 2.
M.E.P. 87.5 lb.
Late ignition of charges
"load, as found."

Fig. 3.
Earlier ignition in
consequence
of adjustment of
both magnetos
by one notch.

Fig. 4.
Ignition of charges
"load, as
left," by
back end
magneto
being
further
advanced
by one
notch.

Figs. 5 and 6. Refer to test as Table 2.
Fig. 5. "Load, as found" rapid ignition due
to early firing and rich mixture.

Compare Fig. 6.

Fig. 6. "Load, as left" reduced supply of gas,
curtailment of exhaust period,
and retarded ignition.