REPORT No. 189

RELATION OF FUEL-AIR RATIO TO ENGINE PERFORMANCE

By STANWOOD W. SPARROW
Bureau of Standards

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SUMMARY.

The purpose of this investigation was to ascertain from engine tests the answers to the following questions:

(1) What gasoline-air ratio gives maximum power?

(2) Is the value of this ratio appreciably affected by such changes in air pressure or temperature as are encountered in flight?

(3) What percentage of its maximum power does an engine develop when supplied with a mixture giving minimum specific fuel consumption?

This report was prepared for publication by the National Advisory Committee for Aeronautics and the tests upon which it is based were made at the Bureau of Standards between October, 1919, and May, 1923. From these it is concluded that: (1) with gasoline as a fuel, maximum power is obtained with fuel-air mixtures of from 0.07 to 0.08 pounds of fuel per pound of air; (2) maximum power is obtained with approximately the same ratio over the range of air pressures and temperatures encountered in flight; (3) nearly minimum specific fuel consumption is secured by decreasing the fuel content of the charge until the power is 95 per cent of its maximum value.

Presumably this information is of most direct value to the carbureter engineer. A carbureter should supply the engine with a suitable mixture. This report discusses what mixtures have been found suitable for various engines. It also furnishes the engine designer with a basis for estimating how much greater piston displacement an engine operating with a maximum economy mixture should have than one operating with a maximum power mixture in order for both to be capable of the same power development.

INTRODUCTION.

Of the published information on the relation of fuel-air ratio to engine performance, little has been derived directly from tests of aviation engines. Nor have many tests been made at low air pressures and temperatures, conditions of major importance from an aviation standpoint. Much of the information that does relate directly to aviation problems is contained in Technical Reports Nos. 48, 49, and 108 of the National Advisory Committee for Aeronautics. The titles and authors of these reports are given in the bibliography.

Measurements of engine performance with various fuel-air ratios have been obtained in the course of tests of aviation engines in the altitude laboratory of the Bureau of Standards. In most instances these tests were not made primarily to investigate the effect of changes in fuel-air ratio, and hence the range of mixtures studied was sometimes rather narrow. In general however, the information covers a wide range of fuel-air ratios, air pressures, air temperatures, engine speeds, and engine loads. Moreover, such data have been obtained from tests of several engine types. It is believed that an analysis of the above-mentioned data will contribute materially to existing knowledge of the relation between fuel-air ratio and engine performance. The following report is the result of such an analysis.

FUEL-AIR RATIO AND ENGINE PERFORMANCE.

What gasoline-air ratio gives maximum power?—In adjusting the carbureter to obtain maximum power, the following method was employed. First the mixture was altered until approximately maximum power (for the chosen set of conditions) was obtained. As will be shown later values of power within 1 per cent of the maximum are obtained over a wide range of fuel-air ratios. Hence little difficulty was experienced in obtaining a mixture to give approximately maximum power. The next step was to find the leanest mixture with which this power could be developed. To accomplish this the mixture was made so lean as to cause a material decrease in power and then enriched just sufficiently for maximum power to be regained.

This method of adjustment is that usually employed in engine performance tests when there is time for operating with but one fuel-air ratio at each condition of engine speed, load, etc. The table of fuel-air ratios immediately following is based very largely upon data obtained in this fashion.

When time permits, it is preferable to follow the "mixture ratio run" method rather than to depend upon a single adjustment for maximum power. Runs of this type are made in the following manner. A series of runs is made with all controlled conditions maintained the same except the fuel-air ratio and the engine torque. Such a series shows the power and specific fuel consumption for various fuel-air ratios. Ordinarily sufficient measurements of friction horsepower are obtained to permit the indicated horsepower (brake horsepower + friction horsepower) corresponding to any brake horsepower measurements to be calculated.

TABLE I.

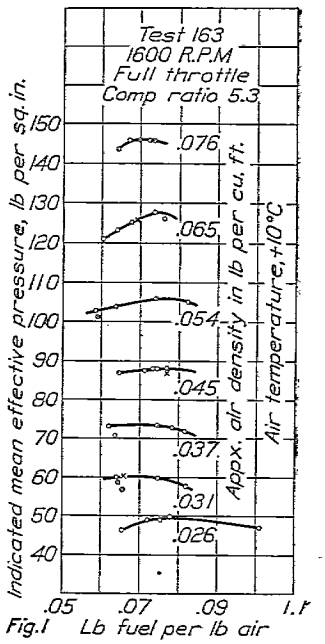
Engine data.	R. P. M.	Mixture ratio giving maximum power.	
		Pound gasoline per pound air.	Pound air per pound gasoline.
8 cylinders—bore 4.72 in., stroke 5.12 in.	1,600	0.077:1 to 0.071:1	13:1 to 14:1
8 cylinders—bore 5.51 in., stroke 5.91 in.	1,600 1,800	.074:1 to .067:1	13.5:1 to 15:1
12 cylinders—bore 5.00 in., stroke 7.00 in.	1,600 1,700	.083:1 to .071:1	12:1 to 14:1
6 cylinders—bore 6.50 in., stroke 7.09 in.	1,000 1,200 1,400 1,600	.083:1 to .071:1	12:1 to 14:1
6 cylinders—bore 5.90 in., stroke 7.09 in.	1,000 1,200 1,400 1,600	.077:1 to .071:1	13:1 to 14:1
12 cylinders—bore 6.62 in., stroke 7.5 in.	1,400 1,600 1,800 2,000	.083:1 to .067:1	12:1 to 15:1
6 cylinders—bore 6.62 in., stroke 7.5 in.	1,000 1,200 1,400 1,600	.071:1 to .059:1	[1] 14:1 to 17:1
8 cylinders—bore 5.51 in., stroke 5.91 in.	1,400 1,600 1,800 2,000	.078:1 to .070:1	13:1 to 14:1

[1] It seems improbable that maximum power should have been obtained with a mixture of 0.059 pound fuel per pound air not because this value is so much leaner than any of the others shown here but because it is considerably leaner t[illegible] The value is included because no particular incon[illegible] her engines having very large cylinders have shown [illegible] lean mixtures.

The information given in Table I is in part composed of results obtained from mixture ratio runs. The results obtained by both methods are in close agreement and it is probable that differences even between engines of the same type overshadow errors likely to result from the use of the first method described. From results to date it is concluded that ordinarily maximum power, at least in so far as aviation engines are concerned, is obtained with gasoline-air ratios of between 0.07 and 0.08 pounds of fuel per pound of air (12.5 to 14.5 pounds of air per pound of fuel).

Is a constant ratio of fuel to air desirable over the range of air pressures encountered in flight?—The answer to this question is "Yes," judged by results of mixture ratio runs with several engines over a wide range of conditions of engine operation. This statement is believed to be true whether the desired condition is maximum power or minimum specific fuel consumption.[1] There are less data in this report as to the latter condition because in many of the tests the carbureter did not furnish a mixture lean enough to permit minimum specific fuel consumption to be obtained.

Figure 1 shows a typical group of mixture ratio curves at entrance air pressures corresponding to altitudes ranging from sea level to 30,000 feet. In this group of curves the range of mixtures was limited by the carbureter rather than by the inability of the engine to operate at mixtures richer or leaner than those shown. From this figure it appears that approximately the same fuel-air ratio gives maximum power[2] over the range of pressures investigated. Inasmuch as within one per cent of maximum power can be obtained over a wide range of fuel-air ratios, the selection of the mixture ratio giving maximum power from curves such as those given in Figure 1 is somewhat uncertain. Obviously, if the power remains approximately the same over a given range of fuel-air ratios then the specific fuel consumption will vary almost directly as the fuel-air ratio. Hence, the specific fuel consumption at maximum power mixture ratios is very sensitive to changes in mixture ratio. A satisfactory method for determining whether or not the same fuel-air ratio is desirable over a given range of conditions would appear to be the following. From a group of curves such as shown in Figure 1 select the fuel-air ratio that appears to give maximum power. Next note the variation in specific fuel consumption (from curves similar to Figure 1 but with specific fuel consumption plotted versus fuel-air ratio) with this fuel-air ratio over the range of conditions investigated.



Test on 8-cylinder engine, bore 4.72 inches, stroke 5.12 inches.

If over this range the same fuel-air ratio gives essentially the same specific fuel consumption it would seem justifiable to conclude that the same fuel-air ratio is desirable. Figures 2, 3, 4, 5, 6, and 7 show results obtained in this fashion. These show the effect of changes in entrance air pressure for about 30 conditions of engine speed, load, compression ratio, etc. In a very few instances there appears to be a consistent increase or decrease in specific fuel consumption with change in entrance air density (at a constant air temperature). Nearly all, however, show no appreciable increase or decrease. From the information just presented it would appear that a constant ratio of fuel to air is desirable over the range of entrance air pressures studied.

Is a constant ratio of fuel to air desirable over the range of entrance air temperatures encountered in flight?—Again the answer is "Yes," so long as the fuel is aviation gasoline and the temperature range no greater than that studied in these experiments. Figure 8 shows a typical group of curves obtained from tests at several air temperatures. Ninety-five per cent of maximum power is seen to have been developed with nearly the same fuel-air ratio over the range of air temperatures investigated. The significance of this appears when it is shown later that ordinarily minimum specific fuel consumption results from impoverishing the mixture sufficiently to cause a 5 per cent decrease in power. An analysis of a large number of tests

[1] Specific fuel consumption is expressed as pounds of fuel per indicated horsepower hour or as pounds of fuel per brake horsepower hour.

[2] At constant engine speed, horsepower = $K \times$ mean effective pressure. The value of K can be calculated when the engine speed and piston displacement are known.

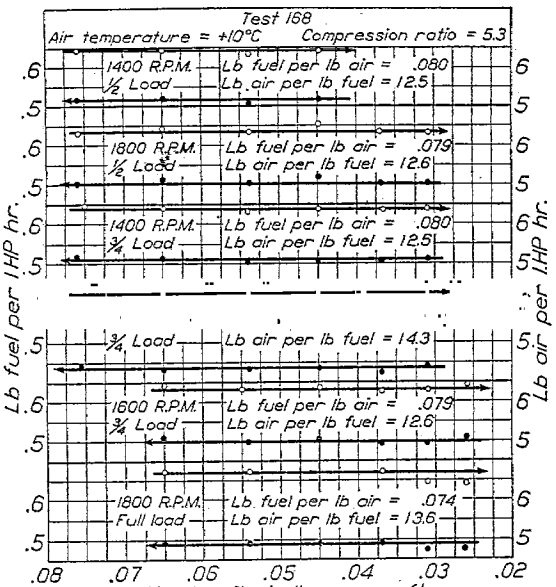


Fig.2

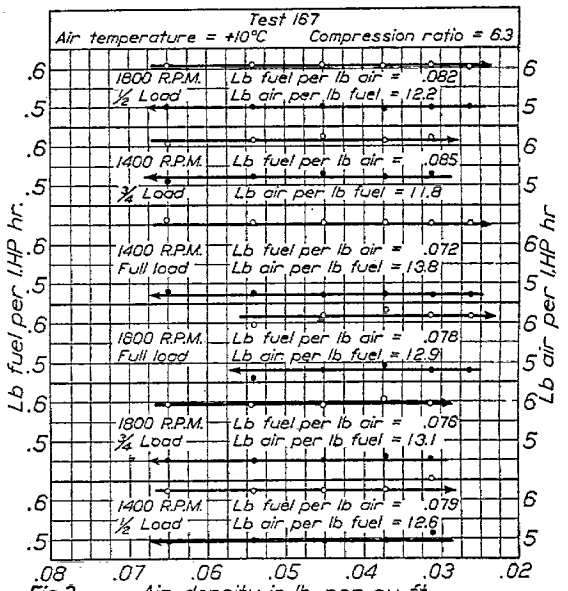


Fig.3

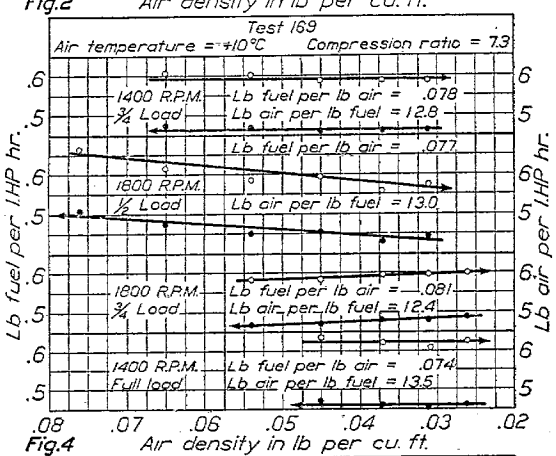


Fig.4

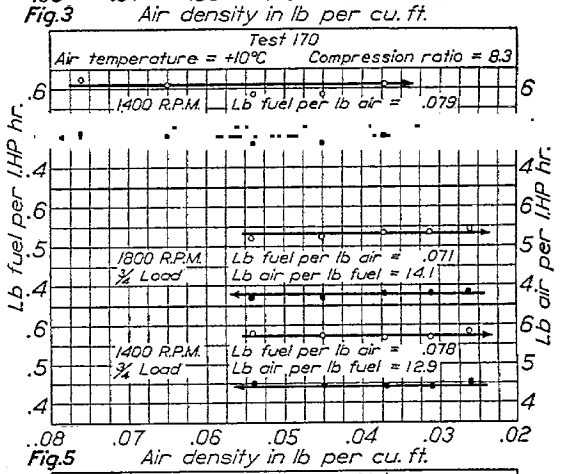


Fig.5

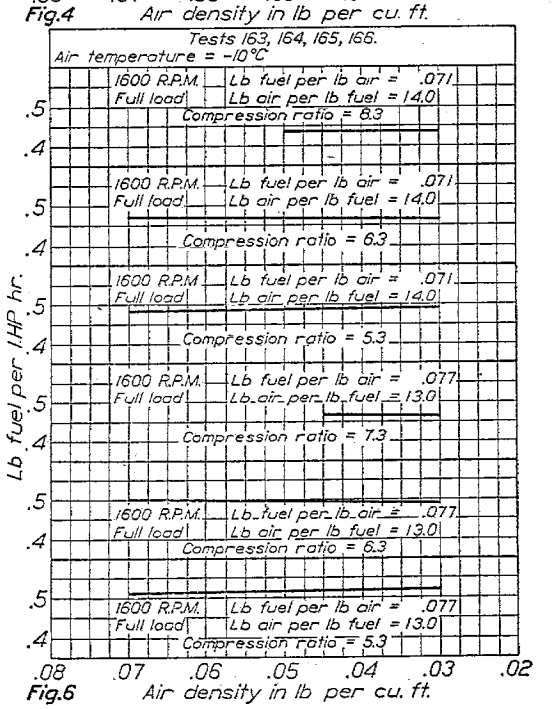


Fig.6

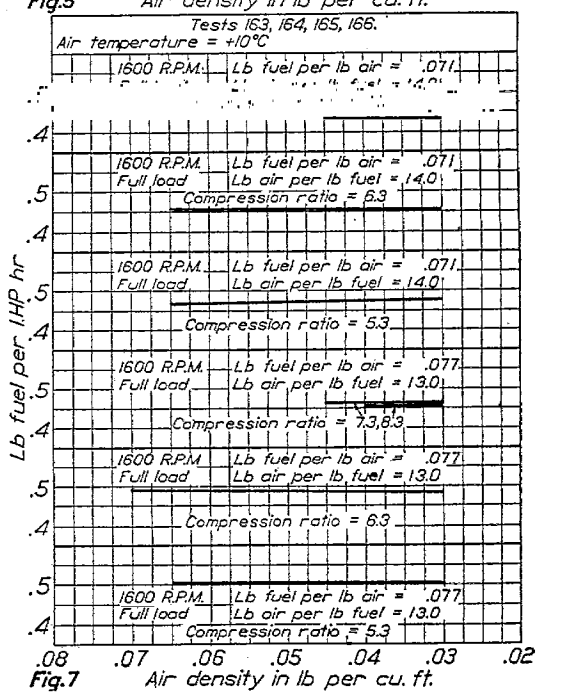
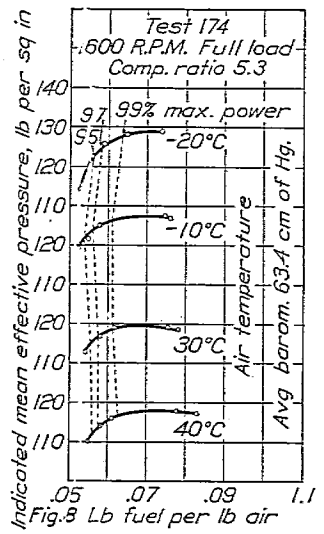


Fig.7

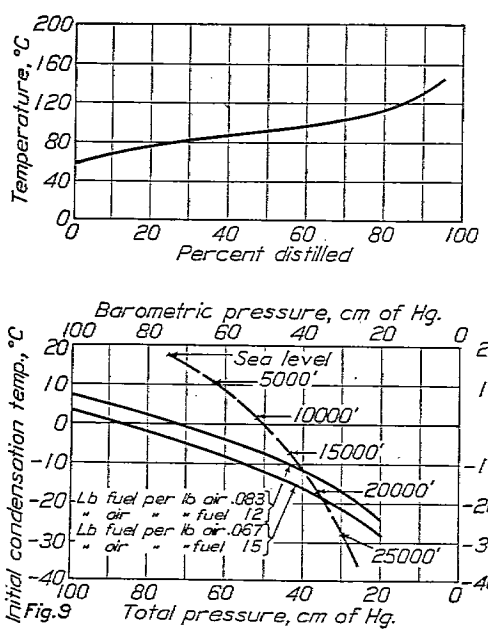
Engine used in test, 8 cylinder, bore 4.72 inches, stroke 5.12 inches.

covering a temperature range of from $-20°$ to $+40°$ C. shows maximum power to be obtained with approximately the same fuel-air ratio at each temperature. Similar results have been found in tests of motor-car engines using much less volatile fuels.[3] The volatility of the fuel is in reality the determining factor in this question. A constant fuel-air ratio is desirable only so long as a change of air temperature does not change appreciably the relative quality of the mixture supplied to the various cylinders or the amount of fuel that has been vaporized at the time the compression stroke is completed When this is not the case the mixture ratio should be changed when the temperature changes in order to compensate as far as possible for the change in vaporization or distribution that has taken place.



Test on 8-cylinder engine, bore 4.72 inches stroke 5.12 inches.

In so far as aviation work is concerned the conclusions cover a somewhat wider range of temperatures than the actual values would indicate. At an altitude of 25,000 feet the average air temperature is $-28°$ C., somewhat lower than the temperature usually reached in these experiments. However, tests were made at $-20°$ C. at an altitude of 5,000 feet, and a fuel vaporizing under these conditions would vaporize as completely at a considerably lower temperature at the lower pressures prevailing at 25,000 feet. The explanation for this lies in the fact that for a given ratio of fuel vapor and air the ratio between the pressure of the vapor in the charge after complete vaporization and the pressure of the air remains constant regardless of what the pressure of the air actually is. At 25,000 feet altitude the pressure of the air is much lower than at 5,000 feet. Hence the vapor pressure will be lower and complete vaporization can take place at correspondingly lower temperatures. This will be evident from Figure 9. The lower full-line curves show initial condensation temperatures for two fuel-air ratios plotted against total pressure. The dash line shows average air temperatures at various barometric pressures (altitudes). For a fuel-air ratio of 0.083 the condensation temperature at a total pressure corresponding to an altitude of 5,000 feet is $-3°$ C., while for a pressure corresponding to an altitude of 25,000 feet it is $-17°$ C. Inasmuch as the difference between these temperatures is 14° C. it seems entirely justifiable to conclude that vaporization at $-28°$ C. at 25,000 feet altitude would be no less complete than at $-20°$ C. at 5,000 feet. Hence it is believed that the results here presented cover average conditions between sea level and 25,000 feet.



Fuel characteristics of domestic aviation gasoline (from Wilson and Barnard).

In connection with the above discussion it is of interest to consider whether vaporization tends to become more or less complete as the altitude is increased. A decrease in air pressure and a decrease in air temperature are the two major consequences of an increase in altitude.

[3] Intake Manifold Temperatures and Fuel Economy, by H. C. Dickinson, W. S. James, and S. W. Sparrow. Journal of Society of Automotive Engineers August, 1920.

The former tends to make vaporization more complete, the latter to make it less complete. Their combined effect can be inferred from Figure 9. Initial condensation temperatures have been taken from Wilson and Barnard.[4] At a pressure corresponding to an altitude of 25,000 feet initial condensation temperatures are about 20° C. lower than at sea-level pressure. The actual decrease in temperature for this same change in altitude is given by the dash line as 46° C., more than twice as great. Hence under normal conditions vaporization tends to become less complete as the altitude is increased. As has been shown, with fuels and engines no worse than present-day types, this tendency does not manifest itself to an extent demanding any material enriching of the mixture over the range of altitudes investigated.

One must not lose sight of the distinction between constant fuel-air ratio and a constant carbureter adjustment. To obtain the former the carbureter adjustment must be manipulated very frequently in present-day carbureters. The first problem that confronts the carbureter engineer is to provide a carbureter capable of being adjusted under any condition of operation to give the desired mixture. Having accomplished this he can then bend his energies toward a reduction in the number of such adjustments that must be made in order to maintain the desired fuel-air ratio.

What percentage of its maximum power does an engine develop when its specific fuel consumption is a minimum?—The chemical combining ratio of a hydrocarbon fuel and air is understood to be a ratio such that the products of complete combustion are carbon dioxide and water with no carbon monoxide or oxygen. As is well known, maximum engine power is obtained when the fuel-air ratio is in excess of, and minimum specific fuel consumption when the fuel-air ratio is less than, that giving the proportions for chemical combination. This can be attributed in part at least to imperfect mixing. An excess of fuel is necessary to the complete utilization of the air, while an excess of air permits complete utilization of the fuel. To obtain maximum power the air should be utilized completely. To obtain minimum specific fuel consumption the fuel should be utilized completely.

Tizard and Pye [5] have made a much more complete analysis of this problem than will be attempted here. From the conclusions they have reached it appears that even with perfect mixing maximum power should be expected with a mixture richer, and minimum specific fuel consumption with one leaner, than the so-called chemical combining ratio.

Before passing to the curves mention might be made of a phase of the relation between mixture ratio and power that has often caused confusion. As a basis for discussion assume the products of combustion of a rich mixture to be carbon dioxide, carbon monoxide, and water. Table II [6] shows for typical hydrocarbon fuel the percentage of available energy per pound of fuel for mixtures of several degrees of richness. It is apparent that the energy available theoretically per pound of fuel must decrease when the mixture is made richer than that theoretically giving complete combustion. The energy available depends upon the amount of air present as well as upon the amount of fuel. Supplying excess fuel, since it does not increase the amount of air, does not increase the total amount of energy available and hence must *decrease* the energy available per pound of fuel. It will be observed that when the fuel content of the charge is 50 per cent in excess of the theoretical combining ratio there is a decrease of nearly 50 per cent in the available energy. At first glance this appears in marked contrast with the comparatively small decrease in engine power that results from using a mixture of this degree of richness.

[4] Further Data on the Effective Volatility of Motor Fuels, by Robt. E. Wilson and Daniel P. Barnard, 4th. Journal of Society of Automotive Engineers, March, 1923. The actual values there given have been questioned by some writers. (See paper presented by Gruse at New Haven meeting of American Chemical Society in April, 1923.) The disagreement as to actual values does not extend to the *change* in condensation temperatures with change in pressure which is the point of interest in this discussion.

[5] The Character of Various Fuels for Internal Combustion Engines, by H. T. Tizard and D. R. Pye. The Automobile Engineer, February, March, April, 1921.

[6] Taken from The Economical Utilization of Liquid Fuel, by C. A. Norman, Bulletin No. 19 of the engineering experiment station of the Ohio State University.

TABLE II.

Pound fuel per pound air	0.100	0.091	0.083	0.077	0.071	0.067
Pounds air per pound fuel	10	11	12	13	14	15
Percentage of available energy per pound fuel	53	63	73	82	91	100

The reason is that in the usual mixture ratio run the change in richness is effected by changing the fuel content of the charge. Hence the change in power depends not only upon the available energy per pound of fuel but also upon the pounds of fuel available. Taking an illustration from Table II, when the pound fuel per pound air is 0.100, the fuel content of the charge is $\frac{0.100}{0.0667}$ as great as when the ratio is 0.0666. Although the available energy per pound of fuel is only 53 per cent of that available with the 0.0667 mixture, the corresponding energy per unit weight of charge is $\frac{0.100}{0.0667}$ 53 or 80 per cent. While Table II gives a satisfactory picture from the standpoint of specific fuel consumption, Table III is more satisfactory from the standpoint of power.

TABLE III.

Pound fuel per pound air	0.100	0.091	0.083	0.077	0.071	0.067
Pounds air per pound fuel	10	11	12	13	14	15
Percentage of available energy per pound air	80	86	91	95	97	100

Figures 10, 11, 12, 13, 14, and 15 show specific fuel consumptions at various percentages of maximum indicated horsepower. With the exception of three dotted curves in Figure 15, the results are all based on tests made at the Bureau of Standards. Aviation engines of various types were used in obtaining the greater portion of these data but four and six cylinder motor-car engines and single-cylinder experimental engines were employed to some extent.

Considering the entire group of curves the most striking feature is the small difference between the minimum specific fuel consumption and the specific fuel consumption obtained with a mixture impoverished until the power is 95 per cent of its maximum value. Frequently the actual minimum value is not reached until the power has been reduced to 85 per cent of its maximum value. In such cases, however, the difference between the specific fuel consumptions at 85 per cent and 95 per cent of maximum power is comparatively small while the difference between the specific fuel consumption at 95 per cent and at maximum power is large. Hence very nearly minimum specific fuel consumption may be obtained by decreasing the fuel content of the charge until the power developed is 95 per cent of its maximum value. After impoverishing the mixture to this extent, the margin of safety against firing back into the carbureter is still ample provided the engine possesses a reasonably good distribution system. From the above information it is evident that an engine designed for operation with a minimum specific fuel consumption mixture should have a piston displacement about 5 per cent greater than one designed to be operated with a maximum power mixture. It should not be inferred that there is some peculiar virtue inherent in the 95 per cent value that makes it vastly superior to 94 per cent or 93 per cent. In most cases the latter values give slightly lower specific fuel consumptions but at the cost of an appreciable reduction in the margin of safety against firing in the intake pipe. All things considered the 95 per cent value appears to be a satisfactory compromise.

Since, in Figures 10 to 15, the actual values of specific fuel consumption are separated so widely, it at first seems surprising that the 95 per cent value should be so near the minimum in

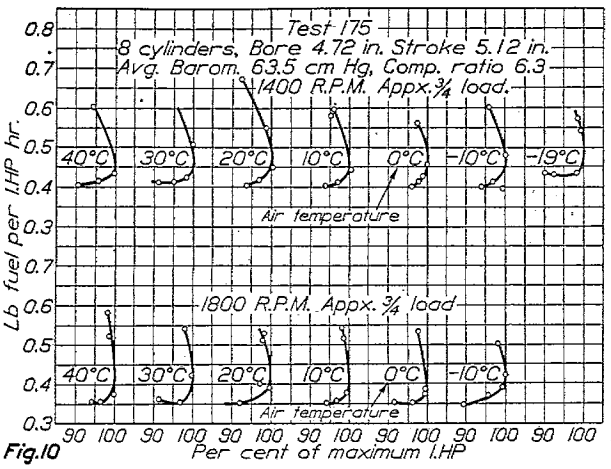


Fig.10

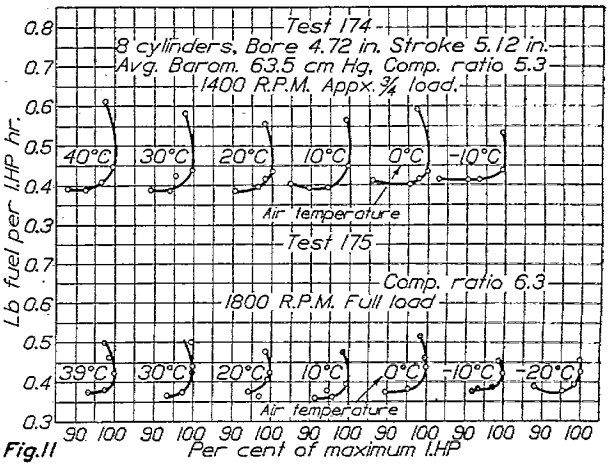


Fig.11

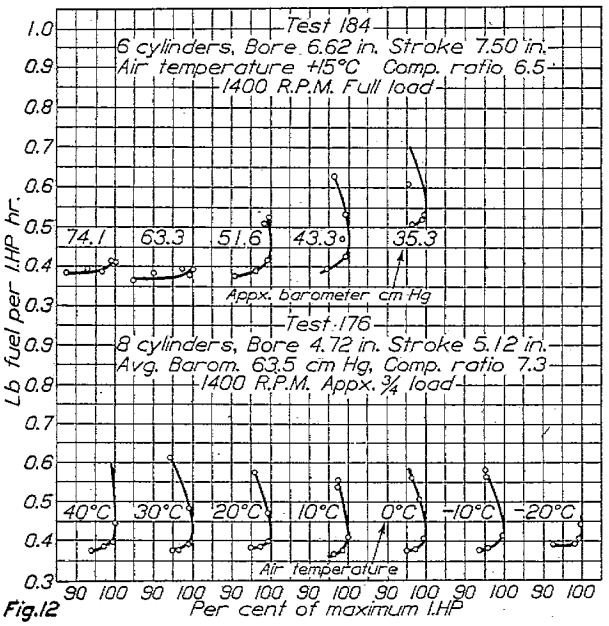


Fig.12

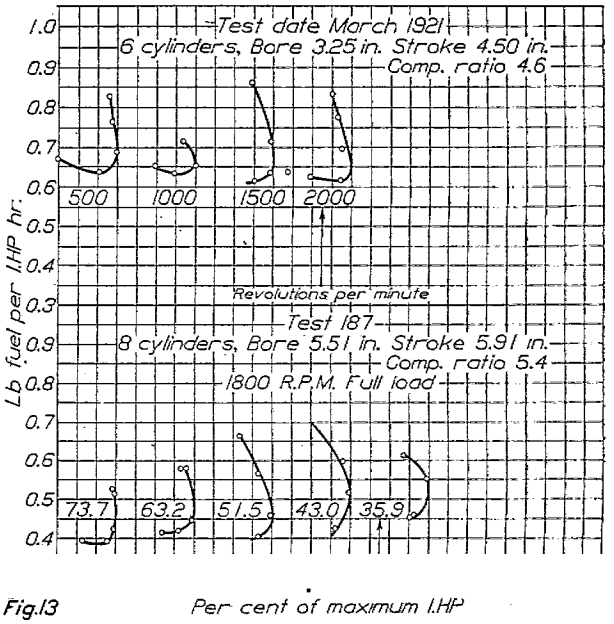


Fig.13

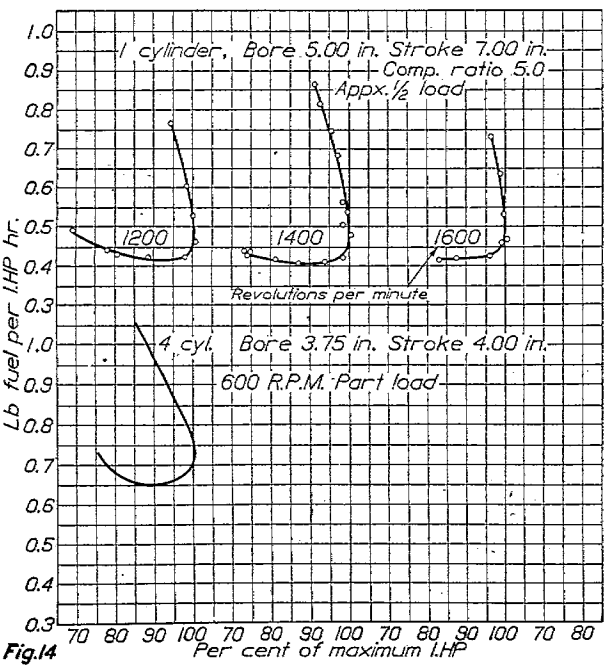


Fig.14

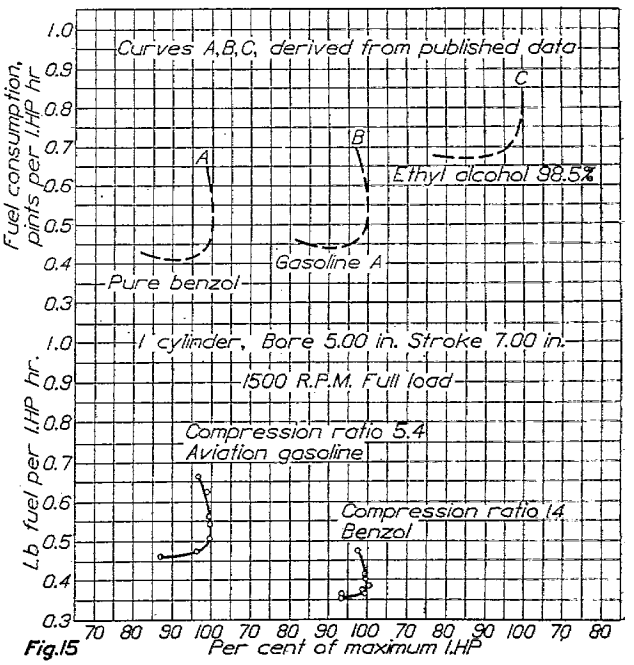


Fig.15

Curves A, B, and C, Figure 15, derived from data published by Ricardo in Automotive Industries, August 4, 1921, page 212.

every case. To some extent the mystery disappears when one appreciates the difference between the effective mixture in the cylinder and the ratio of fuel to air leaving the carbureter. The effective mixture ratio in the cylinder is that mixture which determines how much heat is liberated by combustion. Generally speaking, when the resulting increase in temperature is a maximum, the power is a maximum; when the increase in temperature per pound of fuel is a maximum the specific fuel consumption is a minimum. Obviously, there is a fairly definite relation between the effective mixture ratio for maximum power and that for minimum specific fuel consumption and hence a definite relation between the powers developed in the two cases. Actual values of power and specific fuel consumption are governed by the relation of the actual to the effective ratio and by the cyclic efficiency which determine how much of the heat liberated by combustion is converted into work. Hence such values are likely to vary between wide limits. Such variations do not disturb the relation between the effective mixture and the amount of heat liberated by combustion. Consequently they do not disturb the relation between maximum power and the power giving minimum specific fuel consumption.

Thus far, the curves for the most part have shown results based on indicated rather than on brake horsepower. General relations have been sought and not values which would change with any change of mechanical efficiency. Ultimately, however, minimum specific fuel consumption on a brake horsepower basis is desired. Fig. 16 has been plotted to show the effect of the mechanical efficiency upon the pounds of fuel per brake horsepower hour and to aid in converting results from an indicated to a brake horsepower basis. When a change in power is effected by a change in fuel-air ratio the mechanical efficiency changes solely because of the change in indicated power, the friction remaining substantially constant. Mechanical efficiency $=\frac{\text{I.HP}-\text{F.HP}}{\text{I.HP}}$. The lower group of curves in Figure 16 was obtained by a method described in Appendix 1. From these curves, the mechanical efficiency at any per cent of maximum power can be determined if the efficiency at maximum power is known. This permits converting results from pounds of fuel per brake horsepower hour to pounds of fuel per indicated horsepower hour since $\frac{\text{pound fuel per I.HP hour}}{\text{Mechanical efficiency}}=$ pound fuel per B.HP hour.

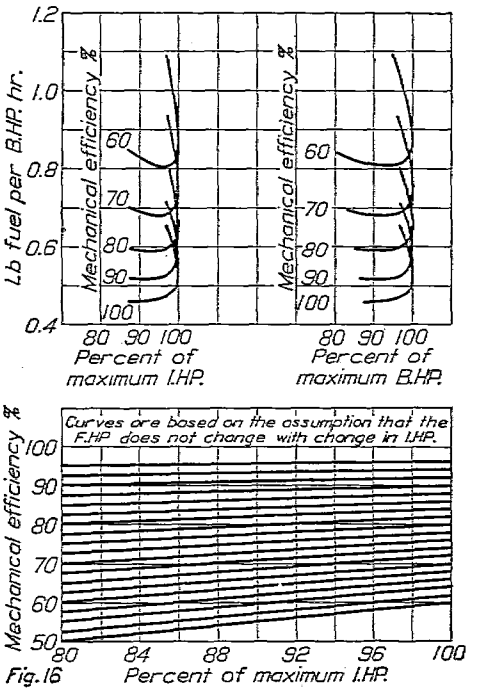


Fig. 16

Effect of changes in mechanical efficiency upon the percentage of maximum power at which the minimum specific fuel consumption is obtained.

The upper left-hand portion of Figure 16 gives values of pounds of fuel per brake horsepower hour corresponding to mechanical efficiencies of 60, 70, 80 90, and 100 per cent at maximum power. At the right the same values are plotted but in the latter case versus per cent maximum brake horsepower instead of versus per cent maximum indicated horsepower. Per cent B.HP corresponding to any per cent I.HP can be determined from the lower curves of Figure 16 by multiplying per cent I.HP by the ratio between the mechanical efficiency at that per cent I.HP and the mechanical efficiency at maximum power. Figure 16 shows nearly minimum specific fuel consumption on a B.HP basis also to be obtained both at 95 per cent of maximum I.HP and at 95 per cent B.HP. The general applicability of this 95 per cent value can be explained by the fact that there is so little difference between the mechanical efficiencies at maximum and at 95 per cent of maximum power. From the foregoing it is concluded that very nearly minimum specific fuel consumption (per B.HP hour or per I.HP hour) is obtained

when the fuel-air ratio is decreased until the power (B.HP or I.HP) is 95 per cent of its maximum value.

Carbureter engineers may desire to know, for certain of the curves shown in Figures 10 to 16, the relation between the change in fuel content of the charge and the specific fuel consumption. This information can be determined readily as will be evident from the following analysis:

A = pound fuel per hour at a per cent of maximum power.
B = pound fuel per hour at b per cent of maximum power.
k = horsepower at maximum power.
$\frac{ak}{100}$ = horsepower at a per cent of maximum power.
$\frac{bk}{100}$ = horsepower at b per cent of maximum power.
C = pound fuel per I.HP hour at a per cent of maximum power.
D = pound fuel per I.HP hour at b per cent of maximum power.

$$C = A \div \frac{ak}{100} = \frac{100A}{ak}.$$

$$D = B \div \frac{bk}{100} = \frac{100B}{bk}.$$

$$\frac{A}{B} = \left(\frac{100\ A}{ak} \div \frac{100\ B}{bk}\right) \cdot \left(\frac{a}{b}\right) = \left(\frac{a}{b}\right)\frac{C}{D}.$$

This may be stated in words as follows. The ratio of the fuel content of the charge at a given percentage of maximum power to the fuel content of the charge at some other percentage of maximum power is equal to the ratio of the products of specific fuel consumption and per cent power for the two conditions. In general 95 per cent of maximum horsepower is obtained when the fuel content of the charge is between 80 and 85 per cent of that which gives maximum power.

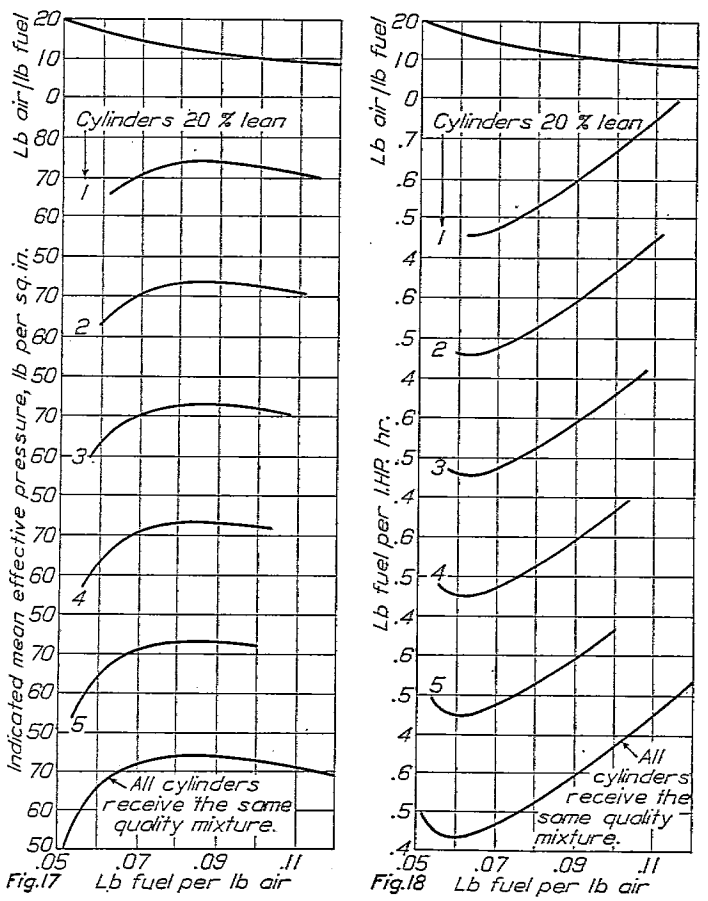
How does faulty distribution affect power and specific fuel consumption?—Note that the question does not refer to the cause of faulty distribution but to the effect. In the discussion which follows, distribution is considered faulty when all cylinders do not receive the same quality of mixture. Occasionally one cylinder requires a mixture of a quality different from that of another cylinder, but such a requirement usually testifies to poor engine condition or design. Attention already has been directed to the difference between the effective fuel-air ratio in the cylinder and the ratio of fuel to air that leaves the carbureter. The latter ratio will be the one termed mixture ratio throughout the ensuing discussion. Figures 17, 18, and 19, illustrate faulty distribution. The lower curve of Figure 17 is plotted from experimental data obtained with a single-cylinder engine. It represents what could be obtained from an engine having 6 similar cylinders each of which received the same quantity and quality of charge. The remaining curves show the result when 1, 2, 3, 4, or 5 of the six cylinders receive a fuel-air mixture whose fuel content is 20 per cent less than that of the remainder.

All calculations are based on the assumption that each cylinder when supplied with a certain fuel-air ratio develops the I.M.E.P.[7] shown by the lower curve of Figure 17 to have been developed by the single-cylinder engine. In performance tests measurements are made of the total weights of fuel and air received by the engine and of the total power developed by it. Results such as would be obtained from such measurements under the conditions specified are shown by the various curves. To illustrate how the curves are derived consider the case when 3 of the cylinders are 20 per cent lean. These will receive a mixture of fuel and air in

[7] I. M. E. P.=indicated mean effective pressure.

the ratio 0.8(0.08) when the other 3 cylinders receive an 0.08 mixture. The apparent mixture ratio will be $\frac{3(0.8)\ (0.08)+3(0.08)}{6}$ which equals 0.072. For a fuel-air ratio of 0.8(0.08) = 0.064, the lower curve of Figure 17 gives an I.M.E.P. value of 68.8 and for a ratio of 0.08 the value is 73.4. Hence the apparent I.M.E.P. will be $\frac{3(73.4)+3(68.8)}{6}=71.1$.

The lowest maximum I.M.E.P. for the group of curves shown in Figure 17 is 73.2 while the highest, obtained with perfect distribution, is 73.8. In Figure 18 are similarly obtained curves of specific fuel consumption. The highest minimum specific fuel consumption is 0.458 while the lowest, with perfect distribution is 0.432. Figure 19 is a recapitulation of the data



Effect of changes in distribution of 6-cylinder engine.

presented in the two previous figures. In this one instance points indicate values from faired curves instead of experimental data. This has been done in preference to drawing curves which would overlap so much as to make it extremely difficult to distinguish one from the other. A change in distribution unless greater than 20 per cent might appear to be of no great moment since it results in no great change in either maximum power or minimum specific fuel consumption. If the mixture could be and were adjusted closely for each change of condition the above conclusion would be valid. In service the tendency is to adjust the mixture so that the engine will function regularly over as wide a range of conditions as possible in order to reduce the frequency with which adjustments must be made. An architect plans a doorway so that it will be of adequate size for the tallest and fattest likely to pass through. In much the same fashion an engine operator is likely to adjust the mixture to be amply rich for any condition likely to arise.

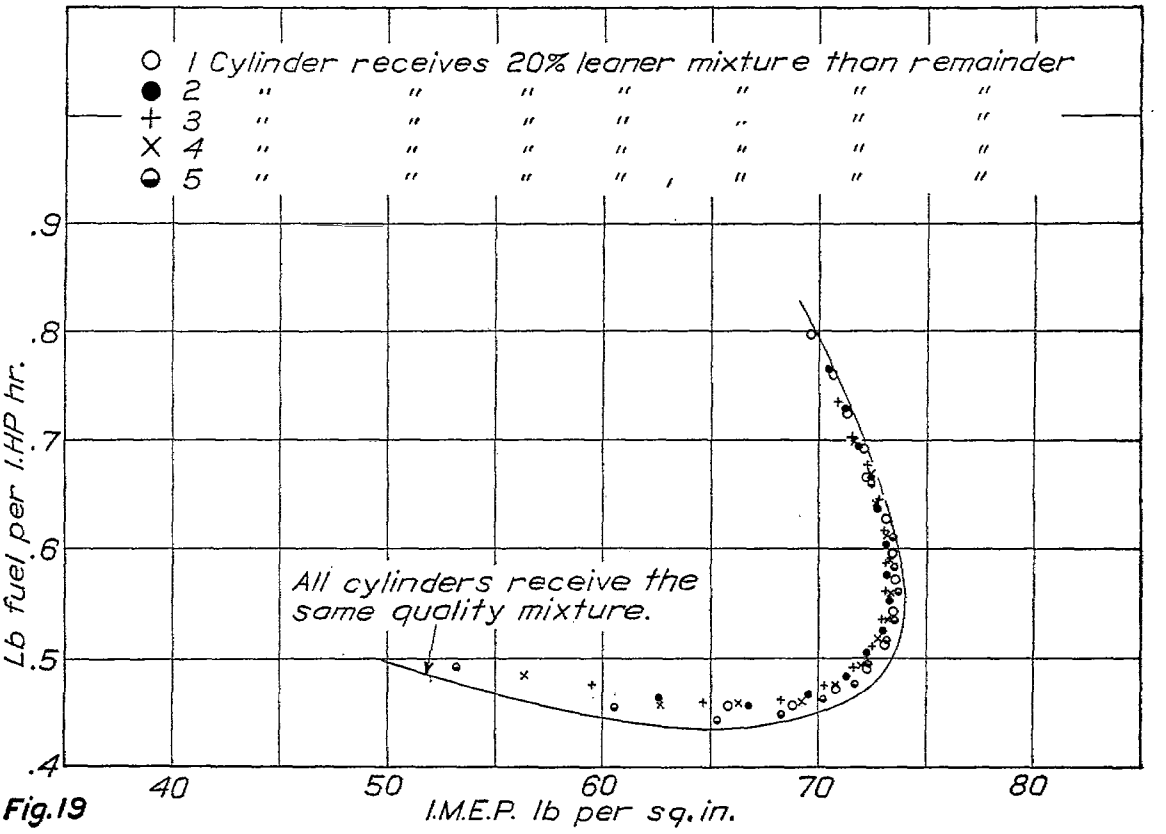


Fig. 19

Effect of changes in distribution of 6-cylinder engine.

In such a case the mixture ratio adjustment would depend upon the leanest cylinder, in other words it would be such that this cylinder would operate satisfactorily under extreme conditions. With perfect distribution such an adjustment might result in a considerable waste of fuel because it would be likely to provide a fuel-air ratio richer than necessary during the major portion of the operating time. A similar adjustment when one of 6 cylinders is 20 per cent lean would cause the remaining 5 cylinders to be proportionately richer than necessary throughout the entire range. In such a case the specific fuel consumption might be 20 per cent greater than that with perfect distribution.

CONCLUSIONS.

General conclusions are as follows:

(1) When using gasoline as a fuel, maximum power usually is obtained with fuel-air mixtures of between 0.07 and 0.08 pounds of fuel per pound of air.

(2) Maximum power is obtained with approximately the same fuel-air ratio over the range of air pressures and temperatures ordinarily encountered in flight.

(3) Nearly minimum specific fuel consumption results from decreasing the fuel content of the charge until the power is 95 per cent of its maximum value.

APPENDIX.

The curves in the lower part of Figure 16 were calculated for a change in mechanical efficiency resulting from a change in engine power unaccompanied by a change in friction. Essentially this condition exists when the fuel-air ratio is changed and the load on the engine is adjusted so as to maintain a constant speed.

Let

A = maximum I.HP
B = B.HP when A = I.HP
C = F.HP when A = I.HP
m = mechanical efficiency when A = I.HP
a = I.HP such that $\frac{a}{A}=r$
b = B.HP when a = I.HP
c = F.HP when a = I.HP
x = mechanical efficiency when a = I.HP

then

$$x=\frac{b}{a}=\frac{a-c}{a}=1-\frac{c}{a}$$

$c=C$ by assumption

$$x=1-\frac{C}{a}$$

$$a=Ar$$

$$x=1-\frac{C}{Ar}$$

$$C=A-B$$

$$B=Am$$

$$C=A-Am=A(1-m)$$

$$x=1-\frac{A(1-m)}{Ar}=1-\frac{(1-m)}{r}$$

Values given in Figure 16 have been calculated from this relation.

To obtain the group of curves in the upper right-hand corner of Figure 16 it was necessary to determine percentages of B.HP corresponding to known percentages of I.HP. The following analysis shows how this can be accomplished. Let subscript $_A$ represent the maximum power condition and subscript $_B$ the condition for which the per cent B.HP is to be determined.

Then

$$\text{B.HP}_A = (\text{mech. effic.}_A)\ (\text{I.HP}_A)$$

$$\text{B.HP}_B = (\text{mech. effic.}_B)\ (\text{I.HP}_B)$$

$$\frac{\text{B.HP}_B}{\text{B.HP}_A}=\frac{\text{I.HP}_B\ (\text{mech. effic.}_B)}{\text{I.HP}_A\ (\text{mech. effic.}_A)}$$

For any value of $\frac{\text{I.HP}_B}{\text{I.HP}_A}$ the mechanical efficiency can be determined from the lower group of curves in Figure 16. $\frac{\text{B.HP}_B}{\text{B.HP}_A}$ can then be determined from the above equation. The following table shows percentages of maximum brake horsepower corresponding to various percentages of maximum indicated horsepower for conditions where the mechanical efficiency is 90 per cent, 80 per cent, 70 per cent, and 60 per cent.

TABLE IV.

Per cent of maximum I HP.	Per cent of maximum B. HP when mechanical efficiency at maximum power is—			
	90 per cent.	80 per cent.	70 per cent.	60 per cent.
100	100	100	100	100
98	97.8	97.6	97.1	96.6
96	95.6	95.0	94.2	93.3
95	94.4	93.9	92.8	91.7
94	93.4	92.4	91.4	89.9
92	91.1	90.1	88.6	86.6
90	88.9	87.5	85.7	83.4
88	86.6	85.0	82.8	80.1
86	84.4	82.6	80.0	76.6

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