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ENGINE PERFORMANCE AND KNOCK RATING OF FUELS FOR HIGH-OUTPUT AIRCRAFT ENGINES

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SUMMARY

Data are presented to show the effects of inlet-air pressure, inlet-air temperature, and compression ratio on the maximum permissible performance obtained on a single-cylinder test engine with aircraft-engine fuels varying from a fuel of 87 octane number to one of 100 octane number plus 1 ml of tetraethyl lead per gallon. The data were obtained on a 5-inch by 5.75-inch liquid-cooled engine operating at 2,500 r.p.m. The compression ratio was varied from 6.50 to 8.75. The inlet-air temperature was varied from 120° F. to 280° F. and the inlet-air pressure, from 30 inches of mercury absolute to the highest permissible. The limiting factor for the increase in compression ratio and in inlet-air pressure was the occurrence of either audible or incipient knock. The data are correlated to show that, for any one fuel, there is a definite relationship between the limiting conditions of inlet-air temperature and density at any compression ratio. This relationship is dependent on the combustion-gas temperature and density relationship that causes knock. The report presents a suggested method of rating aircraft-engine fuels based on this relationship. It is concluded that aircraft-engine fuels cannot be satisfactorily rated by any single factor, such as octane number, highest useful compression ratio, or allowable boost pressure. The fuels should be rated by a curve that expresses the limitations of the fuel over a variety of engine conditions.

INTRODUCTION

The performance obtained from a spark-ignition engine with a given fuel is limited by the severity of the engine operating conditions to which the fuel can be subjected without knocking. The major engine variables that must be controlled to prevent combustion knock are the inlet-air pressure, the inlet-air temperature, the compression ratio, the engine temperature, the spark timing, and the engine speed. For aircraft engines, high inlet-air pressure is desirable for take-off conditions when maximum power is needed. A high compression ratio is desirable chiefly from considerations of fuel economy, although an increase in compression ratio is accompanied by an increase in power. A high inlet-air temperature is undesirable because it decreases the mass of air inducted into the engine. The use of a supercharger, however, results in increased inlet-air temperatures unless an intercooler is provided.

The introduction of aircraft-engine fuels of 100 and higher octane numbers makes it possible to increase considerably the power and economy of aircraft engines. The maximum power and economy that can be obtained depend on the particular engine and on the previously mentioned engine variables. Data on engine performance with high-octane fuels have been presented in references 1, 2, 3, and 4; the test results reported therein have shown the need of a systematic investigation of the effect of the different engine variables on the maximum permissible engine output obtainable with high-octane fuels. In the present tests, the effects of inlet-air pressure, inlet-air temperature, and compression ratio on the maximum engine performance as limited by knock were determined with a liquid-cooled single-cylinder engine for a range of fuels from 87 octane number to 100 octane number plus 1 ml of tetraethyl lead. The investigation was conducted under the direction of the N.A.C.A. Subcommittee on Aircraft Fuels and Lubricants. The tests are to be continued to cover the effects of engine speed, combustion-chamber design, and cooling medium.

APPARATUS

The single-cylinder test-engine unit used in the tests was designed for high-speed operation at different compression ratios over a range of inlet-air pressures and inlet-air temperatures. A diagrammatic sketch of the unit is shown in figure 1. The engine has a bore of 5 inches and a stroke of 5.75 inches (113 cubic inches displacement). The following engine conditions were maintained constant throughout these tests:

Valve timing - - - - Inlet opens 20° B.T.C.
Inlet closes 71° A.B.C.
Exhaust opens 56° B.B.C.
Exhaust closes 32° A.T.C.

Valve lift - - - - - - 0.5 inch.

Engine coolant - - - Prestone.

Engine-coolant temperature - - - 250° F.

Engine speed - - - - - 2,500 r.p.m.

The cylinder head is of cast iron with a flat-disk combustion chamber (fig. 2). It has two exhaust valves and two inlet valves, each with a diameter of 1-7/8 inches. The exhaust valves have sodium-cooled stems. All sharp edges in the combustion chamber, such as exposed spark-plug threads, have been removed. The piston is made of aluminum alloy with a ribbed undercrown for cooling (fig. 2). The compression ratio can be varied from 4.50 to 9.50 by raising or lowering the head and cylinder as a unit.

The ignition system is operated from a battery and the timer is driven by an independent gear train directly from the crankshaft. The variation of the ignition spark is ±2.5 crankshaft degrees. Two BG 3B-2 spark plugs were located on opposite sides of the combustion chamber, one between the exhaust valves and one between the intake valves, and were fired simultaneously. The spark plugs were water-cooled.

The carburetor has a double throat with 2-1/2 inch venturi tubes. Needle valves replaced the main metering jets.

A closed cooling system, using a pump driven from the engine, was installed. A water-cooled heat exchanger kept the Prestone at the desired temperature.

The fuel consumption was measured by an electrically operated system, which indicated the time and the number of engine revolutions required to consume a given weight of fuel. The mixture strength was indicated during the tests by a Cambridge mixture-ratio indicator. The peak pressures were shown by the N.A.C.A. balanced-diaphragm indicator.

The inlet-air temperature was measured above the carburetor. The inlet-air pressure was measured in the surge tank mounted before the inlet-air heater, as shown in figure 1. The exhaust temperatures, engine-coolant temperatures, and inlet-air temperature were measured with thermocouples in conjunction with a potentiometer.

The engine torque was measured by a direct-current dynamometer in conjunction with a calibrated direct-reading scale.

Various methods of indicating the occurrence of knock were tried. The recording of the start of audible knock was believed to be a satisfactory method and was used throughout most of the tests. The start of incipient knock below the audible range was also of interest and a satisfactory indication of it was obtained by using the M.I.T. knockmeter (reference 5) in conjunction with a cathode-ray oscillograph. The use of the cathode-ray oscillograph as the indicating unit instead of the damped galvanometer originally supplied with the M.I.T. unit made it possible to indicate knock in the individual engine cycles. When the engine is not knocking, the cathode-ray tube shows a horizontal trace; when knock occurs, there is a vertical rise in this trace. Knock was clearly indicated before it became audible.

An R.C.A. piezoelectric engine indicator was installed in the engine to check the modified M.I.T. method of indicating incipient knock. The R.C.A. unit can be connected to a cathode-ray tube so that time-pressure records are shown on the tube for each engine cycle. A motion-picture camera, driven from the engine crankshaft at one-half engine speed, was focused on two cathode-ray tubes operated by the two indicator units. By means of this apparatus, a photograph was obtained each engine cycle of the time-pressure record on one cathode-ray tube and of the knockmeter record on the second tube. A section of the motion-picture film is reproduced in figure 3. In the first cycle shown, the time-pressure record appears smooth and the knock record is a horizontal line. In each of the following three cycles, the engine was knocking, as indicated by the vibrations in the time-pressure record starting at or slightly before peak pressure. The corresponding knock records show a vertical rise near the right end. Examination of the film showed that knocking vibrations on the time-pressure record were accompanied in each case by a vertical rise on the knockmeter record. Consequently, it was decided to use the knockmeter method for recording knock before the knock became audible. This preaudible knock will be designated "incipient knock." With incipient knock, the vertical line on the knock record was about 1/16 to 1/8 inch high and, with audible knock, it was about 3/4 to 1 inch high.

An engine condition in which knock is audible may be unstable in that appreciable knock is accompanied by a temperature rise of critical surfaces in the combustion chamber, which in turn may cause a more severe form of knock. The existence of this unstable knocking condition in an engine is probably a matter of design and the severity of the operating conditions. Another reason for using incipient knock as the indication is the rapid depreciation of valves and piston rings when an engine is operating with audible knock. The foregoing reasons for limiting knock to the incipient stage become increasingly important as the octane number of the fuel is increased. The high inlet pressures possible with the high-octane fuels cause very severe operating conditions when audible knock is present.

The tests showed, under some operating conditions, a record of incipient knock, which disappeared on further increase of the inlet-air pressure. At a still higher inlet-air pressure, incipient knock again occurred, becoming progressively more intense as the inlet-air pressure was increased and finally becoming audible. In the test results presented for incipient knock, this second incipient knock was used.

FUELS

Two base fuels were blended for these tests. The first was a technical iso-octane of very nearly the same composition as S.A.E. S-1 fuel. It had a freezing point, determined at the National Bureau of Standards, of -108.98° C., an octane number (C.F.R. method) of 99.75, and a specific gravity of 0.6934. The second fuel was a fuel of 18 octane number and was similar to S.A.E. M-1 fuel. The iso-octane and the 18-octane fuel were blended in proportions of 85-15, 90-10, and 95-5, respectively. The octane numbers of the blends, as determined by the C.F.R. method and by the Army Air Corps method, were as follows:

Blend	Octane number	
	C.F.R. method (average from 9 laboratories)	Army Air Corps method (1 laboratory)
85-15	86.8	86.9
90-10	90.9	91.6
95-5	95.2	95.4
	(1 laboratory)	
100-0	99.75	

Throughout the discussion, these fuel blends will be designated by the following respective octane numbers: 87, 91, 95, and 100. In addition to these fuels, tests were made of the 100-octane fuel plus 1 ml of tetraethyl lead per gallon.

METHOD OF TESTS

The following test limits were agreed upon:

Compression ratio: 6.50 to highest permissible (in increments of 0.75).

Inlet-air pressure: 30 inches of mercury absolute to highest permissible (in increments of 2.5 inches of mercury).

Inlet-air temperature: 120°, 160°, 200°, 240°, and 280° F.

Spark advance: Maximum power for each compression ratio at 32.5 inches of mercury inlet-air pressure and 200° F. inlet-air temperature.

In each case the limiting values, where no upper limit is designated, were the highest permissible for either audible or incipient knock.

Each test was run with the air-fuel ratio giving approximately maximum power and with the air-fuel ratio giving the minimum fuel consumption because these two values are of particular interest in aircraft engines. Sufficient mixture loops were obtained for the various test conditions to establish accurately the air-fuel ratios for maximum power and for minimum fuel consumption. After these values of the ratios were obtained, necessary additional runs were made only at these determined values. The air-fuel ratios determined from exhaust-gas analyses were: for maximum power, 12.8; and for minimum fuel consumption, 14.4.

The mixture for maximum power was taken slightly on the lean side of the mixture loop, which corresponded to a reduction in power of about 1 percent. Similarly, the mixture for minimum fuel consumption was taken slightly on the rich side of the maximum-economy point. Throughout the report the mixture for 1 percent reduction in maximum power is designated "best-power mixture," and the mixture for 1 percent increase above the minimum specific fuel consumption is designated "best-economy mixture."

During the tests it was found difficult to hold the inlet-air temperature within the limits desired. Consequently, for the test conditions in which mixture loops were obtained, it was generally impossible to determine the exact inlet-air temperature for the best-power or for the best-economy mixtures. The temperature variation, however, was always within ±10° F. and was usually much less.

The spark advance for the 6.50 compression ratio was 38° and was decreased 2° for each 0.75 increase in the compression ratio; engine tests had shown that these values met the conditions originally prescribed and that the optimum spark advance was approximately constant for all inlet-air pressures at any one compression ratio.

In the tests, the compression ratio and the inlet-air temperature were held constant and the inlet-air pressure was increased in increments of 2.5 inches of mercury until the knock became audible. Check runs were made in some cases for which the inlet-air pressure required for both audible and incipient knock was recorded to within 0.1 inch of mercury. After the pressure required for audible knock was determined, the inlet-air pressure was decreased to that required for incipient knock.

Particular care was taken to distinguish between knock and preignition or afterignition caused by a hot spot in the engine. Preignition was indicated by a loss in engine power, and afterignition by continued firing after the ignition switch was cut off. When preignition or afterignition occurred before audible knock was reached, efforts were made to remove the hot spot that was the igniting source; the tests were then repeated. Spark plugs and other plugs in the combustion-chamber wall were a frequent source of trouble until water-cooled. Considerable difficulty was experienced with the leaded fuel (100-octane fuel plus 1 ml tetraethyl lead) because of a hot spot in the center of the top of the combustion chamber. This hot spot was eliminated by removing the bushing around the spark-plug hole in this position and permitting the engine coolant to flow over the plug. (See fig. 2.) Previous to this alteration, the plug had been cooled by the lubricating oil from the valve gear. Special reference will be made to the tests with and without this additional cooling.

All data were computed on the basis of indicated performance. The indicated horsepower was obtained in the conventional manner by adding to the measured brake horsepower the friction horsepower determined by motoring at the boost pressure.

TEST RESULTS

Figure 4 shows the maximum permissible inlet-air pressures for the 100-octane fuel at compression ratios of 6.50 and 7.25. Only the data for the 100-octane fuel are included in this figure since the trend of the curves is similar for the other fuels tested. The curves show that the difference in maximum permissible inlet-air pressure for maximum power and for minimum fuel consumption was within the increment of 2.5 inches of mercury used in most of the tests. At each ratio, as the inlet-air temperature was increased, the curves for incipient knock approached those for audible knock. The points on the curves for indicated mean effective pressure show the experimental variation. During the tests, frequent check runs were made at previously tested conditions. These runs were considered to be satisfactory when the power was within ±5 percent of that obtained in the previous run under the same conditions.

A summary of the maximum permissible inlet-air pressures for all the conditions tested is presented in table I.

Although these data are for maximum power, they serve equally well for minimum fuel consumption within the limits of experimental accuracy. (See fig. 4.) The second set of data checked the first set within the precision of the tests for the 87- and 100-octane fuels, but the second set of data for the leaded fuel shows appreciably higher permissible inlet-air pressures. The increase was permitted by the increased cooling of the plug in the center of the top of the combustion chamber. As indicated in table I, before the improvement was made in the cooling, the leaded fuel showed preignition or afterignition from a hot spot at the two lower compression ratios. The other four fuels did not show this secondary ignition. Removing the hot spot improved the characteristics only of the fuel that was showing the secondary ignition and had no appreciable effect on the other four fuels.

Figure 5 shows the effect of compression ratio on the fuel consumption for the two air-fuel-ratio settings. The plotted points represent the average of all the data obtained at the compression ratios indicated. At any one ratio, the indicated fuel consumption was independent of either the inlet-air pressure or the inlet-air temperature. The decrease in fuel consumption with an increase in compression ratio is shown by the curves.

The indicated mean effective pressures for the different test conditions are shown in figures 6 and 7; cross plots give the limits for the different fuels. The limit for the 100-octane fuel plus 1 ml tetraethyl lead is incipient knock, and for the other fuels it is audible knock. The dashed portions of the curves represent extrapolated data. The indicated mean effective pressure decreased steadily with increase of the inlet-air temperature and increased, as expected, with compression ratio except for the values at the lowest compression ratio tested.

The indicated peak cylinder pressures for the air-fuel ratio giving best power are shown in figure 8. The pressures shown represent the averages of the highest values indicated by the peak-cylinder-pressure indicator and correspond to the last intermittent flashes of the neon tube. The peak cylinder pressures corresponding to an almost steady flash of the neon tube in the maximum cylinder pressure gage were about 125 pounds per square inch lower than those shown in this figure.

To what extent the data obtained on the test engine can be applied to a full-scale aircraft engine cannot be said. It seems reasonable to believe that general trends of the results are applicable to a full-scale engine. The data show clearly a decrease in maximum permissible power with a given fuel as the temperature of the incoming air is increased. Also, the data show the gain in maximum permissible power obtained by operating the engine at a low compression ratio, a low inlet-air temperature, and a high boost pressure. The data show the permissible decrease in minimum fuel consumption obtained by operating the engine at a high compression ratio or at a low boost pressure to avoid knock. The data indicate that in a boosted engine the maximum permissible i.m.e.p. is considerably decreased if no intercooler is provided between the supercharger and the engine cylinders.

A comparison of the results presented herein with the results that might be obtained on another engine with the same fuel would probably show the greatest discrepancy in the variation of maximum permissible boost with inlet-air temperature. This variation will depend on the rate of heat transfer between the cylinder walls and the air-fuel mixture during the intake stroke, the compression stroke, and the combustion period up to the time of knocking. If the incoming mixture is at a lower temperature than the walls of the cylinder and of the combustion chamber, the charge will be heated during the intake stroke and the first part of the compression stroke and the amount of heating will depend on the rate of heat transfer. If the charge enters at a temperature higher than that of the walls, the charge will be cooled. Therefore, depending on these rates of heat transfer, the same fuels in another engine might show a greater or a lesser drop in maximum permissible boost pressure with increased inlet-air temperature. The data undoubtedly give a comparative picture of the increase in power and the decrease in fuel consumption that can be expected from the introduction of isooctane as an aircraft-engine fuel.

The range of engine operating conditions is sufficient to permit the results to be used in an analysis of the problem of rating aircraft-engine fuels. Such an analysis is presented in the following section.

ANALYSIS OF THE DATA FROM CONSIDERATIONS OF THE RATING OF AIRCRAFT-ENGINE FUELS

Analysis of effects of inlet-air pressure, inlet-air temperature, and compression ratio on knock.- A successful method of rating aircraft-engine fuels must give results from which it is possible to predict the maximum performance obtainable from an aircraft engine using any specified fuel. Furthermore, given a choice of fuels and a definite set of engine operating conditions, the rating of the fuels should permit the choice of the fuel best suited for the particular engine conditions. No satisfactory method of fuel rating that meets these requirements has yet been found.

The phenomenon that limits the severity of engine conditions to which a fuel can be subjected is knock. Any basis of fuel rating should consequently be based on the factors that cause knock. Although not all the chemical and physical processes accompanying knock are understood, sufficient knowledge has been accumulated to permit certain definite conclusions to be drawn.

The most generally accepted theory is that knock in an internal-combustion spark-ignition engine results from the almost simultaneous burning of the end gases in the combustion chamber. This burning is sufficiently rapid to cause a sudden increase in the pressure in parts of the combustion chamber. The pressure increase takes place at a rate more rapid than the rate at which the pressure is transmitted to the remaining sections of the combustion chamber. A system of pressure waves is therefore set up within the chamber. These gas vibrations striking the combustion-chamber wall induce vibrations in the engine structure that give rise to the metallic knock.

More recent data obtained at this laboratory have led to the conclusion that the volume of gas causing the knock may not necessarily be the end gas, because knock has been observed to take place after the combustion has apparently traversed all the combustion chamber. Regardless of the section of the gas in which the knock takes place, the effect on the pressures within the cylinder is the same - a sudden increase in the local pressures and, with heavy knock, a sudden increase in the mean pressure throughout the chamber.

Since knock is a phenomenon of combustion, it must be controlled by the physical state of the gases in the combustion chamber as well as by the chemical composition of the gases. It seems most reasonable to believe that the gas density and the temperature immediately preceding knock are the controlling physical properties. The engine conditions that control these two properties are:

1. Compression ratio, R.
2. Spark advance.
3. Inlet-air temperature, T_1.
4. Inlet-air pressure, P_1.
5. Cylinder-wall and combustion-chamber-wall temperature.
6. Engine speed.
7. Air-fuel ratio.
8. Exhaust-gas dilution.

The first five factors are the major independent variables. The last three factors also affect the density and temperature of the gas, but the other effects they have on the combustion may be of more importance. The effect of air-fuel ratio can be eliminated by considering that, for any given set of conditions for factors 1 to 4, any air-fuel ratio that causes knocking is being considered. Exhaust-gas dilution does not vary much over the normal full-throttle range of engine operating conditions and will not be considered in this analysis. The effect of engine speed will be discussed later in more detail.

If the assumption is accepted that the two physical properties controlling knock are the gas density, and the gas temperature, it can be said that, for each gas density, there is a minimum gas temperature at which knock will occur. If this contention is true, it follows that a fuel can be accurately rated by determining the relationship between the gas temperature and the gas density that results in knock. A second, and equally important, contention is that it will be impossible to rate a fuel accurately by determining one and only one temperature and density at which knock occurs. A fuel should be rated, then, not by octane number, highest useful compression ratio, compression pressure, or any other single value, but by a curve of density against temperature.

The gas density ρ, and the gas temperature that are the immediate causes of knock are the density and the temperature of that portion of the charge in the knocking region of the combustion chamber the instant before knock occurs. This density can be measured fairly easily and accurately but the temperature cannot. The feasibility of using the temperature and density at some other time in the cycle must be determined. Since all fuels burn with approximately the same flame speed, the density and temperature at the start of combustion or at top center (assuming no combustion before top center) should provide a satisfactory measure of the conditions in the knocking region. The density at top center, if it is assumed that all the fuel is vaporized, depends on the compression ratio, the inlet-air pressure (including volumetric efficiency), the inlet-air temperature, and the heat of vaporization of the fuel. Inasmuch as the heat of vaporization of all hydrocarbon fuels is about the same, the speed of combustion and the heat of vaporization need not be considered. If a constant spark advance is assumed, it can be stated that

$$\rho \propto R\, P_1 \frac{1}{T_1}$$

From this relationship, RP_1/T_1 can be substituted for the air density.

The temperature at top center can be estimated from computations considering the effect of the variation of the specific heats of the gases with temperature and the effect of the residual gases. Values from such computations are shown in table II. The table shows that, whereas an increase in compression ratio from 6.50 to 8.75 increases the compression temperature 100° F., an increase in inlet-air temperature from 120° F. to 240° F. at the lower compression ratio increases the compression temperatures 280° F. It can be concluded that from considerations of temperature alone, an increase in compression ratio in the present normal operating range should have no great effect on the fuel requirements of the engine. Therefore, the chief effect of increasing the compression ratio must lie in the increase in the gas density at top center.

For use in rating fuels, the temperature-density relationship for knocking combustion should be determined over a sufficient range of engine conditions to establish a definite curve. If a linear relationship is assumed, the rating curves for two fuels of different chemical properties might appear as shown in figure 9. In this case, fuel B is superior to fuel A at low gas temperatures and fuel A is the better at high temperatures; fuel B is also more susceptible to temperature variation than fuel A.

The effect of engine speed has not yet been discussed. Decreasing the engine speed has three major effects: It decreases the turbulence within the combustion chamber; it changes the gas temperatures because of the increased time for heat transfer; and it increases the time interval during which the gases in the cylinder are subjected to the increasing temperature during the compression stroke. The temperature and time effects are probably of most interest. Increasing the gas temperatures has the effect of shifting to the left the curves shown in figure 9 because, in the computation of the compression temperatures, the question of heat flow to the walls was not considered.

The effect of the lengthened time interval is more complicated. If there are no appreciable chemical changes in the gases during compression, the effect of time alone can probably be neglected. If there are appreciable chemical changes, which vary with the time required for completion of the compression of the gases, each fuel will have to be rated at different engine speeds; the change, either detrimental or beneficial, must be charged to the fuel and not to the engine. Some of the effects of engine speed on the maximum permissible boost pressure have been presented by Heron and Gillig in reference 3.

In order that the foregoing analysis may be thoroughly checked, a series of fuels must be tested in several different engines. Each engine must be run on each fuel over a range of compression ratios and inlet-air temperatures and pressures, and at different jacket temperatures and engine speeds. Such a set of data is not available in the literature.

Application to the analysis of the data presented.- The data presented herein, from tests of only one engine, show the maximum permissible inlet-air pressures for a series of compression ratios, inlet-air temperatures, and fuels. The fuels, although differing in octane number, are similar in chemical properties. Table I shows the maximum permissible inlet-air pressures for different fuels, inlet-air temperatures, and compression ratios. In the first series of tests, up to the time the cooling in the center of the head was improved, the inlet-air pressures were recorded to the closest 2.5 inches of mercury. In the second series, the pressures were recorded to within 0.1 inch of mercury. The data for the conditions resulting in preignition or afterignition have purposely been omitted from the table. Before the cooling to the cylinder head was altered, this secondary ignition occurred with the leaded fuel at the two lowest compression ratios (6.50 and 7.25); and, after the cooling had been improved, the secondary ignition occurred at a compression ratio of 7.25 and an inlet-air temperature of 280° F. The tests were not run at a compression ratio of 6.50.

The results in table I show that the improved cooling of the head permitted higher inlet-air pressures to be used with the leaded fuel but not with the other fuels. This fact and the analysis of the data indicated that, when either preignition or afterignition occurred, the data must be interpreted differently than when knocking occurred without this secondary ignition.

In figure 10 the air-density factor RP_1/T_1 for audible and incipient knock is plotted against the estimated compression temperature for the 100-octane fuel and the 100-octane fuel plus 1 ml of tetraethyl lead. The data in each case are those obtained after the additional cooling was supplied to the top of the combustion chamber. For the 100-octane fuel, the points form a smooth curve with the exception of the data for the two higher ratios at 120° F. inlet-air temperature. When the data were plotted, the recorded inlet-air temperatures were used in determining the compression temperature. These temperatures varied by ±10° F. from the values given in table I. The data for the leaded fuel are not so satisfactory as those for the unleaded fuel, probably because of the more severe operating conditions.

The problem of determining the curves for the different fuels will be simplified if recorded test temperatures can be used in place of the estimated compression temperature. The compression temperature is approximated by $T_1 R^{\gamma-1}$. Assuming the value of γ to be 1.4, $R^{\gamma-1}$ at a compression ratio of 6.50 is 2.11 and, at a ratio of 8.75, is 2.38, a variation of ±6 percent from the mean of the two values. Consequently, plotting the values of RP_1/T_1 against T_1 should be accurate to within this value.

In figure 11 the value of RP_1/T_1 for two of the fuels is plotted against inlet-air temperature. For the 100-octane fuel, the maximum variation of the points from the curve is ±0.25 RP_1/T_1 which represents a maximum variation in inlet-air pressure of ±3.5 inches of mercury. For the 100-octane fuel plus 1 ml of tetraethyl lead, the variation is approximately the same with the exception of two points.

When values of RP_1/T_1 are plotted against inlet-air temperature instead of compression temperature, it is automatically assumed that, for a given inlet-air temperature, the factor RP_1/T_1 is a constant, regardless of compression ratio. The data indicate that this factor is approximately constant for the engine tested over the range of compression ratios from 6.50 to 8.75. Data obtained at two other laboratories (table III) for three different engines of a size similar to that used in the present tests and over a corresponding range of ratios also show this factor to be approximately constant. The assumption appears to be justified.

Figure 11 indicates that a single curve can be used for both maximum power and minimum fuel consumption, which simplifies the fuel rating. The lower curve shows that no improvement was obtained with the 100-octane fuel after the additional cooling was applied to the top center of the combustion chamber; nor was any improvement observed with the 87-octane fuel.

The marked improvement obtained with the 100-octane fuel plus 1 ml of tetraethyl lead after the cooling had been improved indicates that fuels subjected to secondary ignition because of a hot spot in the combustion chamber can be used under more severe engine conditions if the hot spot is removed; whereas, fuels that knock without preigniting of afterigniting are not improved. In these particular tests, the hot spot probably occurred only with the high rate of heat flow through the cylinder head that accompanied the high inlet-air pressures permissible with the 100-octane fuel plus 1 ml of tetraethyl lead. A more important conclusion is that preignition and afterignition are phenomena separate from knocking and must be treated as such. Either of these secondary ignitions may give rise to knocking.

A summary of all the results obtained for the fuels tested is presented in figure 12. The curves of T_1 against RP_1/T_1 are presented for each fuel. Curve 6 is for incipient knock and the other five are for audible knock. The curves give the limiting engine conditions to which each fuel can be subjected. The fact that the curves are similar is to be expected because the fuels are similar. A cross plot of RP_1/T_1 against octane number indicated that curve 5 represents a fuel with an octane number of 106, whereas curve 6 represents an octane number of 127 at 120° F. inlet-air temperature and 138 at 280° F. inlet-air temperature. The leaded fuel is apparently less susceptible to temperature than the unleaded fuels. This variation of the temperature susceptibility of the different fuels is of extreme importance and is clearly indicated by the slope of the curves shown in figure 12. Some fuels, such as toluene, are much more susceptible to temperature than a fuel that is predominately iso-octane (2, 2, 4 trimethylpentane). As a result, toluene shows an octane number much in excess of 100 at low temperatures but below 100 at high temperatures (reference 3).

In the present tests, the coolant temperature was not varied. The temperature factor should, however, express the temperatures both of the inlet air and of the engine coolant or of the walls of the cylinder and the combustion chamber. Some data on the effects of engine-coolant temperature given in references 3 and 8 indicate the same general relationship as was observed in the tests reported herein. From the data presented by Heron and Gillig, the variation in the rate of temperature depreciation for different fuels can be shown.

As has been previously mentioned, any change in the engine speed will alter both the gas temperature and the time during which the gases are subjected to these temperatures. Consequently, in any investigation of the effects of engine speed, the effects of these two variables must be separated. Data on the rating of fuels at different engine speeds are contained in references 3 and 9, in which it is shown that the change in highest useful compression ratio or in maximum permissible boost pressure with engine speed varies considerably for different fuels.

Other variables, such as the effect of humidity and of exhaust gases, must be more completely investigated. In the present tests no attempt was made to maintain these two factors constant. From the uniformity of the results, however, it is questionable whether the effect of either of these two variables will prove of much importance.

From the present analysis and the application of the test results, it is believed that a method of rating aircraft-engine fuels must be based on a relationship, similar to that described, which expresses the dependency of the gas density on the gas temperature at conditions causing knock. Such a method of rating expresses by a single curve the value of a fuel under a variety of engine operating conditions.

CONCLUSIONS

The following conclusions are drawn from the test data and the analysis presented:

1. In this investigation an increase in octane number from 87 to 100 permitted an increase in i.m.e.p. from 178 to 210 pounds per square inch at a compression ratio of 6.50 or a decrease in the indicated specific fuel consumption from 0.39 to 0.35 pound per indicated horsepower-hour, obtained by increasing the compression ratio from 6.50 to 8.00. The addition of 1 ml of tetraethyl lead per gallon to the 100-octane fuel permitted a further improvement in i.m.e.p. of about these same values, provided that preignition or afterignition did not occur.

2. The indicated fuel consumption is independent of either the inlet-air pressure or the inlet-air temperature.

3. In these tests the maximum permissible boost pressure was approximately the same for best-power and best-economy settings.

4. Aircraft-engine fuels cannot be rated satisfactorily by a single value, such as: octane number, highest useful compression ratio or allowable boost ratio.

5. A satisfactory method of rating aircraft-engine fuels may be based on the temperature-density relationship of the combustible gas for the condition of knock combustion.

6. In the rating of fuels, particular care must be taken to determine that knock is not caused by a hot spot in the combustion chamber, which would produce a secondary source of ignition.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 18, 1938.

REFERENCES

1. Klein, F. D.: Future Possibilities of 100-Octane Aircraft-Engine Fuel. S.A.E. Jour., vol. 39, no. 2, Aug. 1936, pp. 304-312.

2. DuBois, R. N., and Cronstedt, Val: High Output in Aircraft Engines. S.A.E. Jour., vol. 40, no. 6, June 1937, pp. 225-231, 262.

3. Heron, S. D., and Gillig, F.: Essais de Détonation avec Suralimentation. World Petroleum Congress, Paris, June 14-19, 1937. Published in Shell Aviation News, Dec. 1937.

4. Boerlage, G. D.: Detonation and Autoignition. Some Considerations on Methods of Determination. T.M. No. 843, N.A.C.A., 1937.

5. Taylor, C. F., Draper, C. S., Taylor, E. S., and Williams, G. L.: A New Instrument Devised for the Study of Combustion. S.A.E. Jour., vol. 34, no. 2, Feb. 1934, pp. 59-62.

6. Mucklow, G. F.: Experiments with a Supercharged Single-Cylinder Unit. R. & M. No. 1460, British A.R.C., 1932.

7. Taylor, Philip B.: Increasing the Thrust Horsepower from Radial Air-Cooled Engines. S.A.E. Trans., vol. 26, 1931, pp. 531-541.

8. Edgar, Graham: Jacket and Cylinder-Head Temperature Effects upon Relative Knock-Ratings. S.A.E. Trans., vol. 26, 1931, pp. 452-456.

9. King, R. O., and Moss, H.: Detonation, Spark-Plug Position, and Engine Speed. Engineering, vol. CXXXII, no. 3421, Aug. 7, 1931, pp. 177-180.

TABLE I

Effect of Inlet-Air Temperature on Maximum Permissible Inlet-Air Pressure at Different Compression Ratios

Best-Power Mixture

Knock	Fuel octane number	Inlet-air temperature (°F.)	Inlet-air pressure (in. Hg) Compression ratio 6.50	7.25	8.00	8.75
Audible	87	120	32.5			
		160	32.5			
		200	32.5			
		240	30.0			
		280				
Audible	91	120	35.0	32.5		
		160	35.0	32.5		
		200	32.5			
		240	32.5			
		280	32.0			
Audible	95	120	37.5	35.0	30.0	
		160	37.5	35.0		
		200	35.0	32.5		
		240	32.5			
		280	30.0			
Audible	100	120	40.0	37.5	32.5	30.0
		160	40.0	32.5	32.5	30.0
		200	35.0	32.5	30.0	
		240	35.0	32.5		
		280	30.0	30.0		
Audible	100 + 1.0 ml tetraethyl lead	120	Maximum inlet-air pressure limited by preignition or afterignition		37.5	32.5
		160			35.0	32.5
		200			32.5	30.0
		240			30.0	
	Improved cooling in center of combustion chamber					
Audible	87	120	34.4	29.5		
		160	33.1			
		200	32.1			
		240	29.9			
		280	29.7			
Audible	100	120	40.7	35.8	34.2	31.4
		160	41.6	35.6	32.4	27.8
		200	39.8	33.2	29.4	
		240	36.6	30.9		
		280	33.0	27.6		
Incipient	100 + 1.0 ml tetraethyl lead	120		48.5	43.9	41.8
		160		48.2	45.6	41.2
		200		46.2	39.3	33.1
		240		42.9	34.7	32.5
		280			32.7	30.3

TABLE II

Estimated Compression Temperatures for Various Compression Ratios and Inlet-Air Temperatures, Considering Effect of Residual Gases and Variation of Specific Heats with Temperature. Constant Inlet-Air Pressure

Compression ratio	Compression temperature (°F.)			
	Inlet-air temperature (°F.)			
	120	160	200	240
6.50	930	1,020	1,120	1,210
7.25	960	1,060	1,150	1,250
8.00	990	1,100	1,190	1,280
8.75	1,030	1,130	1,230	1,320
9.25	1,060	1,160	1,260	1,350
11.00	1,120	1,230	1,330	1,440
12.50	1,190	1,300	1,400	1,500

TABLE III

Effect of Compression Ratio on Allowable Boost Pressure
Inlet-Air Temperature Constant for Each Series of Tests

Engine	Fuel	Compression ratio	Maximum induction pressure (in. Hg)	$\frac{RP_1}{10}$
Single-cylinder Napier (reference 6)	Petrol	4.5	42.3	19.0
		4.0	54.3	21.7
		3.5	60.8	21.3
Single-cylinder Rolls-Royce (reference 6)	Benzole	4.0	65.4	26.1
		5.0	56.8	28.4
		5.5	51.4	28.3
		6.0	50.9	30.6
		6.5	45.3	29.4
		7.0	41.1	28.8
N.A.C.A. Universal test engine (reference 7, fig. 11)	Domestic aviation gasoline	3.5	44.0	15.4
		4.0	37.5	15.5
		4.5	32.5	15.3
		5.0	30.0	15.5

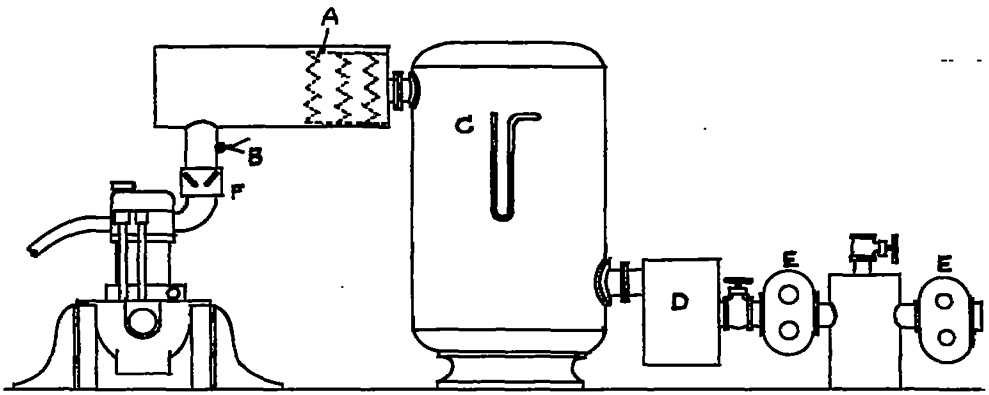


Figure 1.— Diagrammatic layout of test unit. A, electrical air heaters. B, thermocouple for intake temperature. C, surge tank. D, air cooler. E, Roots blower. F, carburetor.

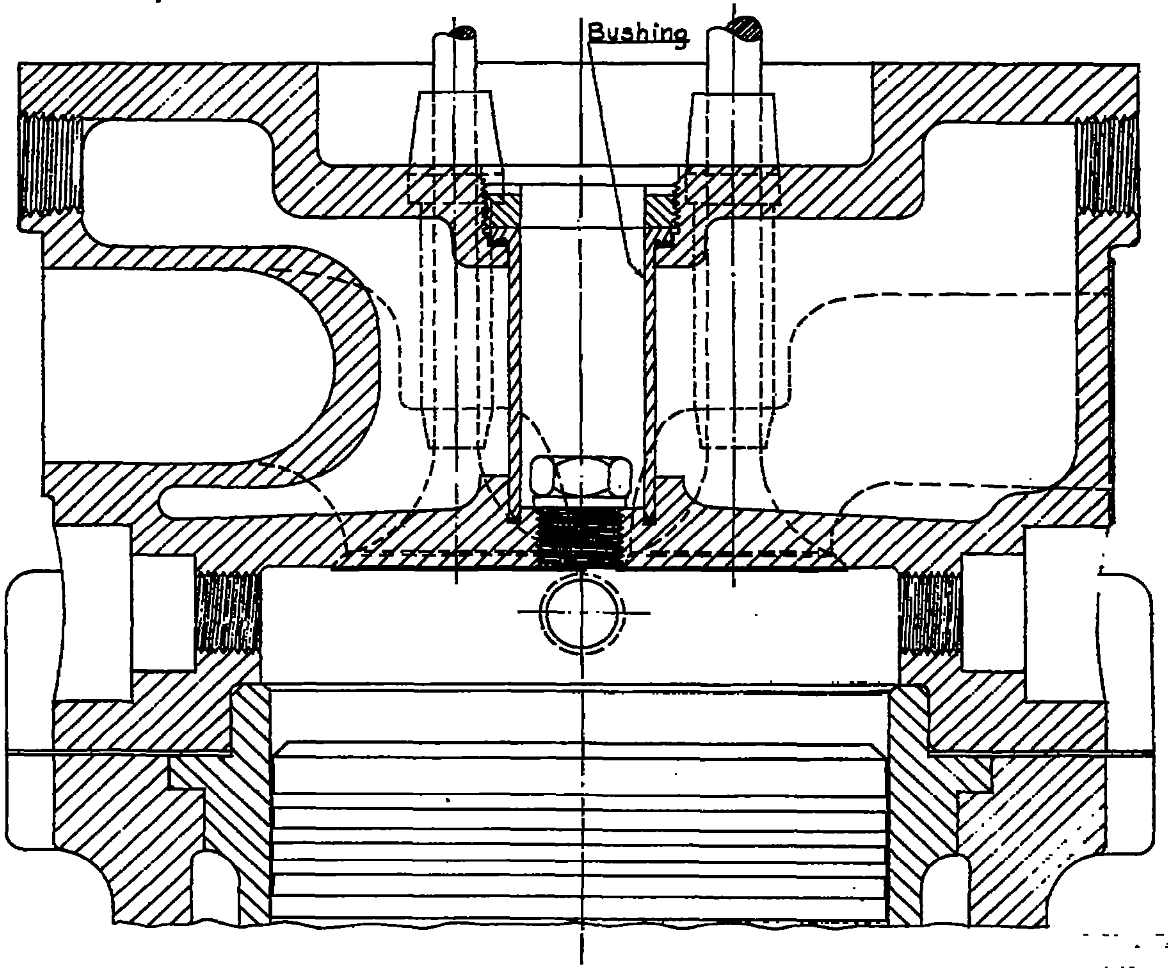
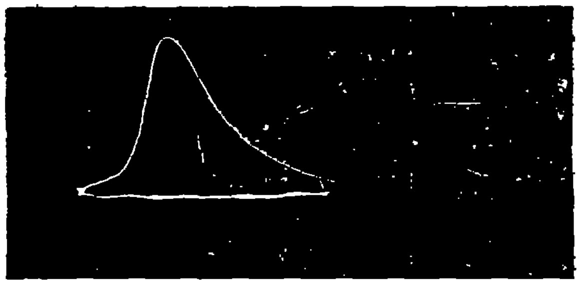
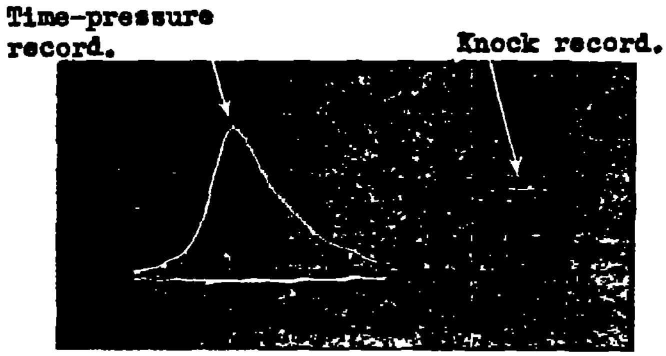


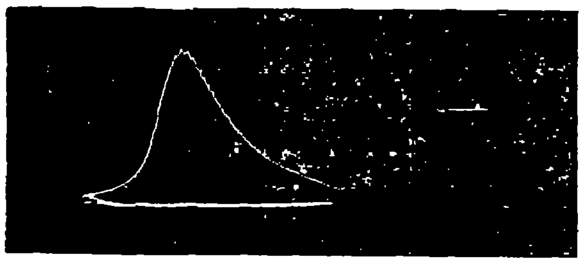
Figure 2.- Section through cylinder head.



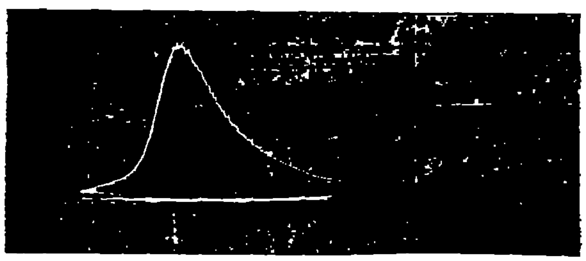
(1) No knock



(2) Knocking



(3) Knocking



(4) Knocking

Figure 3.- Motion pictures of time-pressure record and of knock record for four successive engine cycles.

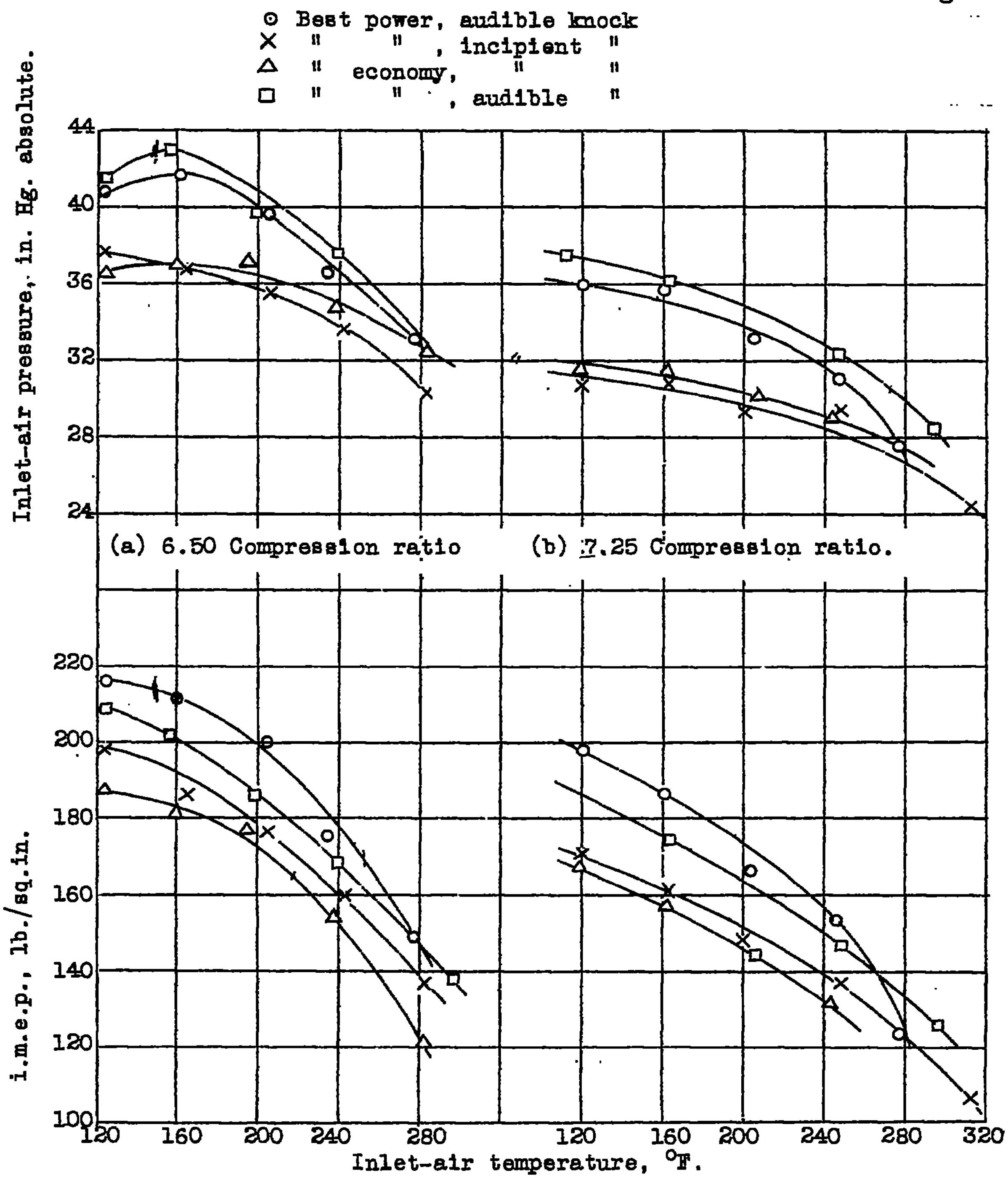


Figure 4.- Engine performance as limited by knock(100-octane fuel)

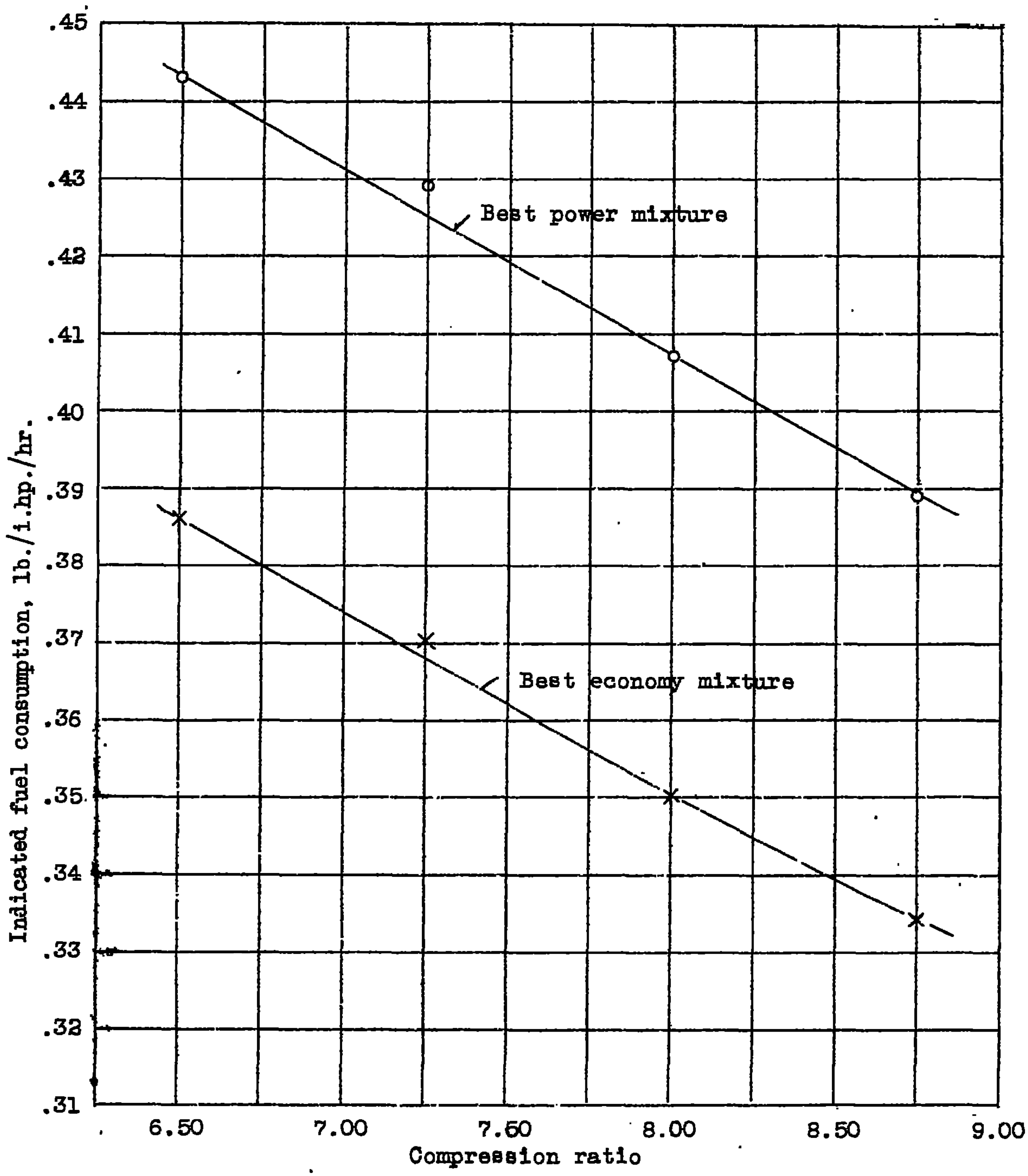


Figure 5.- Average fuel consumption for different inlet-air pressures and temperatures.

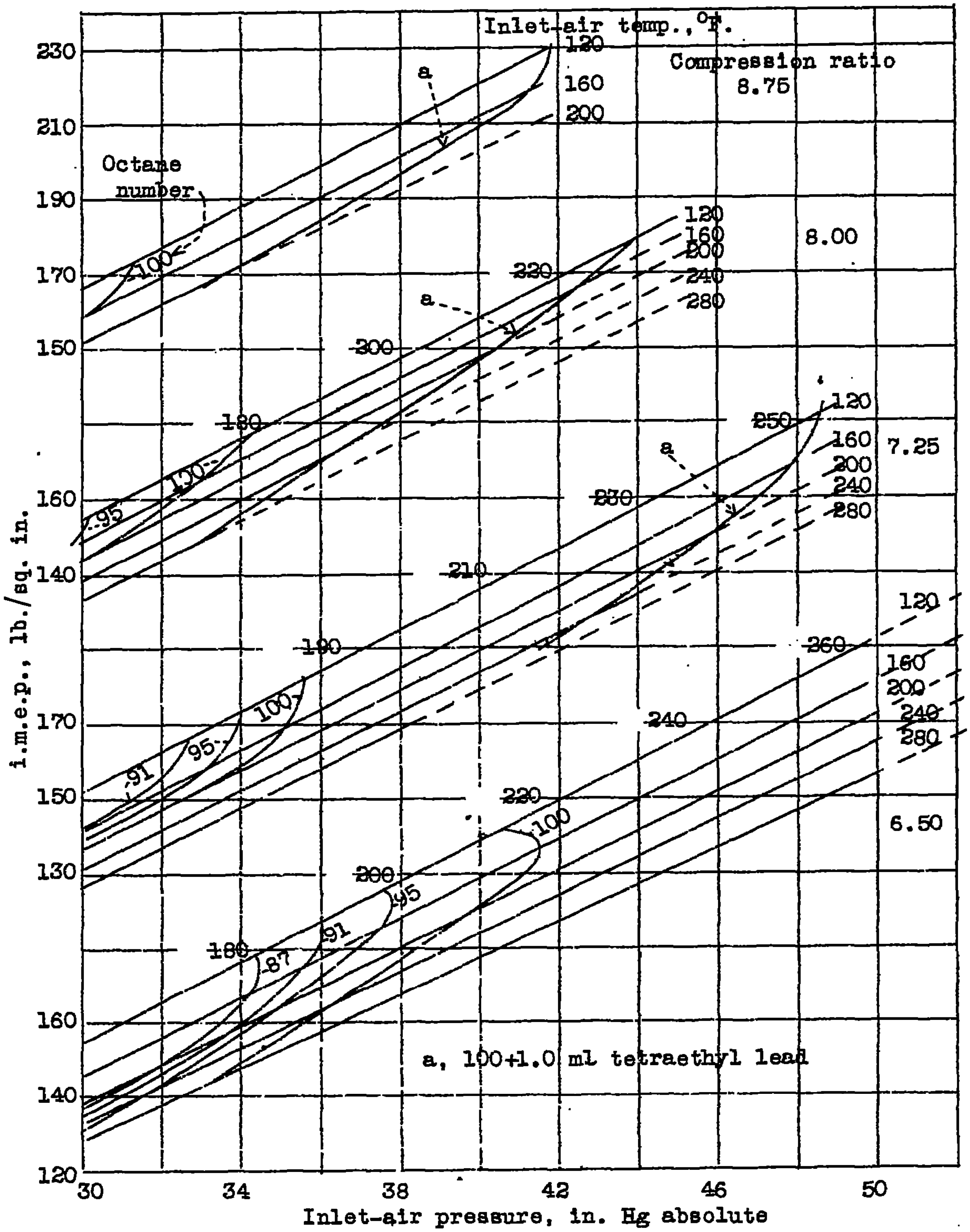


Figure 6.- Engine performance with best-power mixture(audible knock)

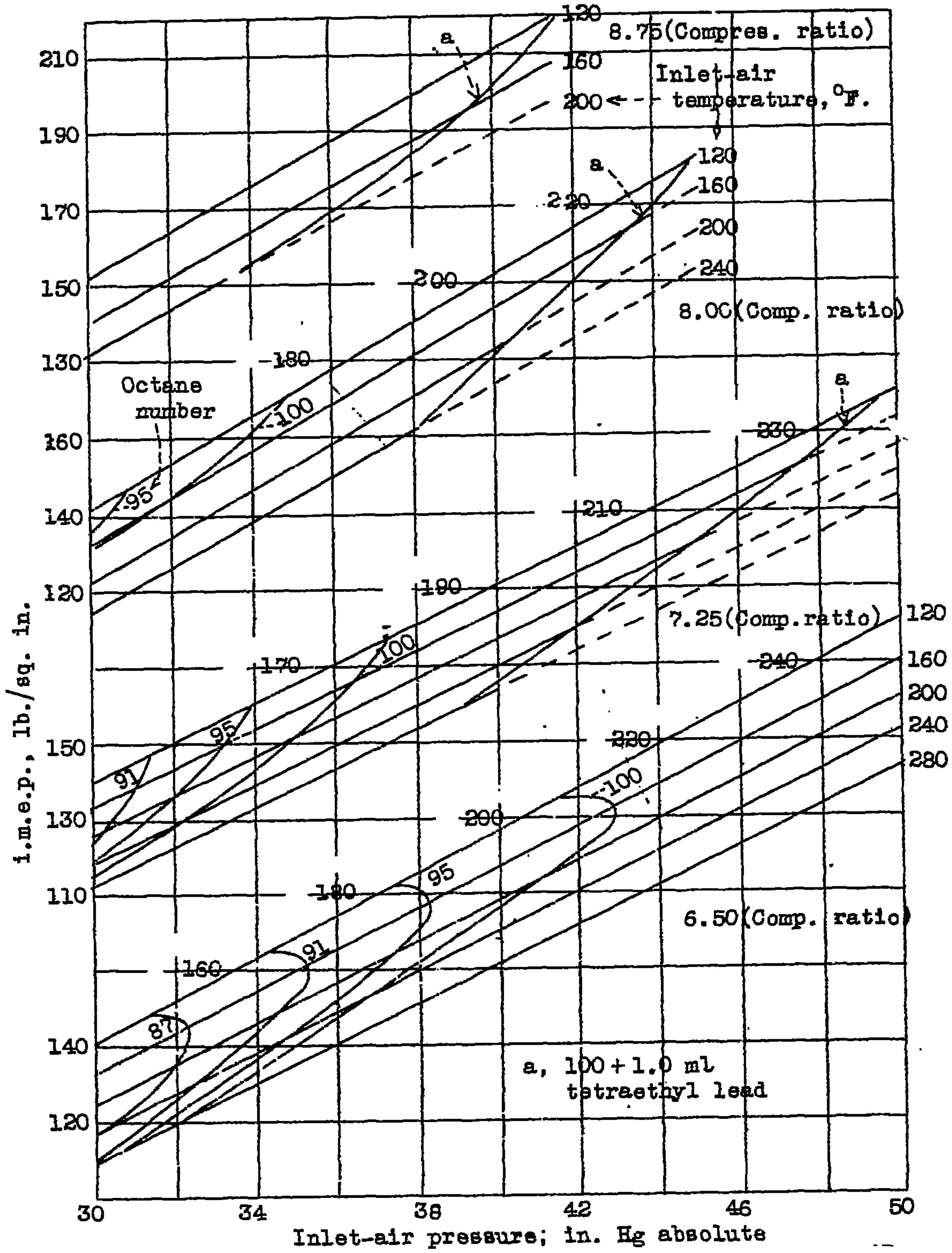


Figure 7.- Engine performance with best economy mixture(audible knock).

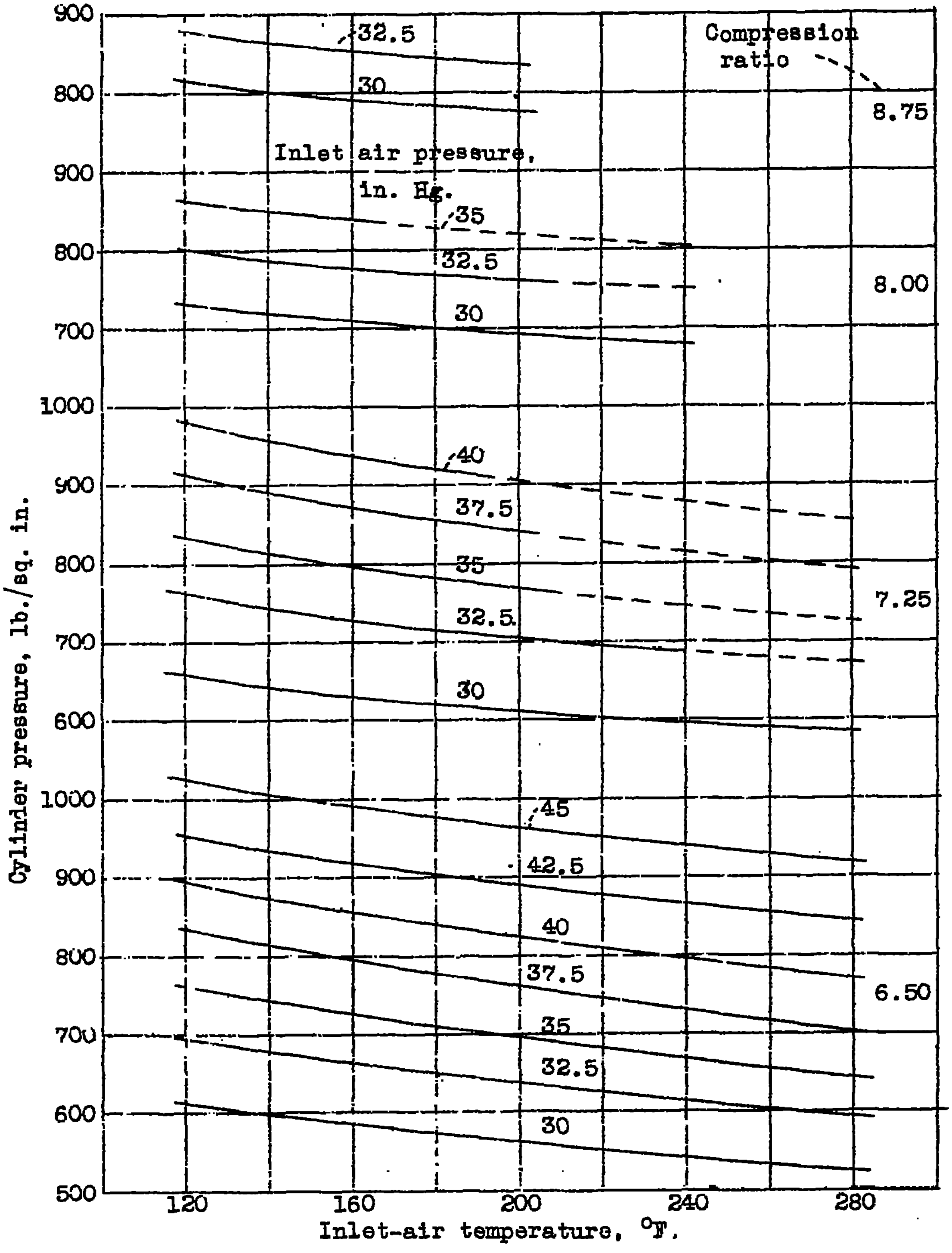


Figure 8.- Cylinder pressures with best-power mixture.

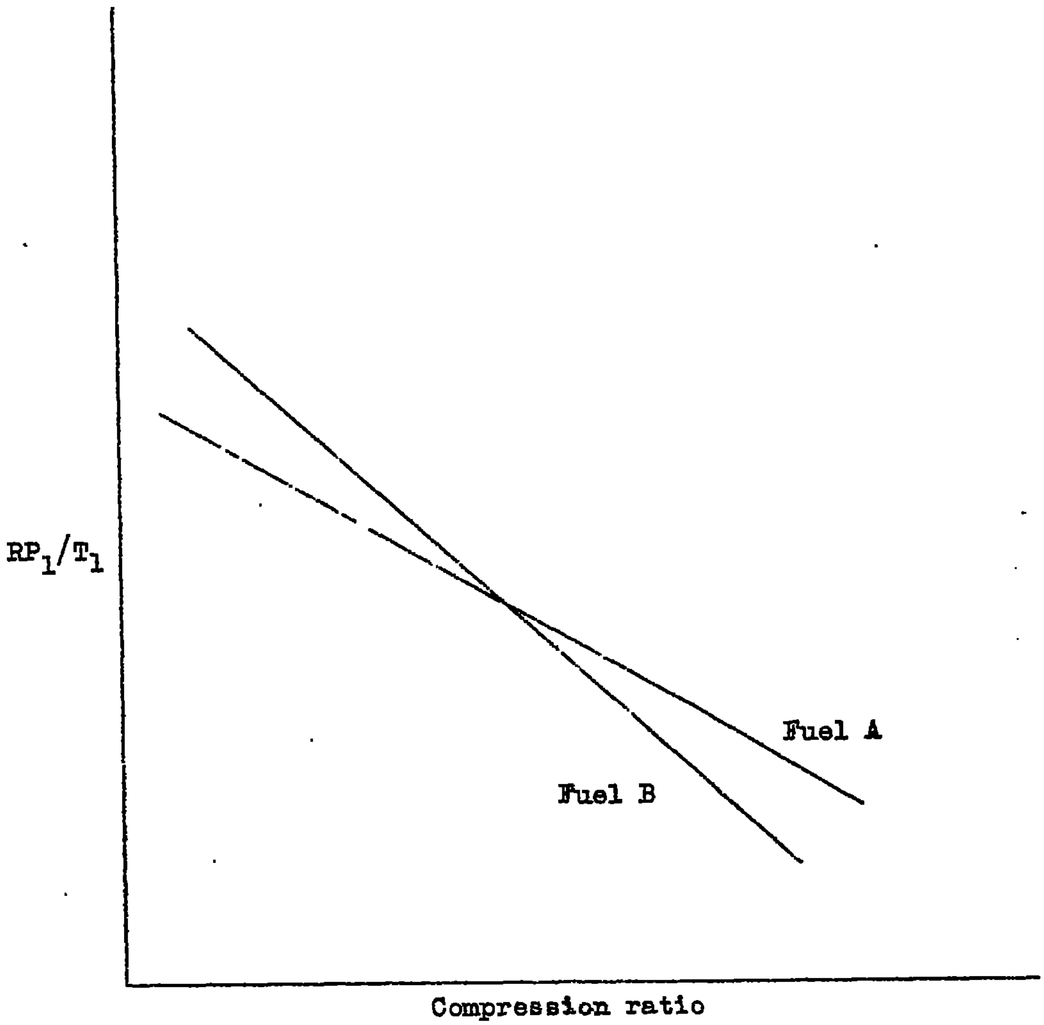
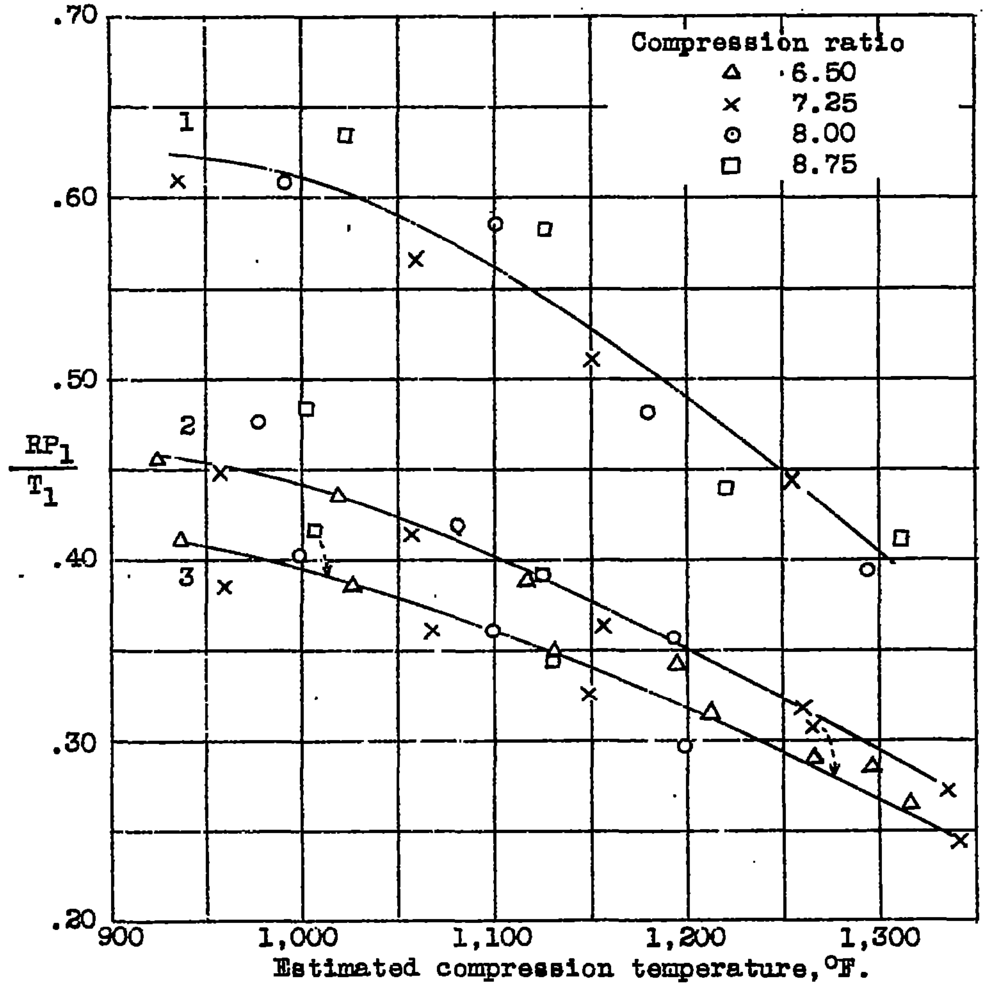
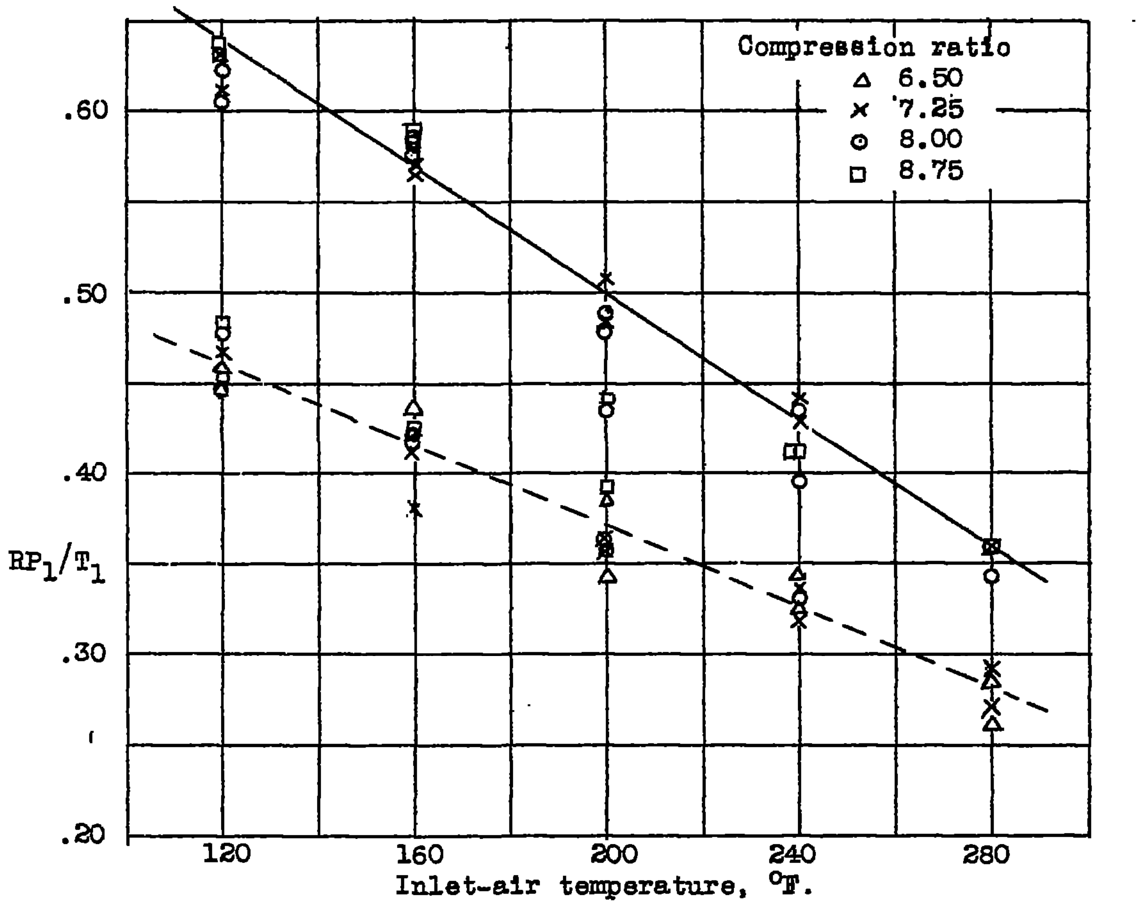


Figure 9



1. 100-octane fuel + 1ml tetraethyl lead, incipient knock
2. 100-octane fuel audible knock.
3. 100-octane fuel incipient knock

Figure 10.- Relationship between estimated compression temperature and air-density factor RP_1/T_1 for 100-octane fuel and for 100-octane fuel + 1.0 ml tetraethyl lead. Improved cooling in center of combustion chamber.



———— 100-octane fuel + 1.0 ml tetraethyl lead incipient knock, maximum power and minimum fuel consumption, improved cooling in center of combustion chamber.

– – – – – 100-octane fuel, audible knock maximum power, with and without improved cooling to center of combustion chamber.

Figure 11.- Effect of inlet-air temperature on air-density factor RP_1/T_1. Best power mixture.

Curve	Octane number	Type of knock
1	87	Audible
2	91	"
3	95	"
4	100	"
5	100 + 1.0ml tetraethyl lead	"
6	100 + 1.0ml tetraethyl lead improved cooling in center of combustion chamber.	Incipient

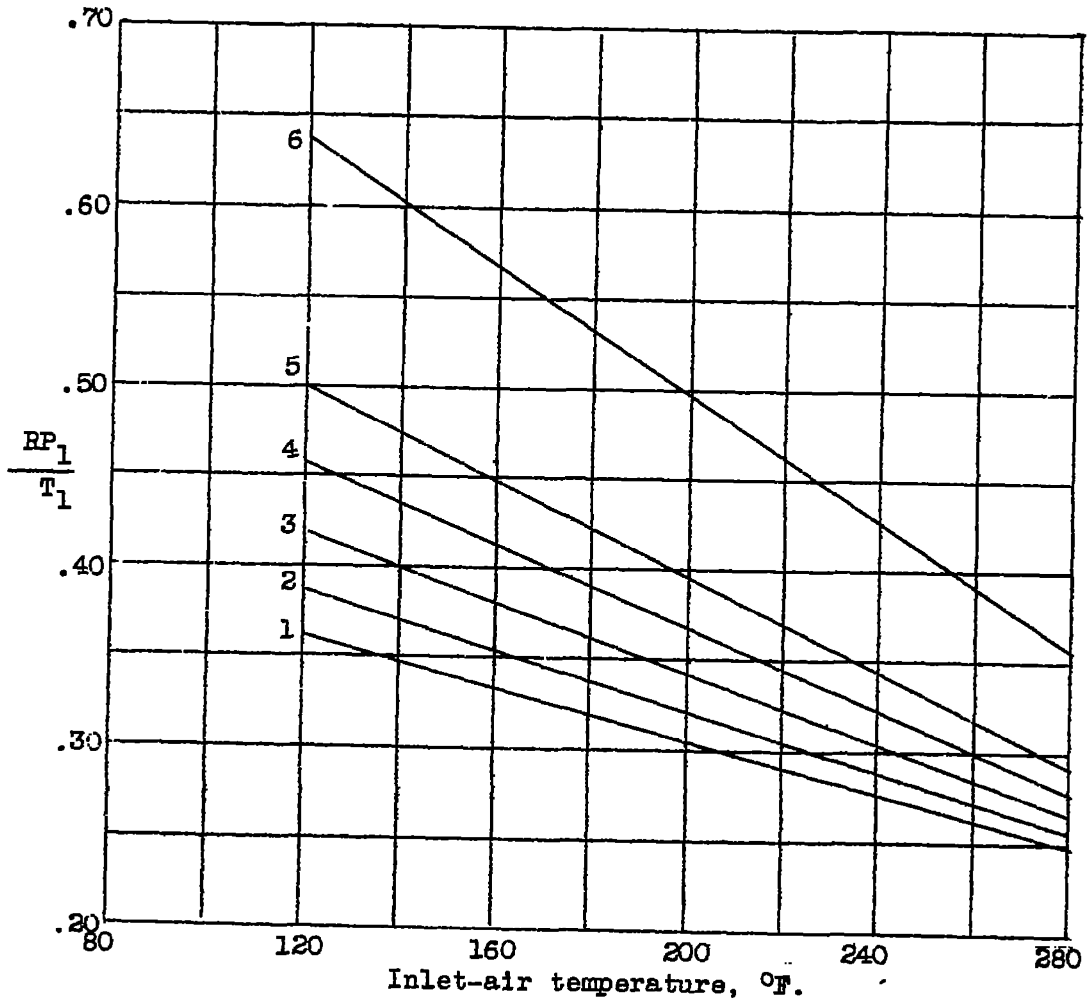


Figure 12.- Effect of inlet-air temperature on air-density factor at top center at start of detonation. Best-power mixture.

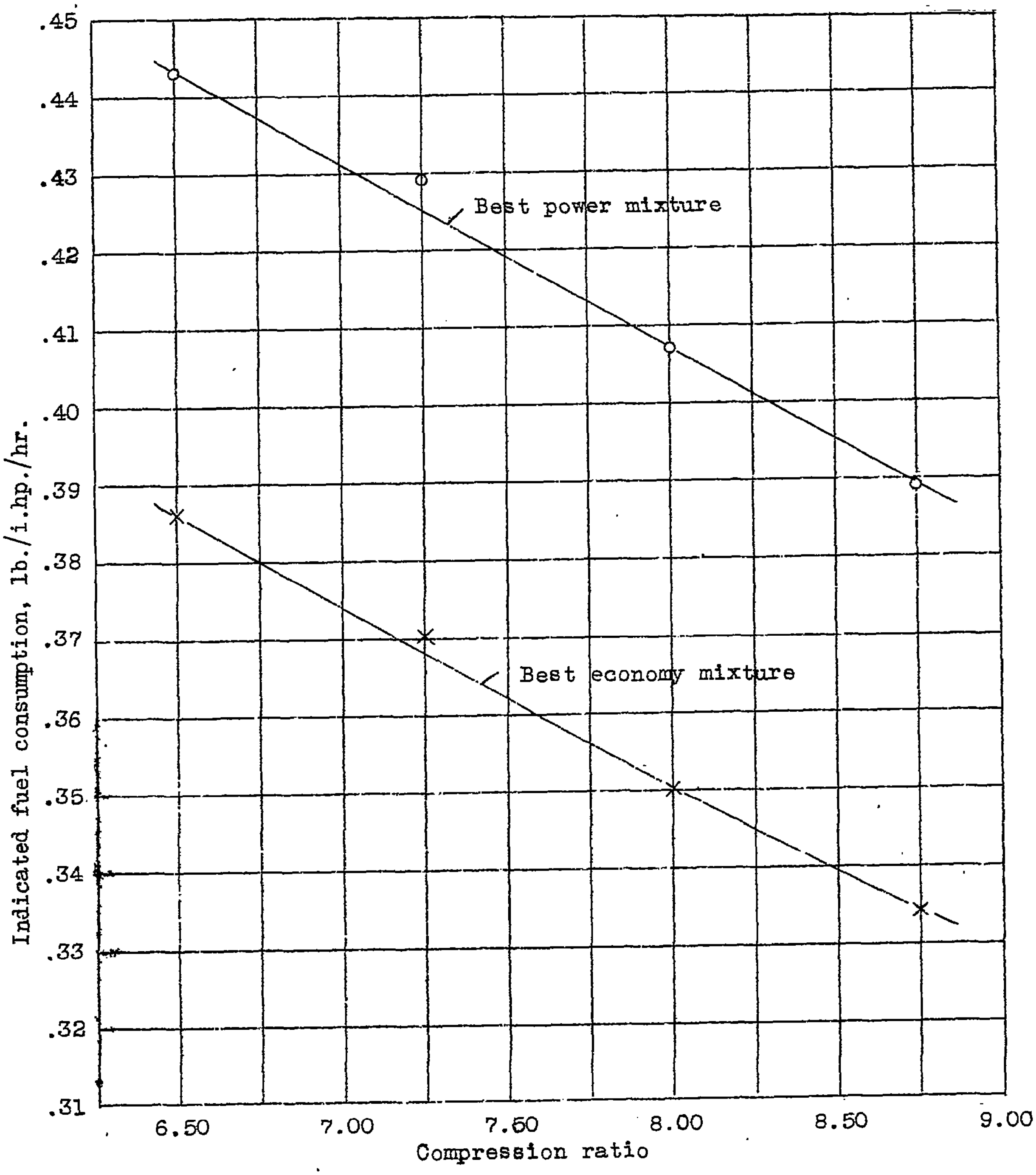


Figure 5.- Average fuel consumption for different inlet-air pressures and temperatures.

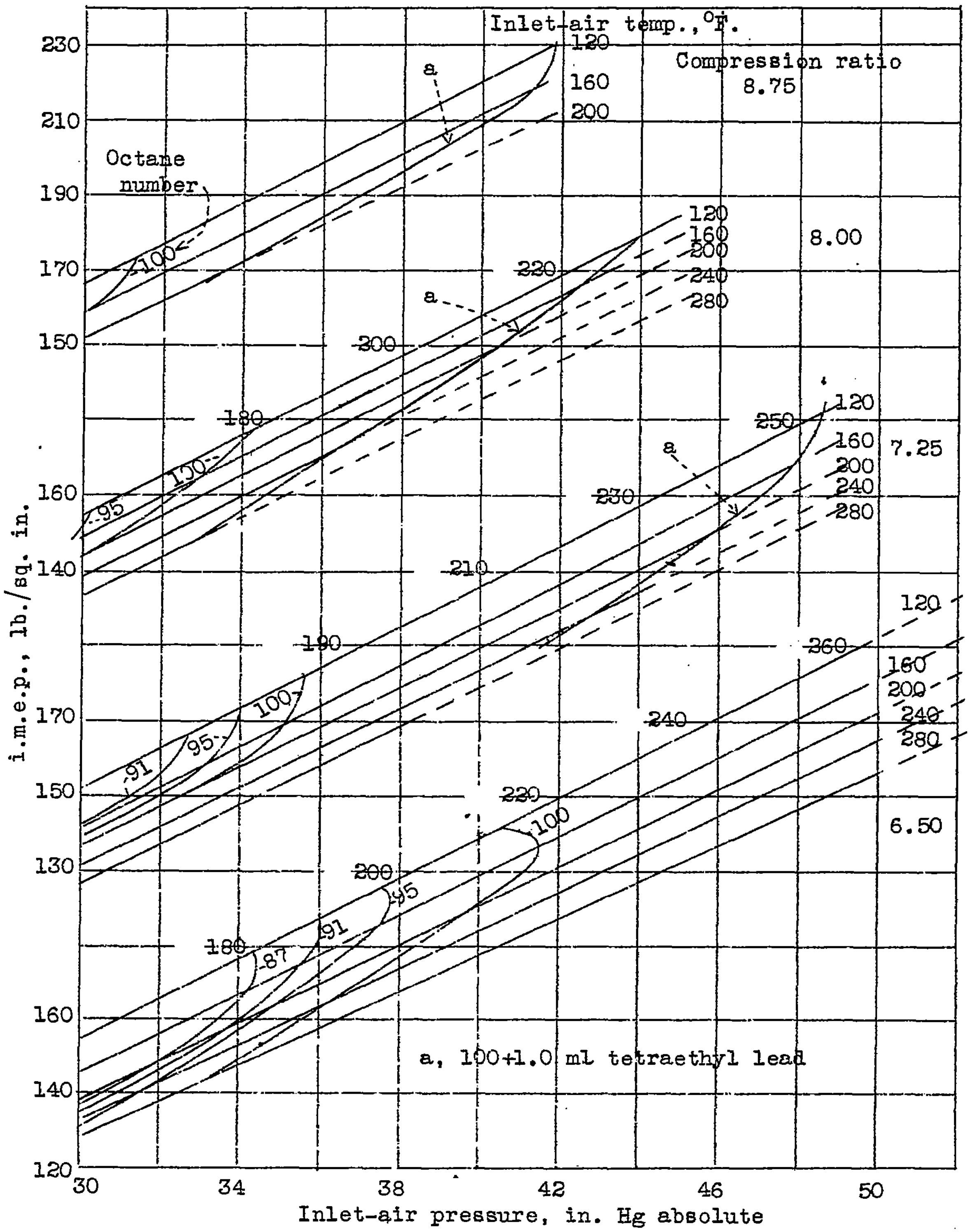


Figure 6.- Engine performance with best-power mixture(audible knock)

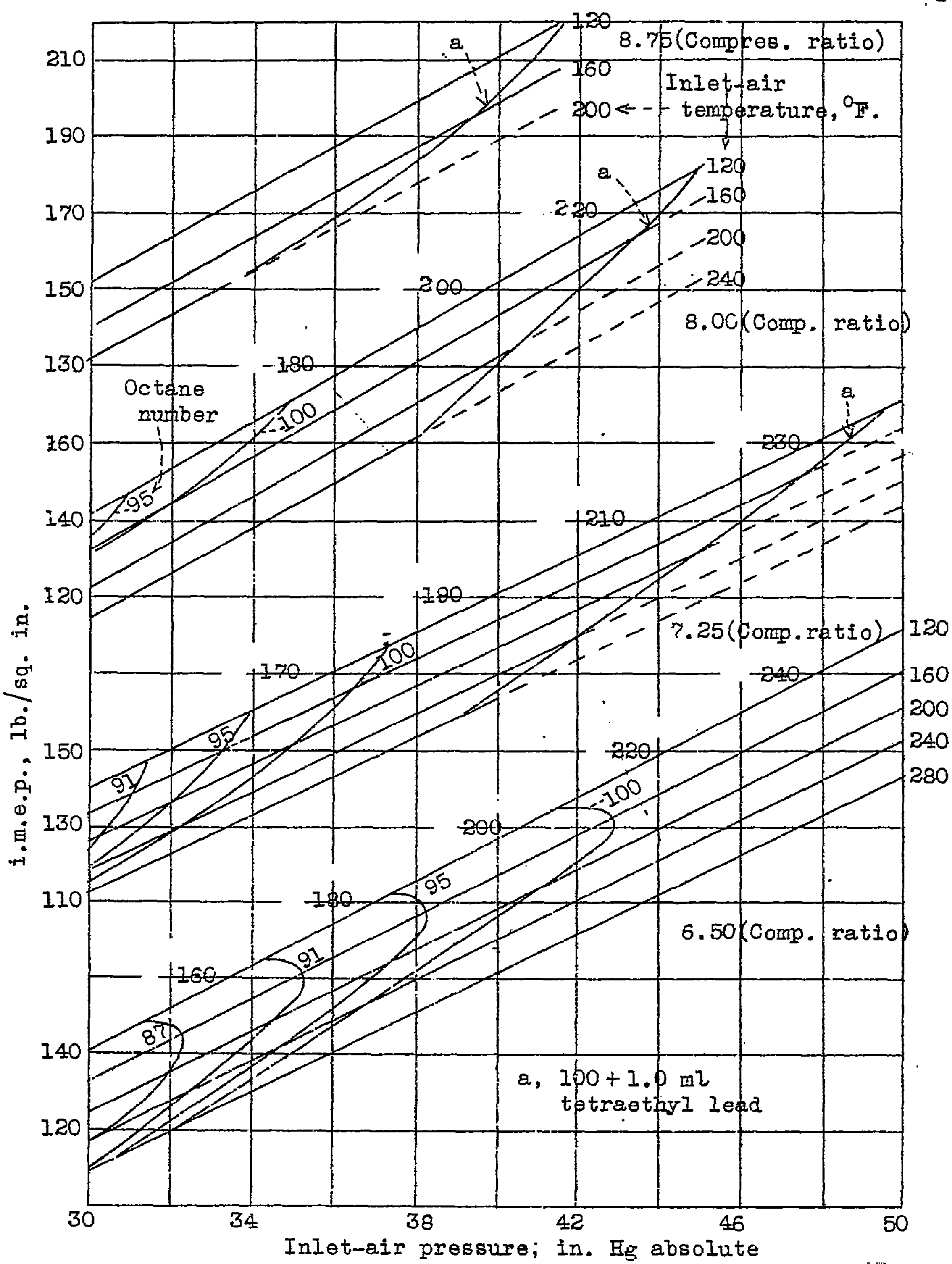


Figure 7.- Engine performance with best economy mixture(audible knock).

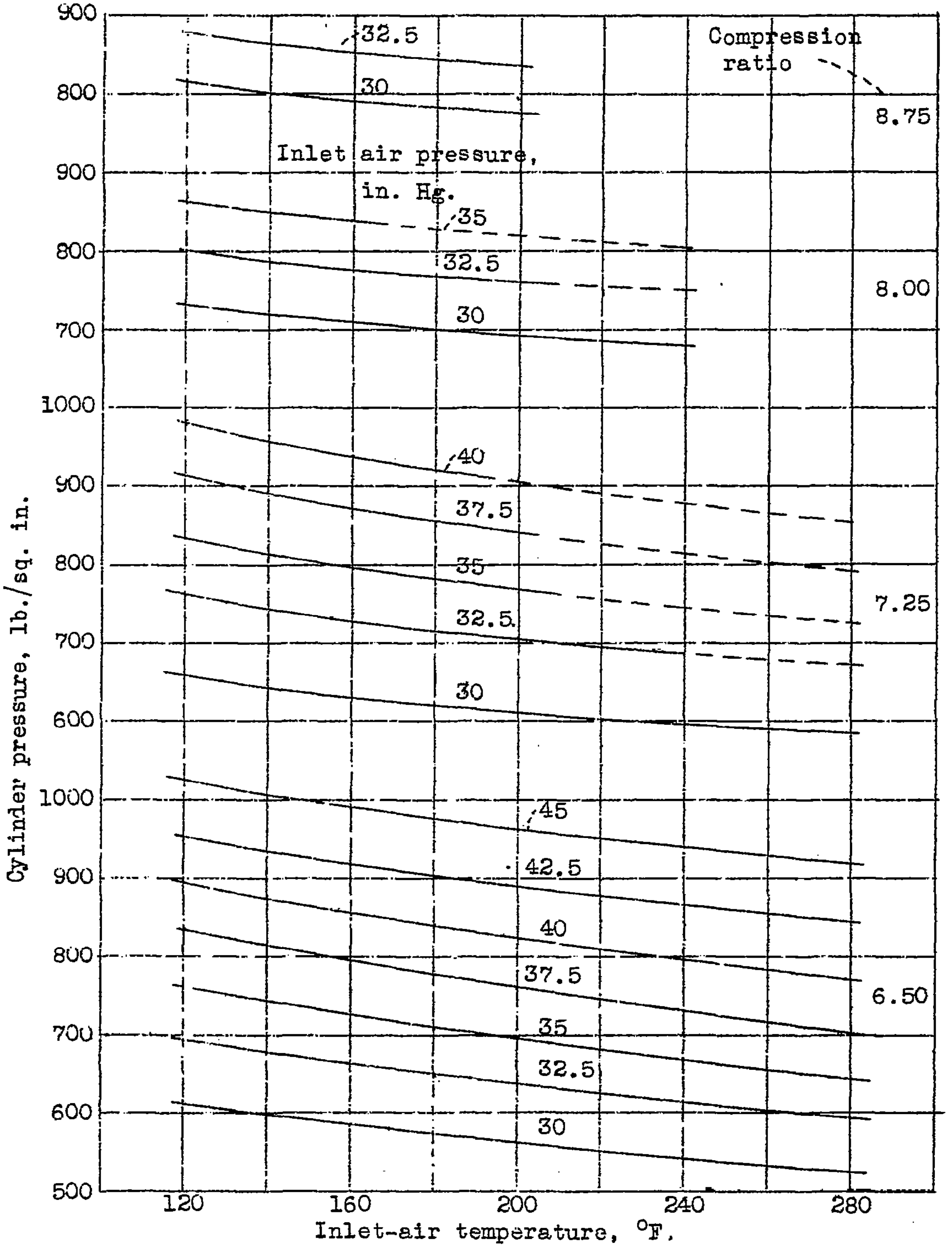


Figure 8.- Cylinder pressures with best-power mixture.

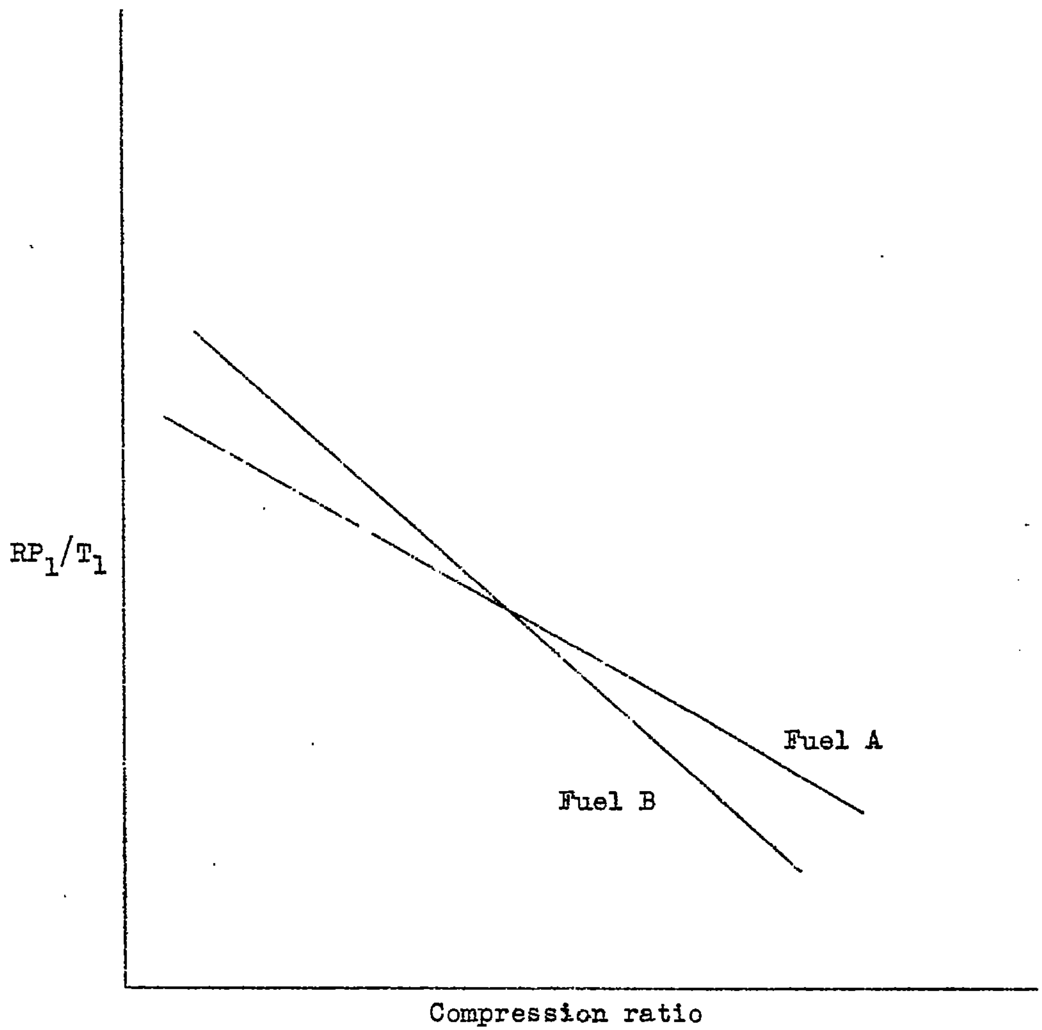
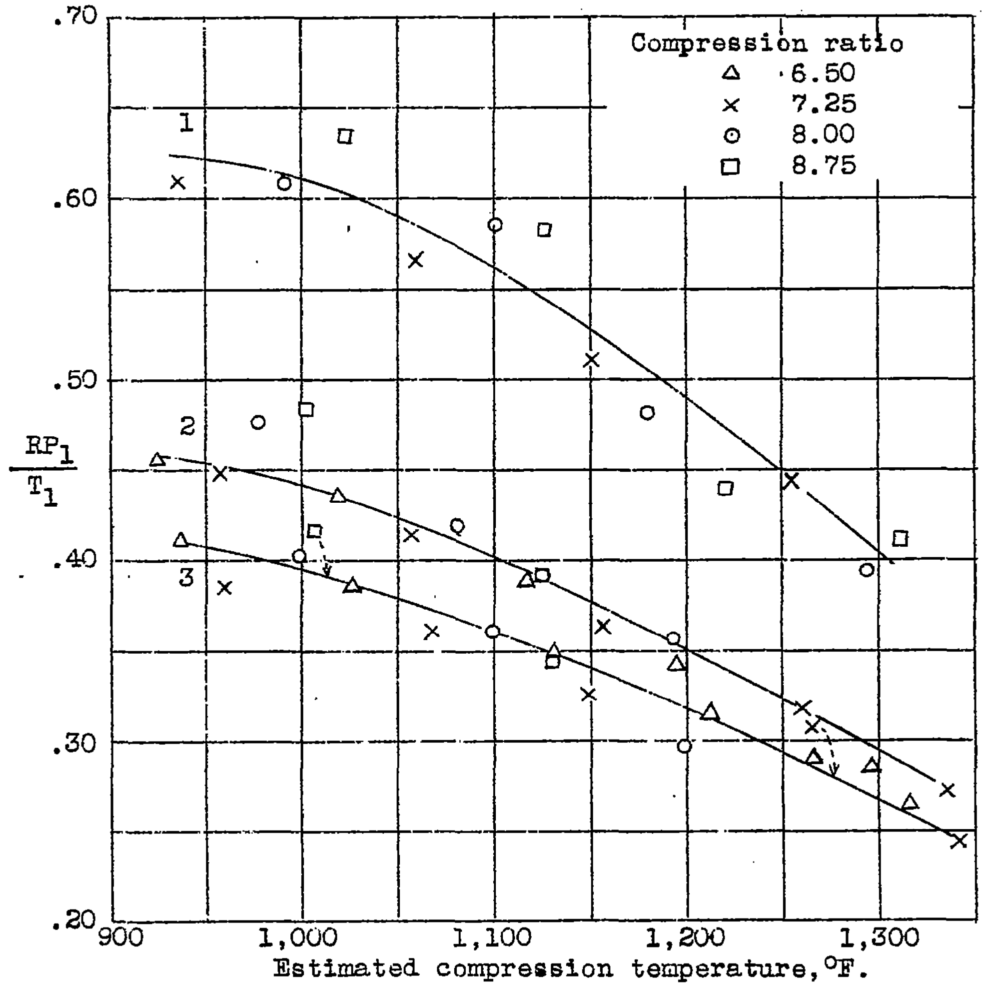
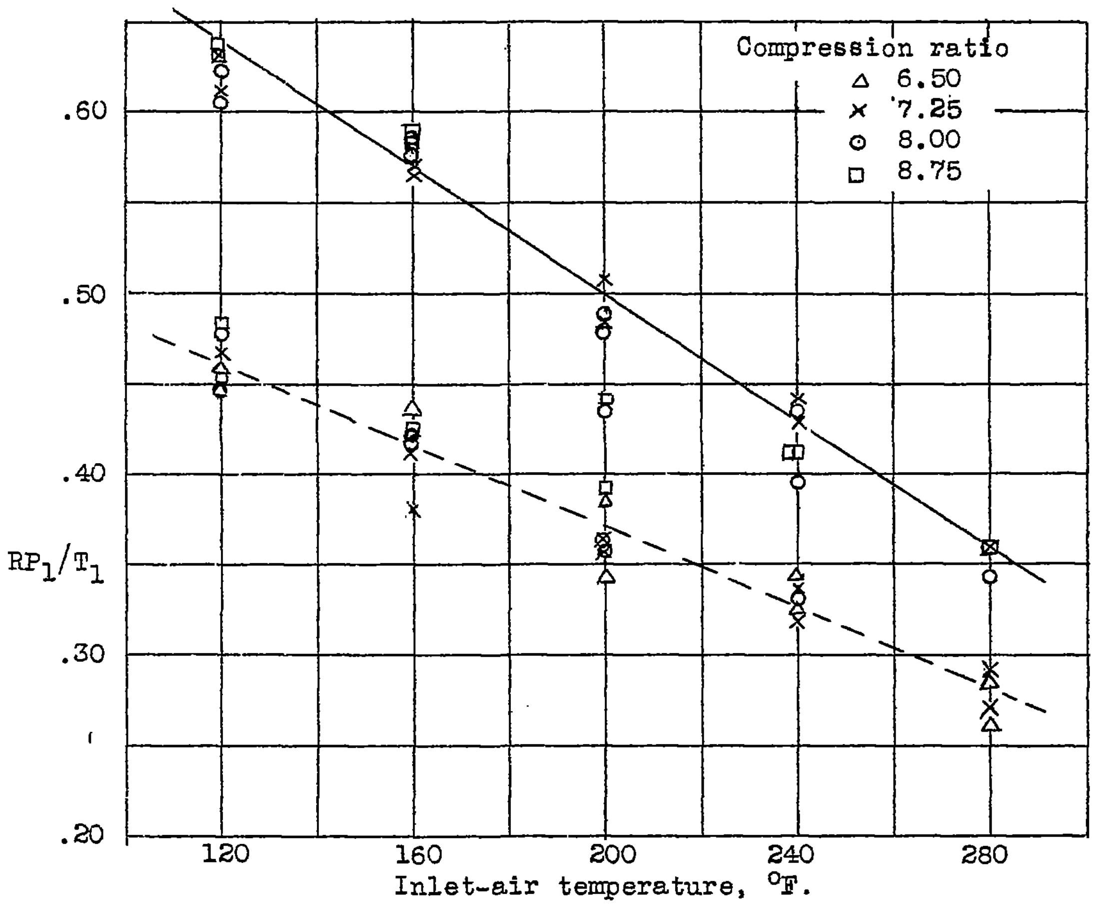


Figure 9



1. 100-octane fuel + 1ml tetraethyl lead, incipient knock
2. 100-octane fuel audible knock.
3. 100-octane fuel incipient knock

Figure 10.- Relationship between estimated compression temperature and air-density factor RP_1/T_1 for 100-octane fuel and for 100-octane fuel + 1.0 ml tetraethyl lead. Improved cooling in center of combustion chamber.



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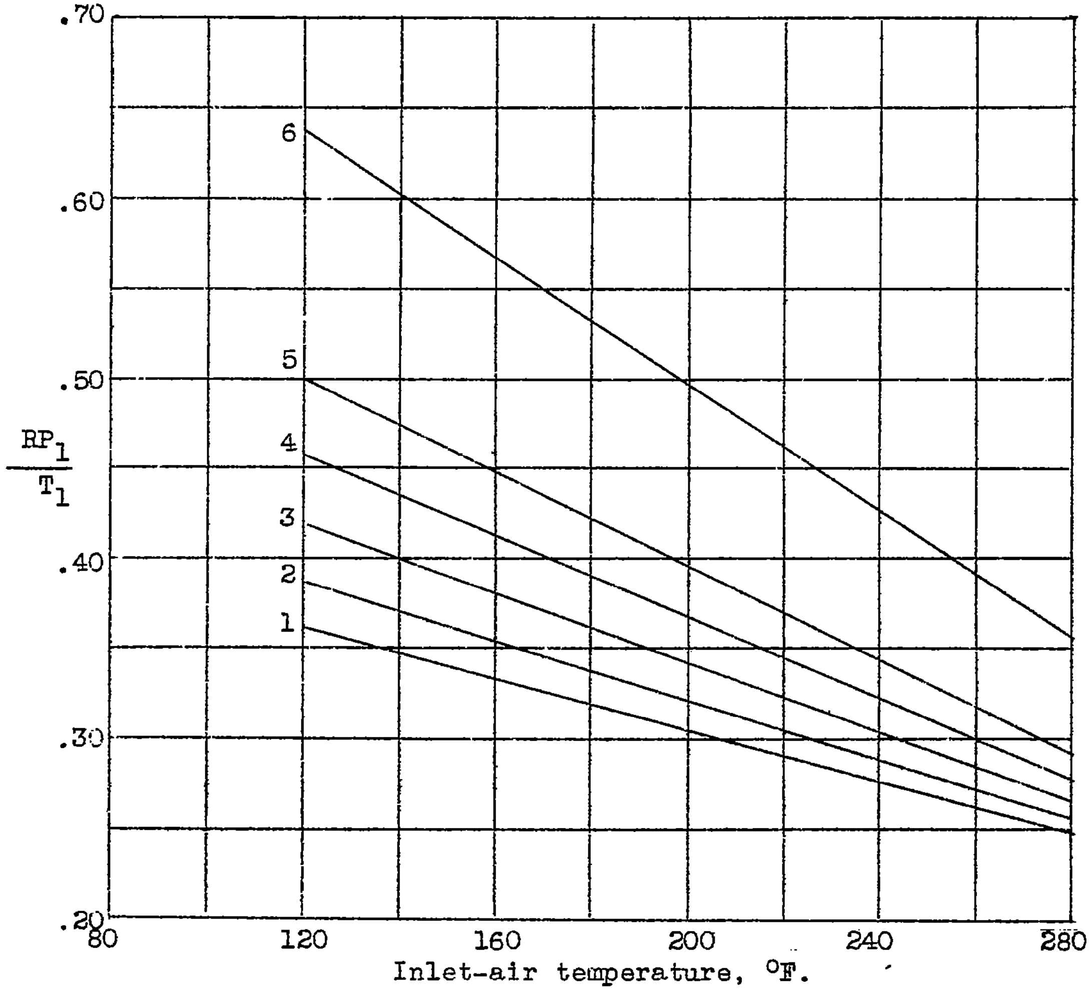

Figure 12.- Effect of inlet-air temperature on air-density factor at top center at start of detonation. Best-power mixture.