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COMPRESSION-IGNITION ENGINE PERFORMANCE AT ALTITUDES AND AT VARIOUS AIR PRESSURES AND TEMPERATURES

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SUMMARY

Engine test results are presented for simulated altitude conditions. A displacer-piston combustion chamber on a 5- by 7-inch single-cylinder compression-ignition engine operating at 2,000 r.p.m. was used. Inlet-air temperatures equivalent to standard altitudes up to 14,000 feet were obtained by using solid CO_2, Prestone solution, and kerosene in an air-cooling and dehumidifying apparatus. The inlet air was throttled and the exhaust surge tank evacuated to give pressures corresponding to the standard altitudes. The inlet-air temperature, inlet-air pressure, and inlet and exhaust pressures were also varied over a wide range and over a range of fuel quantities from part load to maximum load.

Comparison between maximum performance at altitude of the unsupercharged compression-ignition engine and a carburetor engine showed that the compression-ignition engine compared favorably with the carburetor engine.

Analysis of the results for which the inlet-air temperature, inlet-air pressure, and inlet and exhaust pressures were varied indicates that engine performance cannot be reliably corrected on either the basis of inlet-air density or weight of air charge. Engine power increases with inlet-air pressure and decreases with inlet-air temperature very nearly as straight-line relations over a wide range of air-fuel ratios. Correction factors are accordingly suggested.

INTRODUCTION

The effect of altitude on the performance of carburetor engines has been thoroughly investigated, but very little actual experimenting has been done in this country to determine the effect of altitude on the performance of a compression-ignition engine. The purpose of this report is to present the results of tests that were made during the latter part of 1936 at the Langley Field laboratories of the N.A.C.A. Tests were made on a compression-ignition engine for simulated altitude conditions and various combinations of inlet-air temperature and pressure and exhaust back pressure.

In order to make the most accurate altitude tests of any type of engine, an altitude chamber similar to the one at the National Bureau of Standards (reference 1) is desirable; however, if such equipment is lacking, reliable results can be obtained by the methods described in the present paper. The general test procedure used in this investigation may be called an "approximate" method. Results obtained by this approximate method have been directly compared with results obtained by the National Bureau of Standards in an altitude chamber (reference 2); the discrepancy between the data obtained by the two methods is so small as to be within the limits of experimental accuracy. The approximate method of making altitude tests has been used for some time by the air services for testing carburetor engines.

All changes in altitude are, fundamentally, changes in air density as a result of changes in the temperature and pressure. These factors are present regardless of supercharging and have a pronounced effect on engine performance. The scope of these tests was accordingly broadened to include the effect of a wide range of temperatures and pressures of the inlet air.

APPARATUS AND TESTS

Test Engine

The development of the displacer-piston combustion chamber and fuel-spray arrangement used in these tests (see fig. 1) has been completely described in references 3 and 4. The more important parts of the test unit and some test conditions were as follows:

Engine	Single-cylinder 4-stroke cycle, 5-inch bore by 7-inch stroke (137.5 cu.in. displacement).
Engine speed	2,000 r.p.m.
Compression ratio	14.5.
Valve timing	Inlet opens 27° B.T.C. Exhaust opens 66° B.B.C. Inlet closes 28° A.B.C. Exhaust closes 41° A.T.C.
Fuel	Auto Diesel fuel; 0.83 specific gravity at 60° F.; 42 sec. Saybolt Universal viscosity at 100° F.; 62 cetane number.
Fuel-injection pump . . .	N.A.C.A. cam-operated, constant-stroke type.
Fuel-injection valve . . .	N.A.C.A. automatic, spring-loaded to 3,500 lb. per sq. in. opening pressure (injection period 25 crank degrees at 3.56×10^{-4} lb. per cycle).
Power measurement and absorption	Electric dynamometer unit.
Blowers	Inlet: 4-inch Roots type, separately driven. Exhaust: 8-inch Roots type, separately driven.
Operating temperatures . .	Water (out) 170° F. Lubricating oil (out) 175° F.
Air- and fuel-consumption measurements	Synchronized electrically operated stop watches and revolution counters.
Maximum-cylinder-pressure indicator	Trapped-pressure type.

Air-Conditioning Equipment

A photograph of the equipment assembled to simulate altitude conditions is reproduced as figure 2 and a diagrammatic representation of the apparatus is presented in figures 3 and 4. In figure 3 by an adjustment of the gate valve D in the air line to the inlet surge tank L any reduction in inlet pressure could be maintained at the engine inlet, the pressure being indicated by a mercury manometer E connected at a point about 18 inches from the intake port. The Roots blower H connected to the exhaust tank I was used to evacuate the tank to the pressure corresponding to the altitude that was being simulated.

The chief difficulty in altitude tests is, of course, the problem of reproducing the corresponding air temperature. For these tests the air-cooling apparatus shown in figure 4 was designed and constructed. Because of the necessity of taking care of the moisture as it was condensed out of the air, the cooling of the air was divided into two stages. In the first stage a 50-50 solution of Prestone and water was used as the coolant, Prestone being selected because it is hygroscopic and can be used to absorb water condensed from the cooled air. The 50-gallon tank of the coolant was directly charged with 40-pound cakes of solid CO_2 until the temperature was reduced to approximately -20° F. The rate of charging was controlled to hold this temperature during the operation of the system. In the second stage, kerosene was used as the coolant because the temperature could be lowered without a decided increase in viscosity. As before, 40-pound cakes of solid CO_2 were placed into the 50-gallon tank of kerosene and the temperature was maintained between -35° and -40° F.

Inlet air for the engine was brought into the first-stage cooler for dehumidifying and cooling. This cooler consisted of a radiator having 60.9 square feet of cooling area with 27.7 square inches of area for the air flow. The rate of flow for the engine-operating speed of 2,000 r.p.m. was approximately 70 cubic feet per minute at sea-level pressure. Circulation of the cold Prestone-water solution through the tubes of the radiator cooled the first-stage cooler. A secondary de-icing circulation was maintained to spray the outside of the tubes with the same solution. This de-icing spray was necessary to prevent the radiator from becoming clogged with ice. The air and de-icing spray at a temperature of about -5° F. passed to the snow box where the entrained solution, which had taken up the moisture from the air, was settled out. In the second stage the cold dry air went to two kerosene coolers of the same capacity as the Prestone cooler, arranged in parallel, where it was further cooled to -30° F.

Although the temperature of the air leaving the second-stage coolers could be kept at -30° F., the lowest air temperature at the engine was -3° F. owing to the absorption of heat from the room. This rise in temperature obtained despite 2 inches of hair-felt lagging on the piping and surge tank. Computations indicated that little benefit would be gained by additional lagging. With a reduction in inlet pressure and the consequent reduction in rate of flow, the lowest air temperature that could be held was 8° F. which, in a standard atmosphere, corresponds to an altitude of 14,300 feet (reference 5).

The equipment just described was used to make engine tests at simulated altitudes from sea level to 14,000 feet and runs for which the inlet-air temperature, inlet-air pressure, and exhaust back pressure were controlled as single variables. Electric air heaters were used to obtain inlet-air temperatures from room temperature to 256° F.

RESULTS AND DISCUSSION

Engine Performance at Altitude

Unsupercharged.- Figure 5 shows the variation of indicated and brake engine performance for the obtainable range of standard altitudes from sea level to 14,000 feet. The maximum cylinder pressures decreased with increasing altitude, the values shown being optimum to give maximum mean effective pressure at each altitude. Any further increase in injection advance angle at any altitude would have increased the maximum cylinder pressure with no further gain in engine performance. It is noteworthy that the family of curves of mean effective pressure converge to a single curve below 1.5×10^{-4} pounds of fuel per cycle. Figure 5 also shows that, at any altitude, maximum power is obtainable with but little increase in fuel consumption over that at sea level.

The decrease in maximum sea-level power with altitude for the single-cylinder test engine is shown in figure 6 compared with that of a 12-cylinder unsupercharged carburetor engine. The carburetor-engine data are given on a brake-horsepower basis and are representative of the best carburetor-engine performance obtained under standard altitude conditions (reference 6). Both brake and indicated single-cylinder performances are shown because the sea-level mechanical efficiency was only 76 percent, whereas that of the carburetor engine was 88 percent. A multicylinder compression-ignition engine would have a sufficiently high mechanical efficiency (reference 7) to give a percentage change in power with altitude equal to or better than that of the carburetor engine.

Previous reports of the altitude performance of aircraft compression-ignition engines have indicated that this type of engine loses power much less rapidly with increasing altitude than does the carburetor engine. It is possible that this conclusion may have been drawn because the engines were operated with excess air at sea level so as to give a clear exhaust; whereas with increasing altitude the air-fuel ratio was decreased toward maximum power (fig. 5) at the expense of a smoky exhaust. Comparison under these conditions is unfair to the carburetor engine. The results of figure 6 show that, for the same inlet-air conditions, the performances of the two types of engines are approximately the same.

When the altitude performances of the two types of engine are compared, however, consideration must be given the fact that the compression-ignition engine can induct its air at the low temperatures existing at altitude and thereby obtain a maximum weight of air charge.

For the simulated altitude tests of figure 5 there was no sign of misfiring at the 14,000-foot altitude conditions but, with the continued decrease in compression temperature and pressure, a critical altitude might be reached where compression ignition would cease. Then heat would have to be added, or the inlet-air pressure boosted, so that more heat - although not a higher temperature - would be available to cause ignition. If ignition continues and the compression-ignition brake curve of figure 6 is extended, zero brake mean effective pressure is indicated at about 34,000 feet for the unsupercharged engine. For a multicylinder engine with its greater mechanical efficiency the maximum altitude of operation would be correspondingly higher.

There remains the question of whether the temperature at the end of compression is sufficiently high at 34,000 feet to cause ignition. In order to answer this question, the temperature at the end of compression for a series of inlet-air temperatures from 250° F. to 0° F. was calculated from the compression pressure and weight of air charge and the results plotted as a curve of final temperature against inlet-air temperature. The curve was then extrapolated back to the minimum temperature of the troposphere, -67° F., and the temperature at the end of compression obtained from the curve. This temperature, 980° F., was considered sufficiently high to insure against failure of ignition owing to low inlet-air temperature. Therefore, the prediction made from the extension of the altitude curve shown in figure 6 seems reasonable, i.e., that operation of the engine could be obtained up to an altitude of 34,000 feet. It seems that the inlet air would have to be heated but little, if any, to insure ignition even at the lowest atmospheric temperatures.

In May 1934 a Bristol Phoenix compression-ignition engine was flown to 27,450 feet where the atmospheric air temperature was -40° F. (reference 8). This engine had a compression ratio of 14.0 and was supercharged to 7,000 feet. No failure of combustion was indicated at the maximum altitude attained.

A summary of the effects of altitude temperature and pressure on friction and charging characteristics of an unboosted engine is shown in figure 7. The decreasing weight of air charge causes the motoring compression pressure to decrease and likewise causes the friction mean effective pressure to decrease. The mechanical efficiency also decreases because the brake mean effective pressure decreases much faster than the friction mean effective pressure. The low compression pressure of 290 pounds per square inch at 14,000 feet resulted in an increase in ignition lag from 11° to 21°, the rates of pressure rise became extremely high, and engine operation became rough.

<u>Supercharged</u>.- In the case of a supercharged compression-ignition engine, full blower pressure can be used at sea level and for any length of time as the engine has no limitation imposed by detonation or preignition characteristics of the fuel. Figure 8 shows the effect of boosting with sea-level exhaust conditions and with constant inlet-air temperatures of 87° F. Power increases quite steadily with boost pressures but, for the pressure-

rise type of combustion upon which this engine operates, it is necessary to increase the maximum cylinder pressure in order to obtain the maximum increase in power from the higher boost pressure. Engine operation is very smooth under boosted conditions but the power is not quite maximum as the maximum cylinder pressure is limited to 1,100 pounds per square inch at 20 inches boost. The fuel consumption decreases at practically all fuel quantities with increase of boost pressure. The results of this test and of the following tests of the effects of boosting are not corrected to a multicylinder basis nor for power to drive the supercharger, factors that would tend to cancel each other. The power and fuel consumption as discussed and as shown on the curves are, therefore, on a gross basis.

Results for a similar range of boost pressures were also obtained for a series of exhaust back pressures equivalent to altitudes up to 19,000 feet. The boosted tests at the altitude exhaust pressures had the same general characteristics as shown in figure 8, except that each decrease in exhaust back pressure caused an increase in mean effective pressure and a decrease in fuel consumption.

Further boosted-altitude data for maximum power are shown in figure 9, for which the boosted brake mean effective pressure is corrected to show the value for induction air at the standard altitude temperature, as will be discussed later. The unboosted brake mean effective pressure decreases rapidly; whereas, by boosting to constant manifold pressures and cooling the inlet air to standard altitude temperature, the gross brake mean effective pressure will increase with altitude. The increases in the brake mean effective pressure result from diminishing exhaust back pressure and, to a greater extent, from the low air temperatures of the particular altitude. The results at 35 and 45 inches of Hg manifold pressure are for limiting conditions of air temperature as cooling to the altitude temperature could never be entirely achieved. Furthermore, the boost pressure of 45 inches of Hg is extremely high, approximately 31 inches of Hg above the altitude pressure at 19,000 feet, so that the cost of obtaining the boost pressure would be large. The gross brake mean effective pressure of about 225 pounds per square inch, however, is obtainable at a 19,000-foot altitude at a maximum cylinder pressure of about 1,100 pounds per square inch. At 35 inches of Hg absolute pressure and at an altitude of 19,000 feet, the torque required to operate a blower, if an over-all adiabatic efficiency of

70 percent is assumed, would be equivalent to 26 pounds per square inch mean effective pressure, leaving a net brake mean effective pressure of 158 pounds per square inch. Under the same conditions, but with 45 inches of Hg boost, approximately 43 pounds per square inch mean effective pressure would be required, leaving a net brake mean effective pressure of 182 pounds per square inch. In both cases, the power required assumes the air delivered to the engine to be cooled to the altitude temperature. As has been previously pointed out, this condition is impossible and is only presented as representing the maximum power conditions.

Effect of Air Pressure on Engine Performance

In order to determine how engine performance is influenced by reduction in inlet-air pressure alone, variable fuel-quantity tests were made for several degrees of throttling of the inlet air to pressures, as noted in figure 10. The temperature of the inlet air and the exhaust back pressure were kept constant at 66° F. and 30.5 inches of Hg, respectively. Engine operation was becoming rough at an inlet pressure of 21 inches of Hg and a run at an inlet pressure of 17 inches of Hg could not be made because the engine would not maintain the test speed of 2,000 r.p.m. even without load. For the conditions of these tests where valve overlap was used and the exhaust pressure was greater than the inlet pressure, the scavenging and charging of the engine were exceptionally poor. The variable fuel-quantity curves have the same characteristics as those of the altitude tests and show the same convergence at decreasing fuel quantity and inlet-air pressure. Although the maximum cylinder pressures are different for the different inlet pressures, the mean effective pressures are optimum in all cases.

In order to determine the effect of air pressure on inlet and exhaust, the intake air pressure and exhaust back pressure were varied together with constant intake temperature of 82° F. This condition can be considered as an an altitude test using an air heater to maintain the inlet air at a constant temperature, a common practice in the operation of carburetor engines.

The test results are shown plotted on figure 11. The shapes of the power curves are similar and, except for the values represented, are identical with those of the truealtitude tests. In this case, too, the maximum cylinder pressure decreased with decrease in air pressure even though the injection advance angle was at all times maintained at an optimum value. The maximum cylinder pressure could have been kept nearly constant during the variation in air pressure but there would have been no increase in power and the rates of pressure rise would have been excessive. At each air pressure the minimum advance angle was used that would give maximum power.

The operation of the engine became rough with decreasing air pressure until, at the lowest pressure for which a variable load run was made, there was considerable combustion knock. This knock occurred at a pressure altitude of 19,200 feet; on a density basis the equivalent altitude would have been 24,700 feet. At a pressure altitude of 25,000 feet the engine would no longer run at 2,000 r.p.m.; however, operation could be obtained at lower speeds and at 1,500 r.p.m. the brake load was appreciable. Operation was obtained at a pressure altitude of 30,000 feet but the maximum load was very light and the speed was only 850 r.p.m. The compression pressure under these conditions was 120 pounds per square inch. The exact point at which firing stopped could not be obtained with the equipment assembled for these tests but it was only slightly in excess of a pressure altitude of 30,000 feet.

A summary of the effects of inlet-air pressure on engine power and maximum cylinder pressure is shown in figure 12. The mean effective pressures plotted in figure 12 are the maximum obtainable and the points at pressures less than sea level were taken from figure 10 and figure 11 at the lowest fuel quantity giving the maximum power. It so happened that the air-fuel ratio was nearly constant for these maximum points. The boosted section of the curves of figure 12 is for optimum power regardless of maximum cylinder pressure and also for power when limited by maximum cylinder pressure.

The slope of the boosted curves can be influenced by maximum cylinder pressure but the slope of the throttled pressure curves is influenced only by inlet-air pressure. Although only three points were taken for the test in which inlet pressure only was varied, additional results also indicate that the trend with inlet-air pressure is practically a straight line of 7.4 pounds per square inch increase in both brake and indicated mean effective pressure for 1 inch of Hg increase in inlet-air pressure. This rate of increase holds only for throttled inlet air as shown by a comparison with the unlimited cylinder pressure boosted tests. The high rate of increase in the throttled tests, where the exhaust pressure is greater than the inlet pressure, is due to the change in scavenging as well as charging with increase in inlet pressure. When the inlet-air pressure becomes equal to or greater than the exhaust pressure, the combustion chamber is well scavenged and the increase in mean effective pressure is due only to increased weight of air charge.

When inlet and exhaust pressures were varied, the slope of the line for maximum indicated mean effective pressure shown on figure 12 is 6.0 pounds per square inch per inch of Hg absolute, which is also at a constant air-fuel ratio. The effect of pressure at different air-fuel ratios was investigated by picking the corresponding indicated mean effective pressures off the curves shown in figure 11; the results are plotted in figure 13. A family of curves of this type could be used for correcting the power of this compression-ignition engine over a wide range of loads for changes in barometric pressure.

Effect of Inlet-Air Temperature on Engine Performance

The effect of inlet-air temperature on engine performance under sea-level conditions of inlet and exhaust pressure was determined for various fuel quantities and the results are plotted in figure 14. During these tests the barometric pressure variation was ±0.4 percent and the experimental error was approximately ±1 percent. The test results show the effect of inlet-air temperature for a practically constant air pressure. The curves of mean effective pressure and fuel consumption have the same convergence as the curve of altitude and air-pressure variation previously discussed. Maximum power for each temperature run of figure 14 occurs at an air-fuel ratio that is nearly constant at 12-1/2.

When replotted against temperature in figure 15, the indicated mean effective pressures at a series of air-fuel ratios from 12-1/2 to 25 are seen to vary nearly as straight lines. From air-fuel ratios 12-1/2 to 20 the slope of the lines is practically constant. For purposes of correcting indicated mean effective pressure for differences in inlet-air temperature, the slope of the curves shown in figure 15 may be used. For the engine tested, the slope of the curves for air-fuel ratios from 12-1/2 to 20, inclusive, was 0.22 pound per square inch increase in mean effective pressure for each degree Fahrenheit decrease in temperature of the inlet air.

A summary of subordinate test results similar to figure 7 is shown in figure 16 for both pressure and temperature variations. In the analysis of these curves it should be remembered that increasing air temperature and air pressure have opposite effects on air density and weight of air charge. This fact explains why the curves of figure 16 are of opposite slopes and in most cases cross each other. Although the injection advance angle was increased with increasing inlet-air temperature to maintain a constant maximum cylinder pressure, the engine operation did not become rough. In fact, engine operation was smooth throughout the range of temperatures investigated.

A section of the curve of air weight against pressure is shown as a broken line because, at inlet pressures greater than standard sea level, the overlap of the engine valves permitted some air to pass through the engine so that the actual air-charge weight was less than the measured weight. A volumetric efficiency of 100 percent was assumed for such inlet conditions and weights of boosted air charge were calculated on this basis. It is recognized that, because of the valve overlap of 68° used, all air weights presented are subject to question; however, for unboosted conditions the error should be small. Variation of compression pressure, friction mean effective pressure, and mechanical efficiency follow in most cases from the variation of weight of air charge. When the inlet pressure alone was varied, there was a large change in volumetric efficiency, but for the other two conditions the change was not very great. A small but definite increase in volumetric efficiency can be noted with increase in inlet-air temperature. Volumetric efficiency, as used in this report, is defined as the ratio of the actual volume of air inducted by the engine on each cycle at the temperature and pressure conditions of the air in the inlet manifold to the displacement volume of the engine.

Effect of Air-Charge Density and Weight on Engine Performance

In most engine-performance corrections, air-fuel ratio and inlet-air density are considered fundamental factors. In this report a range of air-fuel ratios including the one giving maximum engine performance has been considered and comparisons have been made on the basis of maximum engine performance. Figure 17 is a plot of maximum engine performance for inlet-air densities obtained by independently varying the temperature and pressure to determine the existence of a direct variation of engine performance with inlet-air density. For the same air densities the curves of mean effective pressure are displaced one from another and are of different slopes depending upon how the inlet-air density was obtained. Evidently density of inlet air cannot be used as a basis for correcting engine power because power does not vary directly as the inlet-air density.

From a further continuation of the analysis, it was thought that the air-charge weight differed when the temperature and pressure were independently varied. Figure 18 was prepared on the basis of weight of air charge, and better agreement is shown over a longer section of the curves. At low weights of air charge, as given by heating the inlet air, there still is increasing divergence of the curves. Apparently weight of air charge is a better method of correction than density of inlet air, but even then there is not complete agreement for corrections at high inlet-air temperatures. The variations of power for the boosted section of the curves are straight lines because in these tests a maximum cylinder pressure of 1,100 pounds per square inch was selected for the pressure at 20 inches of Hg boost and, for each increase in boost above 5 inches of Hg, the maximum cylinder pressure was allowed to increase in equal increments.

In this report, maximum engine performance has been stressed regardless of air-fuel ratio. The air-fuel ratio for the altitude test for maximum performance was 12-1/2; for the inlet-pressure variation, 11-1/2; for the inlet and exhaust-pressure variation, 13; and for the inlet-air-temperature variation, 12-1/2. If a constant air-fuel ratio had been chosen, the performances obtained would not have been maximums in all cases. Neither would performances at the same air-fuel ratio have been equal on the curves of air density or of weight of air charge. For example, if a constant air-fuel ratio had been taken in figure 18, the curves would have been separated rather than being in partial agreement. Although maximum performance was used for the purposes of comparison, the curves at other air-fuel ratios, presented in figures 13 and 15, are necessary for the complete calibration of the engine.

Variation in humidity is not believed to have influenced the test results inasmuch as the maximum variation in weight of water vapor was only ±0.6 percent. Carburetor-engine tests (reference 9) have indicated that humidity affects engine power only to the extent of displacing air with water vapor, thus reducing the weight of air available for combustion; the variation caused by humidity changes was less than the experimental error.

In the foregoing analysis, methods have been kept in mind of correcting compression-ignition engine performance to standard conditions. The most commonly accepted method is based on density of the inlet air. Results in figure 17 show this method to be incorrect. The commonly accepted method for spark-ignition engines, i.e., directly as the inlet-air pressures and inversely as the square root of the absolute temperatures, was tried and it was found that it did not apply to compression-ignition engines. Before the correction factors presented in this report can be generally applied, calibrations similar to those of this investigation are needed on many types and designs of compression-ignition engines.

Effect of Exhaust Back Pressure on Engine Performance

The effect of exhaust back pressure on the performance of a compression-ignition engine is important because, first, back pressure decreases with altitude and, second, back pressure increases with the application of an exhaust-driven turbocentrifugal supercharger. Figure 19 shows the effect on the mean effective pressures of varying the exhaust back pressure as a single variable. Inlet air was maintained at sea-level pressure and 85° F. The curves are discontinuous at sea-level back pressure because the curves are from two series of tests made at different maximum cylinder pressures, as noted on the figure. With decreasing back pressure the steady reduction in friction mean effective pressure causes most of the improvement in brake mean effective pressure. The trend of the indicated-power curve does not show the expected steady increase with decrease in back pressure. A possible explanation for its variable trend is that the decreasing back pressure first helps to improve clearance-volume scavenging and to increase the weight of air charge and then, finally, the large pressure difference during the valve-overlap period upsets the ensuing air charging. For pressures greater than those prevailing at sea level, the engine performance is adversely affected and at an increasing rate.

These curves showing the effect of back pressure on the exhaust indicate that a turbosupercharger would be desirable for use with this type of engine, inasmuch as the part of the curve at reduced exhaust pressure shows that relatively little gain in power is obtained from the reduction in back pressure. Therefore, if the pressure on the exhaust is maintained constant and the increased pressure drop through the turbine with increase in altitude is used to hold the inlet pressure constant, the net loss of power to the supercharger is relatively small. The curves of positive pressure show that care must be exercised in the design to insure that the exhaust pressure does not become greater than the inlet pressure because the power drops off rapidly with increase in back pressure.

Indicator Cards

Figure 20 shows five indicator cards obtained while the engine was operating at the several conditions of this series of tests. When studying these indicator cards, it must be remembered that widely different inlet-air temperatures and pressures were used. Both weight of air charge and weight of fuel charge were varied with each condition so that an indicated mean effective pressure comparison is usually not possible. Card (c) was taken while the engine was operating at normal unboosted sea-level conditions and is presented for purposes of comparison. For card (c) engine operation was smooth and regular. Comparing card (a) with card (c) shows the effect of altitude on the indicator card. The compression pressure is lowered, although it is about 50 pounds per square inch higher than for the motoring compression data of figure 7 owing to heat absorption from the cylinder walls. This lowered compression pressure with the resultant decrease in air density and temperature caused the ignition lag to increase, as can be seen from the cards, and permitted a greater accumulation of fuel prior to ignition. Then, upon ignition the rate of pressure rise is higher and is nearly a straight line as the rough operation previously noted had indicated. The high maximum cylinder pressures are of little use because they do not appreciably increase the area of the indicator card.

Card (b) was taken while the engine was operating with sea-level inlet air and exhaust back pressure but with an inlet-air temperature of 1° F. Ignition lag is affected little, if any, by the low inlet-air temperature while smoothness of operation was further improved, as the lowered rate of pressure rise would indicate. Comparing cards (a) and (b) shows the effect of air pressure or density on ignition lag. Although the inlet-air temperatures were slightly different, 8° F. compared with 1° F., the large decrease in ignition lag is caused by the increase in inlet-air pressure or density.

Effects of high inlet-air temperature are shown by cards (d) and (e), the difference between the two cards being maximum cylinder pressure and rate of pressure rise as controlled by injection advance angle. Card (d) is for the same injection advance angle as card (c) and shows the effect of inlet-air temperatures of 258° F. and 71° F. At the higher temperature the ignition lag was decreased, which in turn decreased the fuel accumulated at ignition and decreased the ensuing rate of pressure rise. Even the 23-1/2° injection advance angle of card (e) did not give rough operation even with the early pressure rise that the card shows. The high inlet-air temperature and correspondingly short ignition lag prevented excessive fuel accumulation so that the rate of pressure rise is relatively low.

CONCLUSIONS

1. The altitude performance of an unsupercharged compression-ignition engine compared favorably with a carburetor engine; the low temperatures of altitude were especially important in maintaining the power at altitude of the compression-ignition engine.

2. The sea-level performance of this unsupercharged compression-ignition engine cannot be accurately corrected on the basis of air density or weight of air charge for differences of air temperature and pressure. Maximum per-

formance varied differently from part-load performance with air pressure and temperature changes.

3. Maximum sea-level unsupercharged performance of this compression-ignition engine can be corrected, when maximum cylinder pressure does not limit output, as follows:

For each inch of Hg increase in inlet-air pressure with constant sea-level exhaust pressure, add 7.4 pounds per square inch indicated or brake mean effective pressure.

For each inch of Hg increase in inlet and exhaust pressure, add 6.0 pounds per square inch indicated or brake mean effective pressure.

For each °F. increase in inlet-air temperature, subtract 0.22 pound per square inch indicated or brake mean effective pressure.

4. Maximum sea-level boosted performance can be corrected as follows:

For each inch of Hg increase in inlet-air pressure with conservative maximum cylinder pressures, add 4.0 pounds per square inch indicated or brake mean effective pressure.

For each inch of Hg increase in inlet-air pressure with unlimited maximum cylinder pressure, add 5.0 pounds per square inch indicated or brake mean effective pressure.

5. Reduced exhaust back pressure increased engine power slightly and increased exhaust back pressure decreased engine power at an increasing rate.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
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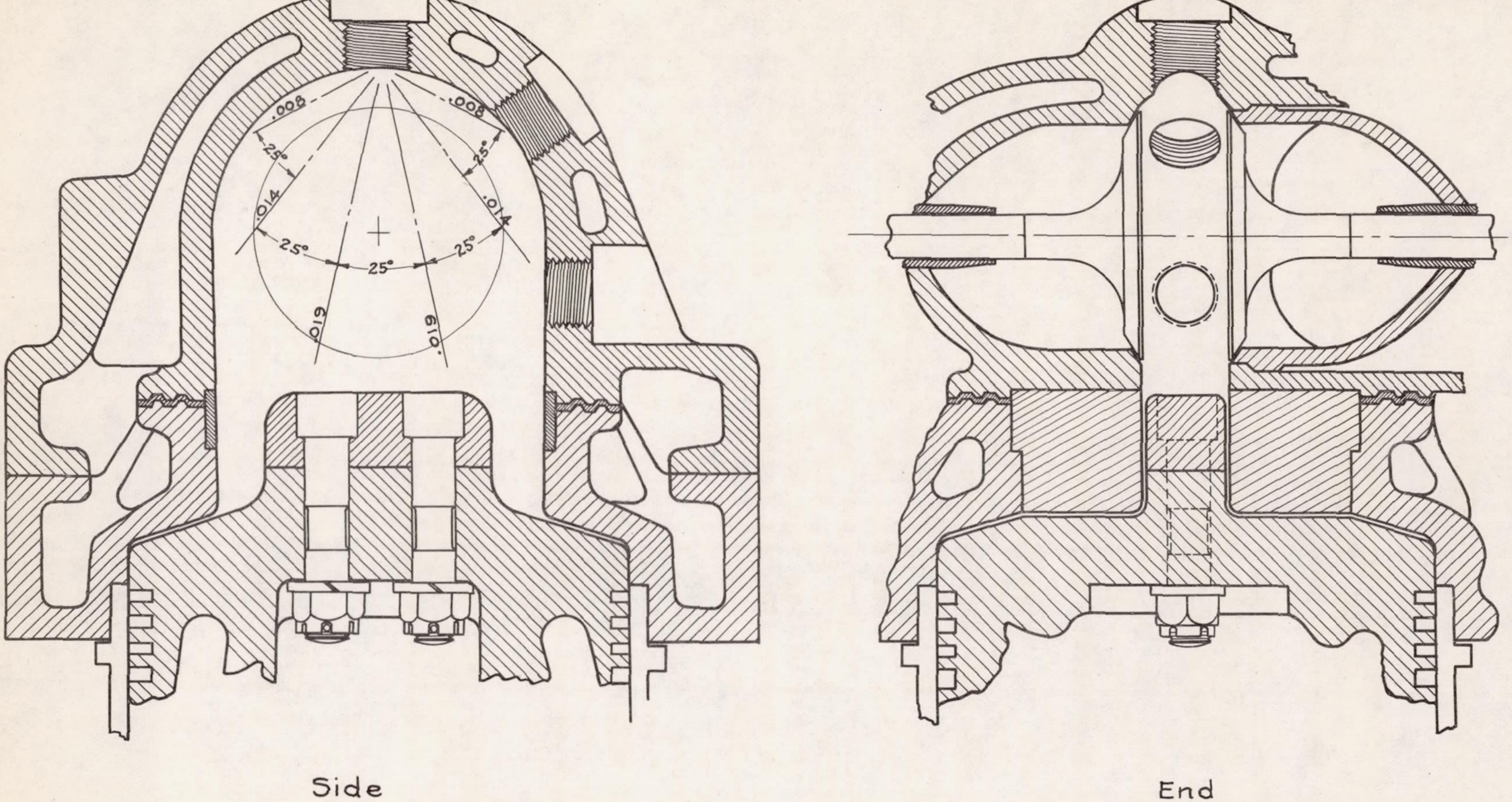


Figure 1.- Combustion chamber and fuel-spray arrangement.

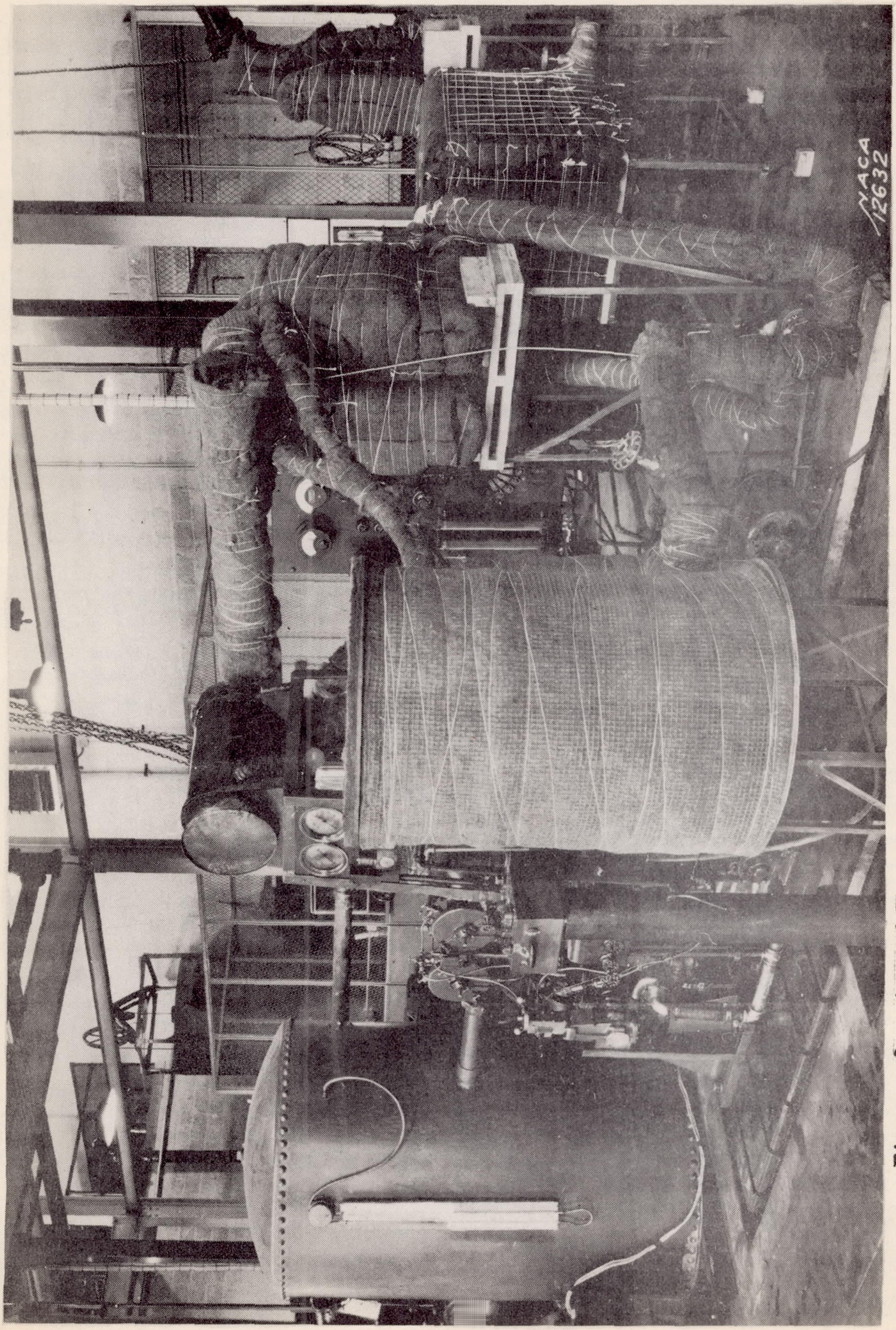


Figure 2.- Assembly of test engine and air-conditioning equipment.

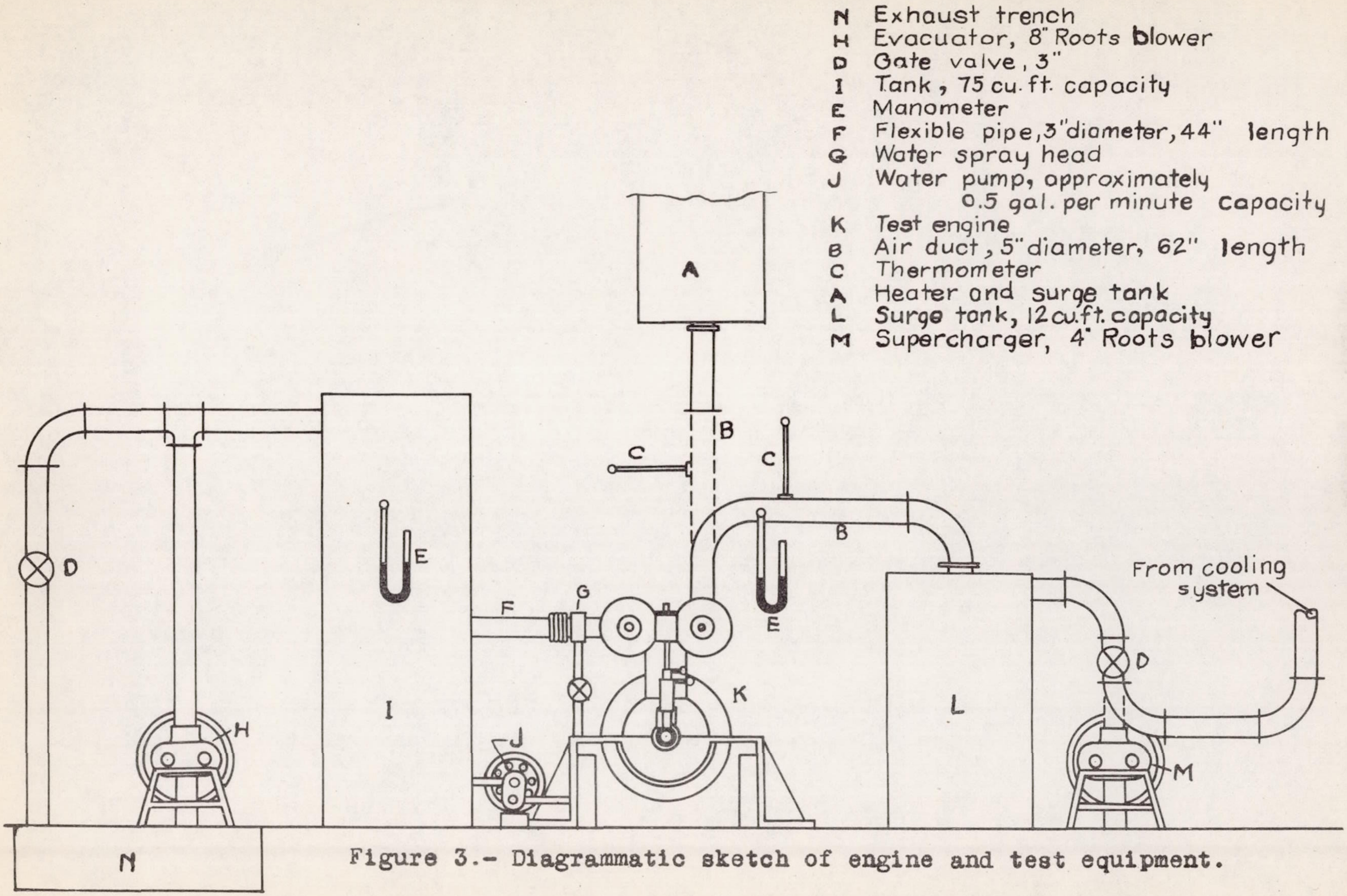


Figure 3.- Diagrammatic sketch of engine and test equipment.

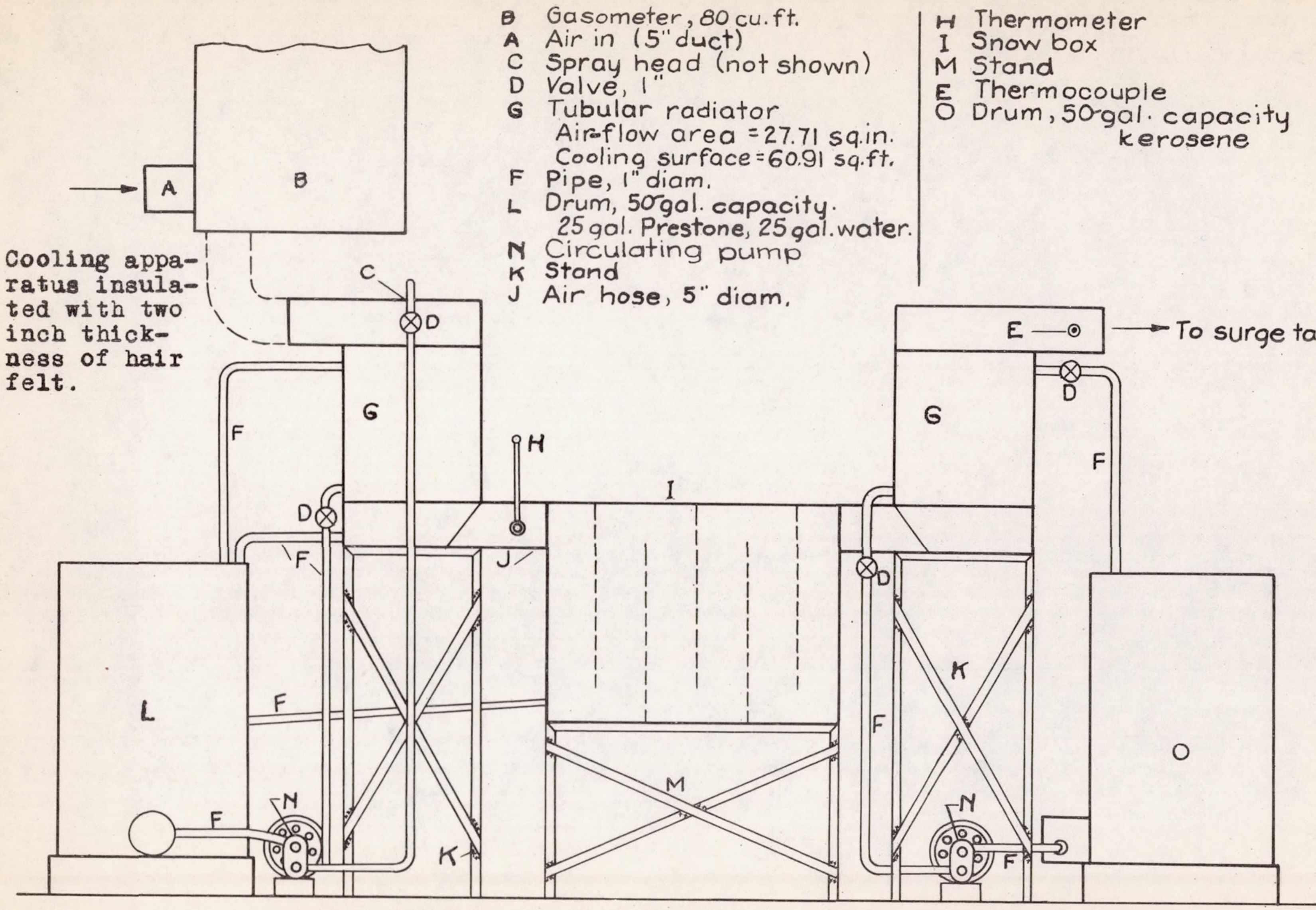


Figure 4.- Diagrammatic sketch of air-cooling equipment.

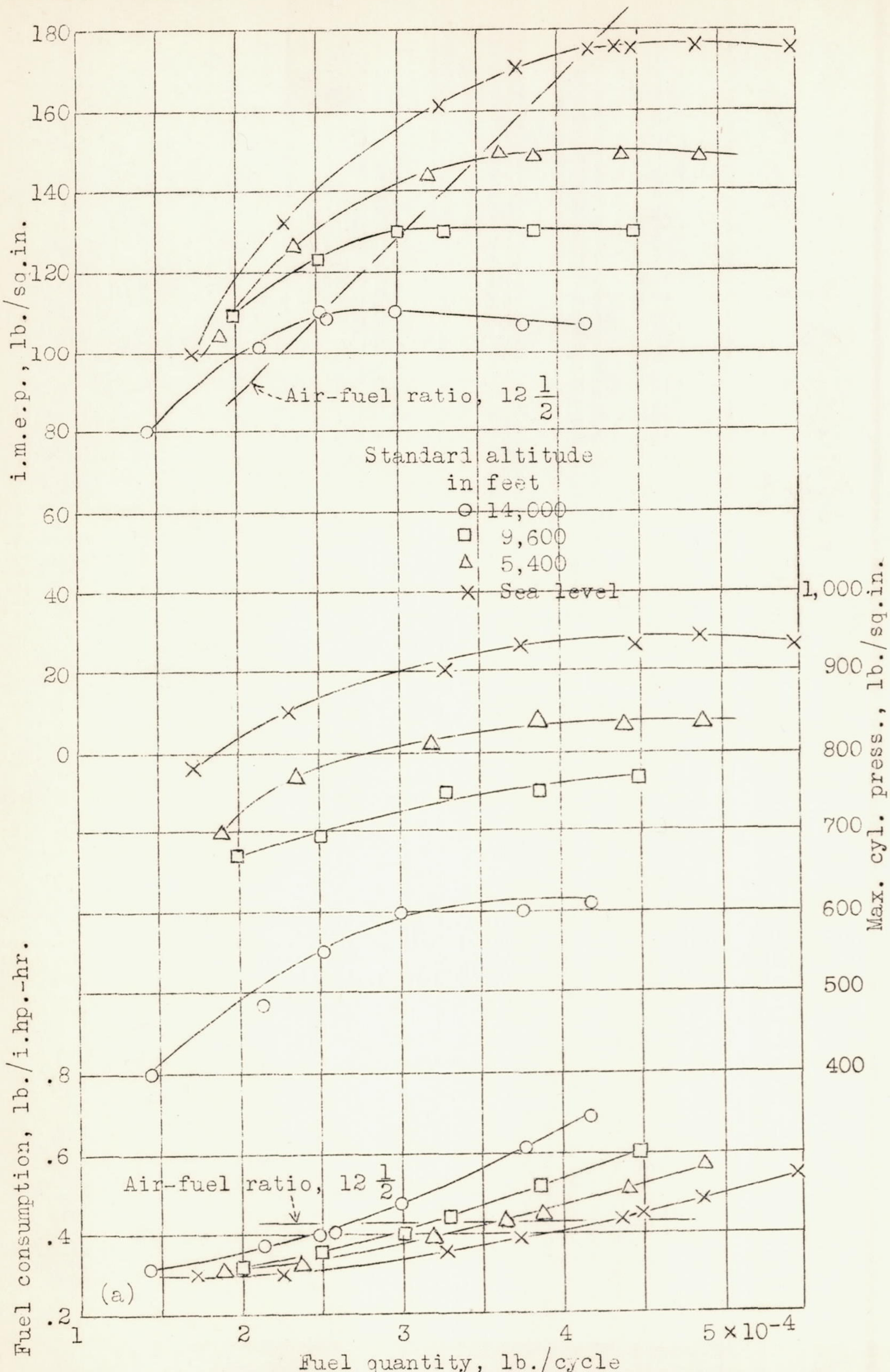


Figure 5.- Effect of altitude (air temperature and pressure) on performance. (a) Indicated performance.

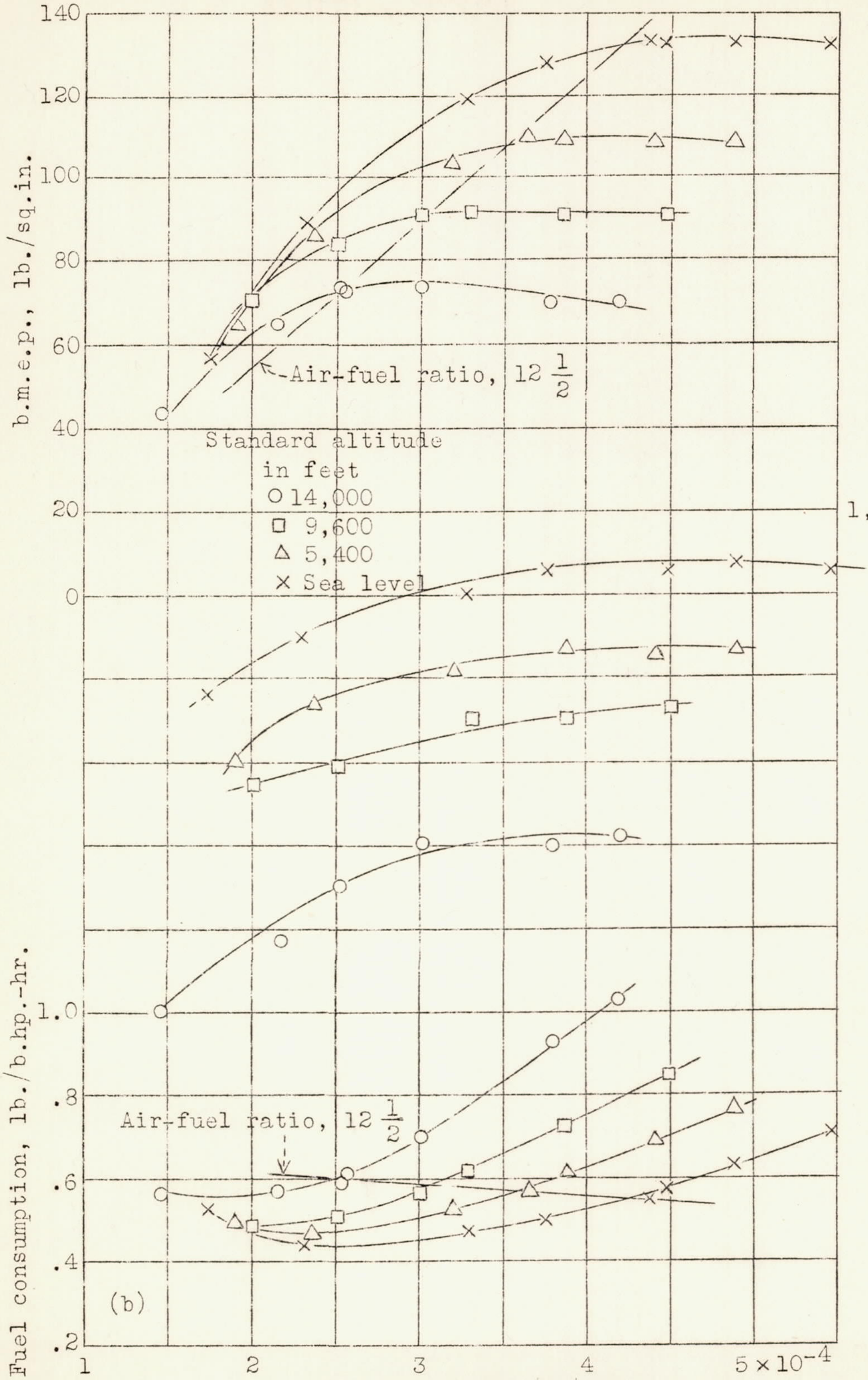


Figure 5.- Effect of altitude (air temperature and pressure) on performance. (b) Brake performance.

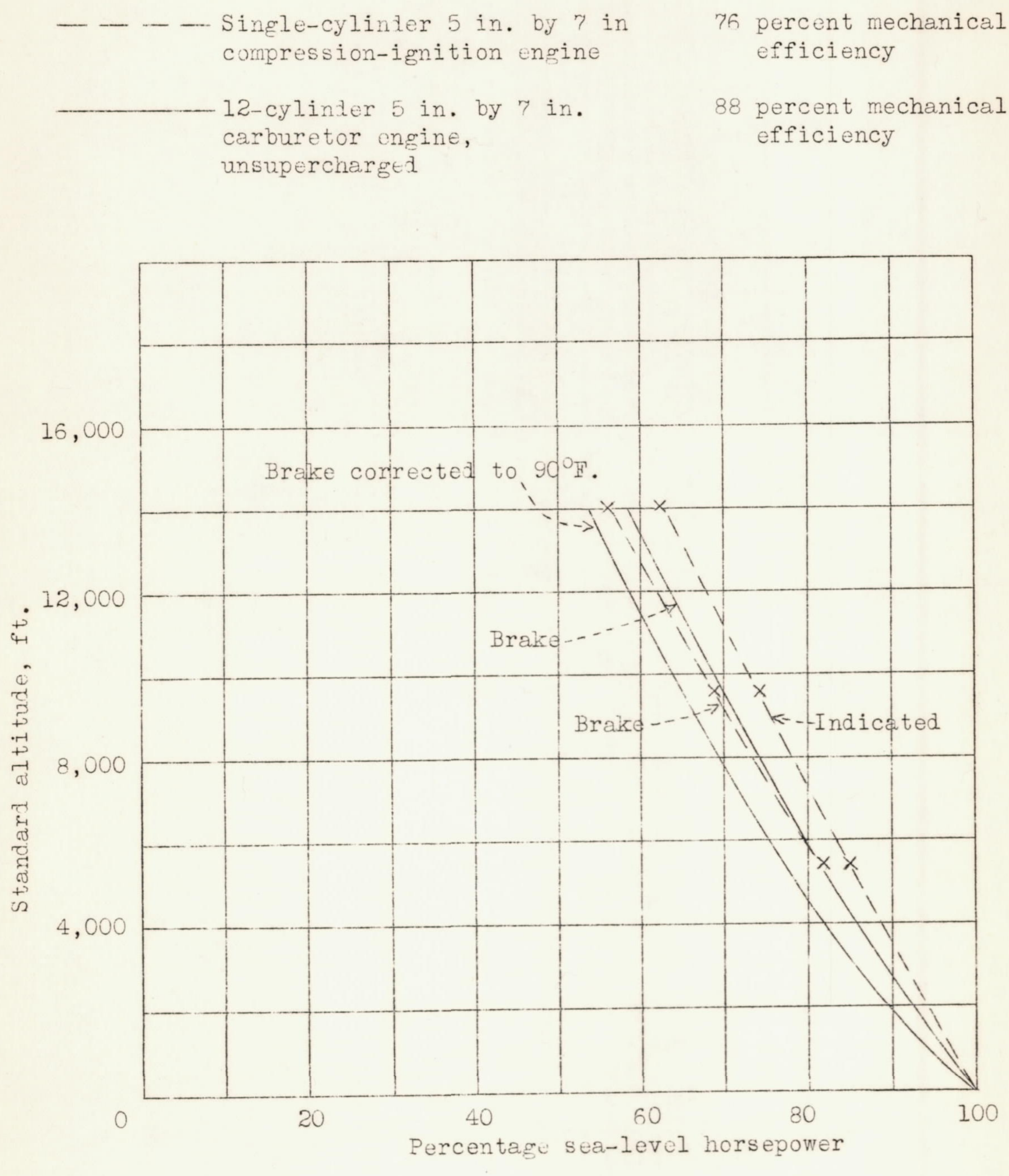


Figure 6.- Comparison of maximum powers of compression-ignition and carburetor engines at altitude.

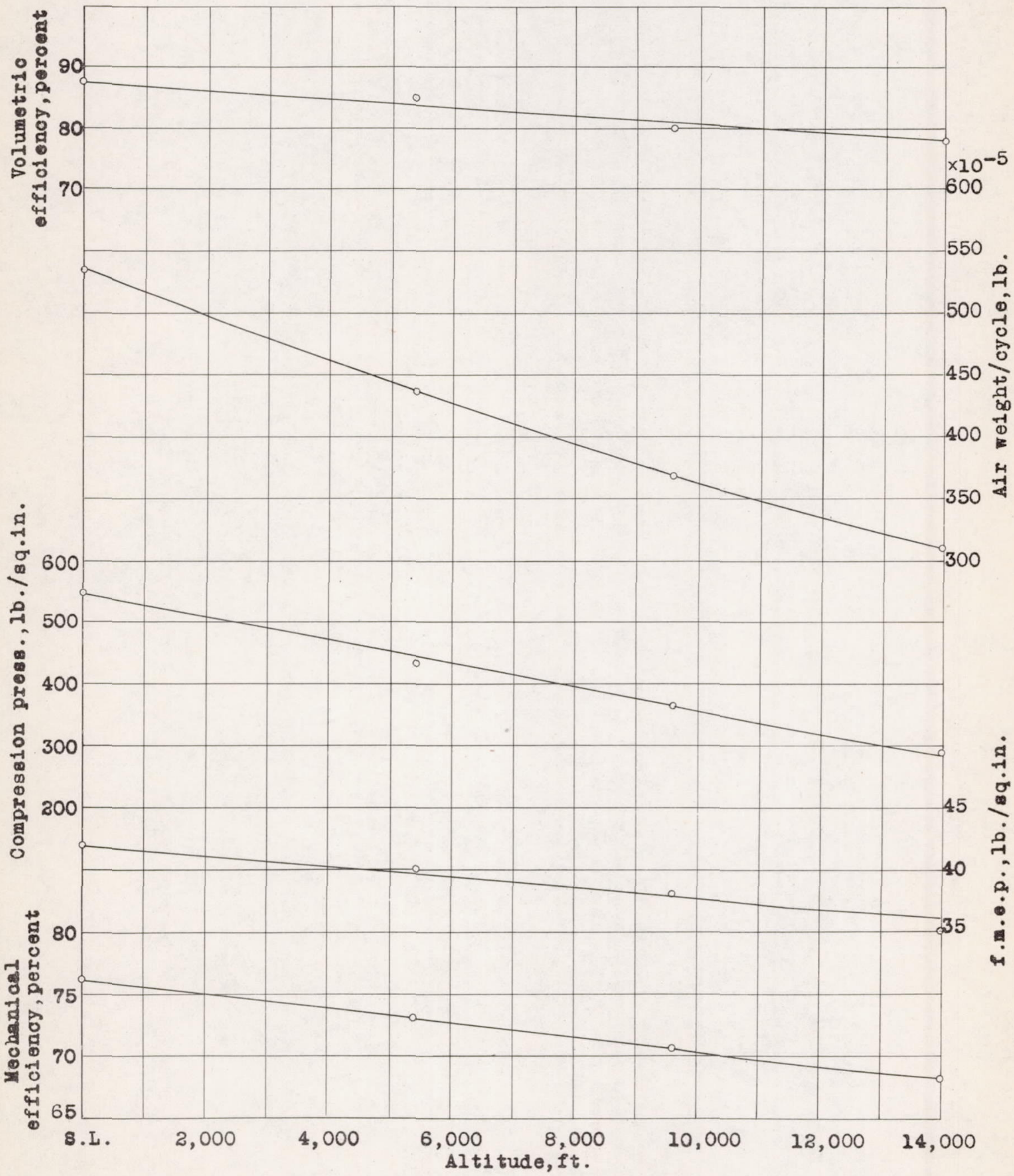


Figure 7.- Effect of inlet-air conditions at altitude on engine friction and charging characteristics.

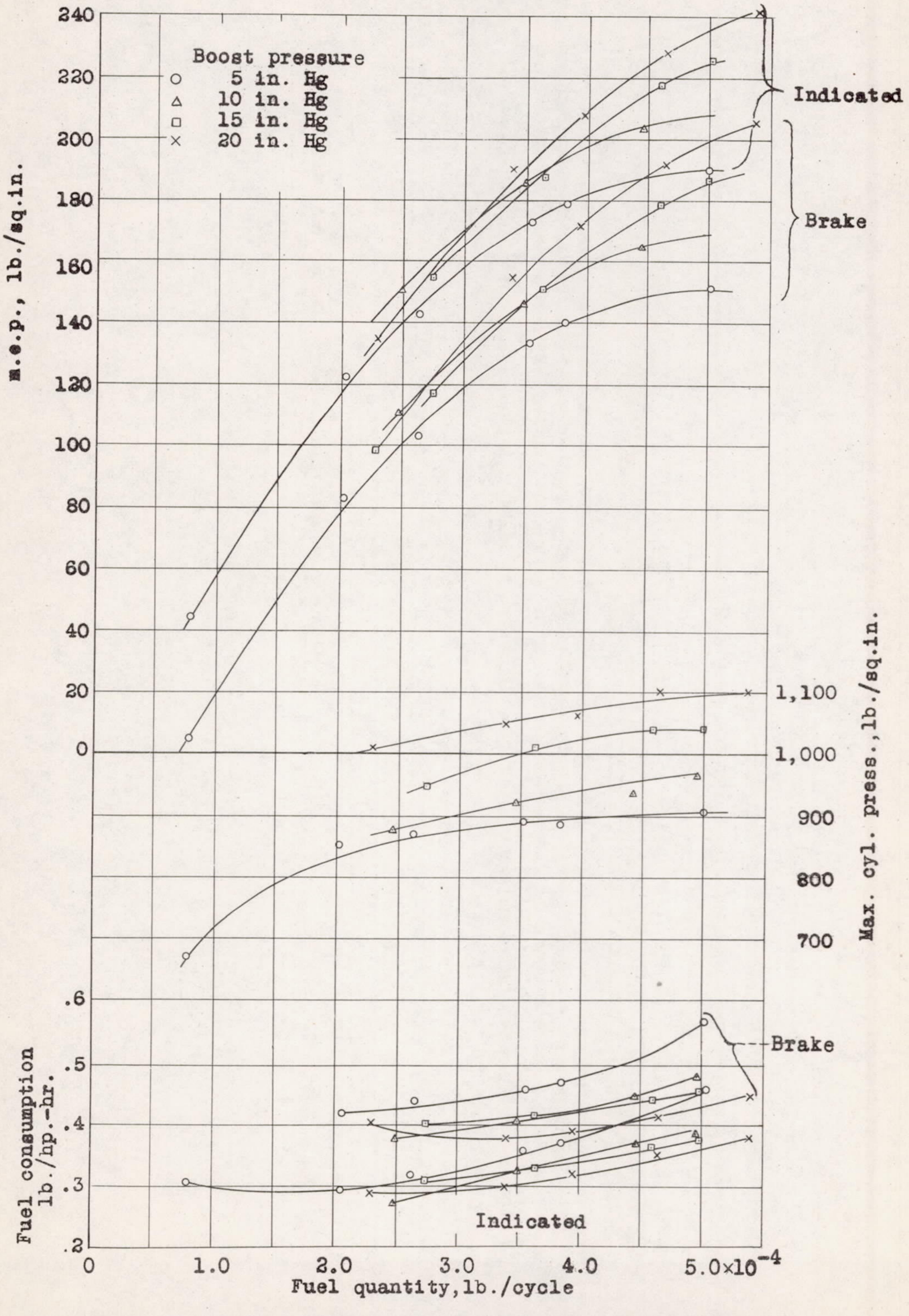


Figure 8.- Effect of boost pressure on engine performance; inlet-air temperature, 87° F.; sea-level exhaust pressure.

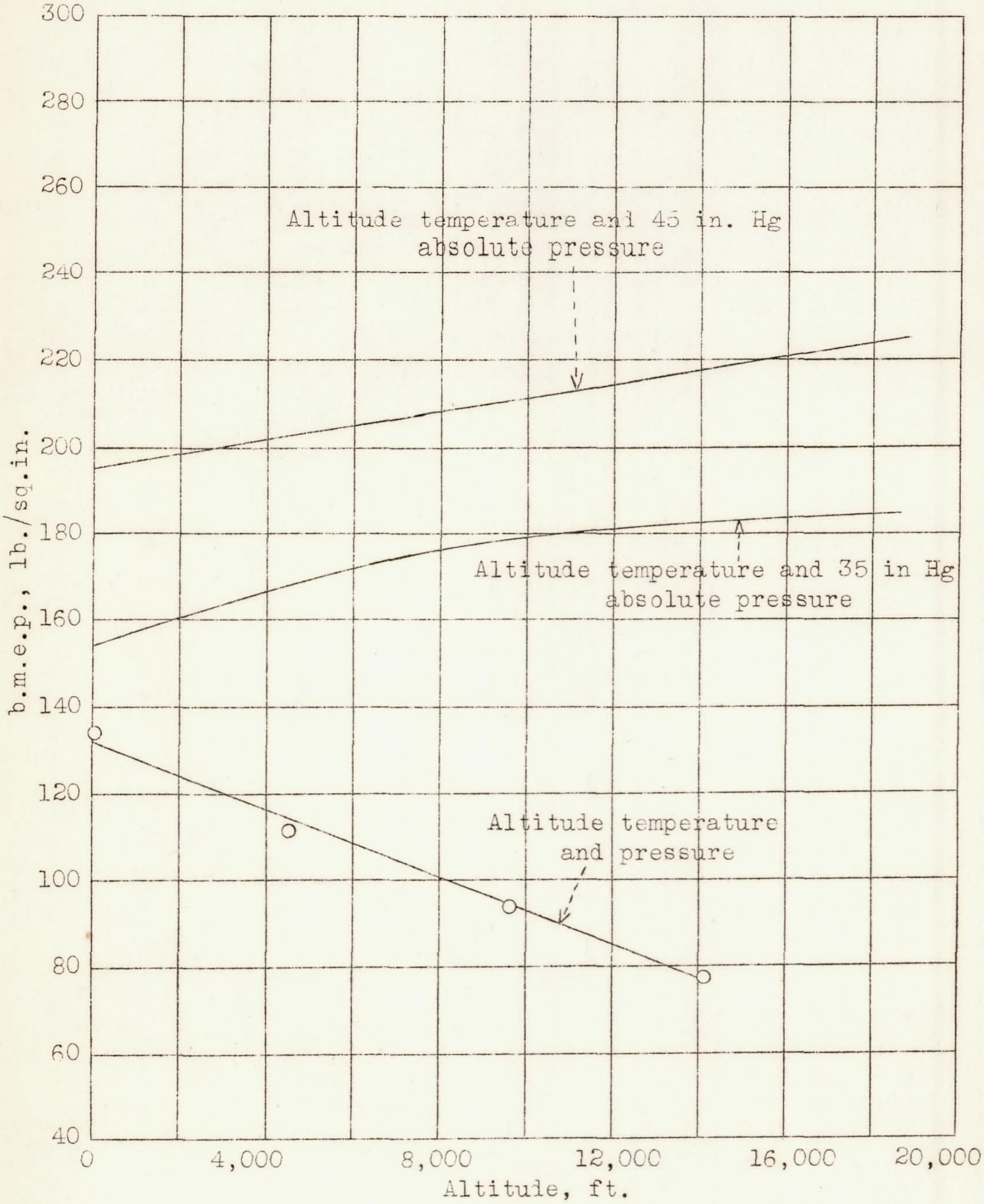


Figure 9.- Effect of inlet-air conditions at altitude on maximum gross brake mean effective pressure; single-cylinder engine.

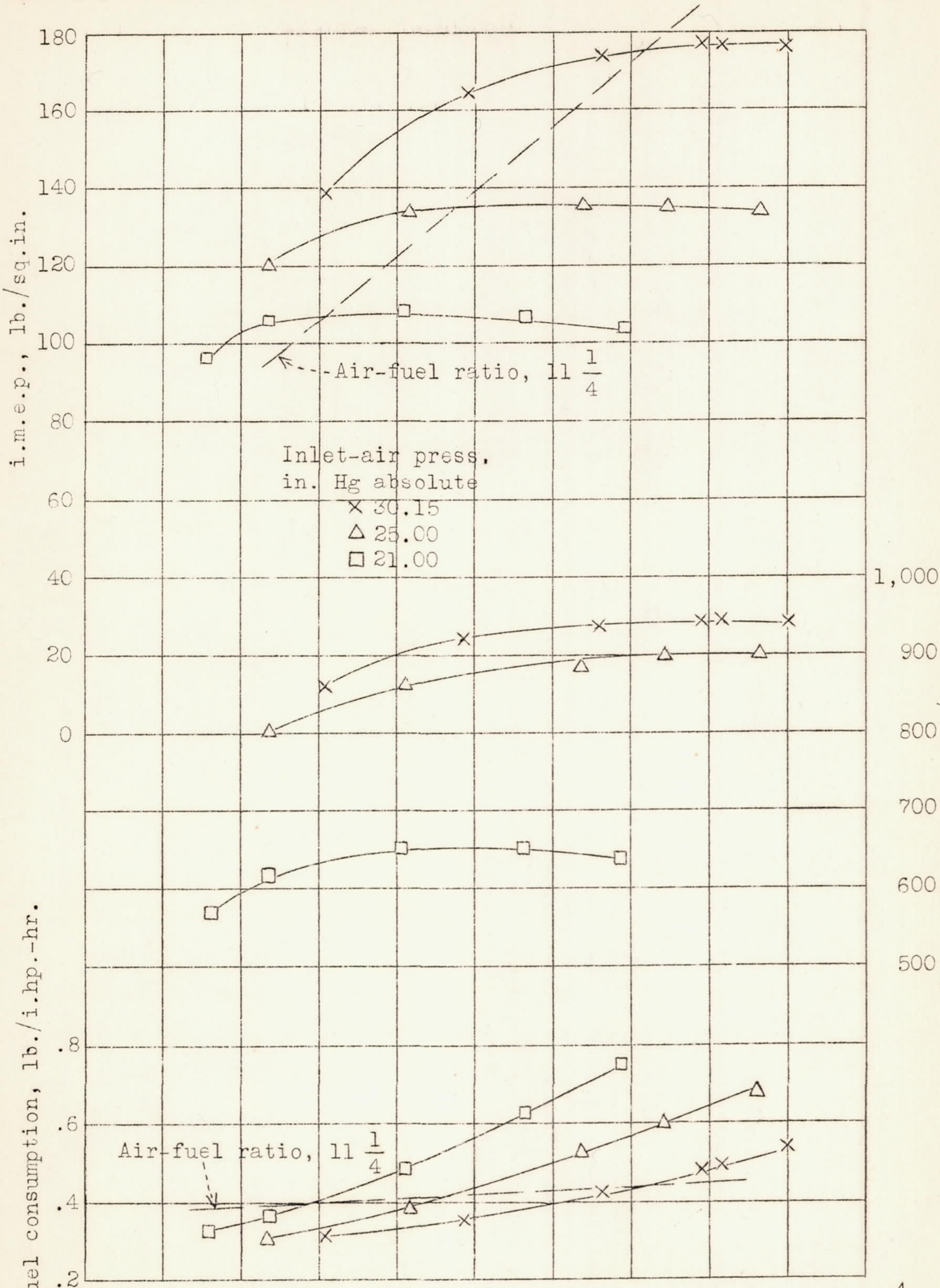


Figure 10.- Effect of reduced inlet-air pressure on indicated performance; inlet-air temperature 66°F., sea-level exhaust back pressure.

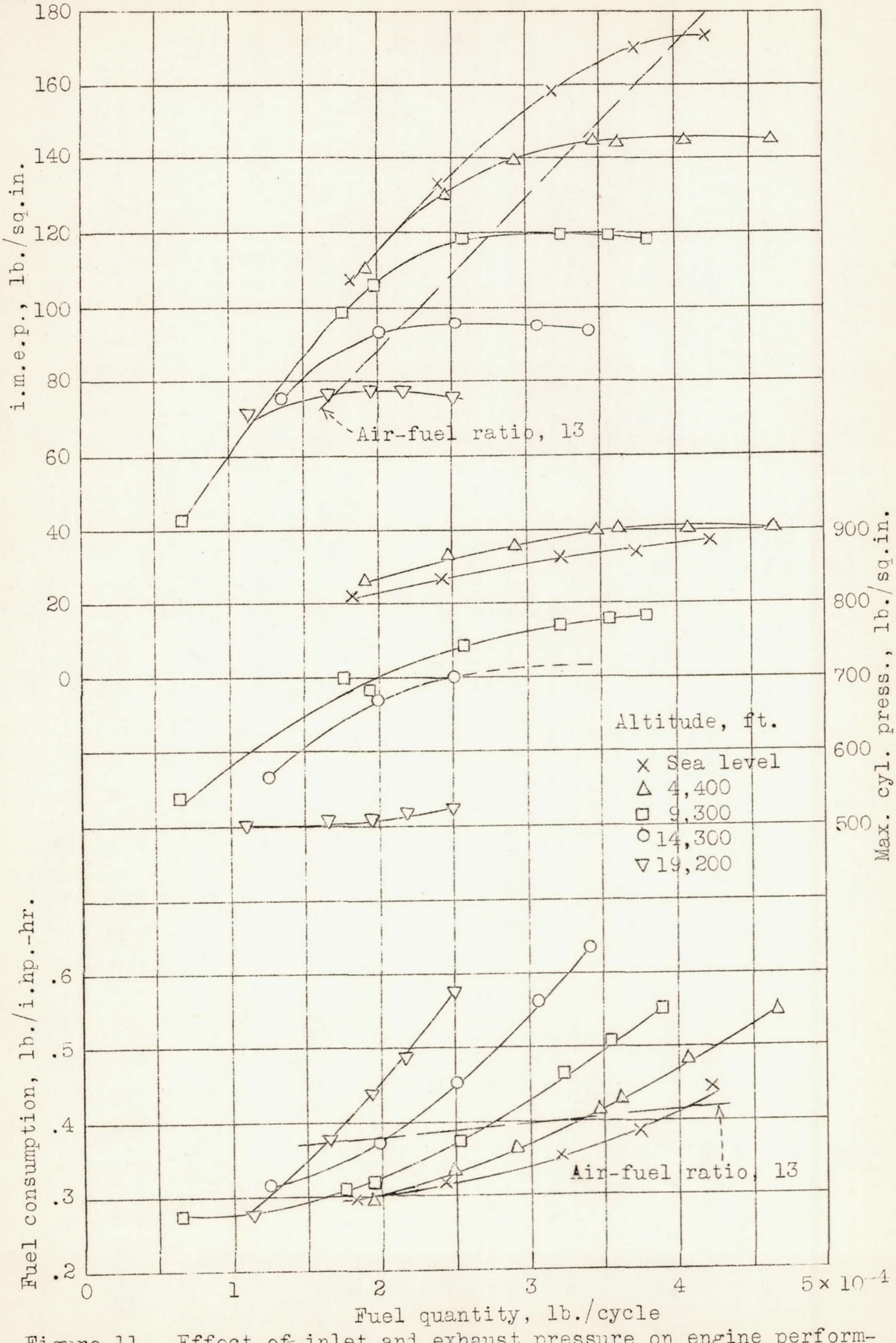


Figure 11.- Effect of inlet and exhaust pressure on engine performance; inlet temperature 82°F.

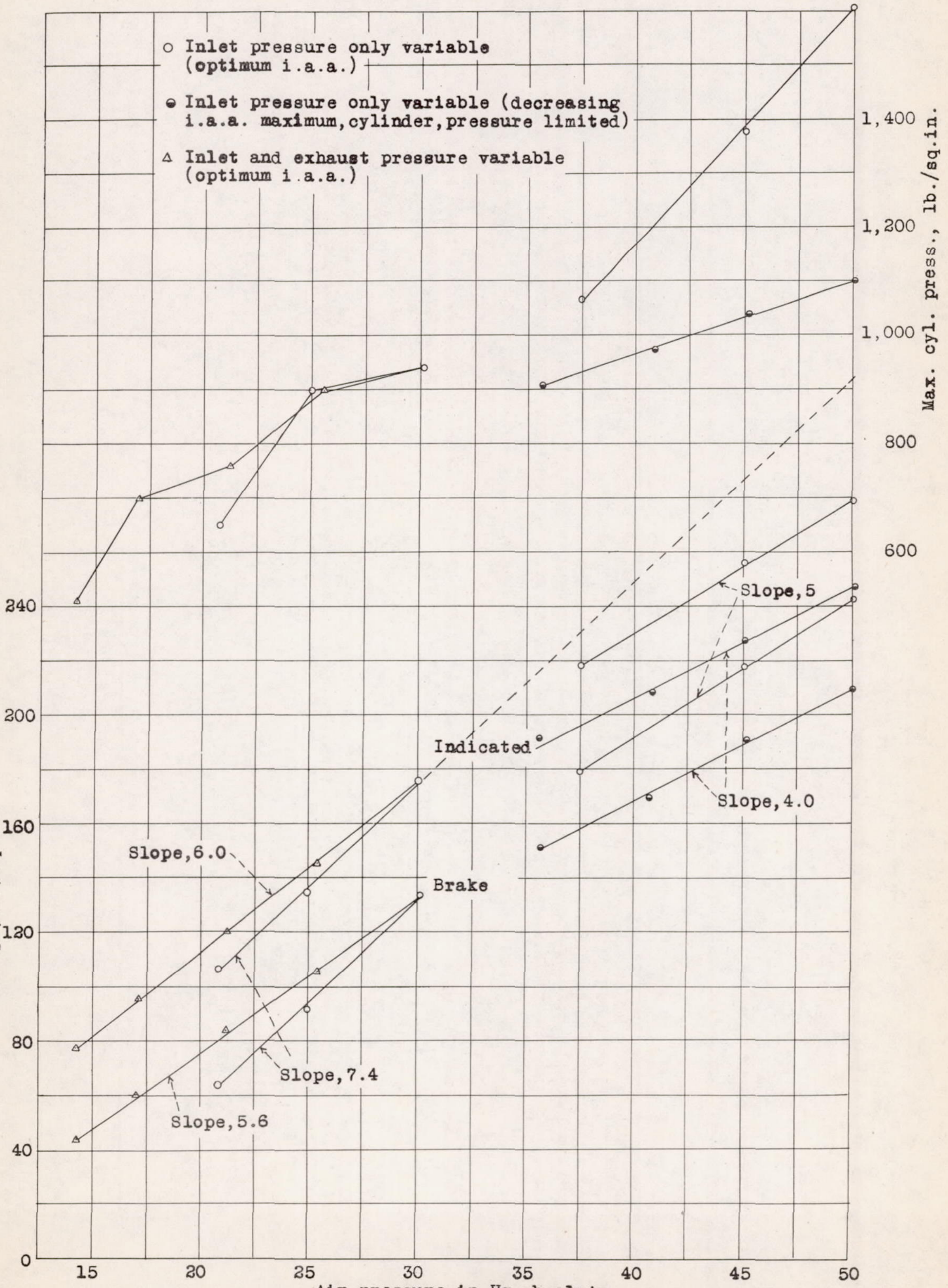


Figure 12.- Effect of inlet-air pressure on maximum sea-level performance; temperature, 66° F.

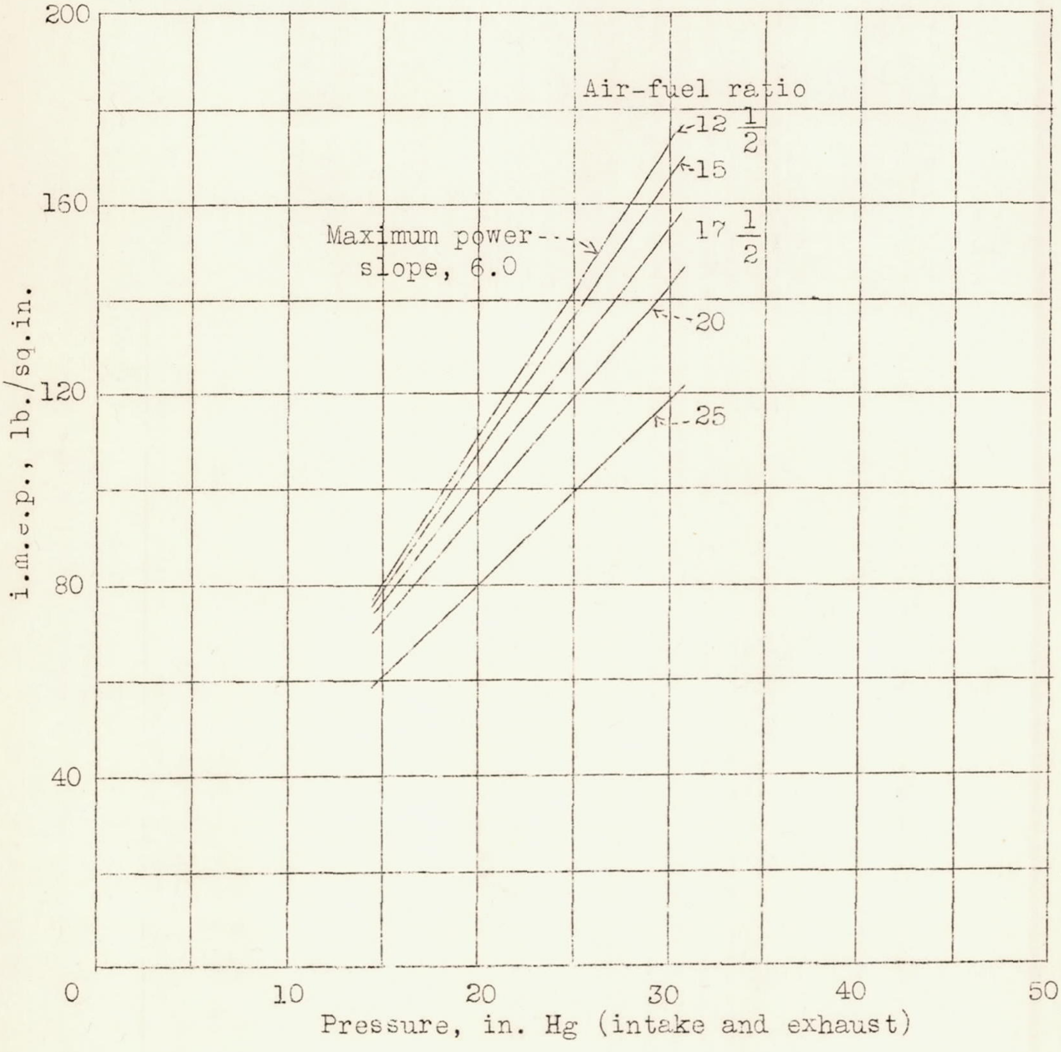


Figure 13.- Effect of inlet and exhaust pressure on indicated mean effective pressure over a range of air-fuel ratios; inlet-air temperature, 82°F.

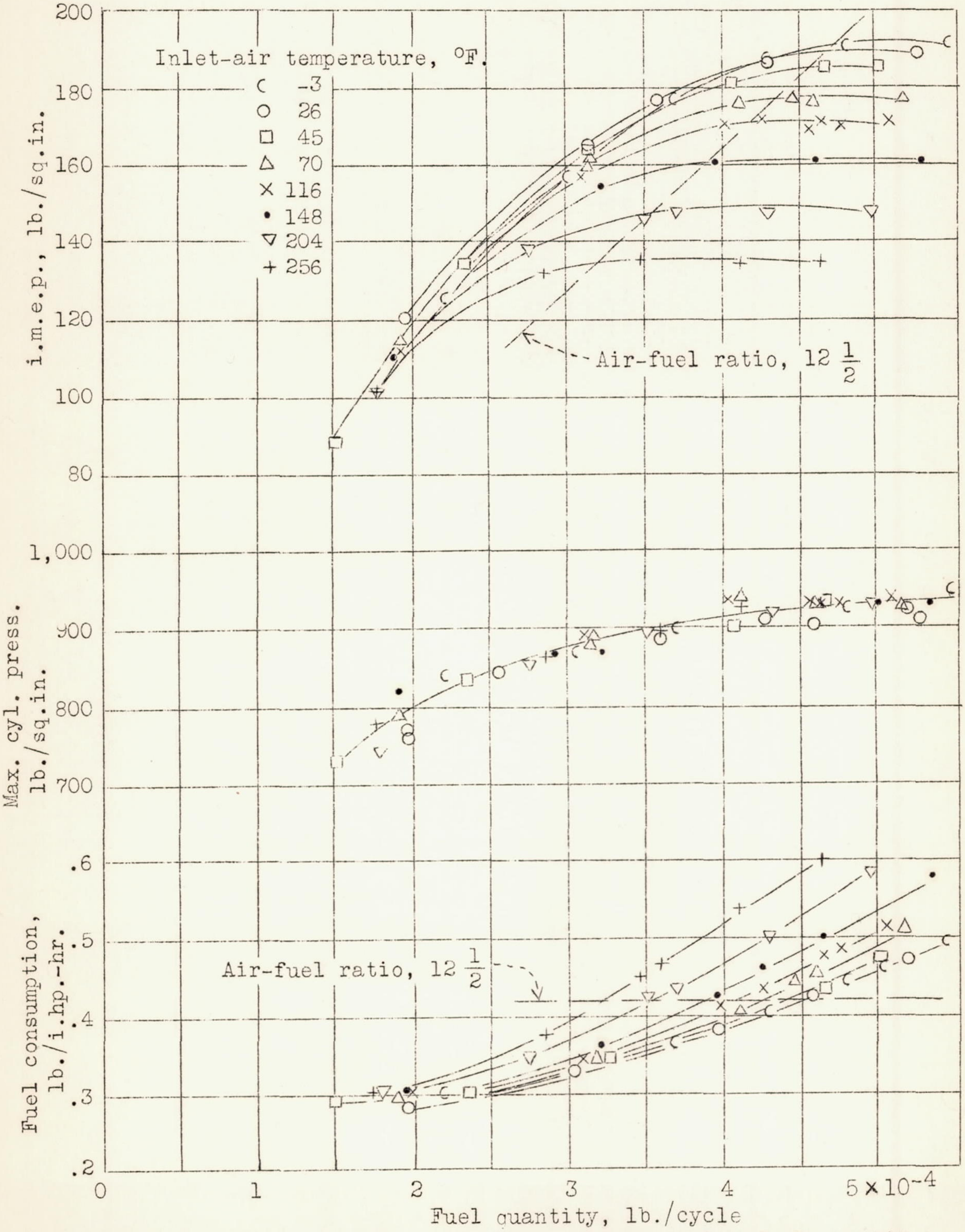


Figure 14.- Variation of sea-level performance with fuel quantity for several inlet-air temperatures.

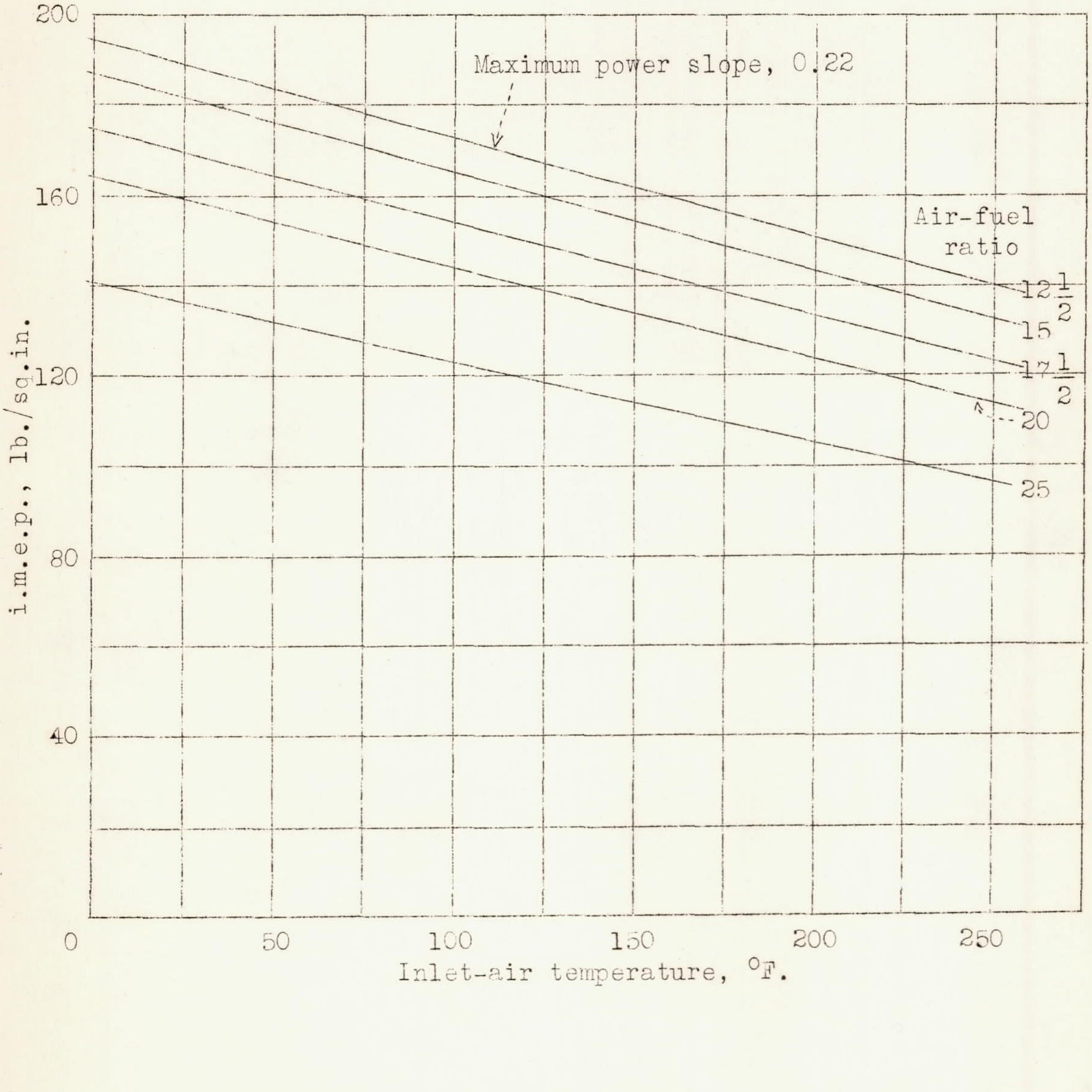


Figure 15.- Effect of inlet-air temperature on sea-level performance over a range of air-fuel ratios.

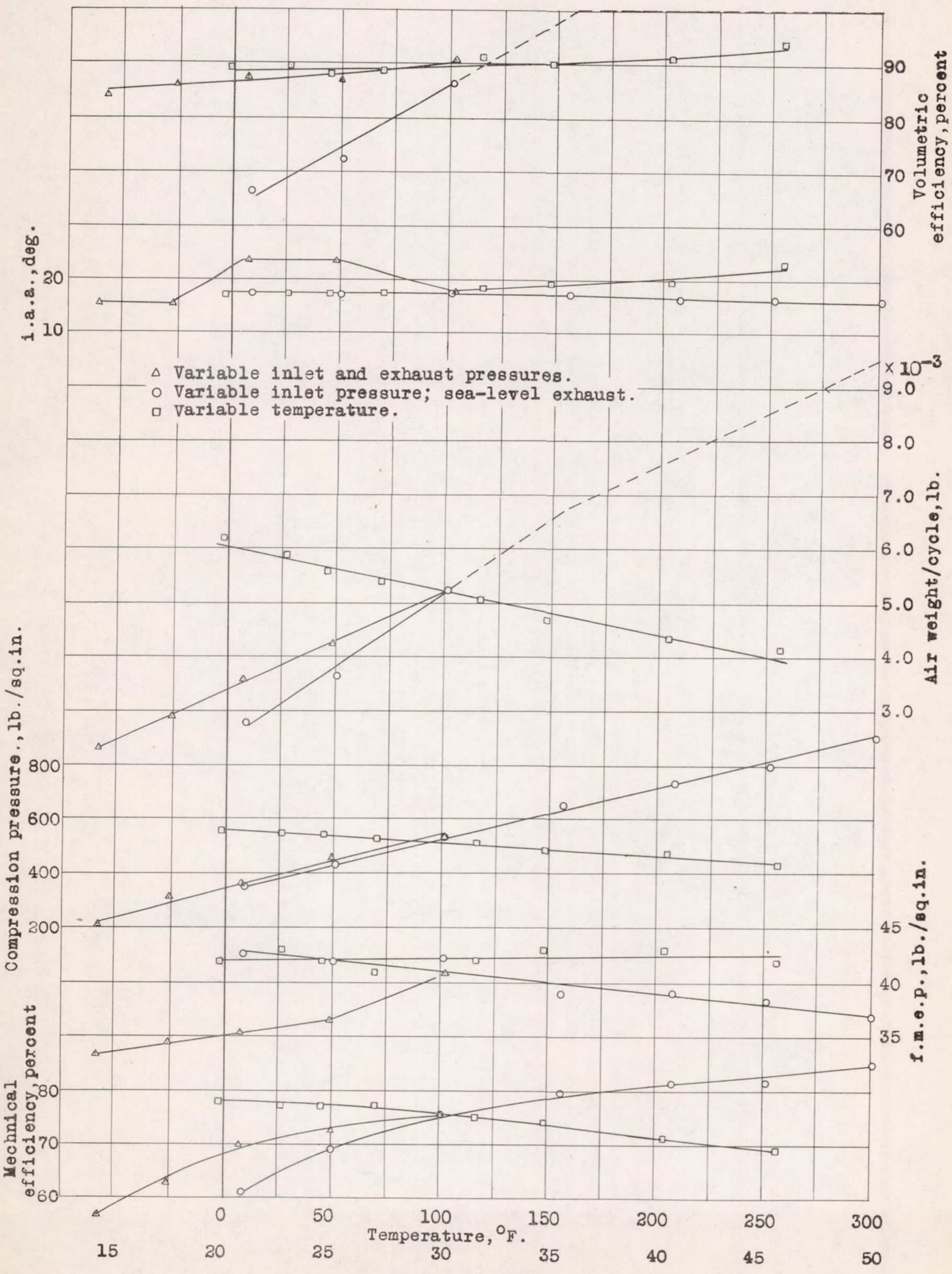


Figure 16.- Effects of inlet-air pressure and temperature on various engine characteristics at sea level.

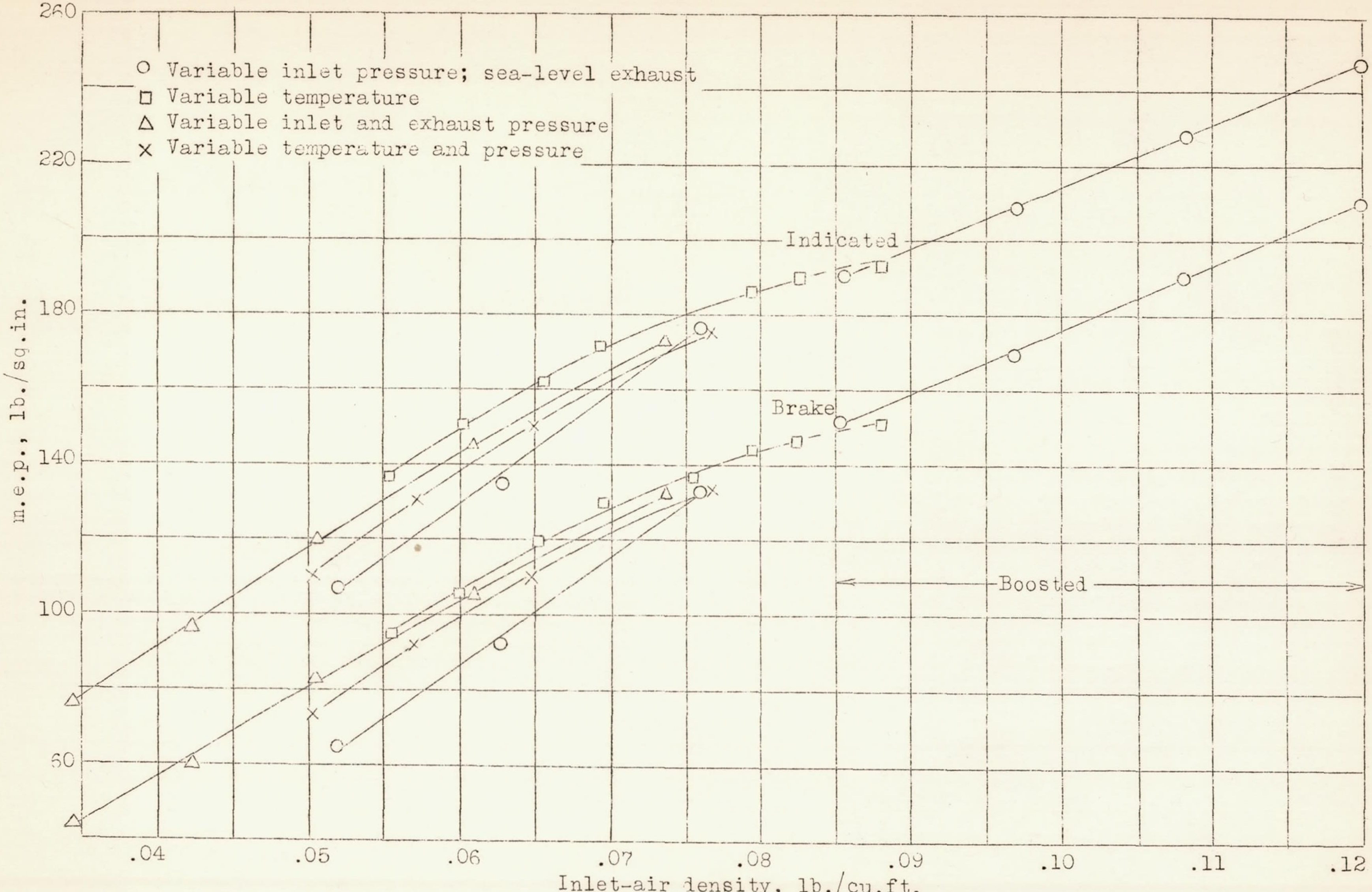


Figure 17.- Effect of inlet-air density on maximum mean effective pressure at sea level.

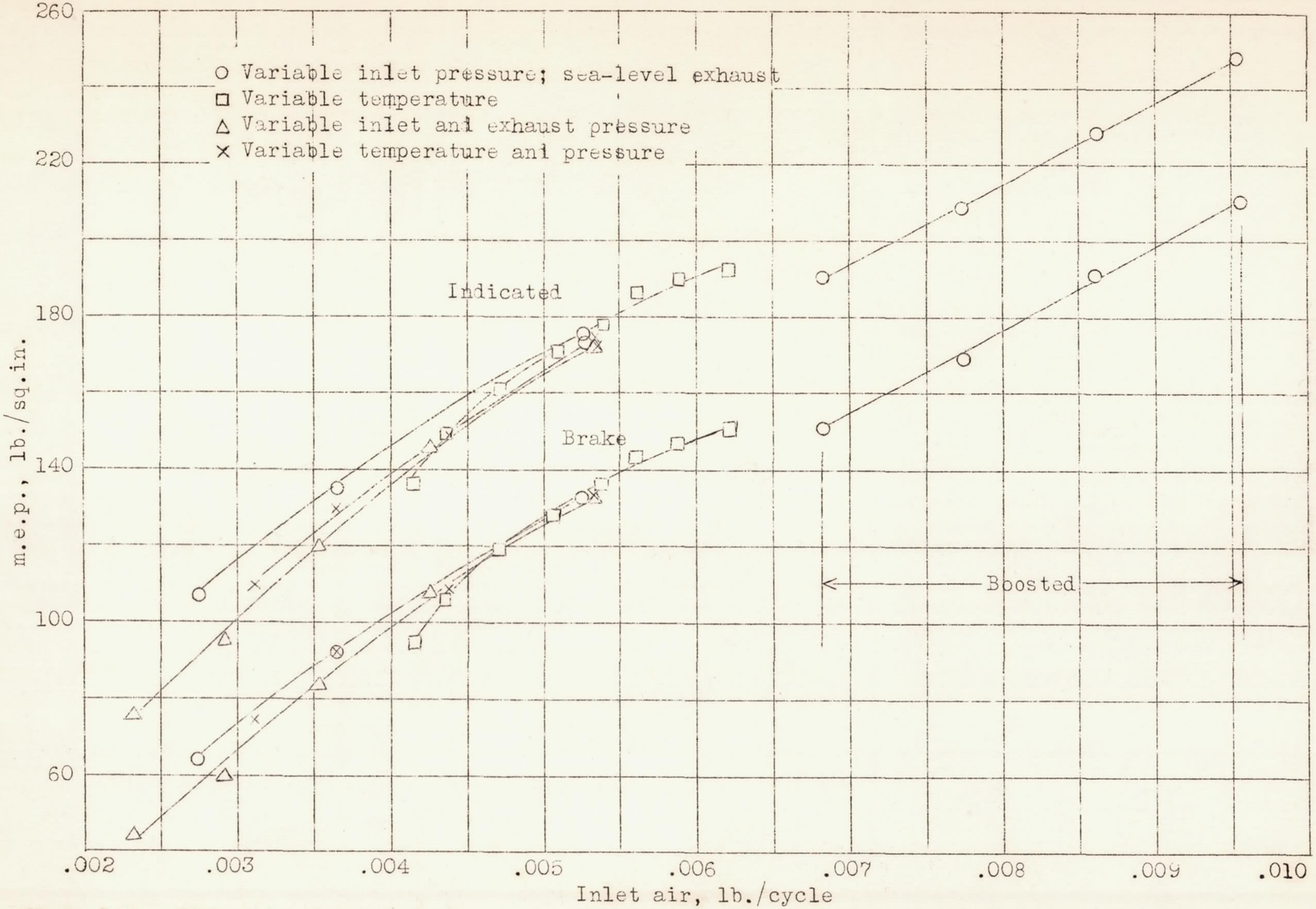


Figure 18.- Effect of weight of air charge on maximum mean effective pressure at sea level.

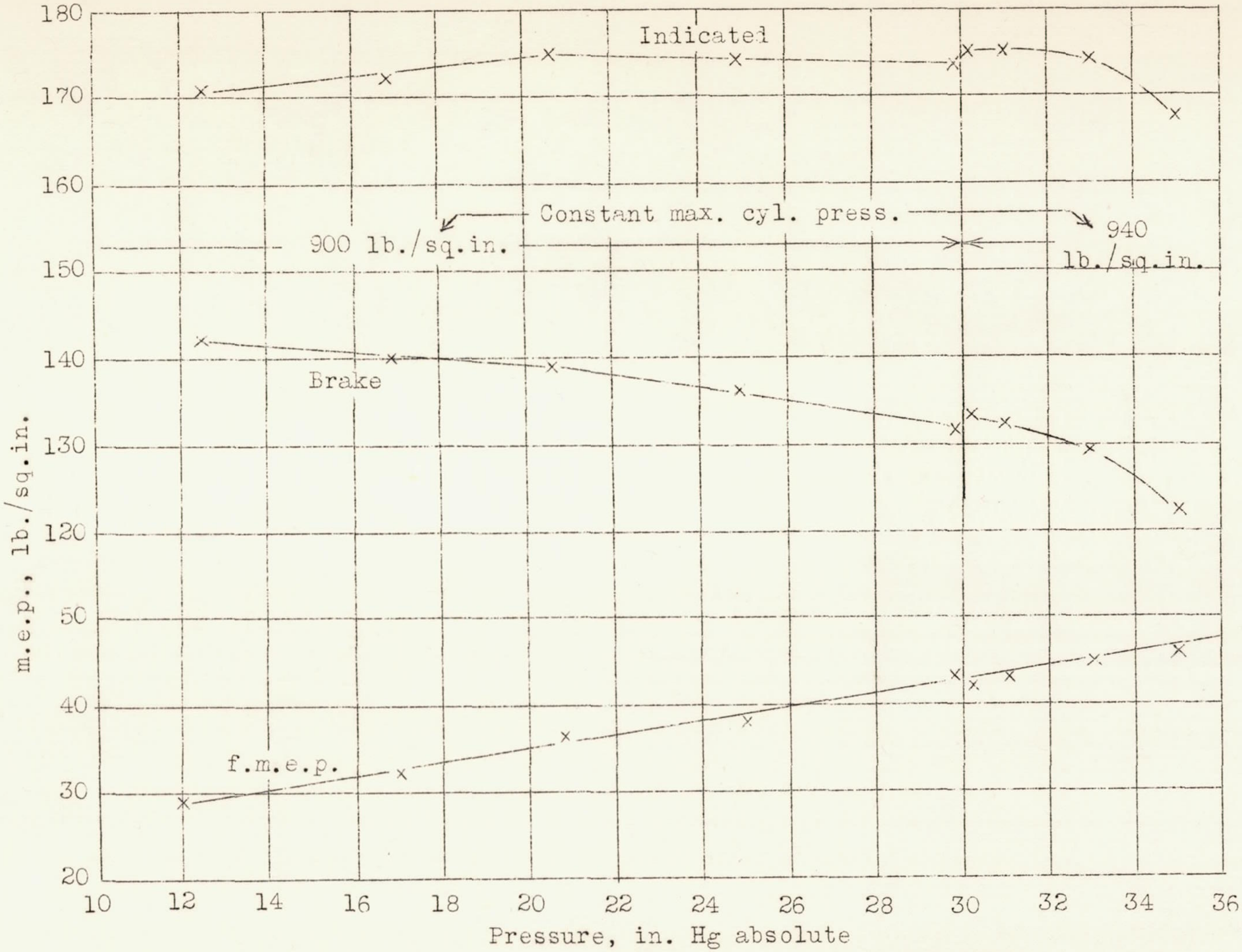
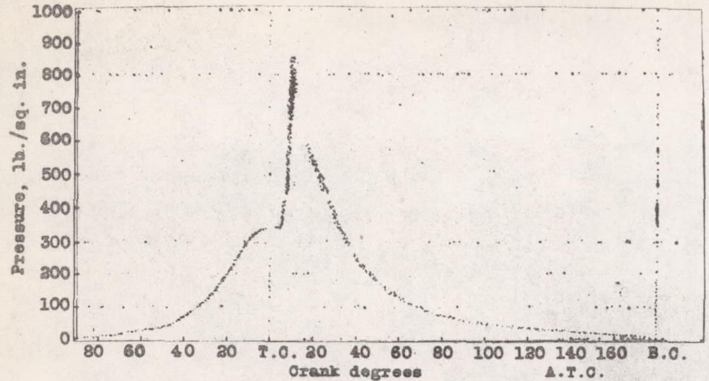


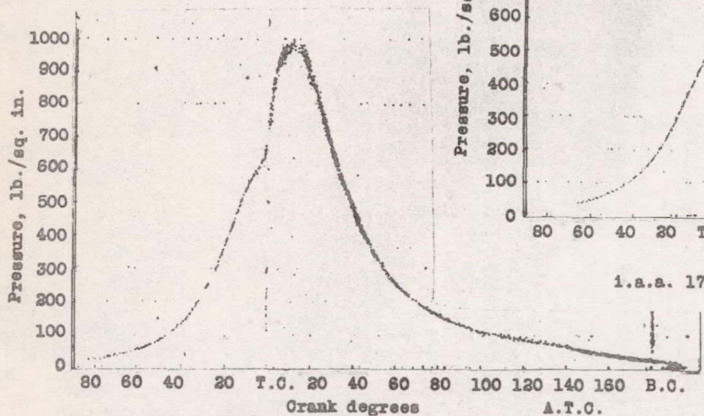
Figure 19.- Effect of exhaust-back pressure on maximum mean effective pressure; sea-level inlet pressure.

Figure 20.- Indicator cards for various conditions.



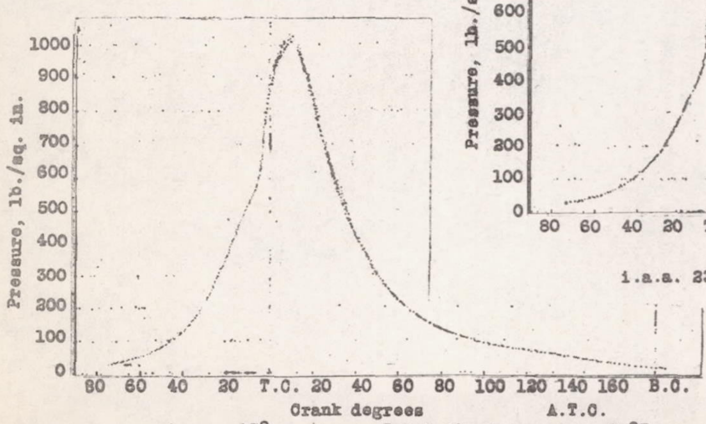
i.a.a. 15° Simulated altitude 14,000 ft.

(a) i.m.e.p., 111.2 lb./sq.in.
Max. rate of pressure rise
118 lb./sq.in./deg.



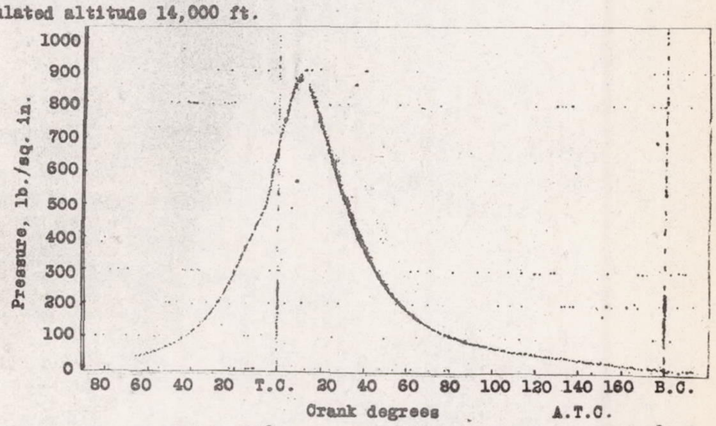
i.a.a. 14 1/2° Inlet air temperature 1°F.

(b) i.m.e.p., 184.3 lb./sq.in.
Max. rate of pressure rise
60 lb./sq.in./deg.



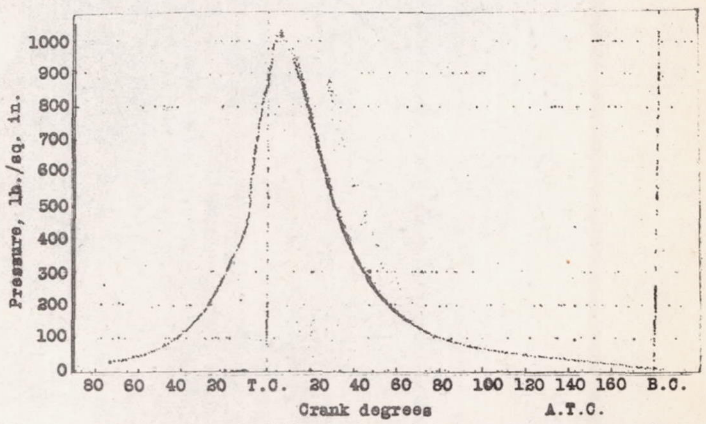
i.a.a. 17° Inlet air temperature 71°F.

(c) i.m.e.p., 174 lb./sq. in.
Max. rate of pressure rise
73 lb./sq.in./deg.



i.a.a. 17° Inlet air temperature 258°F.

(d) i.m.e.p., 132.1 lb./sq.in.
Max. rate of pressure rise
37 lb./sq.in./deg.



i.a.a. 23 1/2° Inlet air temperature 256°F.

(e) i.m.e.p., 132.1 lb./sq.in.
Max. rate of pressure rise
76 lb./sq.in./deg.