REPORT No. 108

SOME FACTORS OF AIRPLANE ENGINE PERFORMANCE

By VICTOR R. GAGE
Bureau of Standards

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RÉSUMÉ.

This report was prepared for the National Advisory Committee for Aeronautics and is based upon an analysis of a large number of airplane engine tests made at the Bureau of Standards. It contains the results of a search for fundamental relations between the many variables of engine operation.

The data used came from over 100 groups of tests made upon several engines, primarily for military information. The types of engines were the Liberty 12 and three models of the Hispano-Suiza. The tests were made in the altitude chamber, where conditions simulated altitudes up to about 30,000 feet, with engine speeds ranging from 1,200 to 2,200 r. p. m. The compression ratios of the different engines ranged from under 5 to over 8 to 1. The data taken on the tests were exceptionally complete, including many pressures and temperatures, besides the brake and friction torques, rates of fuel and air consumption, the jacket and exhaust heat losses.

With the Liberty engine, operating at from 500 to 2,000 r. p. m. and with the Hispano-Suiza 300 h. p. operating from 1,400 to 2,200, it is found that the friction torque increases approximately as a linear function of engine speed at a given air density, and approximately as a linear function of density at a constant speed. This means that the friction horsepower increases approximately as the square of the speed. Actually the relation of torque and speed is such that the friction horsepower increases with speed raised to a power between the first and second, this power increasing with speed, approaching the square. The relation depends upon the engine design and speed and density of the air. Any statements as to the distribution of the friction losses are based upon incomplete evidence; the indications are, however, that the pumping losses are about half of the total friction.

There is no doubt that for a given process of combustion and at a constant speed the engine power is directly proportional to the weight of charge supplied; in other words, proportional to the charge density at the beginning of compression. As a consequence, if operating conditions are sensibly constant except for altitude, the engine power will be closely proportional to the air density. The volumetric efficiency increases with increase of air temperature at constant pressure, so that power does not decrease as fast as the air density when the temperature is raised, due to changes in vaporization and heat transfer.

In order to compare the action of the gasoline engine with the theoretically perfect heat engine operating on the same cycle, it is necessary to base the heat balance of the actual engine upon the heat actually made available by combustion, not upon the heat supplied in the fuel. By summing up the exhaust and jacket heat losses with the brake power, an approximation is made of the true heat available, accurate to within perhaps 5 per cent. Basing the heat balance upon the heat thus accounted for, it is fairly well established that the energy distribution is not appreciably altered by change of either altitude or speed. It is, of course, altered by compression ratio changes. The exhaust heat, as per cent of the heat accounted for, is practically the same as the theoretical rejection of heat computed for the same compression ratio.

I. INTRODUCTION.

This report was prepared for and by the direction of the National Advisory Committee for Aeronautics, and is an analysis of a large number of tests made in the altitude laboratory of the Bureau of Standards. Many of the tests used in this report were made upon engines supplied by the Aviation Section, Signal Corps, United States Army, and the Army Air Service, Engineering Division, McCook Field. Much of the work was made possible by the hearty cooperation and aid of the National Advisory Committee for Aeronautics, the Army Air Service, the Navy Department, and the Bureau of Mines.

The very nature of this report depends upon data taken during a long period of time, under the supervision of Messrs. W. S. James and S. W. Sparrow. Dr. H. C. Dickinson and D. R. Harper, 3d, contributed much to the value of the paper. Mr. H. S. White aided in interpreting the various test conditions. Dr. Donald MacKenzie helped by his interest in working up the results. The author wishes to acknowledge his indebtedness to these, and to others with whom he was associated during this work.

The purpose of this study was to glean any general information which could be found from a comparison of many groups of tests, each group having been made for some special purpose, generally for military information. The tests here considered were made upon several engines of the Liberty 12-cylinder and the Hispano-Suiza 8-cylinder type. Various compression ratios were used. All of the tests were made in the altitude chamber, and the determinations included brake torque, rates of fuel and air consumption, jacket and exhaust heat losses, as well as pressures and temperatures at many points in and about the engines. These tests were made at several speeds and with air pressures corresponding to different altitudes, but generally with a constant air temperature. With some exceptions, the mixture ratio and time of ignition were adjusted to give maximum power, as most of the tests were made in the war period, when maximum power was always the goal. Certain operating conditions have been selected as laboratory standards, such as air supply temperature, although the standard jacket water temperature is not the same for the Liberty as for the Hispano-Suiza. Some later tests have been made to determine the effect on horsepower and general performance of special variations, such as of mixture ratio, air temperatures, jacket temperatures, different oils, etc. Generally, but not always, some means was provided for reducing the gasoline supply sufficiently to secure a proper mixture ratio at the extreme altitudes. An auxiliary device of this kind is necessary because the altitude adjustment on stock carburetors is inadequate above about 45 cm. barometer (15,000 feet). Complete determinations of friction torque at various speeds and altitudes were made as a part of the later tests. During these friction runs no fuel was supplied, and there was no ignition spark passing in the cylinders, but otherwise the operating conditions of air, oil, water, etc., were the same as in the power runs. On the earlier tests not enough power was available to operate the larger engines at normal speeds, so the friction runs cover only the lower speeds.

In any analysis of engine performance the change of indicated power rather than brake power is the fundamental relation to be considered, and the first step in obtaining the indicated power is to study the friction losses, which are the subject of Part II. By adding the friction and brake torques the indicated torque is obtained and its relation to the engine speed and air density are studied in Parts III and IV. Other variables introduce so many complications that it is necessary to first obtain a general idea of the relations of torque, speed, and density with other conditions fairly constant, as in Parts III and IV, before taking up the effect of other variables. Two of the latter, viz, air-supply temperature and mixture ratio, are considered in Parts V and VI, respectively.

An internal-combustion engine is essentially a "heat engine," and a knowledge of the distribution of the energy supplied to it is desirable. The energy which might be obtained by the combustion of the fuel should be considered in two parts, viz, that which is not developed by the combustion as it takes place in the engine and that which is so developed and rendered available for transformation into useful work. The latter must then be further divided into the two parts of that actually transformed to work and that rejected as heat. In this manner a logical comparison can be made between the actual engine performance and that to be expected from the theoretical cycle.

II. FRICTION LOSSES.

INTRODUCTORY REMARKS.

Brake power is the ultimate and practical measure of the usefulness of an engine. Indicated power, or brake plus friction, is the real measure of the performance of an engine. Friction losses are a necessary evil, and must be reduced to as small a quantity as is practicable. For intelligent improvement of mechanical efficiency, it is important to know the relative magnitude of the various factors which make up the friction losses. The study of friction losses is here made for these two purposes, namely, (1) as a means of obtaining the indicated power, and (2) to learn as much as possible concerning the relative distribution of the various items which compose the "friction."

In testing airplane engines in the altitude laboratory of the Bureau of Standards, each engine is usually put through a "friction run," during which the ignition and fuel are shut off and the engine is turned over by operating the electric dynamometer as a motor. The torque required to turn the engine over is measured at each of several speeds and altitudes.

During the friction runs the air, oil, water, and general engine temperatures and conditions are maintained as nearly as possible the same as in the power runs. Unless otherwise specified, all friction runs were made with throttle fully opened.

The friction losses of the Liberty 12-cylinder aviation engines were obtained from altitude laboratory tests Nos. 141 to 144, 146, 148, 152, 153, and 160. The engines used in these tests had compression ratios of approximately 5.6 to 1, except in tests Nos. 152 and 153, where it was 7.2, and in test No. 160, where it was 5.4. The friction losses of the Hispano-Suiza, model H, 300 h. p., 8-cylinder engine were obtained from altitude laboratory tests Nos. 161 and 162, on an engine with compression ratio of 5.3.

METHODS AND DETAILS OF HANDLING TEST DATA.

The data used in obtaining the relations between friction mean effective pressure and speed or density were selected for about normal operating conditions. In tests where conditions were abnormal the data were rejected, or, if plotted, used solely as a qualitative indication. The air temperature was generally maintained constant, so, for convenience, the barometer has been used as equivalent to density. The friction mean effective pressure values were grouped and plotted in two ways—(1) for nearly constant density plotted versus r. p. m., and (2) for nearly constant speed plotted versus density, thus accomplishing the same result as plotting to the three dimensions of f. m. e. p., r. p. m., and density. Figures 1–H and 2–H are examples of this method. In locating the faired curves all three dimensions have to be considered, as, for example, in figure 1–H the curve for f. m. e. p. versus r. p. m. at 64 cm. barometer is placed above the average of the points because in figure 2–H the f. m. e. p. values at this barometer are evidently too small at nearly all speeds.

Figures 1–L, 1–H, and 2–H show the original data upon which the friction results and conclusions are based, the letter L after a figure number signifying Liberty engines, H, Hispano-Suiza engines. The subsequent figures 3 and 4 are reproduced from the faired curves of figures 1–L, 1–H, 2–H, and the omitted 2–L curve, but collected upon one sheet and with the points omitted. The curves have been extrapolated for speeds below 600 r. p. m. in figure 4–L and below 1,400 r. p. m. in figure 4–H. The curves have also been extrapolated for barometers less than 30 cm. in figures 3, except for one estimate based on a closed throttle run on the Hispano-Suiza (fig. 2–H, 1,800 r. p. m.). In figure 3 the curves have been extrapolated to their intercepts on zero barometer; the estimate of pumping losses presented in figures 5 and 6, and discussed under a separate heading, being based upon the intercepts thus found. These intercepts have also been used to estimate the friction of the engine exclusive of the pumping work, presented as the zero barometer curves on figure 7, f. h. p. versus r. p. m.

Only one set of friction runs wherein the engine was throttled was available. This was made upon a Hispano-Suiza engine, 300 h. p., and is shown in figure 2–H, 1,800 r. p. m. Such results were converted to approximately the equivalent value with open throttle by subtracting from the observed throttled friction m. e. p. the change of pressure difference between the exhaust and intake manifolds. This, on an indicator card, would amount to placing the suction line across the full length of the card, at the manifold pressure under open throttle conditions. As the suction line is in fact less than the full length of the card, and as the manifold pressure is greater than the suction pressure in the cylinder, it is possible that the net result of this approximation may not be far from the truth. There are also unknown changes of area of the lower loop of the card, due to change of compression line, of fuel vaporization, etc., with change of throttle position. The above method has been used in a later chapter (see fig. 4, Part III) for converting the mean effective pressure at throttle to an equivalent value at open throttle, and gives results which correspond, within experimental limits, with the mean effective pressures which were obtained with the same weight of air when the throttle was open, and with the air at reduced density. When no altitude chamber is available this method may be used to approximate the power output of an engine at altitude from throttled runs.

ESTIMATE OF PUMPING LOSSES.

By extending the curves of friction versus barometer to zero density, as on figures 3, intercepts are obtained which may and probably do fairly accurately represent the friction mean effective pressure of the engine when there is no air to pump. The difference between the friction losses at zero density and those at another density, but at the same speed, is an approximation of the pumping loss. The pumping loss thus derived includes any effects of change of gas pressure upon piston friction, but later tests have shown that these are practically negligible.

The mean effective pressure required to pump the charge apparently varies directly with the air density at a given engine speed, as shown on figures 5, agreeing with the hypothesis that the weight of air handled at constant speed, and hence the pumping work, should vary directly with the density.

The proportion of the total friction which is used in overcoming the pumping losses is shown for the Liberty engine on figure 6–L, and for the Hispano-Suiza 300 h. p. engine on figure 6–H. It is evident that the two engines have very different pumping characteristics.

CONCLUSIONS RESPECTING FRICTION LOSSES.

An empirical and approximate statement, applicable to the speed and density ranges herein covered, is that the friction torque (m. e. p.) increases as a linear function of speed at a constant air density, and as a linear function of air density at a constant speed. This applies to both the Liberty 12-cylinder and the Hispano-Suiza 8-cylinder engines and is shown on figures 3 and 4. Actually, the true relations of friction torque, engine speed, and air density are much more complex and can not be deduced from the available information. It is known, however, that the friction torque is such that the friction horsepower will increase with engine speed raised to between the first and second power, approaching the square of the speed at the higher speeds, figure 7. The exact relation is dependent on the engine, as well as on the speed and air density. Also, at a given speed, the friction horsepower increases with some varying power of the air density, because of the change of the pumping work. The friction horsepower at constant speed is found to increase slightly more rapidly than does the density.

No systematic change of friction could be connected with change of compression ratio, from the data used in this report, although a slight change is to be expected.

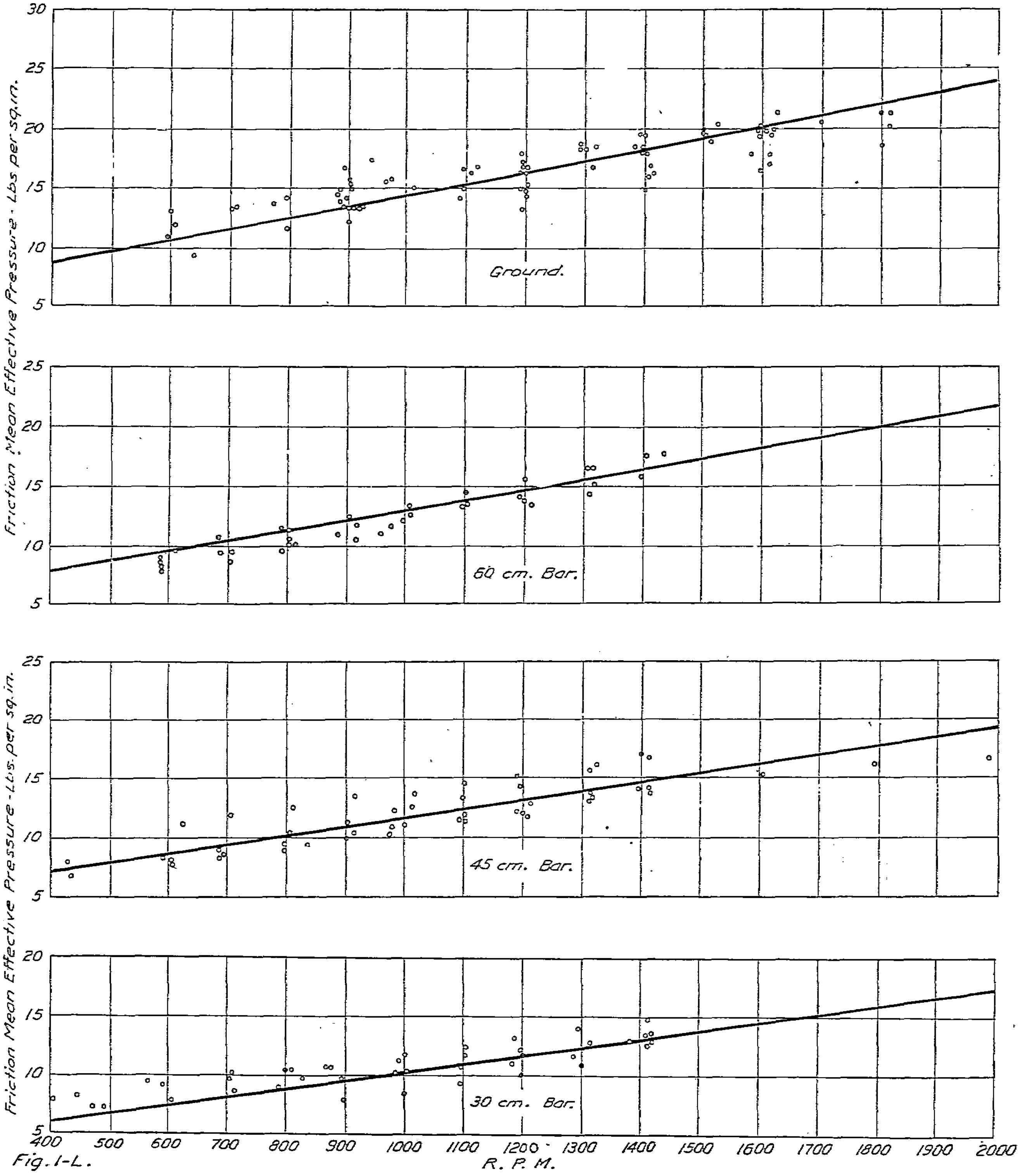
Friction Mean Effective Pressure - Lbs per sq.in.
Friction Mean Effective Pressure - Lbs. per sq.in.
30
25
20
15
10
5
Ground.
60 cm. Bar.
45 cm. Bar.
30 cm. Bar.
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
R. P. M.

Fig. 1-L.

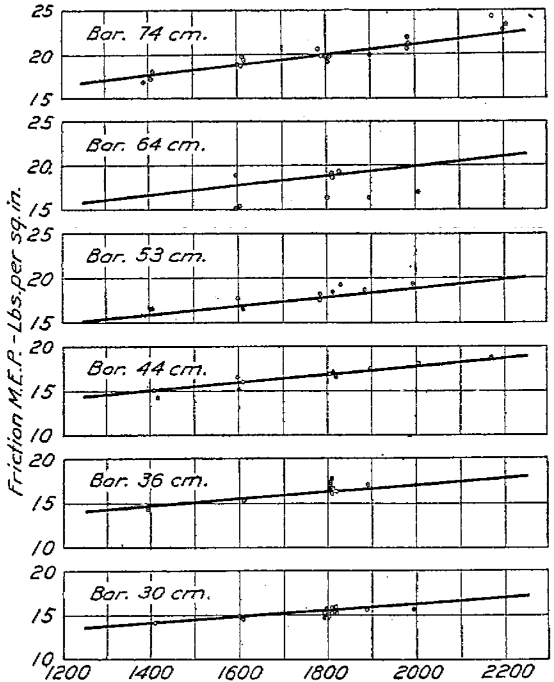

Fig. 1-H.

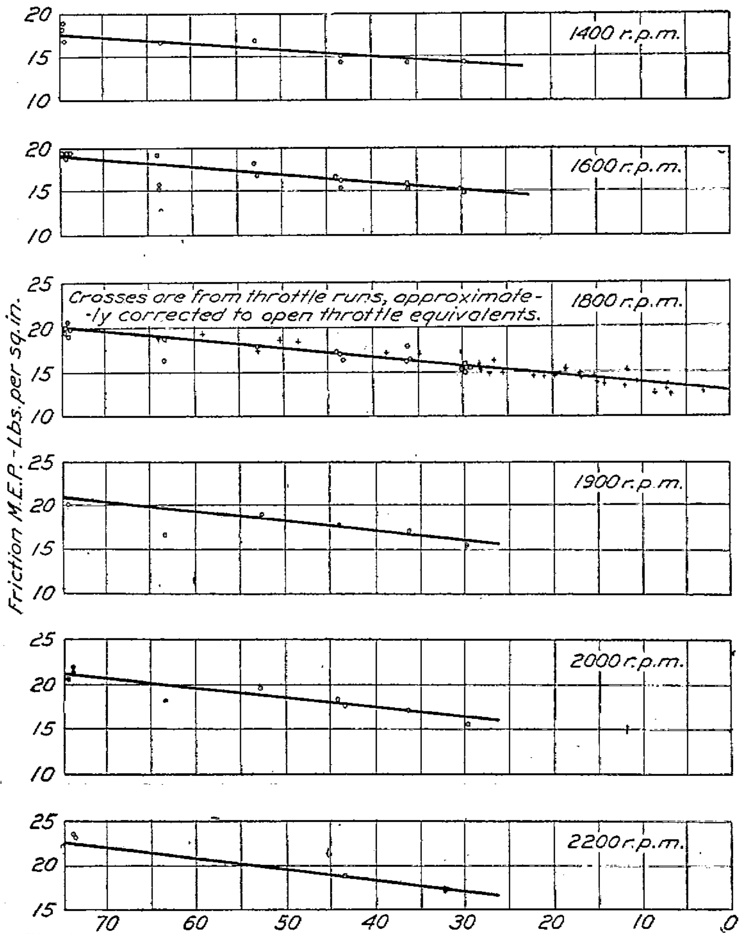

Fig. 2-H.

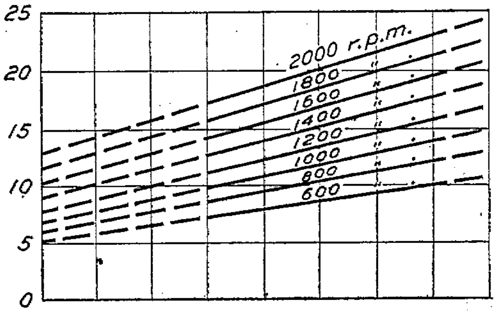

Fig. 3-L.

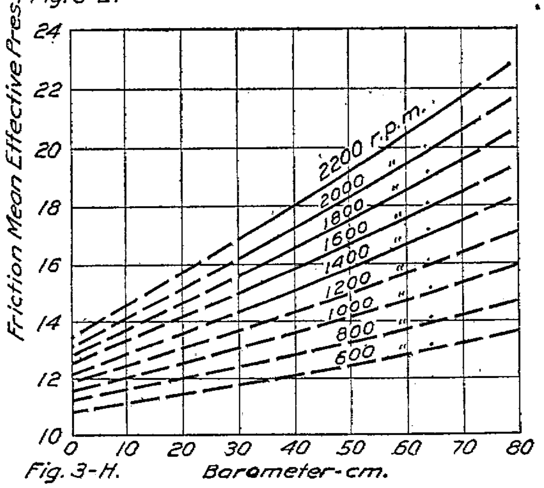

Fig. 3-H.

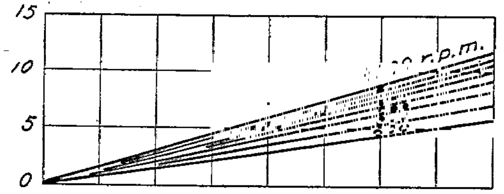

Fig. 5-L.

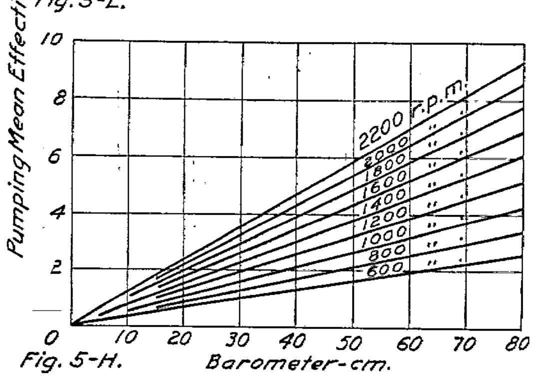

Fig. 5-H.

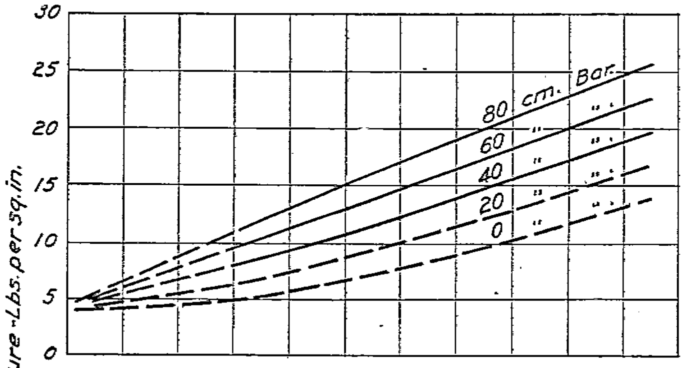

Fig. 4-L.

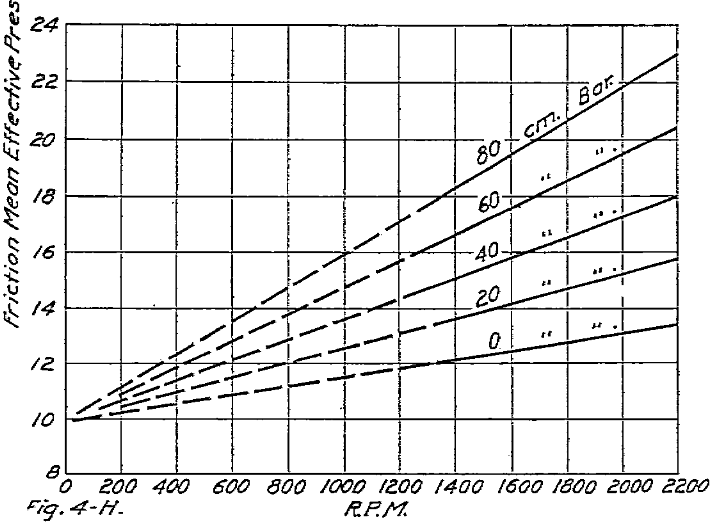

Fig. 4-H.

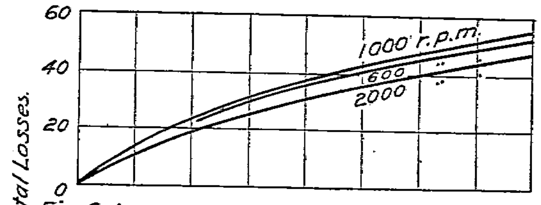

Fig. 6-L.

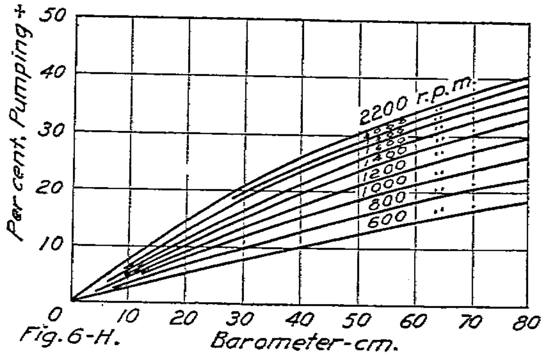

Fig. 6-H.

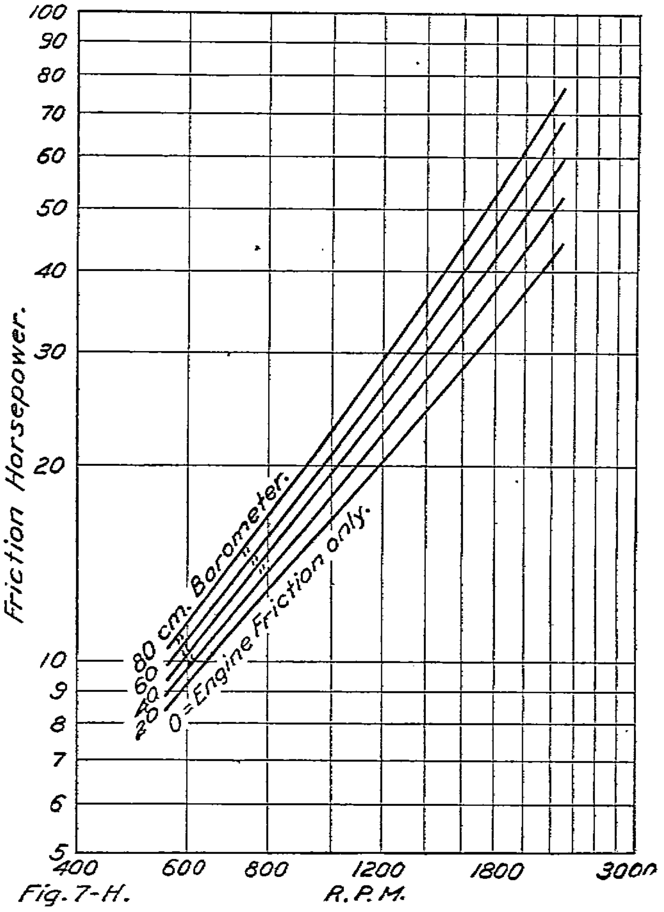

Fig. 7-H.

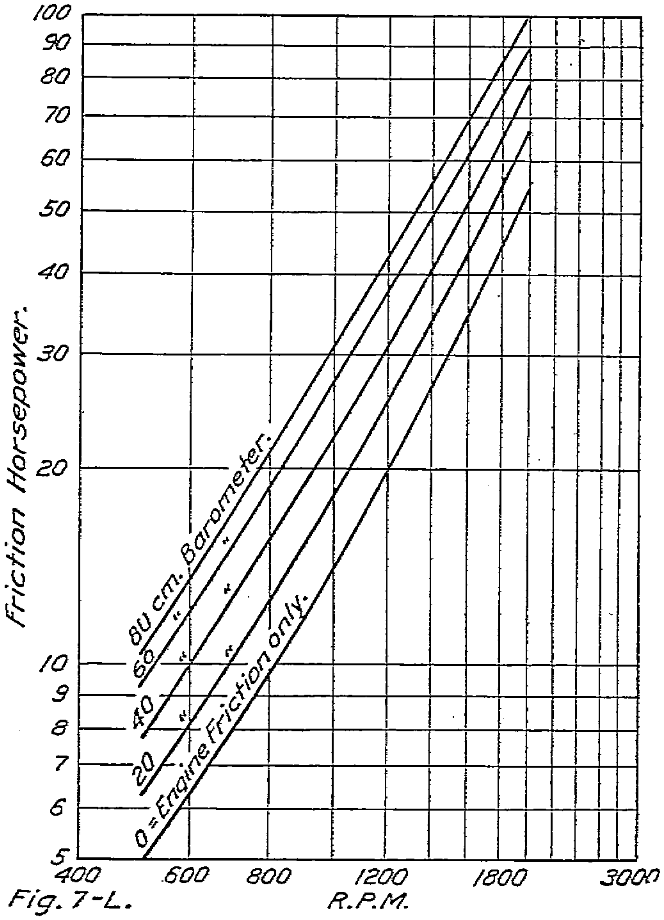

Fig. 7-L.

III. EFFECT OF DENSITY OF AIR UPON POWER.

INTRODUCTORY REMARKS.

The indicated power of a four-stroke cycle internal combustion engine may be defined as the power developed inside the cylinders derived from the combustion of the fuel, and is obtained by adding the friction power (including pumping losses) to the brake power. Change of piston friction due to the increased pressures in the cylinder when the engine is operating seemed to be the most probable source of error when determining the indicated power by this method. However, a consideration of all the evidence, including actual indicator diagrams, leads to the conviction that indicated power is correct when obtained from brake plus friction.

CHANGE OF INDICATED MEAN EFFECTIVE PRESSURE WITH BAROMETRIC PRESSURE.

For a given engine the indicated horsepower may be expressed as i. m. e. p. times speed times a constant. It is shown later that the work obtainable from unit weight of air is independent of speed but is dependent upon conditions of operation, for example, mixture ratio. Hence, at a given density, variation in i. m. e. p. must be due either to a difference in the amount of air taken in per stroke or to a difference in the degree to which it is utilized. Figures 1 and 2 are presented, as a composite photograph, to show the magnitude of such variations under the conditions noted.

Values of brake mean effective pressures used for computing indicated mean effective pressure on figure 1 are from tests on Liberty 12-cylinder aviation engines with 5.4, 5.6, and 7.2 compression ratios (altitude laboratory tests, Nos. 144, 147, 155, 156, 157, 159, and 160). Similar values used on figure 2 are from tests on a Hispano-Suiza, model H, 300 h. p. engine with compression ratio of 5.3. (Tests Nos. 161 and 162.) These engines were operated at speeds of from 1,200 to 2,000 r. p. m. for the Liberty and from 1,400 to 2,200 r. p. m. for the Hispano-Suiza. The barometric pressure ranged from ground (75 cm.) to that corresponding to about 25,000 feet altitude (30 cm.). Only wide-open throttle runs were used on figures 1 and 2. In all cases the fuel was an aviation gasoline which meets the specifications of the Aircraft Production Board for export to the American Expeditionary Forces.[1]

The indicated mean effective pressure versus altitude curves of the two engines, figures 1 and 2, are not comparable above about 15,000 feet (45 cm. barometer), because the Liberty engine tests, except No. 160, were made with special altitude adjustment on carbureter, whereas the Hispano-Suiza tests were made to determine the engine performance when equipped with stock carbureters without special altitude adjustment.

CHANGE OF INDICATED MEAN EFFECTIVE PRESSURE WITH DENSITY AT BEGINNING OF COMPRESSION.

The factor which determines the weight of charge in a given engine cylinder is the density at the beginning of compression. This density is a function of the pressure and the temperature of the gases at this time. The volume occupied by the charge is the volume of the cylinder less the volume occupied by the residual gases held in the clearance space. (At normal speeds the exhaust valve is supposed to be closed in time to prevent the escape of incoming charge, and the end of the charging period and the beginning of compression may be considered as coincident.)

The pressure and temperature of the charge at the beginning of compression and the volume occupied by the products of the previous combustion are unknown. However, certain well justified assumptions can be used in connection with measured quantities to compute the approximate density of the charge at the beginning of compression. This method will be described later.

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[1] For properties and distillation curve of this fuel, see Report No. 47 of the Fourth Annual Report of the National Advisory Committee for Aeronautics, Power Characteristics of Fuels for Aircraft Engines, p. 6 and Plot 1.

Some of the tests included propeller load runs in which the engine was throttled. It was considered of interest to investigate the relative change of mean effective pressure in the two methods of reducing the density, one by changing the operating pressure surrounding the engine, and the other by throttling the incoming charge. When the engine is throttled the suction pressure is caused to fall considerably below the atmospheric pressure, with the result diagrammatically indicated on figure 4 as the change from the solid to the dotted lines, the exhaust pressure remaining substantially in the same relation with respect to atmospheric pressure. When the density is equally reduced by increase of altitude, the changes in exhaust, suction, and atmospheric pressures are such that all three remain in about the same relation as before the change of altitude was made. In order to approximate the equivalent indicated mean effective pressure at open throttle from tests with the throttle partly closed, the value of friction mean effective pressure at open throttle was increased by the mean effective pressure representing the increase in the lower loop of the indicator diagram, figure 4, and this total friction was added to the observed brake mean effective pressure at partially closed throttle positions.

The density of the charge at the beginning of compression was approximated by computations based on the following premises: (1) The total weight of charge per cylinder is the sum of the weights of air and of gasoline supplied per cycle. (2) The total volume of the charge at the beginning of compression may be considered as the total cylinder volume less the volume occupied by the residual gases expanding from clearance volume and exhaust pressure to the suction pressure. (3) The density at the beginning of compression is the weight of charge per cylinder per cycle (1) divided by the volume of charge per cylinder per cycle (2).

In detail, the assumptions made in order to compute the data for plotting figure 3 include the following:

(1) That the exhaust pressure in the cylinder is atmospheric pressure.

(2) That the suction pressure inside the cylinder, *a* or *b* on figure 4, is the pressure measured in the intake manifold close to the intake valves (actually this intake pressure as measured has too great an absolute value and would lie above the suction pressure on the card, thus indicating a smaller lower loop than would be shown by an indicator).

(3) That the exhaust gases filling the clearance volume of the cylinder would expand from the exhaust pressure to the suction pressure according to the relation $PV^{1.3}=C$.

(4) That the corners of the lower loop card were sharp, as in figure 4, and not rounded as they are in fact. (This assumption gives too large an area for the lower loop; assumption 2 gives too small an area, so the errors tend to neutralize each other.)

(5) That all of the fuel supplied was completely vaporized at the beginning of compression.

The data used in studying the change of indicated mean effective pressure with density at the beginning of compression, shown on figure 3, were from a test (No. 160) which included both open throttle and "propeller" or throttle runs, and which was made upon a Liberty 12-cylinder aviation engine with 5.4 compression.

CONCLUSIONS.

Change of indicated mean effective pressure can be taken as directly proportional to change of density of the air supplied when the conditions of operation are constant, except for density changes produced by pressure, and of the best. When the conditions are not the best, the power usually drops off slightly faster than the density. One of the essential conditions for best operation is that the mixture of air and gasoline be in proper portions. The carburetors ordinarily supplied with the engines have insufficient altitude adjustment, so the mixture is too rich above about 15,000 feet (45 cm. barometer).

The change from 5.4 to a 7.2 compression increases the mean effective pressure at a given density, although the change is not very obvious on figure 1. The data are too incomplete to warrant a statement of the amount of increase, as the 7.2 compression engine was tested only at altitudes of 15,000 and 25,000 feet (45 and 30 cm. barometers). Increase of mean effective

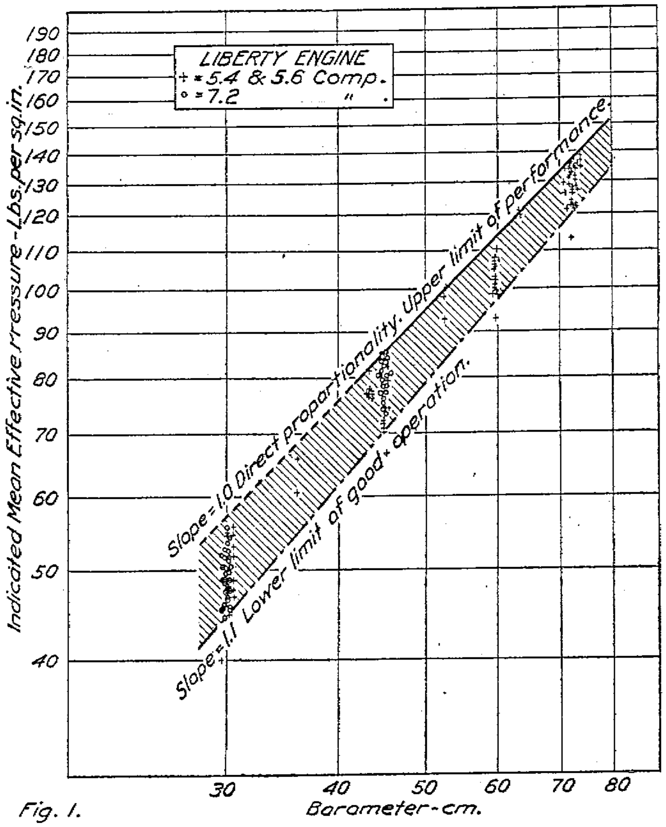

Fig. 1.

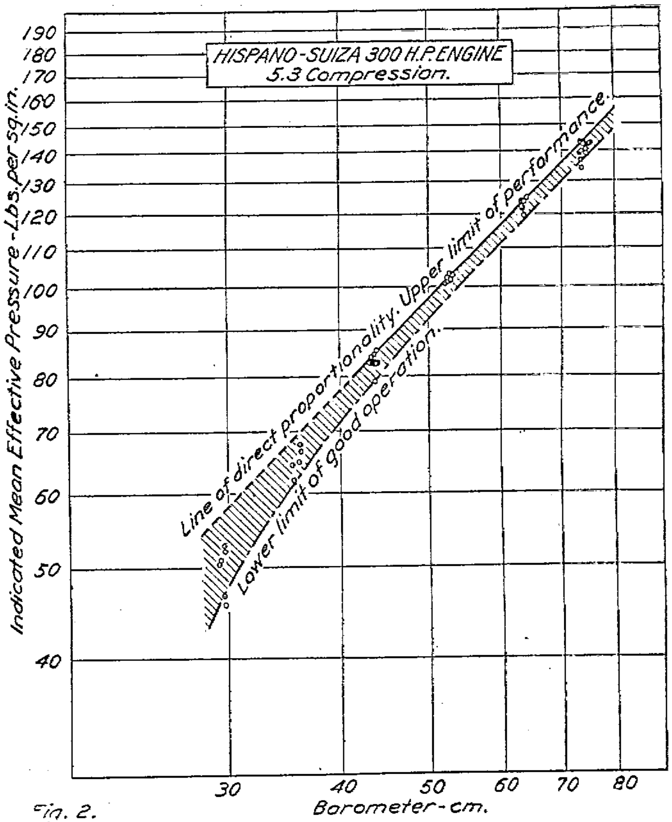

Fig. 2.

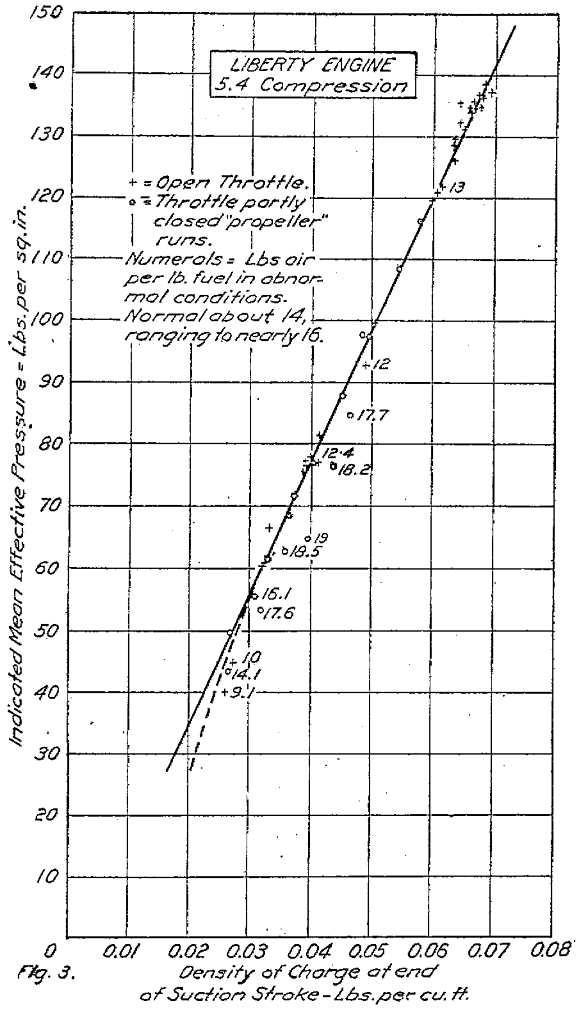

Fig. 3.

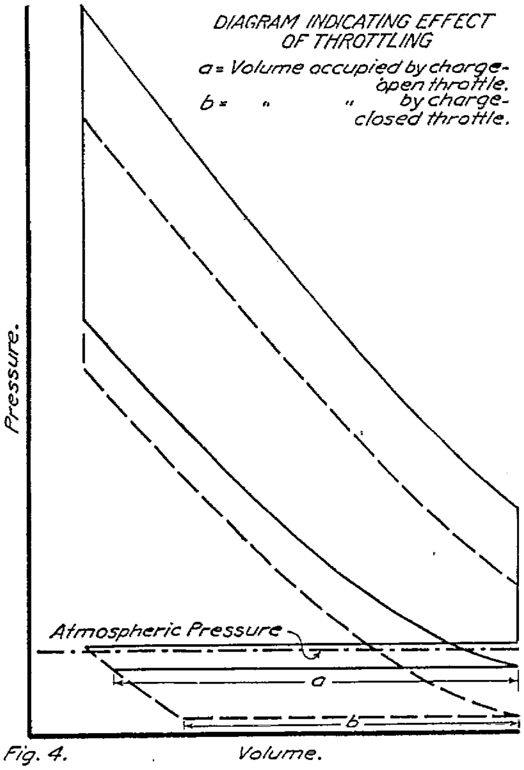

Fig. 4.

pressure with increase of compression ratio is expected because of greater ratio of expansion, and a possible improvement in combustion.

A comparison of figures 1 and 2 shows that the indicated mean effective pressure of the Hispano-Suiza engine is slightly greater than that of the Liberty, at the same air density and compression ratio. This is explained by the less amount of heating with the Hispano-Suiza manifold jackets. When the air supply is at 0° C. (32° F.) the manifold temperature of the Hispano-Suiza is about $-10°$ C. (14° F.), while that of the Liberty is about $+5°$ C. (41° F.). For a given temperature and a given pressure of air supply, the actual density of the air entering the cylinders is reduced by heating, although it is also increased by the cooling resulting from the evaporation of the gasoline. Using the manifold density instead of the supply density, the two engines give the same mean effective pressure for the same density.

Apparently the relation between indicated mean effective pressure and air supply density is based upon the fact that the change of indicated mean effective pressure is proportional to the change of density of the charge at the beginning of compression, irrespective of whether the density is changed by altitude or by throttling.

IV. WORK PER UNIT WEIGHT OF AIR.

One method of rating engines is by the horsepower per cubic inch or liter of piston displacement. This may be somewhat misleading, as it is based on the volume, not the weight, of charge. The piston displacement of an engine is constant, but the weight of charge drawn in on the suction stroke is controlled by the density of the air and by the volumetric efficiency. For example, with a given engine operating with fixed air pressure and temperature, it is possible to alter greatly the horsepower per cubic inch displacement by simply changing the "choke" of the carburetor. The indicated work obtained from unit weight of charge was selected as a means of showing how well the engine or engines utilized the energy supplied, independently of the amount drawn in.

For a first approximation the weight of air was substituted for the weight of charge. The results show that, except for changes due to different compressions and different mixture ratios, the indicated work obtained from unit weight of air is practically constant, and that it makes little difference whether the weight of air per unit time is changed by speed, altitude, air temperature, or volumetric efficiency (throttling the engine changes volumetric efficiency).

The subject of volumetric efficiency is taken up in Part V in connection with the effects of change of air temperature upon engine performance, but it is not out of place to consider it here, in connection with possible increase of engine output by increase of air supplied. The volumetric efficiency is controlled by many different and independent factors, among which are engine speed, temperature, and pressure changes in the air from entrance to cylinder, as well as the design of the whole induction system, including intake valves and ports, valve timing, and manifolds. The magnitude of these factors is generally unknown, except for their combined effect upon volumetric efficiency.

These various reasons for change of volumetric efficiency were considered, and an attempt was made to analyze the magnitude of the effects of some of them. Apparently the change in total pressure drop is relatively unimportant at open throttle. The temperature change from entrance to inside the cylinder is, however, a very important factor. Generally some means is provided for heating the air supply to an engine which of itself reduces the volumetric efficiency, but is counteracted to a greater or less extent by the heat absorption due to evaporation of the gasoline. The net result may be either way, with an added effect of heat transfer to or from the jacket water and piston when the gas is inside the cylinder.

The friction losses in the induction system may be subdivided into those due to (*a*) rubbing friction, (*b*) losses incident to transformations from one form of energy to another. The author has been unable to make the laws of gas friction (flow through pipes) account for changes of volumetric efficiency, and is inclined to believe that a great portion of the friction loss is incidental to transformations from potential to kinetic energy and the reverse. On the whole, the flow through the induction system is essentially a modified "throttling" or "constant heat" process, adiabatic but not isentropic.

Returning to the subject of the indicated work from unit weight of air, the density of the charge at the beginning of compression is a direct measure of the weight of air drawn into each cylinder at each suction stroke. The use of the weight of air per cylinder per cycle avoids the tedious computations which are incident to obtaining the charge density. In the event that only one engine is considered, the process is further abbreviated by taking weight of air per revolution, which is a constant times the weight per cylinder per cycle.

The points in figure 1 represent the indicated work (ordinates) plotted versus the weight of air (abscissæ), or, more strictly, the foot-pounds of indicated work per cylinder per cycle versus the corresponding weight of air used per cylinder per cycle. Figure 1 was plotted as a generalization, using data from many tests of both the Liberty and the Hispano-Suiza engines. The tests plotted include all of the several compression ratios previously mentioned, with the engines operating at the several speeds, altitudes, mixture ratios, and throttle position. On the whole, the points indicate a definite relation between the indicated work and the weight of air supplied, although there is a considerable scattering. The line shown as the curve is really the center of a zone or band, and was located without reference to the points (circles) representing the 7.2 compression data.

As there were many variables included in the tests shown in figure 1, data from one engine, a Liberty 12 with 5.4 compression, was plotted on figure 2, using coordinates proportional to those of figure 1. That is, the indicated mean effective pressure is used in place of the foot-pounds of work per cylinder per cycle, and pounds of air divided by r. p. m. are employed as equivalent to the weight of air per cylinder per cycle. On figure 2 all the variables are eliminated except mixture ratios and possible changes in the efficiency of combustion at different densities. The mixture ratio would be expected to have considerable influence upon the work obtained from a pound of air (when mixed with gasoline), hence the points where the data would plot are marked by numerals which are the values of the corresponding mixture ratios. On the tests plotted in figure 2 the weight of air supplied per cycle was changed mainly by alterations of the density through change of pressure, although changes of speed from 1,200 to 2,000 r. p. m. caused smaller changes in the air weight per cycle at such altitude, and on some of the runs the engine was throttled. In the latter case the changes due to change in the lower loop of the indicator diagram have been handled as previously explained.

The indicated mean effective pressure is found to be nearly, but not quite, proportional to the weight of air supplied per cycle. A reduction in the density of the air causes a slightly more than proportionate decrease in the mean effective pressure, especially at the smaller densities. The mixture proportions have considerable effect upon the work to be obtained from a pound of air, other conditions being constant, and this subject of effect of mixture ratio is discussed in another part of this report. The speed of the engine has no effect, at least for the speed range covered by the data on figure 2.

The explanation of the more rapid falling off of indicated mean effective pressure per pound of air at the greater altitudes was not obvious. It was suspected that this might be due to less complete combustion at reduced densities. Some few exhaust gas analyses had previously been made on a similar engine which was being tested in the altitude chamber. These analyses were examined to see if they showed any change in efficiency of combustion with change of altitude. The determinations of oxygen in the exhaust gas, as shown by these analyses, are plotted versus barometer on figure 3, and apparently indicate a greater amount of uncombined oxygen at the higher altitudes. In obtaining the samples of exhaust gas reasonable precautions were taken to prevent air leaking in, since the result of a leak would be to increase the oxygen content of the sample as the pressure was reduced in the altitude chamber. The excess oxygen in the exhaust at altitude would also be a result of a decrease in the efficiency of combustion. Evidence from recent tests with a *constant* mixture ratio hardly support the assumption that the efficiency of combustion changes appreciably with altitude. But, even so, it would not follow that, with mixture adjusted for *maximum power*, there may not be a change in the process of combustion.

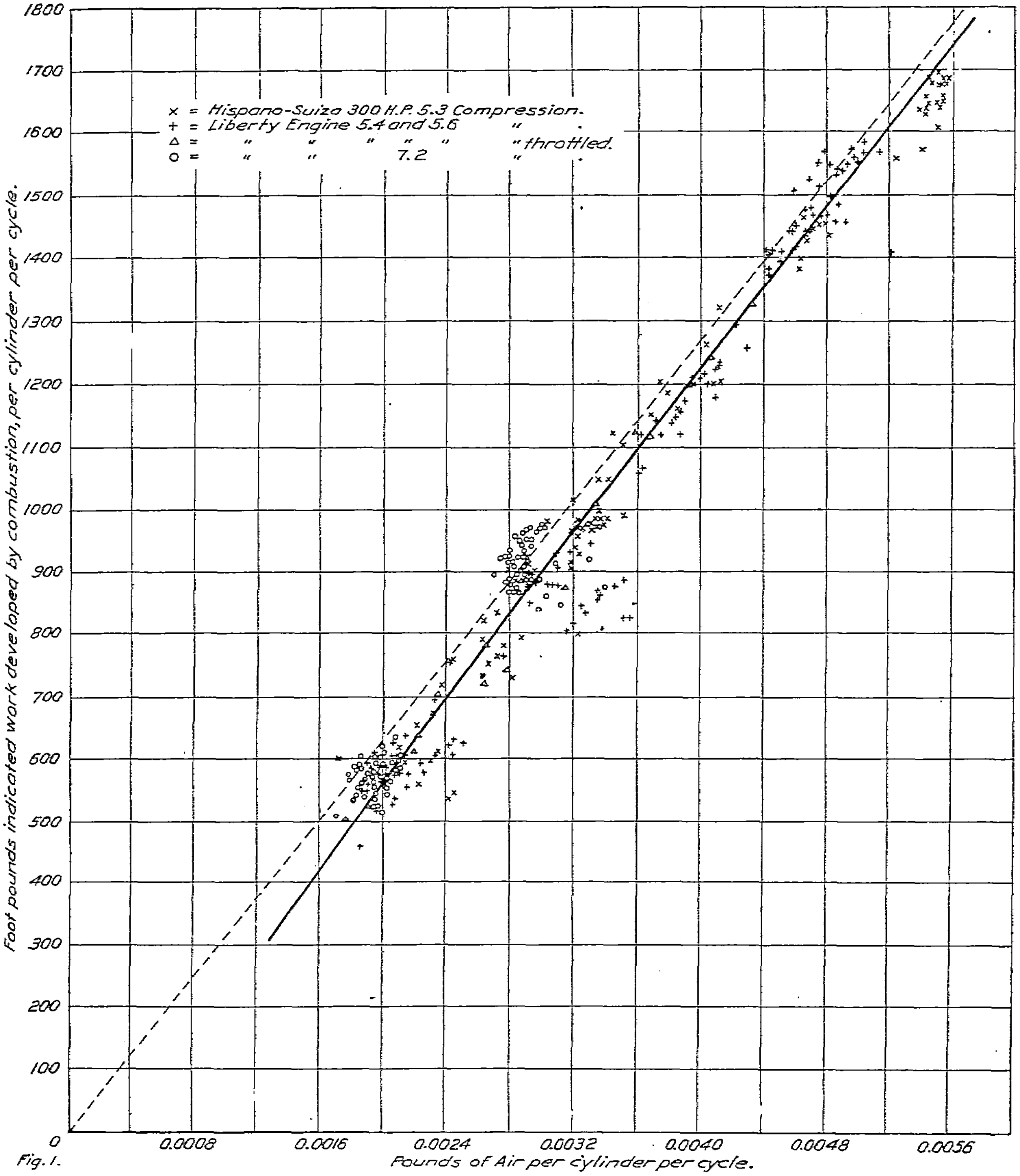
× = Hispano-Suiza 300 H.P. 5.3 Compression.
+ = Liberty Engine 5.4 and 5.6 "
△ = " " " " " " throttled.
○ = " " 7.2 "
Foot pounds indicated work developed by combustion, per cylinder per cycle.
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.0008
0.0016
0.0024
0.0032
0.0040
0.0048
0.0056
Pounds of Air per cylinder per cycle.

Fig. 1.

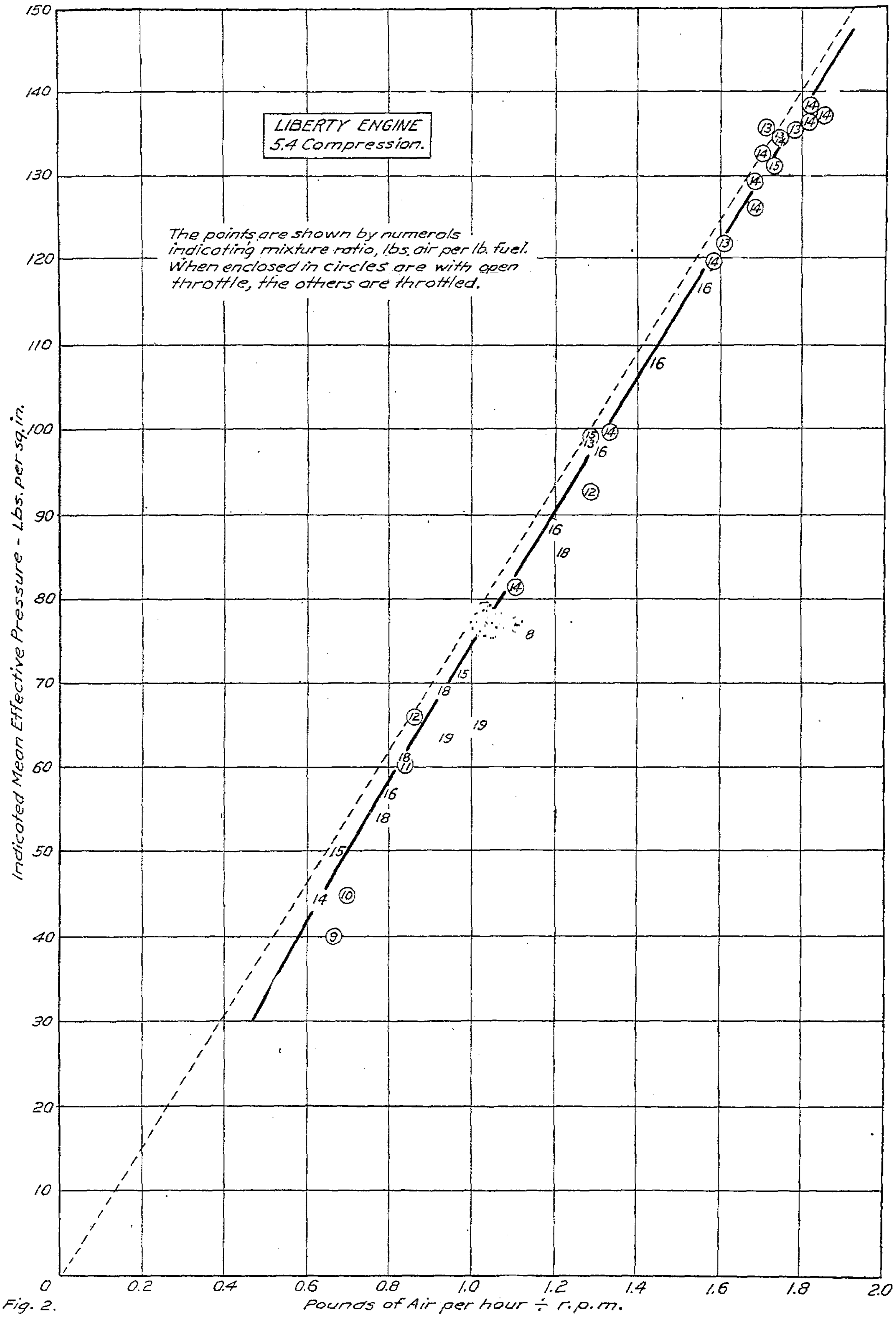
LIBERTY ENGINE
5.4 Compression.
The points are shown by numerals indicating mixture ratio, lbs. air per lb. fuel. When enclosed in circles are with open throttle, the others are throttled.
Indicated Mean Effective Pressure - Lbs. per sq. in.
Pounds of Air per hour ÷ r.p.m.
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
⑨
⑩
14
15
18
16
18
⑪
⑫
19
19
18
15
8
⑭
18
16
⑫
16
13
⑮
⑭
16
16
⑭
⑬
⑭
⑭
⑮
⑭
⑬
⑬
⑬
⑭
⑭
⑭
⑭

Fig. 2.

An approximation of the "Coefficient of utilization of the air" was computed by the formula:

$$\frac{20.9-O_2}{20.9}$$

in which 20.9 is the per cent by volume of oxygen in air and O_2 is the per cent by volume of oxygen in the exhaust gas. The efficiency of utilization as computed from the curve of figure 3 is given on figure 4. Apparently about 5 per cent less of the oxygen is used at 30,000 feet altitude than at the ground when the mixtures is adjusted for maximum power. As to the unburnt fuel, there were few determinations of hydrocarbons in the exhaust, and such as were obtained were vitiated by the presence of derivatives from the lubricating oil.

If the weight of air supplied to the engine per cycle at any given barometric pressure be multiplied by the appropriate coefficient of utilization estimated from figure 4, it will cause the curve of figure 2 to become the dotted straight line passing through the origin. This indicates that the indicated mean effective pressure is directly proportional to the weight of air actually utilized in combustion when the mixture is adjusted for maximum power. For other mixtures the line of proportionality probably will not pass through the origin, but will have an intercept on the abscissæ; in other words, some air will necessarily be unused if there is an excess of air, or may be only partially effective if rich mixtures cause incomplete combustion.

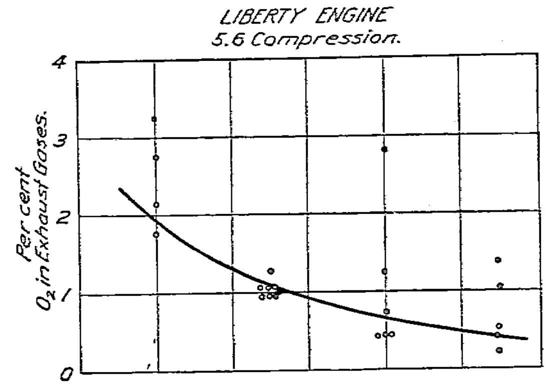

Fig. 3.

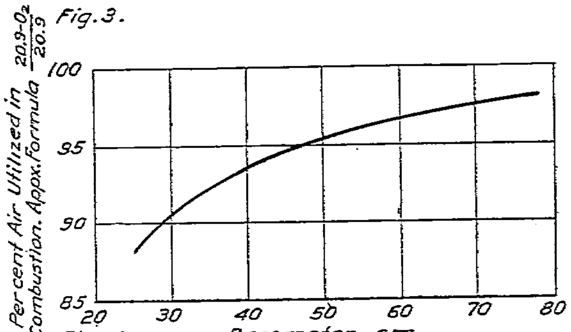

Fig. 4.

The conclusion drawn from the data reviewed in this chapter is that it is possible to use the weight of air supplied per stroke as a measure of the indicated mean effective pressure, or vice versa, over ranges of considerable barometric pressure, provided the mixture ratio is maintained sensibly constant, and, of course, with a constant compression. As for the basic relationship, air utilized versus engine power, it is appreciated that more work must be done in the field of gas analysis before absolute conclusions can be stated, but the relation indicated by the data here considered is the same as that which would be expected from theoretical considerations; namely, that indicated torque is proportional to the weight of air utilized in the combustion, entirely independent of altitude, and approximately independent of speed or of small changes in mixture ratio.

V. EFFECTS OF CHANGE OF TEMPERATURE

It is customary to supply heat to the mixture of air and gasoline in order to aid carburetion and distribution, although this heating reduces the engine power at open throttle. Heating the air supply at constant pressure does not reduce power in proportion to change of air-supply density. It has previously been shown that engine power is proportional to air density when the pressure is changed at constant temperature. These apparently contradictory facts led to the work on which this chapter is based, involving the change of volumetric efficiency with air temperature, and from which it is concluded that the engine power is directly proportional (when conditions are normal) to the weight, or density, of the charge in the cylinder at the beginning of compression.

The outline followed in studying the effects of varying air temperatures was to first find whether the air temperature affected the indicated work obtainable from unit weight of air or of gasoline. Under the conditions and within the limits of these tests no change was discovered. Continuing the study, it was found that the volumetric efficiency increases as the air temperature is increased.

Perhaps it will be well to say that volumetric efficiency as used in this report is defined as the weight of air actually drawn into the engine in a given time, divided by the weight of air required to fill the piston displacement for the same time interval, this latter weight being computed for the density existing at the entrance to the carburetor. When volumetric efficiency is figured in this manner, it gives the net results of the engine performance just the same as does the engine power, and both are affected by any changes in the induction system. For example, a refrigerating coil could be placed in the intake manifold and (assuming the fuel to be noncondensable) with absolutely no other change the engine power could be greatly increased as a result of the greater weight of charge drawn in. The volumetric efficiency could thus be made greater than 100 per cent.

It was necessary to find the reasons for the improvement in the volumetric efficiency with increase of air temperature, so a study was made of the temperature changes in the intake manifold, revealing that there is greater cooling by evaporation of fuel and less heating by jackets as the air temperature is increased. Both of these effects tend toward a higher volumetric efficiency, or, in other words, an increase of relative density inside the cylinder at the higher air temperatures.

One of the suggestions arising from this work is that it may be possible to break up a heavy fuel by intense heating of the air, subsequently cooling the charge in order to minimize the loss of power.

In testing in the altitude chamber, the air temperature is generally maintained constant for each and the same for all tests. However, there are tests in which the air supply temperature was varied, using a Liberty 12-cylinder aviation engine with 7.2 compression ratio, running at 1,700 r. p. m. with open throttle at altitudes of 14,000 and 25,000 feet, and using "X" gasoline for fuel. The intake manifolds had the usual water jackets.

Figure 1, work per pound gasoline versus temperature, is plotted from all the data of these variable temperature tests, divided into groups, each group consisting of a certain range of mixture ratios. Figure 2, work per pound air versus temperature, is plotted from data carefully selected for about maximum power mixtures and for constant relation between the pressures of carburetor supply, engine exhaust, and altitude chamber.

The abscissæ of figures 1 and 2 are manifold temperatures, which could be converted to air supply temperatures by changing the scaling. As the indicated work per pound of gasoline (fig. 1) and per pound of air (fig. 2) does not change with temperature, the numerical values of the temperature scale are immaterial. A comparison of the three ranges of mixture ratio, shown by the three sections of figure 1, indicates that the work obtained per pound of gasoline increases as the mixture becomes leaner. This result is also shown in the chapter on mixture ratios. In the lower section of figure 1, mixture ratios of from 18 to 22, the points indicate a possibility that the work may increase slightly at high temperatures with these very lean mixtures, but as this plot includes quite a range of mixtures, it is also possible that there may be some accidental coincidence, such as a grouping of the leaner mixtures at the higher temperatures, which would give the same appearance. Data sufficient to settle this point are not at present available.

Another feature which should not be overlooked when studying this subject is the existence of what may be termed a critical temperature for each gasoline. To explain this, it has been found that "X" gasoline does not carburet well if the air supply is much cooler than the freezing point of water. Reports from sources outside of the Bureau of Standards indicate that a temperature of at least 15 or 20° C. (60 or 70° F.) is necesaary to handle commercial gasoline. The tests considered in this chapter are not below the "critical temperature" of the fuel used.

Figures 1 and 2 show that the indicated work obtainable from unit weight of charge is not varied by change of temperature. As the volume of an engine cylinder is constant, and as the weight of charge is proportional to its density, and as heating the air does not decrease power as fast as it does density, it follows that the air supply density is not proportional to the charge density inside the cylinder.

Density changes of charge, due to changes in temperature, and perhaps pressure, after the air has entered the carburetor, may be expected to explain these changes of volumetric efficiency. Such changes in charge temperature will not be completed in the manifold, but will continue inside the cylinder, and will alter the volumetric efficiency until the intake valve is closed. Manifold temperatures and pressures indicate the direction and magnitude of the density changes, although the information afforded by them is incomplete, in that the final conditions inside the cylinder are unknown, except indirectly by means of volumetric efficiency. This development is illustrated by figures 3 to 10, inclusive, is outlined in the following discussion, and is based upon data from a Liberty engine of 7.2 compression ratio when conditions were as follows: 1,700 r. p. m., 14,000 feet altitude, 1 part by weight of "X" gasoline with from 14.6 to 16.9 parts of air, spark advance 21.5°, jacket water in about 65° C. (150° F.), out about 73° C. (160° F.), except for three of the several runs at higher air temperatures when jacket was varied, both above and below normal.

The manifold temperature, measured at the intake valve (fig. 3) is higher than the air supply temperature when the latter is below about $-7°$ C. ($+20°$ F.), because the jackets are giving more heat to the charge than is abstracted by evaporation of gasoline. With air supply temperatures above this the heat transfer from the jackets becomes less and less as the air supply temperature approaches the jacket temperature, while at the same time more and more of the gasoline evaporates in the manifold, withdrawing increasingly greater quantities of heat. Figure 4 shows the ratio of absolute temperature of air supply to that of the manifold $\frac{(T_c)}{(T_m)}$ plotted against air supply temperature. If there were no change in pressure drop from entrance to manifold, this ratio would be a measure of the density change. Figure 5 is the plot of absolute pressures of air supply and of manifold, and figure 6 is their ratio $\frac{(P_m)}{(P_c)}$, all versus entrance air temperature. The pressures and their ratios change but little with air temperature, so that the ratio of density in manifold to that at carburetor $\frac{(d_m)}{(d_c)}$ (fig. 7) is practically the same as the absolute temperature ratio $\frac{(T_c)}{(T_m)}$ (fig. 4), and both have the same form, but with a little more than half the magnitude of the volumetric efficiency change (fig. 9, *a*). The actual engine performance, brake mean effective pressure versus air temperature, is shown on figure 8, lower *a* curve, and the indicated m. e. p. is the upper *a* curve. Curves *b* are computed by taking the m. e. p. at 0° F. as a starting point and assuming the m. e. p. to change in direct proportion to the density of air supply. It is seen that the m. e. p. (power) does not decrease as fast as the air supply density when air temperature is changed at constant pressure. Curves *c* are computed by taking the m. e. p. at 0° F. as a starting point and assuming the m. e. p. to vary in direct proportion to the density in the manifold. This assumption (*c* curves) approaches the actual performance (*a* curves) more closely than does the assumption of power varying with air supply density (*b* curves). If the density inside the cylinder were known, it is quite probable that the indicated m. e. p. would be found to vary directly with the density at beginning of compression. Under the conditions of these tests the volumetric efficiency should be a measure of the actual total density changes. Figure 9, *a* is the actual observed volumetric efficiency; *b* and *c* are computed on the same basis as the *b* and *c* curves of figure 8.

It was of interest to see how the indicated mean effective pressure would vary with air supply temperature if volumetric efficiency could be kept constant at 100 per cent. In order to imitate this condition the actual indicated m. e. p. values at the several air temperatures were divided by the corresponding observed volumetric efficiencies, the results being shown by crosses on figure 10. To make a comparison with the assumption that power varies with density, the value of $\frac{\text{i. m. e. p.}}{\text{vol. eff.}}$ at 0° F. was selected as a starting point, and the $\frac{\text{i. m. e. p.}}{\text{vol. eff.}}$ values at other air temperatures were computed upon the assumption that m. e. p. varies directly with the density, density being changed only by change of temperature. The results are shown by circles on figure 10 and they coincide with the points (crosses) from the observed data. This confirms the statement that a change of temperature of entering air alters the power of an engine only as it changes the density of the charge at the beginning of compression, provided that the fuel is properly vaporized or pulverized at the time of ignition. But the reduction of power is not directly proportional to the increase of absolute temperature of the entering air because at the same time there is a reduction of heat transfer from the surrounding media and also a greater cooling effect because more of the fuel is vaporized before the intake valve closes. The extent of these two modifying factors is determined by the design of the engine, the conditions of operation, and the nature of the fuel employed.

There can be no formula of universal application which will convert the engine power or torque actually obtained at one air supply temperature to that which would be obtained by test at another temperature. However, for one engine, operated under constant conditions except air temperature, and using one fuel, an empirical formula may be devised to convert engine power at one air temperature to the power that would be obtained at another air temperature.

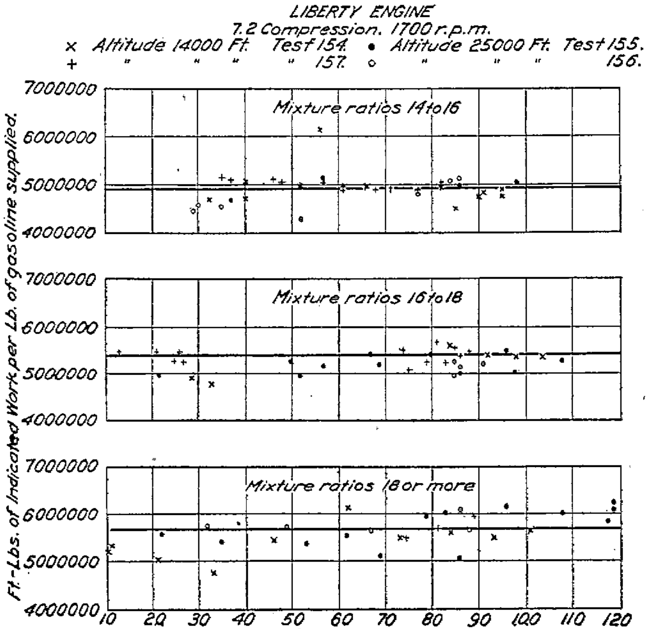

Fig. 1.

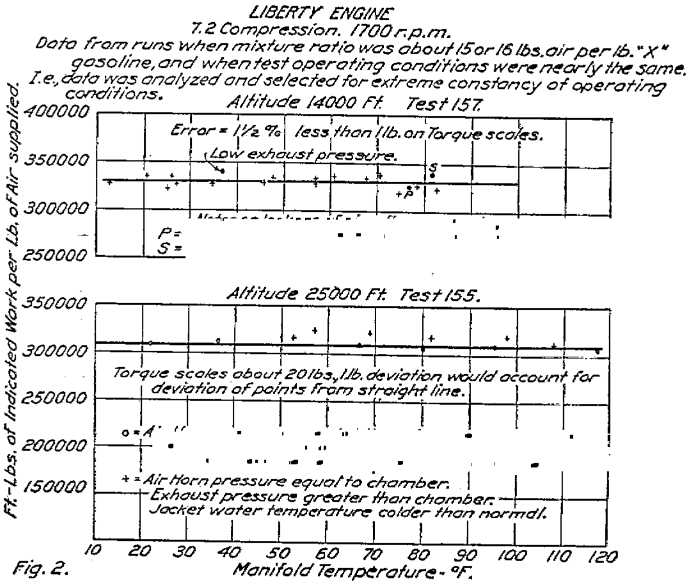

Fig. 2.

LIBERTY ENGINE
7.2 Compression 1700 r.p.m. "X" Gasoline.
Altitude 14000 Ft. Test 157.
Mixture Ratios from 14.6 to 16.9 only. Spark advance 21.5°. Jacket Water in 145 to 150 °F., out 160 to 165 °F., except with Carbureter Air temperatures of 95, 107 & 108° when Jacket out was 129, 144, 176° respectively.

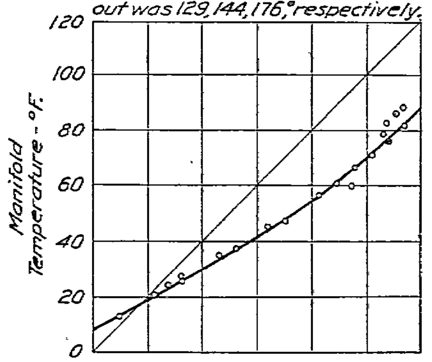

Fig. 3

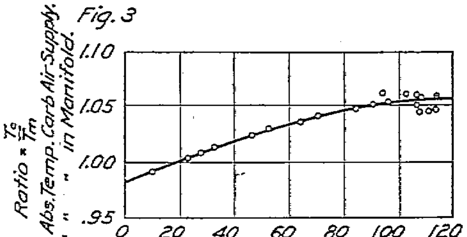

Fig. 4. Carbureter Air Temp. - °F.

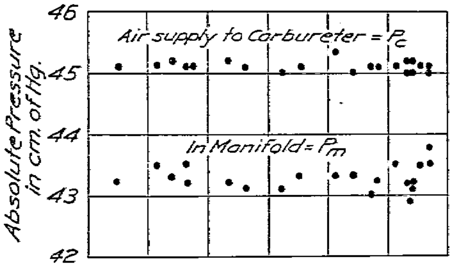

Fig. 5

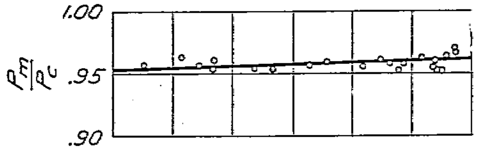

Fig. 6.

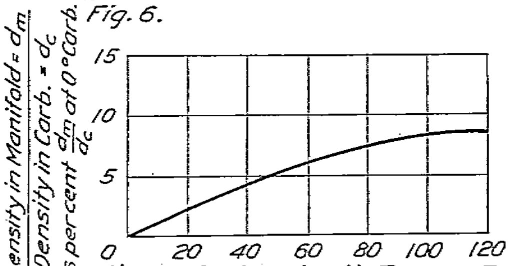

Fig. 7 Carbureter Air Temp. - °F.

a = Test results.
b = Assumption that value is proportional to density of Carbureter supply air.
c = Assumption that value is proportional to density in manifold.

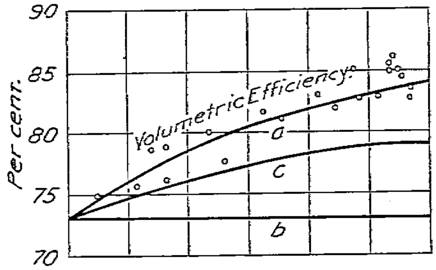

Fig. 9.

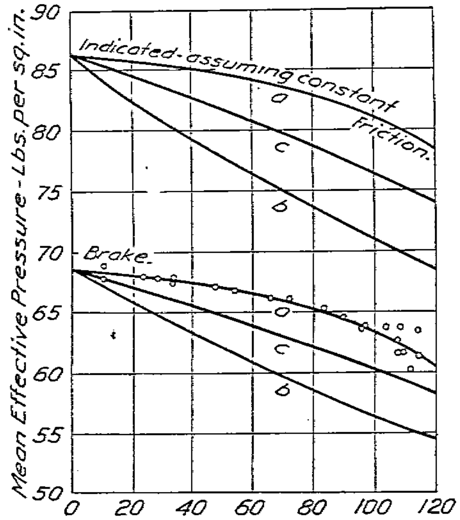

Fig. 8 Carbureter Air Temp. - °F.

+ = I.M.E.P., test values, divided by corresponding Volumetric Efficiency.
o = (I.M.E.P.$_o$ + V.E.$_o$) × (T_c ÷ T_o)

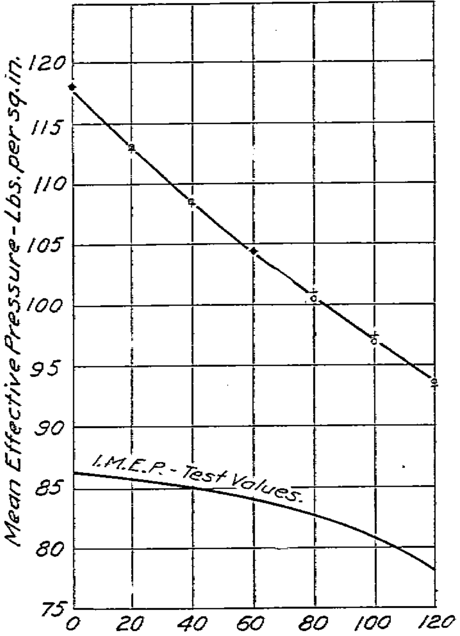

Fig. 10. Carbureter Air Temp. - °F.

VI. EFFECTS OF CHANGE OF MIXTURE RATIO.

The subject of mixture ratios is receiving considerable attention at the present time. The mixture of air and gasoline required for maximum power is known to be slightly richer than that for maximum economy. Either too rich or too lean a mixture results in a loss of both power and economy.

The effect of change of altitude and compression ratio upon the proportion of air and fuel for, say, maximum power is not definitely known. It is possible that the proportion giving maximum economy at the ground may not be the same as that giving maximum economy at another altitude, or with another compression ratio, or at another throttle position. The same statement applies to the mixture for maximum power. If altitude and compression ratio change the required proportion for a desired result, such change may be explained by the effects of changed density and heat content of the charge at the time of ignition upon the process of combustion. Although no evidence of the influence of engine speed could be detected on these tests, at speeds from 1,200 to 2,200 r. p. m., still it is possible that the relation of the velocity of flame to piston travel may have some influence upon power.

This subject of mixture ratio involves the question of how much energy is liberated by the combustion of the fuel under the several conditions. Exhaust gas analysis could well be used in the search for more light upon the subjects. Another point to be considered is the possible difference between the actual mixture ratio, defined as the measured air to measured gasoline, and the effective mixture ratio, defined as the proportions of air and gasoline actually combining inside the cylinder.

At the present time data are being obtained in the altitude chamber upon the effects of change of mixture ratio, but among the older tests there are only a few with much range of mixture, as most of the runs were made with the carburetor adjusted for the best economy consistent with the condition of maximum power. However, the tests upon the 7.2 compression engine also included runs with the mixture purposely made considerably leaner than the maximum power adjustment, and some runs on the engines with about 5.4 compression also included rich mixtures as well as maximum power mixtures.

A general survey was made of the data from practically all of the older tests, using basic relationships. By basic is meant the fundamental relations between mixture ratio and the indicated work resulting from unit weight of (1) gasoline and (2) air supplied. The use of indicated instead of brake work placed the data from all the engines on a more comparable basis and removed some inconsistencies resulting from variations of volumetric efficiency. The results of the general survey indicated that the work obtainable from unit weight of gasoline steadily increased as the mixture was made leaner until the ratio was about 18 or 20 to 1, when the engine performance became erratic, probably due to misfiring. This erratic behavior did not always begin at the same mixture ratio for the various altitudes, compressions, etc. The survey also indicated that the work obtainable from unit weight of air followed the form into which the usual curves of power versus ratio would convert; that is, the maximum power is obtained from unit weight of air with a mixture perhaps slightly richer than the theoretical combining proportion of 15 weights of air to 1 of gasoline.

Guided by these general relations, data were selected so as to segregate the various variables as much as possible, still retaining comparable tests with varying mixtures. These are shown in figures 1 and 2, plotted to the coordinates previously mentioned, namely, mixture ratio as abscissæ for both plots, and ordinates of indicated work per pound of gasoline for figure 1 and per pound of air for figure 2. One plot or section of figure 1 is made with data from a Liberty engine with 7.2 compression, another from a Liberty with 5.4 compression, and the third from a Hispano-Suiza 300-horsepower engine with 5.3 compression. All of the plots of figure 2 are from a Liberty 7.2 compression engine, at different times and different altitudes. In order to reach absolute conclusions it will be necessary to cover the whole range of mixture ratios at each compression, as this is a major factor. It is evident that altitude is also a factor, probably of minor importance, and that speed changes of the magnitude of from 1,200 to 2,200 r. p. m. are absolutely negligible in altering the work obtainable from unit weight of either air or fuel at a given mixture ratio.

The numerical values of figures 1 and 2 should not be used for commercial gasoline, as the fuel used on all these tests was one of high volatility, complying with the specifications for aviation gasoline used during the war for export to the American Expeditionary Forces.

The oil which enters into combustion in the aviation engines could not be considered, although heat balances and gas analyses both indicated that in some cases the oil is a considerable source of fuel.

The tentative conclusions drawn from the study of mixture ratios are that the indicated work obtainable from unit weight of fuel (the indicated thermal efficiency) increases as the mixture is made leaner up to the point when weak mixtures cause erratic engine performance; and that the indicated work obtainable from unit weight of air is at a maximum (meaning that maximum power is obtained) at about the theoretical combining proportions of 15 parts by weight of air to 1 of gasoline, decreasing with change of mixture in either direction, but being fairly constant from perhaps 14 to 16.

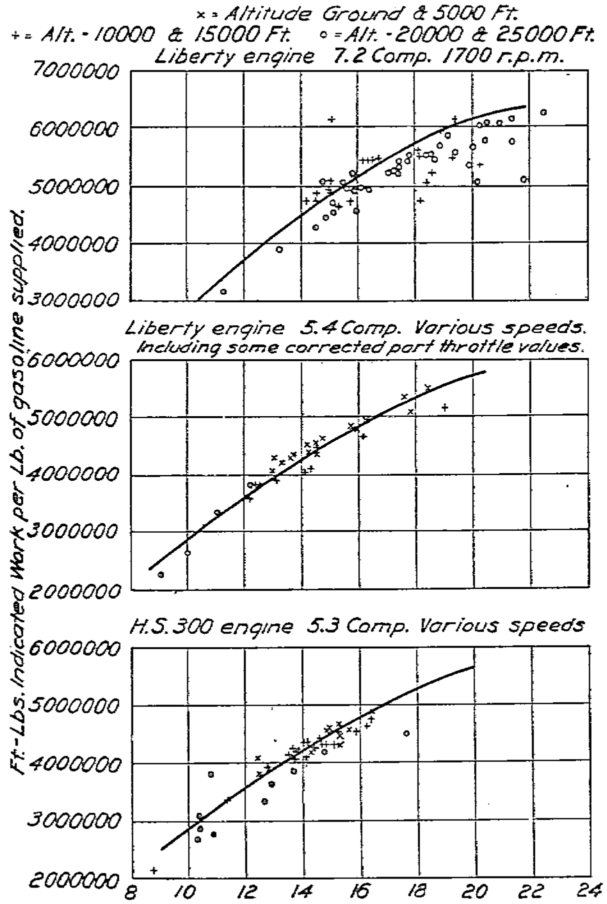

Fig. 1.

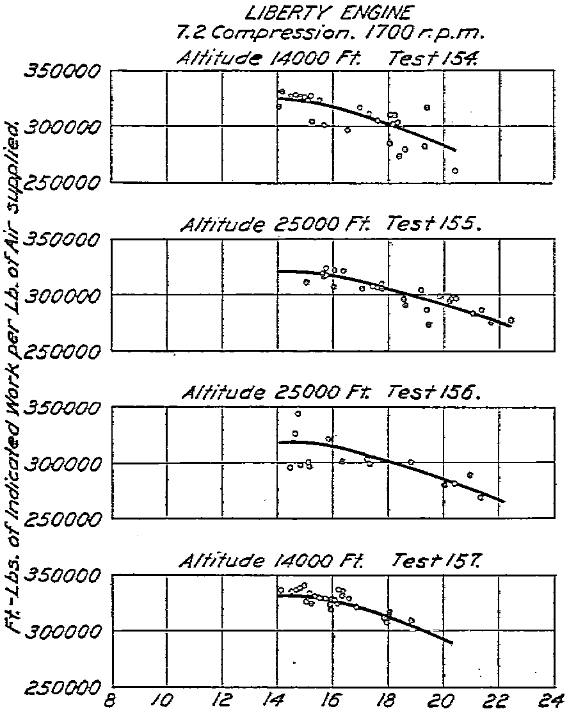

Fig. 2.

VII. HEAT BALANCES.

The heat balance of an engine shows the disposition made of the energy supplied, and is a valuable aid in making improvements in engine performance. The data obtained in the altitude laboratory permit accounting for most of the energy supplied, as it is exceptionally complete in all respects. In this section a comparison has been made between the heat balance obtained from actual engine tests and that computed by thermodynamics from the corresponding theoretical cycle, indicating that the greatest possible improvement in thermal efficiency can be made by increasing the compression ratio.

A major portion of the potential energy supplied is actually made available to the engine by the chemical process of combustion, but not all, as some of the elements or compounds usually escape uncombined. And unburned fuel in the exhaust may be of a different chemical nature from that supplied, in which case chemical changes represent energy changes. For example, if the exhaust contains carbon monoxide, alcohols, or aldehydes, they represent chemical changes and also energy losses.

The thermal efficiency of an engine is usually computed as the actual work divided by the chemical energy supplied. This fails to distinguish between the losses due to incomplete combustion and the losses due to incomplete transformation from heat energy to work. For purposes of analysis of engine performance it would be well to separate the efficiency of combustion from the efficiency of transformation of the energy actually made available to the mechanism, the former probably varying more with change of operating conditions than does the latter.

One method of approximating the efficiency of combustion is by assuming that all the heat made available by combustion appears in the total heat accounted for during an engine test. In these tests the energy accounted for is in (1) the brake power, (2) the exhaust heat, and (3) the jacket water. Going more into detail concerning these items: (1) The delivered work is the useful result obtained from the engine and needs no comment. (2) The exhaust heat was measured by water cooling the exhaust gases to their original temperature and pressure, and measuring the heat thus absorbed. Therefore, the exhaust heat does not include any loss due to inefficiency of combustion, as it is made up entirely of the sensible heat of all the products of combustion, together with the latent and superheat of the water vapor. (3) The jacket losses were obtained from the quantity and the temperature rise of the cooling water. The heat thus represented includes that taken directly from the combustion, from compression, and from piston friction. As a great part of the friction loss is due to piston friction, a large portion of the friction will appear as heat in the jacket water. It should be noted that the sum of brake thermal efficiency, jacket, exhaust, and radiation is 100 per cent of the heat made available, and that if indicated is substituted for brake thermal efficiency in obtaining the heat available, then some of the friction will appear twice in the total. "Radiation, etc.," includes heat losses from the engine system by conduction, convection, and radiation. The "radiation, etc.," excluding losses due to unburned fuel, is probably of the order of 5 per cent of the heat made available by combustion. If unburned fuel is included, the losses are called "residual heat."

The energy accounted for in exhaust, jacket, and brake (an approximation of the heat made available by combustion) is used as a basis for computing heat balances in this chapter, as well as the usual basis of "heat" supplied in the fuel. Both types of heat balance were compared and used as a means for studying the effects of altitude and speed upon the energy distribution in airplane engines. Table 1 presents data from the Liberty 12-cylinder engine and Table 2 from the Hispano-Suiza model H, 300 h. p., 8-cylinder engine. The tests covered the usual range of engine speeds at each of several altitudes. Both engines had about the same compression ratio, a little more than 5 to 1. The tests were made under the usual standard conditions of the altitude laboratory described in previous chapters. The heat balances using heat supplied in fuel as 100 per cent are based upon the higher heating value of the fuel. Whenever possible and desirable, the indicated thermal efficiency is used in place of the brake thermal efficiency, as it gives informaton concerning the internal thermodynamic performance of the engine uninfluenced by the unstable relation of brake power to friction.

Tables 1 and 2 present the items of the heat balances computed upon the two bases previously mentioned, i. e., per cents of heat supplied in gasoline and of heat accounted for in exhaust, jacket, and brake. The last column of Table 1 is an estimate of the quantity of heat removed in the lubricating oil on the Liberty engine, obtained by noting the temperature rise of the oil from inlet to outlet during the test, and subsequently determining the rate of flow of the oil at various engine speeds. Less than one-half of 1 per cent of the heat supplied is removed by cooling the oil.

Exhaust heat and indicated horsepower, as per cent of heat accounted for, taken from Tables 1 and 2, are plotted against air density (at constant temperature) on the upper section of figure 1. Data from the Liberty engine are denoted by circles, and that from the Hispano-Suiza engine by crosses. In the preliminary plotting of data with these same coordinates it had been found that there was no systematic variation with speed, so the different speeds are not distinguished from one another. The lower section of figure 1 is similar to the upper and is plotted from the same data, the difference being that the exhaust and indicated horsepower at the several densities are plotted against the engine speed. Evidently the two engines are thermodynamically alike, and, within the limits of speed, density, and experimental error of these tests, there is no change in the thermal utilization of the heat made available to the engines.

HEAT REJECTED AND COMPRESSION RATIOS.

Tables 1 and 2 and figure 1 show that the heat rejected in the exhaust of the actual engines nearly coincides with the theoretical heat rejection of a perfect engine operating on the same cycle with the same compression ratio. On these engines there is little chance for the water jackets to cool the exhaust after it leaves the cylinder. The heat rejected from the actual engines, expressed as per cent of the heat accounted for, is practically constant for the several densities and speeds. This agreement between theory and test results led to the tabulation of data from tests of engines with several different compression ratios, including some of the first tests made in the altitude chamber. Heat balances as computed from these tests with several different compressions are given in Table 3, wherein the items are as follows:

EJB is the sum of the heat accounted for in the exhaust, jacket, and brake, expressed as per cent of the heat supplied in gasoline.
E is the heat rejected in exhaust, expressed as per cent of heat accounted for in exhaust, jacket, and brake.
J is the heat removed in jacket water, expressed as per cent of heat accounted for.
B is the brake or dynamometer horsepower, expressed as per cent of heat accounted for.

As friction determinations were not complete on some of the older tests because of lack of power, so the indicated thermal efficiencies are not given for this group of tests. In tabulating the data for Table 3, a speed common to all tests was sought, but some of the tests were made at 1,500 r. p. m., while others were made at 1,600. On figure 2 the brake thermal efficiencies at a given range of altitude are shown to increase with increase of compression, but not quite as much as would be expected from the theoretical cycle. A comparison of the three sections of this figure shows that the highest thermal efficiency occurs at the ground. This is because the mechanical efficiency decreases with increase of altitude, so the brake thermal efficiency must decrease likewise, although previous work indicates that the indicated thermal efficiency would be constant if based on heat available.

By expressing the heat rejected in the exhaust as per cent of the heat accounted for, as in Table 3, the data taken at different altitudes are reduced to a common basis for direct comparison. These data are shown as points superposed upon the theoretical heat rejection versus compression ratio curve on figure 3. Evidently the heat lost in exhaust of actual engines is very closely related to the theoretical heat rejection of the Otto cycle. The points plotted on figure 3, being per cent of exhaust, jacket, and brake, will have values slightly greater than if expressed as per cent of true heat available, because the radiation has been omitted from the former basis.

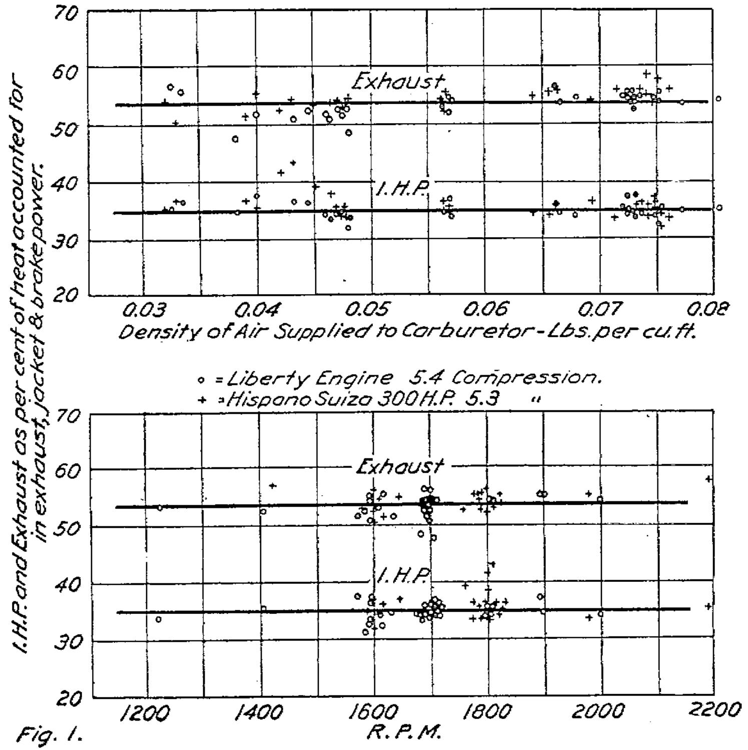

Fig. 1.

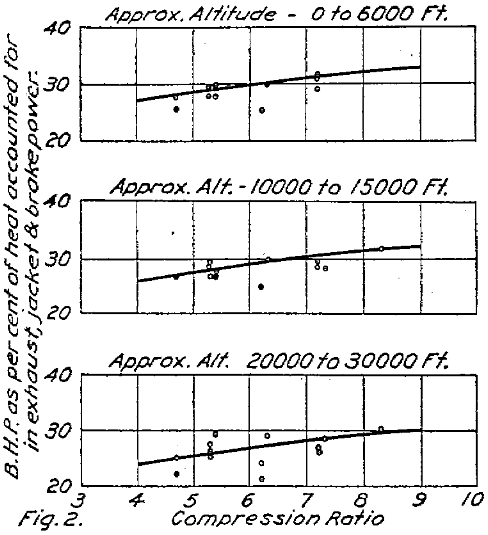

Fig. 2.

"Air Standard" Efficiency $= 1 - \left(\frac{1}{\text{Comp. Ratio}}\right)^{0.408} =$ the efficiency of the Otto Cycle, using air, assuming constant specific heat. $\left(\frac{1}{\text{Comp. Ratio}}\right)^{0.408} =$ heat rejected during the exhaust of this cycle.

The heat rejected in exhaust of actual engines expressed as per cent of heat accounted for (from Table III) is shown by the points superposed upon the theoretical curve.

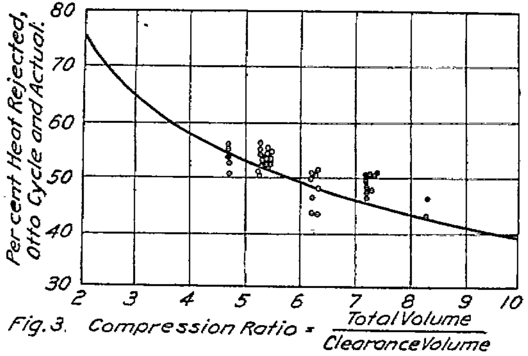

Fig. 3.

CONCLUSIONS.

Of the heat accounted for about 54 per cent is exhausted and 35 per cent is transformed into useful work with an engine of about 5.3 compression ratio. This distribution apparently is not influenced by altitude nor engine speed.

Of the heat made available by combustion, it is estimated that about 52 per cent is exhausted, the same as the theoretical rejection for this compression. The indicated work accounts for about 33 per cent and the jackets remove about 15 per cent not including friction, or about 20 per cent including friction. It is also estimated that the losses due to imperfect combustion are about 10 per cent or more of the energy supplied when the mixture is adjusted for maximum power, increasing at altitude, perhaps because of richer mixtures, perhaps because of less complete combustion.

Increasing the compression ratio is the only method of reducing the exhaust losses, and offers opportunity for a greater gain in efficiency than any other means, although it introduces many problems of its own, including an increased jacket loss as well as the fuel problem.

TABLE 1.—*Heat balance.*

LIBERTY AVIATION ENGINE.

[Test No. 160—Liberty 12-cylinder engine, compression 5.4.]

Run No.	Altitude (approximate).		Air supply density.		Engine speed.	Heat accounted for in exhaust jacket and brake.		Indicated horsepower as per cent of		Exhaust as per cent of		Jacket as per cent of		Residual heat as per cent of heat supplied.	Heat in oil as per cent of heat supplied.
								Heat accounted for.	Heat supplied.	Heat accounted for.	Heat supplied.	Heat accounted for.	Heat supplied.		
			Gms./liter.	*Lbs./ft.³*	*R.p.m.*	*Kg. cal./sec.*	*Btu./hr.*								
A- 5	Ground......		1.17	0.0731	1,225	180	2,571,000	33.9	26.6	53.2	41.6	17.0	13.3	21.5	0.2
6	.....do.......		1.17	.0732	1,406	199	2,830,000	35.8	27.4	52.6	40.2	16.4	12.6	23.4	.2
7	.....do.......		1.17	.0731	1,598	211	3,015,000	37.6	27.1	53.2	38.3	14.7	10.6	27.7	.3
8	.....do.......		1.15	.0719	1,802	244	3,480,000	35.5	27.6	54.8	42.7	15.7	12.2	21.6	.4
9	.....do.......		1.16	.0726	1,794	251	3,590,000	34.6	29.0	54.8	46.0	16.3	13.7	15.7	.4
10	.....do.......		1.16	.0724	1,893	236	3,375,000	37.4	27.4	55.4	40.6	13.8	10.1	26.2	.4
B- 1	.....do.......		1.17	.0729	1,802	253	3,610,000	35.0	28.4	54.5	44.3	16.3	13.3	18.2	.4
2	.....do.......		1.16	.0727	1,898	260	3,710,000	35.0	28.3	55.2	44.8	16.0	13.0	18.5	.4
3	.....do.......		1.16	.0725	1,999	262	3,740,000	34.4	25.5	54.6	40.5	17.7	13.1	25.3	.5
C- 5	.....do.......		1.20	.0751	1,617	253	3,610,000	32.6	27.7	55.1	47.0	17.3	14.7	14.5	.2
6	.....do.......		1.20	.0748	1,699	255	3,650,000	34.1	28.8	54.5	46.2	16.6	14.1	15.0	.3
E-18	.....do.......		1.29	.0808	1,702	241	3,450,000	35.3	26.9	54.5	41.7	15.7	12.0	23.1	.3
19	.....do.......		1.23	.0771	1,697	243	3,470,000	35.0	27.3	53.6	41.9	16.9	13.3	21.3	.3
20	.....do.......		1.21	.0753	1,700	241	3,450,000	35.6	28.9	53.9	44.0	16.1	13.2	17.9	.3
21	.....do.......		1.18	.0735	1,682	246	3,520,000	34.3	29.1	54.4	46.3	16.7	14.2	14.5	.3
	Km.	*Feet.*													
C- 7	1.5	5,000	1.09	.0678	1,692	221	3,150,000	34.0	28.1	54.2	44.9	17.4	14.4	16.9	.3
8	......	....	1.06	.0664	1,610	207	2,960,000	34.8	25.5	53.2	39.0	17.7	13.0	26.2	.3
E-12	......	....	1.06	.0661	1,690	201	2,875,000	36.0	30.5	56.4	47.8	13.6	11.5	14.9	.4
C- 9	3.0	10,000	.91	.0569	1,596	176	2,510,000	33.7	26.3	54.1	42.2	18.3	14.2	21.6	.4
10	......	....	.90	.0565	1,688	168	2,400,000	35.9	23.5	52.4	34.4	19.8	13.0	34.0	.3
D- 1	......	....	.91	.0568	1,707	167	2,380,000	37.0	28.3	54.5	41.8	15.4	11.8	22.9	.4
E- 6	......	....	.90	.0564	1,694	179	2,555,000	34.4	29.3	53.2	40.8	18.8	14.4	22.9	.4
D- 2	4.6	15,000	.77	.0481	1,686	143	2,040,000	33.7	24.2	48.6	34.9	25.5	18.3	27.5	.5
3	......	....	.77	.0481	1,589	150	2,145,000	31.9	25.7	52.7	45.1	....	18.6	13.9	.5
8	......	....	.74	.0466	1,595	136	1,940,000	33.3	23.9	50.8	34.1	21.6	14.5	32.3	.4
E- 1	......	....	.76	.0474	1,632	124	1,767,000	34.8	28.1	51.3	41.6	22.1	17.9	18.2	.5
22	......	....	.75	.0471	1,690	141	2,015,000	34.2	26.3	52.4	39.8	21.1	16.0	23.4	.5
23	......	....	.74	.0464	1,696	141	2,020,000	34.6	23.8	51.5	35.8	21.7	15.0	30.0	.4
24	......	....	.71	.0445	1,697	135	1,930,000	36.0	24.6	52.2	35.8	19.8	13.6	30.9	.5
25	......	....	.69	.0433	1,702	134	1,915,000	36.3	25.8	50.4	35.9	21.6	15.4	30.1	.5
D- 4	6.1	20,000	.64	.0402	1,572	101	1,450,000	37.8	24.1	51.8	32.9	19.0	12.1	35.8	.5
5	......	....	.61	.0382	1,704	110	1,575,000	34.8	20.9	47.6	28.9	27.0	16.3	38.9	.5
D- 6	7.6	25,000	.52	.0324	1,702	71	1,020,000	35.4	14.3	56.4	22.8	21.7	8.5	59.3	.5
7	......	....	.54	.0335	1,595	73	1,040,000	36.4	16.5	55.2	25.3	19.8	9.0	54.0	.5

TABLE 2.—*Heat balance.*

HISPANO-SUIZA AIRPLANE ENGINE.

[Test No. 162—Model H engine, compression ratio 5.3.]

Run No.	Altitude (approximate).		Air supply density.		Engine speed.	Heat to jacket.		Heat accounted for in exhaust, jacket, and brake.		Indicated horsepower as per cent of		Exhaust as per cent of		Residual heat as per cent of heat supplied.
										Heat accounted for.	Heat supplied.	Heat accounted for.	Heat supplied.	
			Grams/liter.	*Lbs./ft.*	*R.p.m.*	*Kg. cal./sec.*	*B.t.u./hr.*	*Kg. cal./sec.*	*B.t.u./hr.*					
A- 1	Ground		1.20	0.0752	1,421	18.5	264,000	146	2,090,000	34.6	27.7	57.2	46.0	19.6
2	do		1.20	.0748	1,642	20.7	295,000	161	2,300,000	37.2	28.4	55.0	42.1	23.5
3	do		1.20	.0747	1,814	27.2	388,000	179	2,560,000	36.7	27.7	53.2	40.2	22.7
4	do		1.19	.0744	1,979	32.5	464,000	205	2,930,000	34.0	29.0	55.5	47.4	14.6
5	do		1.19	.0741	2,192	23.8	310,000	205	2,935,000	35.9	29.0	58.6	47.2	19.4
11	do		1.20	.0752	1,600	29.9	426,000	182	2,600,000	32.0	27.2	55.9	47.7	14.6
12	do		1.19	.0746	1,796	25.9	369,000	185	2,640,000	35.4	26.8	55.5	42.1	24.2
B-25	do		1.22	.0760	1,793	30.2	431,000	191	2,735,000	33.5	27.9	55.6	46.5	16.3
26	do		1.18	.0734	1,774	23.2	331,000	174	2,485,000	36.4	31.3	55.4	47.8	13.7
27	do		1.14	.0712	1,800	30.2	430,000	190	2,710,000	33.4	31.3	55.5	52.1	6.2
28	do		1.11	.0693	1,817	26.1	372,000	172	2,460,000	36.6	31.2	53.8	45.9	14.6
	Km.	*Feet.*												
A-13	1.5	5,000	1.02	.0639	1,610	23.5	336,000	146	2,085,000	34.4	27.3	54.4	43.3	20.5
14			1 06	.0661	1,792	21.3	304,000	154	2,205,000	36.0	28.3	55.8	42.7	23.4
B-11			1.05	.0657	1,780	26.0	371,000	163	2,325,000	33.8	29.3	55.5	48.3	13.0
A-15	3.0	10,000	.90	.0564	1,601	22.2	317,000	119	1,700,000	34.8	25.2	52.5	38.1	27.4
16			.90	.0565	1,808	21.9	313,000	132	1,880,000	35.6	26.9	54.0	40.8	24.7
B- 6			.91	.0566	1,793	19.5	278,000	129	1,845,000	35.9	27.7	55.3	42.8	22.7
A-17	4.6	15,000	.76	.0474	1,591	18.0	256,000	97	1,383,000	35.2	25.9	53.0	38.1	28.0
18			.75	.0472	1,793	19.6	280,000	107	1,530,000	35.6	26.5	53.4	39.7	25.6
B- 1			.76	.0476	1,786	21.4	306,000	111	1,590,000	33.8	26.5	53.7	42.0	21.8
19			.77	.0481	1,783	21.0	300,000	112	1,600,000	33.8	25.7	54.2	41.4	23.7
21			.74	.0465	1,802	15.9	227,000	101	1,445,000	38.3	29.1	53.6	40.7	24.0
22			.72	.0450	1,757	14.3	204,000	94	1,345,000	39.8	24.6	52.9	32.8	38.0
23			.69	.0432	1,809	13.5	193,000	87	1,245,000	43.4	27.2	53.9	33.8	34.9
24			.68	.0422	1,797	13.5	192,000	90	1,280,000	41.5	26.7	52.2	33.6	35.6
A-19	6.1	20,000	.63	.0393	1,620	14.6	208,000	69	990,000	36.6	19.4	51.6	27.4	46.8
20			.64	.0400	1,818	15.9	227,000	88	1,265,000	35.2	23.8	55.3	37.3	32.5
A-21	7.6	25,000	.51	.0321	1,782	13.0	186,000	58	821,000	35.7	16.1	53.8	24.3	54.9
22			.53	.0329	1,599	12.5	179,000	51	724,000	37.2	16.5	50.2	22.3	55.4

TABLE 3.—*Summary of approximate heat balances.*

EJB = per cent of heat supplied in fuel which is accounted for in exhaust, jacket, and brake power.
E = per cent of EJB which is in exhaust.
J = per cent of EJB which is in jacket.
B = per cent of EJB which is in brake power.

Compression ratio.	Items.	Approximate altitude.							Engine—Hispano-Suiza or Liberty.	Test No.	Engine speed (approximate).	Fuel.
		Thousands of feet.										
		0	5-6	10-12	14-15	20	25	30				
		Kilometers.										
		0	1.7	3.5	4.5	6.1	7.6	9.2			*R. M. P.*	
4.7	EJB	91.5	84.0	85.6		86.3		97.0	H.-S. 150	31	1,500	X gas.
	E	50.3	55.2	55.4		52.2		53.0				
	J	23.9	17.3	18.1		22.6		24.8				
	B	25.8	27.6	26.5		25.1		22.2				
5.3	EJB	85.4	79.5	72.6	72.0	53.2	44.6		H.-S. 300	162	1,600	X gas.
	E	55.9	54.4	52.5	53.0	51.6	50.2					
	J	16.4	16.1	18.6	18.5	22.0	24.7					
	B	27.8	29.5	29.0	28.7	27.5	25.2					
5.3	EJB		79.3		87.6		80.9		H.-S. 180	163	1,600	X gas.
	E		52.2		51.0		55.3					
	J		18.4		22.4		18.3					
	B		29.4		26.8		26.5					
5.4	EJB	85.5	73.8	78.4	81.8	64.2	46.0		Liberty	100	1,600	X gas.
	E	55.1	53.2	54.1	51.3	51.8	55.2					
	J	17.3	17.7	18.3	22.1	19.0	19.8					
	B	27.6	29.2	27.6	26.7	29.2	24.4					
6.2	EJB		101.1	90.6		93.4		77.5	H.-S. 150	89	1,500	X gas.
	E		50.8	49.6		46.6		43.3				
	J		24.1	25.5		29.6		35.3				
	B		25.1	24.9		24.0		21.5				
6.3	EJB		73.3		71.1		69.7		H.-S. 180	166	1,600	X gas.
	E		51.5		48.0		43.2					
	J		18.7		22.4		28.0					
	B		29.9		29.7		28.9					
7.2	EJB		90.1		98.4		89.3		Liberty	152	1,600	X gas.
	E		49.2		50.4		47.4					
	J		22.0		20.9		25.9					
	B		29.0		28.8		26.8					
7.2	EJB	85.6	85.7		82.8		82.1		Liberty	152	1,600	Hecter.
	E	50.4	50.4		48.4		46.5					
	J	18.7	18.6		22.4		26.6					
	B	31.0	31.1		29.4		27.1					
7.3	EJB				94.0		79.7		H.-S. 180	165	1,600	X gas.
	E				50.2		47.8					
	J				21.8		23.7					
	B				28.1		28.5					
8.3	EJB				77.3		78.7		H.-S. 180	164	1,600	X gas.
	E				46.6		43.0					
	J				22.0		27.0					
	B				31.5		30.2					