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MAXIMUM PERMISSIBLE ENGINE PERFORMANCE OF EIGHT REPRESENTATIVE FUELS OF 100-OCTANE NUMBER

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MAXIMUM PERMISSIBLE ENGINE PERFORMANCE OF EIGHT REPRESENTATIVE FUELS OF 100-OCTANE NUMBER

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SUMMARY

Knock-limit performance tests were made with eight representative fuels rated at 100-octane number by the C.F.R. aviation method. The procedure consisted of determining the maximum permissible indicated mean effective pressure as a function of the fuel-air ratio. The eight fuels were mixtures of representative blending agents and bases. One of the fuels contained 15 percent benzene. All of the fuels with the exception of one contained 3.0 milliliters tetraethyl lead per gallon.

The data show considerable difference in the maximum permissible performance of these fuels when tested in the Lycoming O-1230 cylinder. This same difference is evident in data determined with some of the fuels in a Wright G-200 cylinder, a $2^5/_8$-inch bore C.F.R. cylinder, and an Ethyl Gasoline Corporation 17.6 cylinder. The data indicate that, as the inlet-air temperature to the engine is increased, the general level of the maximum permissible performance is decreased, but the decrease is less with rich mixtures than with mixtures close to the chemically correct value. The data further show that the fuels have octane numbers, as determined in the Lycoming cylinder, the Wright cylinder, or the Ethyl Gasoline Corporation cylinder, in excess of that for S-1 reference fuel. In particular, one fuel permitted a maximum permissible indicated mean effective pressure 55 percent in excess of that permitted by S-1. The data show that the spark-plug type has no effect on the knock limit, provided that preignition or afterfiring does not occur.

The percentage of naphthenes, paraffins, or aromatics shows no specific relation to the knock levels of the different fuels. There is some indication from the data that fuel volatility is playing a part in the knock-rating curves determined for the fuels.

INTRODUCTION

At the Langley Memorial Aeronautical Laboratory during the past year the National Advisory Committee for Aeronautics has been conducting tests on the maximum permissible performance of representative fuels rated at 100-octane number by the C.F.R. aviation method (reference 1). These tests were made following the recommendation of the NACA Subcommittee on Aircraft Fuels and Lubricants. Data were recorded showing the variations in knock characteristics that occurred among eight such fuels in a full-scale single cylinder when the fuel-air ratio and the inlet-air temperature to the engine were varied. The purpose of this report is to present the results of these tests.

The National Advisory Committee for Aeronautics expresses its appreciation to the Esso Laboratories of the Standard Oil Development Company and to the Ethyl Gasoline Corporation for the use of certain data which were recorded in the laboratories of these companies and which have hitherto been unpublished. Where these data are used in this report, specific mention is made of the source.

FUELS TESTED

Eight representative 100-octane-number fuels referred to as fuels 1, 2, etc. (table I) were chosen by the Subcommittee on Aircraft Fuels and Lubricants of the National Advisory Committee for Aeronautics. All of the fuels with the exception of fuel 2 contain approximately 3 milliliters tetraethyl lead per gallon. Fuel 2 contains 6 milliliters tetraethyl lead per gallon. In tables and figures tetraethyl lead is designated TEL. The first three fuels contain a 74-octane-number base. To fuel 1 a hydrocodimer blending agent has been added. Both fuel 2 and fuel 3 have an alkylate blending agent. A comparison of fuels 1 and 6 shows the effect of the hydrocodimer blending agent with, first, the 74-octane straight run base and, second, a Houdry base. Fuels 3, 4, and 5 show the effect of the 74-octane base, the hydroformed base, or a Houdry base, respectively, in an alkylate blending agent. A comparison of fuel 8 with fuel 7 shows some of the effects of the addition of benzene.

Table II lists the properties of the base stocks and the blending agents of the first six fuels. Table III presents the characteristics of the blended fuels. The data in tables II and III were presented by the Esso Laboratories of the Standard Oil Development Company. The Houdry gasoline was supplied by the Sun Oil Company. Table IV lists the inspection data on fuels 7 and 8 presented by the Standard Oil Company (Indiana). The aromatic for fuel 8 is benzene.

Table V lists the heats of combustion and the hydrogen-carbon ratios of the eight fuels as determined at the Langley Memorial Aeronautical Laboratory. The difference between the values given in this table and those shown in table III is small. A comparison of the heats of combustion as listed in table V shows the maximum difference among the fuels to be a little less than 4 percent.

Fuels 4 and 8, both of which contain 15 percent aromatics, have the lowest heats of combustion and the lowest hydrogen-carbon ratios. Fuels 5 and 6, which have the highest percentage of paraffins, have the highest heats of combustion but not the highest hydrogen-carbon ratios.

The distillation data for the fuels are plotted in figure 1. This figure also contains the distillation curves for S-1 fuel and for S-1 + 2.0 milliliters tetraethyl lead. The saturated vapor pressures of the fuels at different conditions and the heats of vaporization of the fuels are possibly of more significance than the distillation data in estimating the mixing characteristics of the fuels.

The octane numbers of the fuels shown in table I were determined by four different laboratories according to the C.F.R. aviation method (reference 1). The octane numbers of the eight fuels vary from 99.4 to 100 +0.05 milliliters tetraethyl lead. The reference fuels were S-1 and S-1 + TEL.

APPARATUS

A Lycoming O-1230 cylinder with a standard flat-top piston was used in most of the tests. This cylinder is liquid-cooled and has a bore of 5 1/4 inches and a stroke of $4\frac{3}{4}$ inches, giving a displacement of 102.8 cubic inches. The cylinder was set up on one of the original Air Corps type universal crankcases built by the Steel Prodicts Company. A diagrammatic sketch of the set-up is shown in figure 2.

Fuels 7 and 8 were also tested in a Wright G-200 cylinder mounted on a Waukesha CUE crankcase. This cylinder has a bore of $6\frac{1}{8}$ inches and a stroke of $6\frac{7}{8}$ inches. The general set-up was similar to that shown in figure 2.

The following test conditions were maintained constant:

	Lycoming O-1230 cylinder	Wright G-200 cylinder
Engine speed, rpm	2000	2000
Spark advance, °B.T.C.	27	20
Compression ratio	7.0	7.0
Inlet coolant temperature, °F	250	---
Rear spark-plug boss temperature, °F	---	400
Oil outlet temperature, °F	165	200

TEST PROCEDURE

Knock limits.- The inlet-air pressure that caused audible knock was determined over the range of fuel-air ratios from approximately 0.05 to 0.12. The inlet pressure at each test point was reduced 7 percent below the value producing audible knock before the data were recorded, the mixture ratio and other variables being kept constant. The engine was operated for a short period at these conditions before the data were recorded. Data taken previously with this cylinder showed that the M.I.T. knockmeter indicated incipient knock at this condition of operation. Data recorded with an inlet pressure of 93 percent of that producing audible knock represent a practical operating limit. Experience has indicated that this knock level is about the maximum at which the engine can be operated for prolonged periods.

The fuel flow and the inlet-air pressure being separately controlled, it was necessary to increase each alternately in small increments as the knock point was approached in the extremely lean mixture range. Under these conditions the mixture ratio was found to be very critical. At a slightly leaner mixture, the engine would misfire and, at a slightly richer mixture, severe knocking was encountered. The reason for these phenomena is readily understood from figure 3. The dotted line shows the manner in which the fuel flow and the inlet-air pressure were varied in bringing the engine to the knock point. The final adjustment in each case was made by increasing the fuel flow slightly until audible knock was encountered. When the inlet pressure was decreased 7 percent to reach stable operating conditions, it was found necessary to lower the fuel flow first. If the inlet pressure was lowered first, violent knocking would result, as is apparent from figure 3. In many cases, when the knock point was being approached at extremely lean mixtures, the engine would suddenly knock very severely for two or three cycles. For very lean mixtures, light knocks could be occasionally heard at the inlet pressure of 93-percent audible knock, probably because of variation in the mixture strength.

To determine the knock point on the rich side of the curve, the fuel flow was set and the inlet pressure was increased until knock occurred. This method is illustrated by the dashed line in figure 3. In this case it was necessary to lower the inlet pressure first in obtaining the condition of 93-percent audible knock.

<u>Afterfiring</u>.- Afterfiring was checked by cutting the ignition. Particular care was exercised to avoid hot surfaces in the exhaust pipe because their presence might cause ignition after the switch was cut.

<u>Spark advance</u>.- The spark advance in these tests was chosen somewhat arbitrarily. Data were first recorded showing the relation between spark advance and the power output with S-1 fuel. As the variation of power with spark advance was quite small in the maximum-power range, retarding the spark to a 1-percent drop in power was necessary to give a specific value of the spark advance as shown in figure 4. Several of the other fuels were also tested for the effect of spark advance, and the results showed that the spark advance for 1-percent drop from maximum power was within 1° of that for S-1.

Engine friction.- The engine friction was determined by motoring the engine at the desired speed and engine temperatures. Readings were taken of the brake load for various inlet pressures. Care was taken to maintain the oil temperatures at the same value in the friction runs as in the fuel-test runs. A curve was plotted of friction mean effective pressure against inlet pressure, and the values of indicated mean effective pressure were calculated by adding the friction mean effective pressure to the brake mean effective pressure. Friction curves were obtained approximately every 20 hours of engine operation. Sample curves are shown in figure 5. The variation between the two curves represents about the maximum that occurred.

During the tests of fuel 7, the engine was disassembled. When it was reassembled, the data on S-1 fuel did not check the previous readings. For this reason, tests to determine variation of fuel-air ratio with maximum permissible indicated mean effective pressure were repeated on S-1 and S-1 + 1.0 milliliters tetraethyl lead so that the results of the second test on fuel 7 could be compared with S-1. Because the first tests with fuel 8 were limited by afterfiring, tests on this fuel were also repeated with a different spark plug, which eliminated the afterfiring and permitted the knock limit of fuel 8 to be reached.

The electrodes of the spark plugs used in the tests on the Lycoming cylinder were recessed approximately 7/16 inch from the inner surface of the combustion chamber. In the lean region, that is, at fuel-air ratios of less than approximately 0.067, the firing was irregular. Subsequent tests made with this cylinder, in which the electrodes were flush with the inner surface of the combustion chamber, have shown that with this arrangement firing in the lean region is more regular.

Accuracy.- The reproducibility of the data was not checked for all of the fuels. Checks were made each day on the knock limit of S-1 at a fuel-air ratio of 0.07. If the maximum permissible inlet pressure did not check within ±1.0 inch of mercury, the engine was examined for possible causes of the discrepancy. In one case, as mentioned previously, a check could not be obtained. The tests of the fuel in question were repeated together with tests of the reference fuels. Specific mention of these tests is made later in the report.

All values of inlet pressure are given in inches of mercury, absolute.

TEST RESULTS

Maximum permissible indicated mean effective pressure.- In the presentation of the knock characteristics of these eight representative 100-octane-number fuels, it is advisable to compare the results obtained with the data recorded for the S-1 reference fuels.

An examination of the results for S-1 fuel and S-1 plus tetraethyl lead (fig. 6) at the two inlet-air temperatures shows, as is to be expected, that the maximum permissible indicated mean effective pressure at any one fuel-air ratio decreased as the inlet-air temperature was increased. There is also a marked difference in the general shape of the curves. At the lower inlet-air temperature, the curves tend to reach a maximum value of the maximum permissible indicated mean effective pressure at a fuel-air ratio of approximately 0.090. At the higher inlet-air temperature, the curves in general tend to show a continuous increase in the maximum permissible indicated mean effective pressure as the mixture is enriched or, if a maximum occurs, it occurs at a richer mixture than is the case at the lower inlet temperature. This difference in the shape of the curves is not clearly understood. A possible explanation is that vaporization of the fuel is influencing the reaction.

In the lean region the maximum permissible indicated mean effective pressure continued to decrease in all of the cases except one. This continued decrease is in contradiction to results presented at other laboratories. For instance, in the tests made on the C.F.R. engine by the C.F.R. group working on the proposed tentative supercharged method, as the mixture ratio was leaned below approximately 0.065, the maximum permissible indicated mean effective pressure increased. A similar increase for lean mixtures will be presented later in this report for tests with the Wright G-200 cylinder. This difference in the shape of the curves is attributed to the recessed spark plug used with the Lycoming cylinder. Tests now being conducted on this cylinder with the spark-plug electrodes flush with the inner surface of the combustion chamber show that, with this arrangement, the lean mixture operation is improved and the maximum permissible indicated mean effective pressure passes through a minimum at a fuel-air ratio of about 0.065. This change is caused by the position of the spark-plug electrodes and not by the spark-plug type.

Because it was necessary to change the type of spark plug to prevent afterfiring with fuel 8, tests were run with S-1 + 3.0 milliliters tetraethyl lead to determine whether the spark plug had any unforeseen effect on the knock limit of the fuel. Results presented in table VI show that changing the type of spark plug or installing a thermocouple in the center electrode of the spark plug did not affect the maximum permissible inlet pressure or the maximum permissible indicated mean effective pressure.

Figures 7 and 8 show the results for the eight representative 100-octane-number fuels. At both inlet-air temperatures the maximum permissible indicated mean effective pressure reached a maximum: at a fuel-air ratio of approximately 0.080 at the lower inlet-air temperature and at a fuel-air ratio of approximately 0.090 at the higher inlet-air temperature. The fact that these curves of maximum permissible indicated mean effective pressure decline in the rich region - whereas such was not the case with the curves for the reference fuels - means that the octane number of these fuels as determined on the Lycoming cylinder will decrease in the rich region. Whether this decrease applies to the full-scale performance of these fuels is not known. If this difference in the shape of the curves is the result of the fuel volatility, and the data for drawing such a conclusion are admittedly incomplete, it is logical to expect that this volatility will cause a difference between multicylinder-engine and single-cylinder-engine results.

In a multicylinder engine the fuel is first carbureted and then passed through the supercharger. If a two-stage supercharger is used, the fuel is carbureted between the two stages. While the fuel is passing through the supercharger, it is being mixxd with the air. This mixing time is not available in single-cylinder set-ups, in which the injection nozzle or the carburetor is mounted close to the inlet valve of the engine. It is quite possible that in order to reproduce full-scale results it will be necessary to place the carburetor or the fuel-injection nozzle at some distance from the engine so that additional time will be permitted to vaporize the fuels. The data show the need of more information on this subject if fuels are to be properly rated.

The results shown for fuel 8 in figure 7(b) by the solid curve are those for which in most cases the performance of the fuel was limited by afterfiring. When the spark plug was changed to a cooler running plug, this afterfiring was eliminated and the results shown by the dashed curve were recorded. As mentioned in the test procedure, when this second run was made with fuel 8, it was necessary to repeat the data on the reference fuels and, at the same time, a second series of data was recorded for fuel 7. This second test for fuel 7 is also shown as the dashed curve in figure 7(b). Both curves for fuel 7, although differing in actual values, show quite good agreement in regard to the general shape.

Figure 8 shows the data for fuels 7 and 8 determined in the second series of tests together with those for the reference fuels. Figure 8 also shows data on the indicated specific fuel consumption determined in these runs. A single curve can be drawn to represent the indicated specific fuel consumption indicating that the addition of 15 percent benzene caused no measurable increase in the specific fuel consumption.

The exact significance of the afterfiring with fuel 8 is not clear. The afterfiring limit at the higher inlet-air temperature placed this fuel below the other fuels for fuel-air ratios of less than 0.08. The data indicate that afterfiring would not occur at fuel-air ratios greater than approximately 0.095. In the second series of tests, in which the afterfiring was eliminated, the performance of this fuel was entirely satisfactory. Its very marked improvement over the other fuels is noticeable. How much of the improvement in fuel 8 over fuel 7 results from the addition of the benzene and how much of the improvement results from the increase of the phosphoric acid iso-octane content is not clear.

<u>Maximum permissible inlet pressure and maximum cylinder pressures</u>.- The indicated mean effective pressure developed at incipient knock is a function of both the mass of air inducted per cycle and the fuel-air ratio. The inlet pressure at any one inlet temperature is a measure of the mass of air inducted into the engine. The relations between the fuel-air ratio and the maximum permissible inlet pressures are therefore of interest.

Figure 9 presents the recorded maximum permissible inlet pressures and the corresponding maximum cylinder pressures as functions of fuel-air ratio. At the lower inlet-air temperature the maximum permissible inlet pressure first decreased and reached a minimum at a fuel-air ratio of approximately 0.065 to 0.07; although with fuel 2, at the lower inlet-air temperature the maximum permissible inlet pressure continued to decrease, reaching a minimum at a fuel-air ratio of about 0.105. With fuels 1, 3, 4, 5, 6, and 7 at the lower inlet-air temperature the permissible inlet pressure reached a maximum at a fuel-air ratio of approximately 0.09 and a second minimum at a fuel-air ratio of approximately 0.11. Again, the significance of these maximums and minimums is far from clear. At the higher inlet-air temperature, although the minimums at a fuel-air ratio of approximately 0.065 continued to be clearly indicated, the maximums in the rich range either disappeared or became less marked. Again, vaporization of the fuel is suggested as a possible cause, although the course of the combustion as it is possibly affected by the inlet-mixture temperature must not be overlooked. Figure 9(c) presents the results for the second series of tests on the reference fuels and on fuels 7 and 8.

<u>Specific fuel consumptions</u>.- In figure 10 it is seen that at an inlet-air temperature of 250° F, within the limits of experimental error, a single curve represents the indicated specific fuel consumption data for all eight fuels and for the S-1 fuels. The indicated specific fuel consumptions at the lower inlet-air temperature were the same as those at the higher temperature, within experimental error. (See tables VII and VIII.) That is to say, any differences in the indicated specific fuel consumptions that resulted from a difference in the heat contents of the fuels were within the experimental error. The data for brake specific fuel consumption shown in figure 10 scattered considerably. The reason for this scatter is that the friction mean effective pressure is a function of the inlet pressure, as shown in figure 5.

Because the brake specific fuel consumption is not dependent on the fuel-air ratio alone, the use of brake specific fuel consumption should be avoided as much as possible in plotting fuel-rating curves. The situation is further complicated when single-cylinder data are compared with multicylinder data for, in the full-scale engine, the supercharger is driven by the engine. A possible method of overcoming the difficulty of determining the indicated performance on the full-scale engine is to plot the curves as maximum permissible air quantity inducted in pounds per cycle per cubic inch of engine displacement as a function of fuel-air ratio.

In figure 11 the indicated specific fuel consumption is plotted as a function of fuel-air ratio divided by the fuel-air ratio for complete combustion. Again, the variation in the results caused by the difference in the heats of combustion is apperently within the experimental error.

Comparison of results with those recorded for other engines.- In figure 12 are shown the knock-limit results recorded at the Esso Laboratories of the Standard Oil Company of New Jersey for six of the eight representative 100-octane-number fuels. In general, the curves are similar to those determined on the Lycoming cylinder. In figure 13 are shown the Esso data in comparison with the NACA data plotted on the basis of maximum permissible air quantity inducted per cycle per cubic inch of engine displacement as a function of fuel-air ratio. When the data from the Esso Laboratories are compared with the NACA data for an inlet-air temperature of 250° F, the curves for the three fuels listed check quite well. There is no justification for using the NACA data at the inlet-air temperature of 250° F instead of the inlet-air temperature of 150° F, which is more closely in accord with the Esso Laboratories conditions, except that there seems to be better agreement of the NACA data if the higher temperature is used. The data indicate that good correlation can be obtained between different engines under specific operating conditions. The operating conditions required to compare the data from one engine with those from a second may not, however, be the same as those required to compare data from the first engine with data from a third engine.

Figure 14 presents data determined at the NACA laboratories on a Wright G-200 cylinder. In all cases the performance was limited by knock, no afterfiring being recorded. The procedure in determining these data on the G-200 cylinder was the same as that on the Lycoming cylinder, with the exception that, in the Wright G-200 setup, the engine operators were in a separate room from the engine. The knock was listened to by means of a microphone hung over the engine and attached to earphones in the operators' compartment.

The curve for indicated specific fuel consumption (fig. 14) checks reasonably well with the corresponding curve recorded for the Lycoming cylinder for mixtures richer than 0.055.

When the fuel-air ratio was decreased below a value of 0.065 on the G-200 cylinder, the maximum permissible indicated mean effective pressure increased in contradiction to the results recorded with the Lycoming cylinder.

In general, the effects of changing the inlet-air temperature were the same in the Wright G-200 cylinder as in the Lycoming O-1230 cylinder (fig. 15).

Figure 16 presents data from the Ethyl Gasoline Corporation 17.6 engine (17.6 cu in. displacement) recorded by the Ethyl Gasoline Corporation on NACA fuels 7 and 8 and on S-1 and S-1 plus tetraethyl lead. Figure 17 presents the same data plotted with fuel-air ratio as the abscissa. The fuel-air ratios in this case were estimated because air consumption data were not recorded. This estimate was made in the following manner: Data were presented by the Ethyl Gasoline Corporation (not included herein) for the maximum permissible boost pressure for S-1 and S-1 plus tetraethyl lead up to values of 6 milliliters per gallon. These data were for the maximum knock mixture, that is, the mixture ratio which gave the highest thermal-plug reading at a constant inlet pressure. Based on the data presented in this report, this fuel-air ratio is assumed to be 0.07. From this assumption and the indicated specific fuel consumption recorded in the Ethyl Gasoline Corporation tests, the air, in pounds per hour, inducted into the engine as a function of the boost pressure was estimated. It was then further assumed that this curve of boost pressure against air flow did not vary with fuel-air ratio. Although this assumption is not exact, its accuracy is probably sufficient for the present purpose. The variation between the exact values of fuel-air ratio and these estimated values is indicated by the spread of the data for specific fuel consumption as a function of fuel-air ratio, shown in figure 17, and possibly in the spread of the curves of indicated specific air consumption, although these curves might lie in the relative positions shown because of the difference in the hydrogen-carbon ratios and the heats of combustion of fuels 7 and 8.

The curves of maximum permissible inlet pressure as a function of indicated specific fuel consumption (fig. 16) show a similarity between the curves for the S-1 fuels that is not present for the other two fuels. In the S-1 fuels the curves incline as the mixture ratio is increased at a more or less constant rate until the mixture ratio reaches exceedingly rich values. In these curves of maximum permissible inlet pressure the curve does not pass through the points to the same extent as the curves drawn for the maximum permissible indicated mean effective pressure but is faired to give a smooth curve. Curves for fuels 7 and 8 show first a rapid increase in the permissible pressure as the mixture is enriched and then a marked decrease in the slope of the curve representing the experimental data, the slope of the line in this region being less than that for the S-1 fuel. As the mixture is enriched beyond a fuel-air ratio of 0.10, the curves incline more rapidly. The sharp increase in the maximum permissible inlet pressure in the extremely rich mixtures is quite marked.

The general relation of the curves for the two representative 100-octane-number fuels as compared with the S-1 fuels is similar to that obtained in the NACA tests. In each case fuel 7 over the range of fuel-air ratios between 0.060 and 0.100 has a relative knock value about the same as that for S-1 + 1.0 milliliter tetraethyl lead; and, although the data are not shown on the Lycoming cylinder for S-1 + 3.0 milliliter tetraethyl lead in figure 8, it is estimated from figures 6 and 8 that the curve for fuel 8 would show the same similarity in magnitude to the curve of S-1 + 3.0 milliliters tetraethyl lead as do the curves for fuel 8 and S-1 + 3.0 milliliters tetraethyl lead as recorded on the Ethyl Gasoline Corporation 17.6 cylinder. The decrease in permissible indicated mean effective pressure in the rich region that is shown in the results presented in figures 16 and 17 is not accompanied by a decrease in either the permissible inlet pressure or the estimated permissible air quantity inducted. In fact, the air quantity inducted, as estimated from the inlet pressure, continues to increase as the fuel-air ratio is increased. This increase is not sufficiently rapid to offset the drop in indicated mean effective pressure that occurs with rich mixtures and, for this reason, the curves of indicated mean effective pressure reach a maximum at fuel-air ratios of about 0.10.

COMPARATIVE OCTANE NUMBER OF FUELS TESTED AS DETERMINED ON FULL-SCALE CYLINDERS

The goal of rating fuels is to insure that all fuels of the same rating will have the same relative knock characteristics in all engines, regardless of just what the actual performance is. Admittedly, in the present state of knowledge of fuel rating, this goal has not been achieved. With its present inadequacies the octane-number method of rating fuels has, however, been quite advantageous to the development of aircraft engines and aircraft fuels. In the foregoing section of this report it has been pointed out that, although each of the eight representative fuels tested had an octane number of 100 by the C.F.R. aviation method, the performance of the fuels in the different cylinders and under the different conditions of operation presented considerable variation. The most important factor to determine in relation to the fuel rating is the variation in the data obtained for any one fuel under the different conditions of the tests and the variation between the fuels. In the presentation of an analysis of this variation, the fuels are compared relative to S-1, that is, by octane number.

Comparative performance of S-1 plus tetraethyl lead.- In table VII are listed the maximum permissible indicated mean effective pressures recorded with S-1 plus different quantities of tetraethyl lead at the two inlet-air temperatures tested on the Lycoming cylinder. Table IX presents data for the second run on the Lycoming cylinder for S-1 and S-1 + 1.0 milliliter tetraethyl lead. Immediately beneath the values of indicated mean effective pressure are given the relative values of the indicated mean effective pressures with respect to S-1 at the same engine operating conditions and at the same fuel-air ratio. These data are plotted in figure 18 so that the values at the two different inlet-air temperatures can be compared. Figure 18(a) shows the curves for leaded S-1 at an inlet-air temperature of 250° F as determined in the first series of runs, together with the curve for S-1 + 0.5 milliliter tetraethyl lead at the inlet-air temperature of 150° F. In figure 18(b) are the three curves recorded for S-1 + 1.0 milliliter tetraethyl lead. Figure 18(c) shows the two curves recorded for S-1 + 2.0 milliliters tetraethyl lead and 18(d) shows the two curves recorded for S-1 + 3.0 milliliters tetraethyl lead at the two inlet-air temperatures and all the curves for the leaded S-1 at an inlet-air temperature of 150° F. In figure 18(e) are average curves for the leaded S-1.

The curves at the two different inlet-air temperatures indicate that, for fuel-air ratios equal to or in excess of 0.07, the agreement between the data recorded at the two inlet-air temperatures is quite good. For lead quantities of 0.5 and 1.0 milliliter, the curves diverge at the lean-mixture ratios. As has been stated before, too much confidence cannot be placed in the data for fuel-air ratio of 0.05 because the engine did not operate smoothly at this fuel-air ratio. The average curves form a reasonably good family of curves. In general, it can be said that over the operating range of fuel-air ratios, the agreement between the data at the two inlet-air temperatures is reasonably satisfactory.

In table X for each fuel-air ratio at the two inlet-air temperatures there are tabulated the percentages of increase in relative indicated mean effective pressure for each 0.1 milliliter tetraethyl lead for ranges of tetraethyl lead from 0 to 0.5 and from 0.5 to 3.0. These data were determined from cross plots for the curves presented in figure 18. For leaded quantities from 0.5 to 3.0 milliliters tetraethyl lead, there is an increase in relative indicated mean effective pressure of 1.5 percent for each 0.1 milliliter of tetraethyl lead. For the range from 0.0 to 0.5 milliliter tetraethyl lead, the increase in permissible relative indicated mean effective pressure varies with both the fuel-air ratio and with the inlet-air temperature.

<u>Comparative performance of eight representative 100-octane-number fuels</u>.- Tables VIII, IX, XI, XII, and XIII list the maximum permissible values of indicated mean effective pressure for the eight representative fuels under the different test conditions and the percentage values of these indicated mean effective pressures compared with S-1 at the same operating conditions and fuel-air ratios. The percentage values are plotted in figure 19. As the fuel-air ratio is increased from 0.07, the relative indicated mean effective pressures of the fuels in general decrease so that, as the mixture is enriched, the relative values of the fuels approach more closely the value of S-1. The C.F.R. aviation method of knock rating is determined at the fuel-air ratio giving maximum thermal-plug temperature; this ratio, according to the temperature

curves recorded during these tests, should not be in excess of a fuel-air ratio of 0.07. According to figure 19 the variation of the relative performance at this ratio is as great as at the other fuel-air ratios. This fact is in accordance with the analysis presented in reference 2.

In only three cases, that is, with fuels 1, 2, and 3, did the relative performance of the fuel intersect the 100-percent ordinate for S-1. With fuel 1 the intersection occurred at a fuel-air ratio of about 0.12; with fuel 2, at a fuel-air ratio between 0.10 and 0.11; with fuel 3, at a fuel-air ratio of about 0.07 at the lower inlet temperature and at a fuel-air ratio of about 0.10 at both inlet-air temperatures. Fuels 4, 5, and 6 closely approach the value for S-1 at the richest mixture tested.

A comparison of the variation in the relative rating of the different fuels shows reasonably good agreement for the relative rating curves at the two inlet-air temperatures for fuels 1 through 6. The greatest divergence in relative values occurs with fuel 7. This divergence reaches a value of 24 percent, considering all the curves presented. There are admittedly more data for this fuel than for any of the other fuels tested. The maximum divergence for the runs on the Lycoming cylinder is approximately 18 percent and occurs at a fuel-air ratio of 0.07. There is good agreement between the shape of the curves for the two runs on the Lycoming cylinder at an inlet-air temperature of 250° F and the run on the G-200 clyinder at an inlet-air temperature of 150° F. At a temperature of 250° F on the G-200 cylinder the data agree more closely with the data at 150° F inlet-air temperature on the Lycoming. The reason for this apparent reversal of the inlet-air-temperature effect on the two cylinders is far from clear but, according to the analysis presented in reference 2, such differences might be expected. In this relation, reference is made to figure 8 in which it is noted that the curve for S-1 does not show a minimum at as low a value of fuel-air ratio as do the other fuels presented on this figure. This fact causes the curve in figure 19 for fuel 7 for the G-200 cylinder at 150° F to show a sharp increase in relative value between a fuel-air ratio of 0.06 and 0.07.

Curves for fuel 8 for which data are presented on three different cylinders varying in displacement from 17.6 to 202 cubic inches at approximately the same inlet-air temperature show, in general, a high level of relative maximum permissible indicated mean effective pressure. There is a marked similarity between the data determined on the Lycoming cylinder and those obtained with the Ethyl Gasoline Corporation 17.6 cylinder, with the exception that the curve for the Ethyl Gasoline Corporation cylinder is shifted to the right by a difference in fuel-air ratio of approximately 0.01. This difference may possibly be attributed to inaccuracies in estimating the fuel-air ratio for the Ethyl Gasoline Corporation data. The data recorded on the G-200 cylinder do not show the decline in the relative indicated mean effective pressure as the fuel-air ratio is decreased below 0.07.

In figure 20 are presented average curves for each fuel together with the average curves for the leaded S-1 fuels. The data recorded for the Ethyl Gasoline Corporation 17.6 cylinder have not been considered. From these average curves, values of octane number for the different fuels have been determined and are recorded in table XIV. The values for the fuels show, in general, an increase in relative octane number as the fuel-air ratio is increased from 0.05 to fuel-air ratios of about 0.07 to 0.08 and a decrease at the richer mixtures. Of particular interest in this table is the variation in octane rating of each fuel listed. The maximum variation, which occurs with fuel 8, is 1.0 milliliter tetraethyl lead.

The variation in values of the octane ratings for any one fuel at the two inlet temperatures must also be considered (table XV). For fuels 1 and 2 the maximum variation at any one fuel-air ratio is 0.2 milliliter tetraethyl lead. For fuel 3, if the value of fuel-air ratio of 0.05 is neglected, the maximum variation is from 99-octane number (estimated) to S-1 + 0.3 milliliter tetraethyl lead. A drop of one octane number below 100 represents about the same decrease in performance as the increase obtained through the addition of 0.1 milliliter tetraethyl lead above 100-octane number. It is therefore estimated that the maximum variation for fuel 3 is 0.4 milliliter tetraethyl lead. The maximum variation for fuel 4 is 0.3 milliliter tetraethyl lead. In fuel 5 the maximum variation reaches a value of 0.5 milliliter tetraethyl lead, if the value at a full-air ratio of 0.05 is neglected. Fuel 6 shows the least variation of any of the fuels, having a maximum variation of 0.1 milliliter tetraethyl lead. Fuel 7 shows the greatest variation of all of the fuels for which a comparison can be made; this variation is 0.90 milliliter tetraethyl lead at a fuel-air ratio of 0.07.

One fact that must be emphasized in this analysis of the octane number of the fuels is that the fuels are all being compared with the experimental data for S-1. For this reason, any error that occurs in the curve for S-1 will occur in the octane numbers for the different fuels. Figure 7 shows that the four points for S-1 in the lean region are so scattered that a smooth curve cannot be drawn through the points. The construction of this curve will, of course, affect the fuel ratings in the range of fuel-air ratio from 0.05 to 0.07. Rating the fuels from a comparison with S-1 introduces the error that occurs in the curves for the unknown fuels as well as any error that occurs in the curve for the S-1 fuel. This accumulation of error is unavoidable if the fuels are rated by reference to a standard fuel or fuels. The errors resulting from any error in the S-1 curve occur in the data for each of the fuels; for this reason, the comparison of the variation of the eight fuels among themselves is valid, even though the actual values may be in error. For the present analysis, the comparison of the fuels among themselves is more important, for the primary interest is in the variation of the fuels when compared with each other and not in the variation with the fuels from the S-1 reference fuel.

Comparison of fuels based on constituents.- In table XVI a tabulation is made of the fuels in descending order: first, the percentage of aromatics; second, the percentage of naphthenes; third, the percentage of paraffins; and, finally, in order of descending merit as shown from the knock - test data as given in figure 20. There seems to be no agreement between the percentage of the constituents and the order of merit. Just how valid this comparison is, it is difficult to state. More data on the knock characteristics of pure hydrocarbons and the blends of pure hydrocarbons are needed to determine the effects of these constituents.

CONCLUSIONS

1. The data presented in this report have shown that varying the inlet-air temperature changes not only the level of the knock-limit curves of the fuels tested but also the shape of the curves for these fuels. A comparison of the data from different engine cylinders shows that differences occur in the slopes of these curves in

the region of fuel-air ratios from 0.07 to 0.12, apparently in a manner similar to that which occurs through changing the inlet-air temperature in a given engine cylinder. The data indicate that, in cases where the maximum permissible indicated mean effective pressure reaches a maximum at fuel-air ratios between 0.08 and 0.10, this maximum is a function of the engine operating conditions as well as of the fuel.

2. The data indicate that the fuels which have the same octane number according to the C.F.R. aviation method may have markedly different octane numbers when tested in a full-scale single-cylinder engine. This variation may occur over the full range of fuel-air ratios that may be encountered in service operation. Among the eight 100-octane-number fuels tested, the maximum permissible indicated mean effective pressure at a fuel-air ratio of 0.08 had a low value of 105 percent relative to S-1 and a high value of 152 percent relative to S-1.

3. The data show that the octane number of this series of fuels will vary for any one fuel in any one cylinder as the fuel-air ratio is changed.

4. The data indicate that the addition of aromatics to the fuels (fuels 4 and 8) does not present any serious disadvantages from considerations of knock. In no case did the runs made with the fuels containing aromatics show preignition, although afterfiring was present for one of the fuels. This afterfiring was eliminated by changing the type of spark plug.

5. The type of spark plug apparently has no effect on the knock rating of the fuel, provided that preignition does not occur.

6. The data indicate that the knock characteristics of the fuels could not be classified according to the percentage of naphthenes, paraffins, aromatics, or olefins in the fuels.

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1. Anon.: Test Procedures and General Information in Current Use in the Development and Utilization of Aviation, Motor, and Automotive Diesel Fuels. Cooperative Fuel Res. Comm., May 1941.

2. Rothrock, A. M., and Biermann, Arnold E.: The Knocking Characteristics of Fuels in Relation to Maximum Permissible Performance of Aircraft Engines. NACA Rep. No. 655, 1939.

TABLE I

COMPOSITION OF FUELS TESTED

Fuel	Identi-fication	Amount of TEL per gal (ml)	Composition	Average[1] octane number by C.F.R. aviation method
1	PD-1393	3.06	54 percent hydrocodimer blending agent in straight run 74 base	99.9
2	PD-1458	6.17	33.7 percent alkylate blending agent in straight run 74 base	99.8
3	PD-1479	3.06	52.6 percent alkylate blending agent in straight run 74 base	99.7
4	PD-1552	2.98	46 percent alkylate blending agent in hydroformed base	99.4
5	PD-1564	2.97	42 percent alkylate blending agent in Houdry base	100 + 0.05
6	PD-1563	2.96	40 percent hydrocodimer blending agent in Houdry base	100 + 0.02
7	L-5151	2.74	60 percent phosphoric acid iso-octane blending agent in 40 percent light naptha	100
8	L-5152	2.79	70 percent phosphoric acid iso-octane blending agent in 15 percent light naptha and 15 percent benzol.	100

[1]Average of determinations of four laboratories.

TABLE II.- CHARACTERISTICS OF THE COMPONENTS OF FUELS 1 TO 6

[Data from Standard Oil Development Company]

Description	Base stocks				Blending agents			
	Straight run 74		Hydro-formed.	Houdry	Hydrocodimer		Alkylate	
Code letter	E	X	R	S	H	H'	L	K
Gravity, A.P.I..	67.2	67.2	57.9	69.3	71.7	71.6	73.6	72.4
Reid vapor pressure	6.4	6.4	7.0	8.3	7.6	7.1	6.3	6.7
Amount of TEL per gallon, ml	3.15	6.25	2.98	2.97	2.98	2.95	2.98	6.05
Initial boiling point, °F	122	122	113	100	106	91	111	108
Percentage at -								
158° F	13.5	13.5	26.5	41.0	17.0	19.0	15.0	16.5
176	----	----	39.0	57.0	----	25.0	----	----
203	56.0	56.0	53.0	70.0	32.5	33.0	40.5	37.5
212	66.0	66.0	57.0	75.0	36.0	37.0	47.5	43.5
257	92.5	92.5	77.0	92.0	----	----	97.5	96.0
90 percent at, °F	----	----	298	250	233	233	238	234
Final boiling point, °F . .	298	298	355	298	248	249	257	271
Percentage recovery	97.0	97.0	99.0	98.0	97.0	98.0	97.5	97.5
Percentage loss	2.0	2.0	0.5	1.6	2.0	1.0	1.0	1.5
C.F.R. aviation method octane number.	----	----	90.2	95.0	----	100+0.84	100+0.63	100+2.1
Approximate composition:								
Percentage aromatics	5	5	28	10	0	0	0	0
Percentage naphthenes	50	50	20	15	0	0	0	0
Percentage paraffins	45	45	50	70	100	100	100	100
Percentage olefins	0	0	2	5	0	0	0	0

TABLE III

CHARACTERISTICS OF FUELS 1 TO 6

[Data from Standard Oil Development Company]

NACA fuel	1	2	3	4	5	6
Fuel type	Straight run + hydro-codimer + 3 ml	Straight run + alkylate + [illegible] ml	Straight run + alkylate + 3 ml	Hydroformed + alkylate + 3 ml	Houdry + alkylate + 3 ml	Houdry + hydro-codimer + 3 ml
Composition, percentage blending agent in base stock (see table II) . .	54H in E	33.7K in X	52.6L in E	46L in R	42L in S	40H' in S
Gravity, A.P.I.	69.5	68.7	70.6	64.4	71.1	69.9
Reid .apor pressure . . .	6.7	6.5	6.4	6.7	7.1	7.4
Amount of TEL per gallon, ml	3.06	6.18	3.05	2.98	2.97	2.95
Initial boiling point, °F.	108	111	112	106	100	108
Percentage at -						
158°F	16.0	15.0	15.0	22.0	33.0	30.0
176	25.5	28.0	25.0	33.0	42.5	40.0
203	....	51.0	44.0	47.0	58.0	54.0
212	48.0	58.5	54.0	53.0	64.0	58.5
257	97.0	94.0	96.0	87.0	94.0	95.0
90 percent at, °F	240	250	248	266	246	250
Final boiling point, °F . .	277	290	288	342	279	285
Percentage recovery. . . .	98.0	97.5	98.0	98.0	98.0	98.0
Percentage loss	0.9	1.7	1.2	1.0	0.8	1.2
Army gum	....	....	....	3.0	5.0	5.0
Copper dish gum, mg/100 ml	4	18	3	4.0	5.0	5.0
Copper dish corrosion . .	Pass	DNP	DNP	DNP	DNP	DNP
A.S.T.M. gum, mg/100 ml .	....	2	....	....	....	....
Net heat content, Btu/lb .	....	18,947	....	18,379	....	....
C.F.R. aviation method octane number by -						
Laboratory 1	100+0.02	99.9	99.5, 99.2	99.2, 99.7	100+0.05	100+0.02
Laboratory 2	99.6	99.9	99.5, 99.7	99.3	100	100+0.06
Laboratory 3	....	99.9	100	[a]97.6, 98.0	....	....
Laboratory 4	....	99.5	100+0.04	100	100+0.10	....
Approximate composition:						
Percentage aromatics . .	2	3	2	15	6	6
Percentage napthenes . .	23	33	24	11	9	9
Percentage paraffins . .	75	64	74	73	82	82
Percentage olefins . . .	0	0	0	1	3	3
Trial blends[b], percentage from -	H in E	K in X	L in E	L in R	L in S	H in S
Laboratory 1	53	32	54	52	42	41
Laboratory 2	[c]46	[c]19	50	51	38	34
Laboratory 3	54	36	54	40	46	42
Laboratory 4	55	33	52	40	[d]28	[d]23
Average	54	34	53	46	42	[e]39

[a]These results appear to be low inasmuch as 6 percent more alkylate was used in the blend than was originally indicated to be necessary by laboratory 3.

[b]Trial blends resulting in 100 octane number with tetraethyl lead.

[c]This value omitted in average.

[d]Received too late to be included in average.

[e]Value of 40 percent used in blend because result from laboratory 2 appeared low.

TABLE IV

COMPONENTS OF FUELS 7 AND 8

[Data from Standard Oil Company (Indiana)]

	Fuel 7	Fuel 8
Amount of TEL per gallon, ml	2.74	2.79
Percentage aromatics	0	15
Percentage light naphtha.	40	15
Percentage iso-octane blending agent.	60	70
C.F.R. aviation method octane number by		
Laboratory 1	100+0.03	100+0.04
Laboratory 2	99.5	99.6
Laboratory 3	100+0.01	100+0.02
Laboratory 4	99.8	99.8

TABLE V

CARBON-HYDROGEN RATIOS AND HEATS OF COMBUSTION OF NACA FUELS AND S-1

[Heat of combustion determined at constant volume]

Fuel	C/H	C (percent)	H (percent)	H/C	F/A for complete combustion	Gross heat of combustion, (cal/gram)	Gross heat of combustion (Btu/lb)	Grams water produced per gram fuel burned	Heating correction per gram fuel (cal/gram)	Net heat of combustion, (cal/gram)	Net heat of combustion (Btu/lb)
1	5.31 5.32	83.72 83.87	15.78 15.77	0.188 .188	0.0660	11,406 11,445 11,434	20,531 20,601 20,581	1.41 1.41	762 762	10,666	19,200
2	5.32 5.36	84.03 84.10	15.80 15.69	.188 .186	.0661	11,394 11,400 11,408	20,509 20,520 20,534	1.41 1.40	762 758	10,641	19,150
3	5.24 5.26	84.0 83.91	16.0 15.91	.191 .190	.0658	11,463 11,425 11,439	20,633 20,565 20,590	1.43 1.42	772 768	10,672	19,210
4	5.92 5.88	85.18 85.10	14.41 14.49	.169 .170	.0674	11,188 11,173 11,178	20,138 20,111 20,120	1.29 1.29	698 698	10,481	18,870
5	5.44 5.47	83.67 84.45	15.37 15.45	.184 .183	.0663	11,628 11,623 11,592	20,930 20,921 20,866	1.38 1.38	744 744	10,870	19,570
6	5.52 5.46	84.18 84.44	15.26 15.43	.181 .183	.0664	11,432 11,430 11,500	20,578 20,574 20,700	1.37 1.38	738 744	10,713	19,270
7	5.27 5.27	82.96 83.77	15.78 15.92	.190 .190	.0658	11,437 11,431 11,457	20,587 20,576 20,623	1.41 1.42	760 766	10,679	19,220
8	5.68 5.65	84.83 84.31	14.95 14.94	.176 .177	.0667	11,194 11,193 11,198	20,149 20,147 20,156	1.34 1.34	723 723	10,472	18,860
S-1	5.24 5.20	83.75 83.53	15.99 16.08	.191 .192	.0657	11,403 11,447 11,370	20,525 20,605 20,466	1.42 1.42	766 766	10,641	19,150

TABLE VI

EFFECT OF SPARK-PLUG TYPE AND ADDITION OF CENTER-ELECTRODE THERMOCOUPLE ON KNOCK LIMIT OF S-1 FUEL + 3.0 ML TETRAETHYL LEAD

[Lycoming 0-1230 cylinder; engine speed, 2000 rpm; spark advance, 27°; inlet-air temperature, 150° F]

Fuel-air ratio	Maximum permissible inlet pressure (in. Hg)	Indicated mean effective pressure (lb/sq in.)	Indicated fuel consumption (lb/ihp-hr)	Engine temperature: Intake air (°F)	Engine temperature: Oil out (°F)	Engine temperature: Coolant in (°F)	Spark plugs
0.0709	53.2	300.9	0.411	147.2	166	248.0	New Bendix 41-G spark plug with thermocouple and new Bendix 41-G spark plug without thermocouple
.0705	53.4	301.5	.404	147.2	165	248.0	New Bendix 41-G spark plug with thermocouple and old Bendix 41-G spark plug with thermocouple used about 130 hours
.0711	53.1	300.1	.401	149.0	165	249.8	Two new Bendix 41-G spark plugs
.0706	53.2	300.4	.403	149.0	166	246.2	Two new BG 344-S spark plugs
.0685	54.6	303.7	.398	147.2	165	246.2	Two new Bendix 300-A1 spark plugs
.0702	54.2	303.3	.403	150.8	166	246.2	Two new Champion R-J2 spark plugs
.0691	54.2	302.3	.401	149.0	165	249.8	Two new Champion R-J7 spark plugs (hot plug)
.0694	54.4	302.4	.404	150.8	165	248.0	Two new BG 3B-2 spark plugs
.0680	55.1	303.0	.399	149.0	166	248.0	Two new Bendix 41-G spark plugs (check running)
.0700	54.5	306.0	.405	-------	-------	-------	Bendix 41-G used about 130 hours (one with thermocouple and one without)

TABLE VII

RELATION BETWEEN FUEL-AIR RATIO AND MAXIMUM PERMISSIBLE PERFORMANCE OF S-1 AND S-1 PLUS TETRAETHYL LEAD AT TWO INLET-AIR TEMPERATURES

[Lycoming O-1230 cylinder; data from fig. 6]

Fuel-air ratio	Indicated specific fuel consumption (lb/hp-hr)	In the tabulated data below, the upper value gives the imep, in lb/sq in., and the lower value gives the imep relative to S-1, in percent				
		S-1 + 0.5	S-1 + 1.0	S-1 + 2.0	S-1 + 3.0	S-1
Inlet-air temperature, 250° F						
0.05	0.385	185 123	201 134	225 150	230 153	150 100
.06	.365	193 123	208 132	222 141	245 156	157 100
.07	.400	197 118	213 128	232 139	257 154	167 100
.08	.465	207 112	223 121	248 134	271 146	185 100
.09	.535	216 109	236 119	259 130	284 143	199 100
.10	.610	221 108	245 120	---------- ----------	---------- ----------	204 100
.11	.690	222 108	---------- ----------	---------- ----------	---------- ----------	205 100
.12	.775	---------- ----------	---------- ----------	---------- ----------	---------- ----------	207 100
Inlet-air temperature, 150° F						
0.05	0.395	208 112	226 122	256 138	---------- ----------	105 100
.06	.375	225 118	240 126	268 140	297 155	191 100
.07	.405	233 117	249 125	279 140	305 153	200 100
.08	.460	236 113	253 122	285 137	310 149	208 100
.09	.530	236 112	256 121	281 133	---------- ----------	211 100
.10	.600	235 111	257 122	272 129	---------- ----------	211 100
.11	.685	234 111	257 122	---------- ----------	---------- ----------	211 100
.12	.775	---------- ----------	---------- ----------	---------- ----------	---------- ----------	211 100

TABLE VIII

RELATION BETWEEN FUEL-AIR RATIO AND MAXIMUM PERMISSIBLE PERFORMANCE OF NACA FUELS 1 TO 7 COMPARED WITH VALUES FOR S-1

[Lycoming O-1230 cylinder; data from figs. 6 and 7]

Fuel-air ratio	Indicated specific fuel consumption (lb/hp-hr)	In the tabulated data below, the upper value gives the imep, in lb/sq in., and the lower value gives the imep relative to S-1, in percent							
		Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	S-1
Inlet-air temperature, 250° F									
0.05	0.385	------	182	144	180	181	------	184	150
		------	121	96	120	121	------	123	100
.06	.365	189	180	151	181	[a]199	[a]202	182	157
		120	115	96	115	127	129	116	100
.07	.400	[a]204	183	169	[a]207	[a]211	[a]211	185	167
		122	110	101	124	126	126	111	100
.08	.465	[a]221	200	190	[a]217	[a]219	[a] [b]228	[a] [b]228	185
		119	108	103	117	118	123	123	100
.09	.535	[a]232	201	200	[a]220	[a]221	[a]231	[a]234	199
		117	101	101	111	111	116	118	100
.10	.610	[a]229	200	202	219	216	[a]227	[a]229	204
		112	98	99	107	106	111	112	100
.11	.690	221	199	198	218	207	219	[a]222	205
		108	97	97	106	101	107	108	100
.12	.775	198	190	------	217	------	211	-----	207
		96	92	------	105	------	102	-----	100
Inlet-air temperature, 150° F									
0.05	0.395	[a]215	204	[a]209	[a]217	[a]225	[a] [b]238	[a] [b]232	185
		116	110	113	117	122	129	125	100
.06	.375	[a]228	220	211	[a]230	[a]233	[a]235	[a] [b]244	191
		119	115	110	120	122	123	128	100
.07	.405	[a]241	229	213	[a]238	228	[a]246	[a] [b]257	200
		121	115	107	119	114	123	129	100
.08	.460	[a]246	230	215	[a]242	[a]247	[a]252	[a] [b]265	208
		118	111	103	116	119	121	127	100
.09	.530	[a]243	224	215	[a]239	[a]241	[a] [b]247	[a] [b]258	211
		115	106	102	113	116	117	122	100
.10	.600	[a]236	217	211	230	227	[a]240	[a]248	211
		112	103	100	109	108	114	118	100
.11	.685	225	209	206	215	[a]234	232	[a]238	211
		107	99	98	102	111	110	113	100
.12	.775	211	218	198	222	------	223	-----	211
		100	103	94	105	------	106	-----	100

[a]Equal to or in excess of S-1 + 0.5 ml TEL.

[b]Equal to or in excess of S-1 + 1.0 ml TEL.

TABLE IX

RELATION BETWEEN FUEL-AIR RATIO AND MAXIMUM PERMISSIBLE PERFORMANCE

OF NACA FUELS 7 AND 8 COMPARED WITH VALUES FOR

S-1 AND S-1 + 1.0 ML TETRAETHYL LEAD

[Lycoming 0-1230 cylinder; inlet-air temperature, 250°F. Data from figure 8]

Fuel-air ratio	Indicated specific fuel consumption (lb/hp-hr)	In the tabulated data below, the upper value gives the imep, in lb/sq in., and the lower value gives the imep relative to S-1, in percent			
		Fuel 7	Fuel 8	S-1	S-1 + 1.0
0.05	0.380	200 ---	234 ---	--- ---	--- ---
.06	.375	198 113	[a]233 132	176 100	212 120
.07	.420	208 116	[a]268 150	179 100	220 123
.08	.480	[a]234 126	[a]291 156	186 100	230 124
.09	.550	[a]240 124	[a]297 153	194 100	235 121
.10	.625	[a]236 119	--- ---	198 100	235 119
.11	.720	[a]238 119	--- ---	200 100	235 119
.12	.800	--- ---	--- ---	--- ---	--- ---

[a]Equal to or in excess of S-1 + 1.0 ml TEL.

TABLE X

PERCENTAGE INCREASE IN INDICATED MEAN EFFECTIVE PRESSURE

RELATIVE TO S-1 FOR EACH 0.1 ML TETRAETHYL LEAD

[Data from fig. 18]

	Range TEL ml per gallon			
	0.0 to 0.5		0.5 to 3.0	
Inlet-air temperature °F	250	150	250	150
Fuel-air ratio	Percentage increase in imep			
0.06	4.8	3.6	1.5	1.5
.07	3.6	3.4	1.5	1.5
.08	2.4	2.6	1.5	1.5
.09	1.8	2.4	1.5	1.5

TABLE XI

RELATION BETWEEN FUEL-AIR RATIO AND MAXIMUM PERMISSIBLE PERFORMANCE OF NACA FUELS 7 AND 8 COMPARED WITH VALUES FOR S-1

[Wright G-200 cylinder; inlet-air temperature, 250° F. Data taken from fig.14]

Fuel-air ratio	Indicated specific fuel consumption (lb/hp-hr)	In the tabulated data below, the upper value gives the imep, in lb/sq in., and the lower value gives the imep relative to S-1, in percent		
		Fuel 7	Fuel 8	S-1
0.05	0.375	168 118	210 148	142 100
.06	.375	144 125	170 148	115 100
.07	.420	143 126	166 147	112 100
.08	.480	180 130	215 155	139 100
.09	.555	199 121	239 147	163 100
.10	.625	208 117	255 145	176 100
.11	.715	---	---	---

TABLE XII

RELATION BETWEEN FUEL-AIR RATIO AND MAXIMUM PERMISSIBLE

PERFORMANCE OF S-1 AND NACA FUEL 7

[Wright G-200 cylinder; inlet-air temperature, 150° F. Data from fig. 15]

Fuel-air ratio	In the tabulated data below, the upper value gives the imep, in lb/sq in., and the lower value gives the imep relative to S-1, in percent	
	S-1	Fuel 7
0.05	175 100	208 119
.06	165 100	197 119
.07	160 100	216 135
.08	177 100	229 129
.09	194 100	232 120
.10	199 100	232 117
.11	204 100	233 114

TABLE XIII

RELATION BETWEEN ESTIMATED FUEL-AIR RATIO AND MAXIMUM

PERMISSIBLE PERFORMANCE OF NACA FUELS 7 AND 8

COMPARED WITH VALUES FOR S-1

[Ethyl Gasoline Corporation 17.6 cylinder; engine speed, 2700 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 225° F; inlet coolant temperature, 240° F; compression ratio, 7.7. Data from fig. 17]

Fuel-air ratio	In the tabulated data below, the upper value gives the imep, in lb/sq in., and the lower value gives the imep relative to S-1, in percent		
	Fuel 7	Fuel 8	S-1
0.07	226 118	266 139	191 100
.08	236 120	290 148	196 100
.09	248 124	309 155	200 100
.10	245 121	319 158	202 100
.11	234 116	304 149	201 100
.12	221 112	290 146	198 100

TABLE XIV

OCTANE NUMBER OF EIGHT REPRESENTATIVE 100-OCTANE-NUMBER FUELS WHEN DETERMINED FROM AVERAGE RELATIVE CURVES OF INDICATED MEAN EFFECTIVE PRESSURE

[All values are S-1 plus recorded ml tetraethyl lead per gallon. Data from fig. 20]

Fuel-air ratio	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8
0.05	0.5	0.4	0.2	0.5	0.7	1.1	0.7	2.3
.06	.5	.4	.2	.5	.7	.9	.6	2.5
.07	.7	.4	.2	.6	.8	.9	.9	3.2
.08	.8	.4	.2	.7	.9	1.0	1.3	3.2
.09	.8	.3	.1	.6	.7	.9	1.0	3.3
.10	.6	.1	.0	.4	.4	.7	.8	---
Variation ml TEL	.3	.3	.2	.3	.5	.4	.7	1.0

TABLE XV

COMPARISON OF OCTANE NUMBERS OF EIGHT REPRESENTATIVE 100-OCTANE FUELS

[Lycoming O-1230 cylinder; all values except those marked with footnote (a) are S-1 plus recorded ml tetraethyl lead per gallon. Data from figs. 18 and 19]

Fuel-air ratio \ Inlet-air temperature, °F	Fuel 1		Fuel 2		Fuel 3		Fuel 4		Fuel 5		Fuel 6		Fuel 7		Fuel 8	
	250	150	250	150	250	150	250	150	250	150	250	150	250	150	250	150
0.05	----	0.6	0.4	0.5	(a)	0.5	0.4	0.7	0.4	1.0	----	1.4	0.5	1.1	----	----
.06	0.4	.6	.3	.4	(a)	.3	.3	.6	.8	.7	0.8	.9	.4	1.1	0.8	----
.07	.6	.7	.3	.4	0.0	.2	.8	.6	1.0	.5	1.0	.9	.3	1.2	2.6	----
.08	.9	.8	.4	.4	.1	.2	.8	.6	.8	.8	1.1	1.0	1.1	1.3	3.2	----
.09	.8	.7	.2	.3	.0	.1	.6	.5	.6	.7	.8	.8	1.0	1.2	3.6	----
.10	.6	.5	.0	.2	(a)	.0	.5	.5	.4	.4	.6	.6	.7	.8	----	----

[a]Values estimated to be 99 octane number.

TABLE XVI

COMPARISON OF FUELS BASED ON CONSTITUENTS AND ON PERFORMANCE

Fuels arranged according to percentage aromatics		Fuels arranged according to percentage naphthenes		Fuels arranged according to percentage paraffins		Fuels arranged according to knock limit[a]
Percentage aromatics	Fuel	Percentage naphthenes	Fuel	Percentage paraffins	Fuel	
15	4.8	33	2	96[b]	7	8
6	5.6	24	3	83[b]	8	7
3	2	23	1	82	5.6	6
2	1.3	11	4	75	1	1
0	7	9	5.6	74	3	5
		4	7	73	4	4
		2	8	64	2	2
						3

[a]Data from figure 20.

[b]Plus traces of unsaturates.

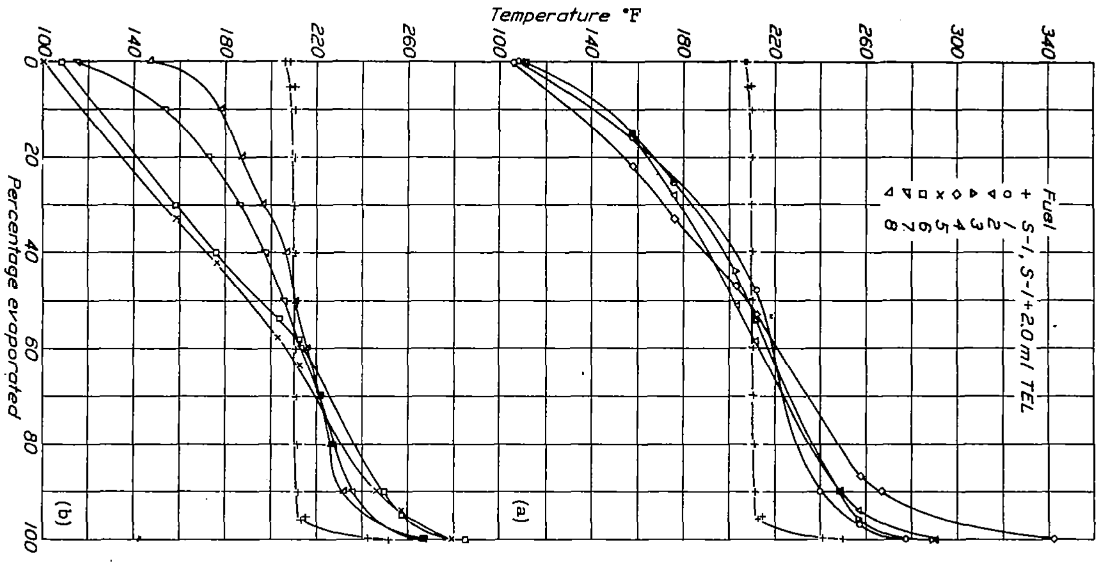


Figure 1.- Distillation curves for S-1, S-1 + 2.0 ml tetraethyl lead, and NACA fuels.
(a) Fuels 1,2,3,and 4.
(b) Fuels 5,6,7,and 8.

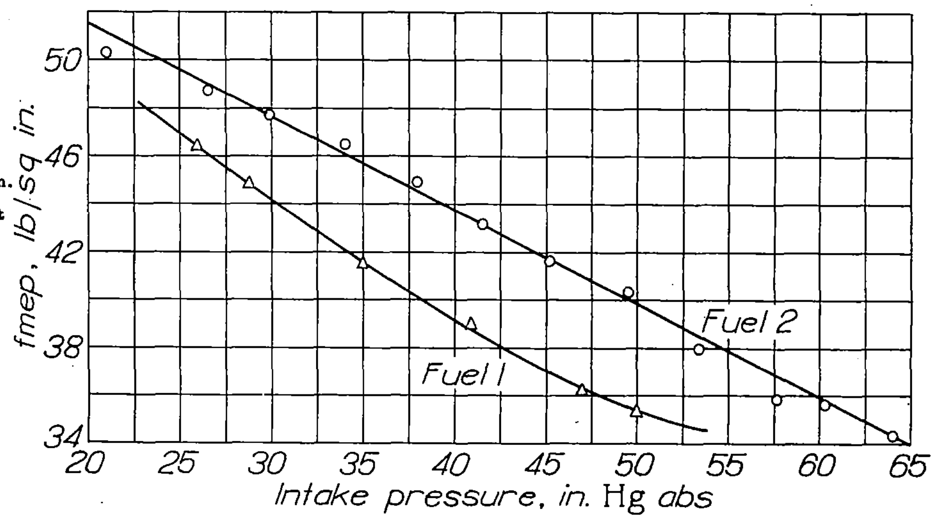
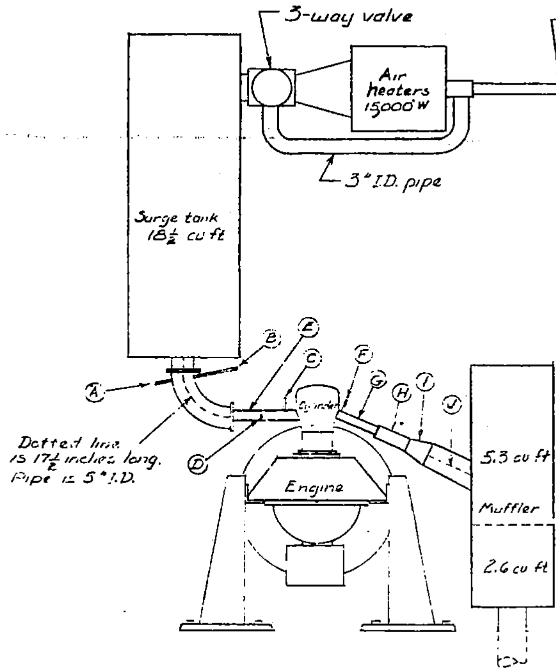


Figure 5.- Effect of intake pressure on friction. Lycoming O-1230 cylinder; engine speed, 2000 rpm; coolant inlet temperature, 250° F; compression ratio, 7.0; inlet-air temperature, 250° F.



A Inlet-air thermocouple

B Thermometer, $3\frac{1}{2}$ in. below bottom of tank

C Mixture thermocouple, $5\frac{3}{4}$ in. from center line of intake valve

D Injection valve, $9\frac{3}{4}$ in. from center line of intake valve

E Pipe, 2 in. I.D., $14\frac{1}{4}$ in. in length

F Exhaust thermocouple, $3\frac{1}{4}$ in. from center line of exhaust valve

G Pipe, $1\frac{3}{4}$ in. I.D., $9\frac{1}{2}$ in. in length

H Pipe, 3 in. I.D., $7\frac{1}{2}$ in. in length

I Pipe, 3 in. I.D. to 5 in. I.D., 4 in. in length

J Pipe, 5 in. I.D., $11\frac{1}{2}$ in. along center line

FIGURE 2.–ARRANGEMENT OF LABORATORY EQUIPMENT.

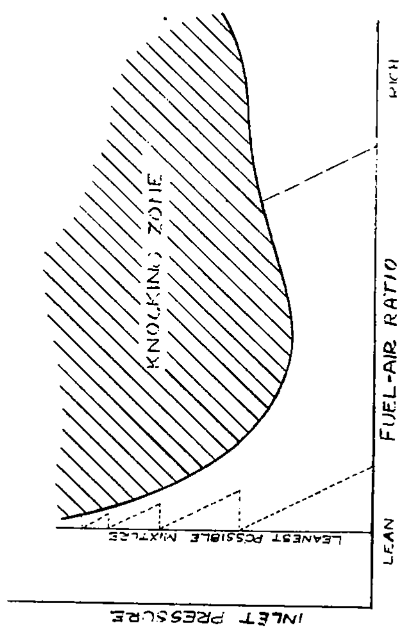


Figure 3.– Procedure followed in adjusting inlet pressure and fuel flow.

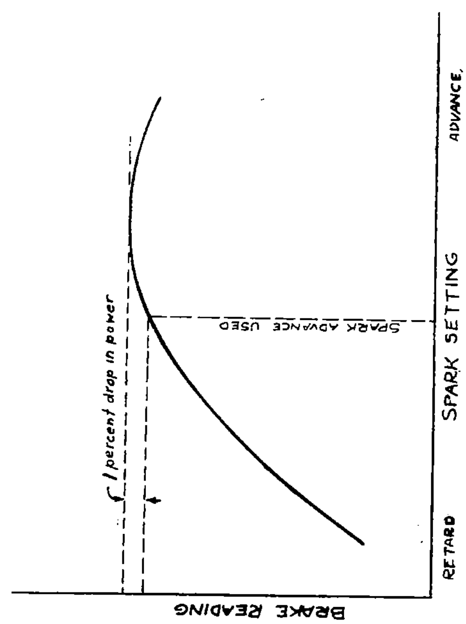


Figure 4.– Relation between power output and spark advance.

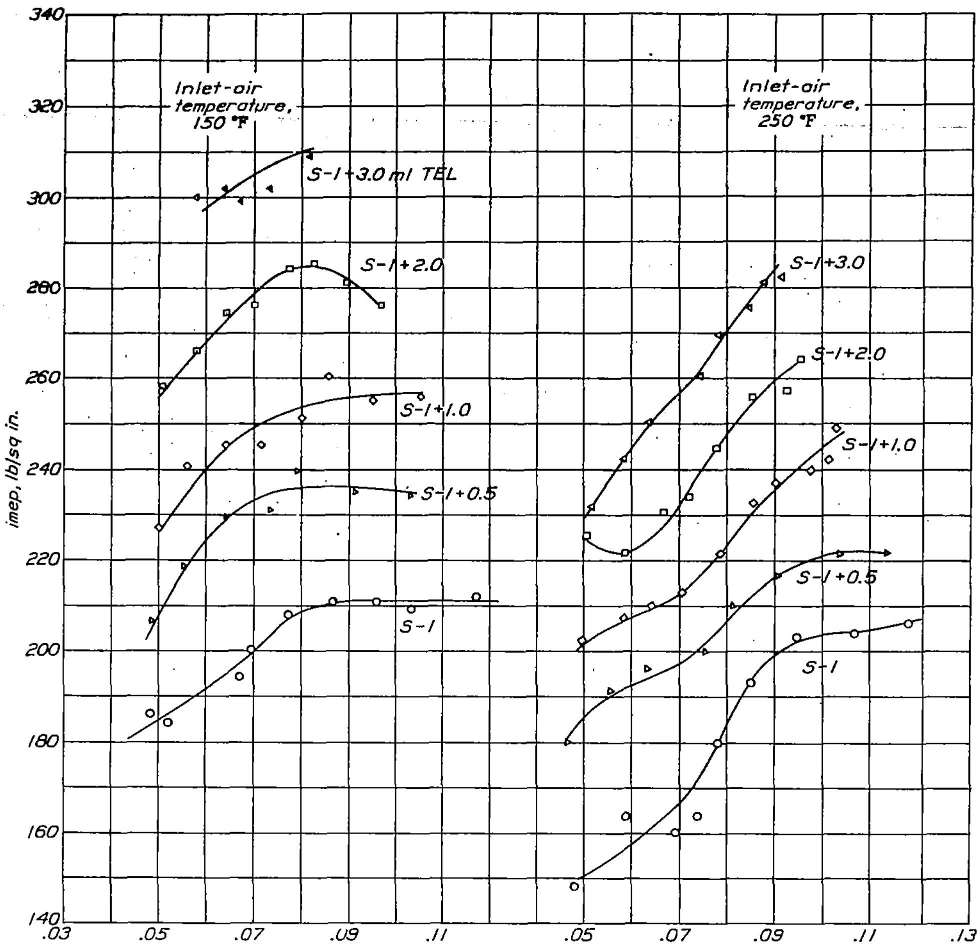


Figure 6.- Effect of inlet-air temperature on relation between fuel-air ratio and maximum permissible indicated mean effective pressure for S-1 and S-1 plus tetraethyl lead. Lycoming O-1230 cylinder; engine speed, 2000 rpm; spark advance, 27°; coolant inlet temperature, 250°F; compression ratio, 7.0.

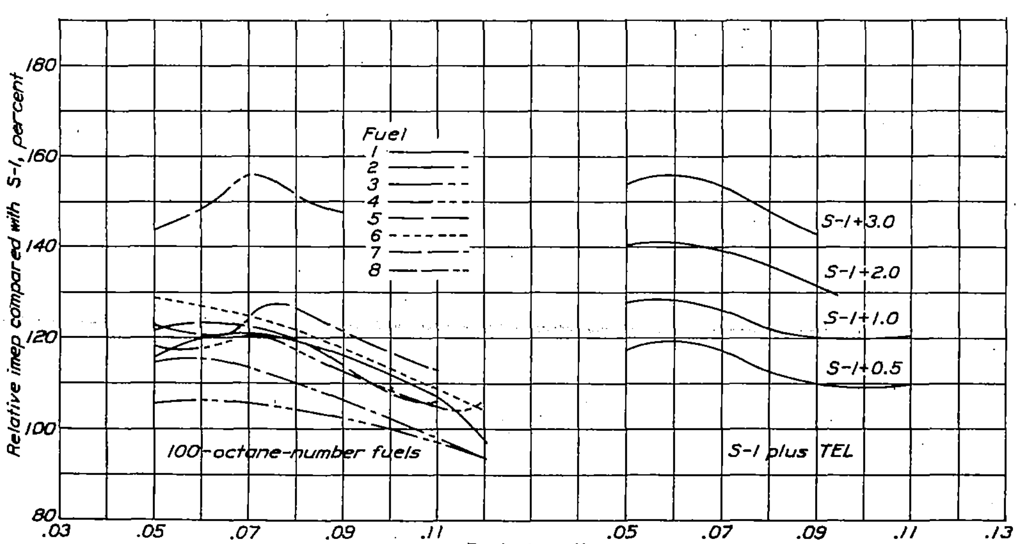
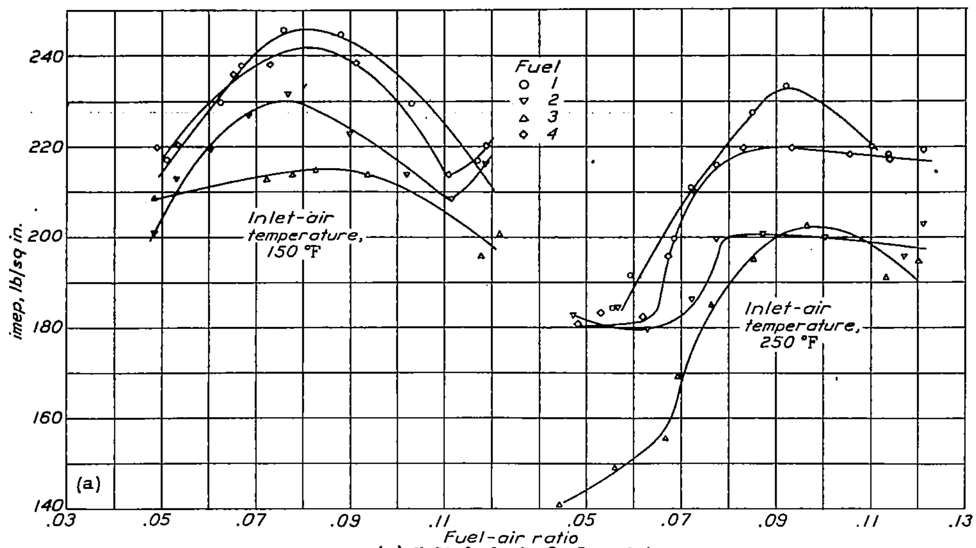
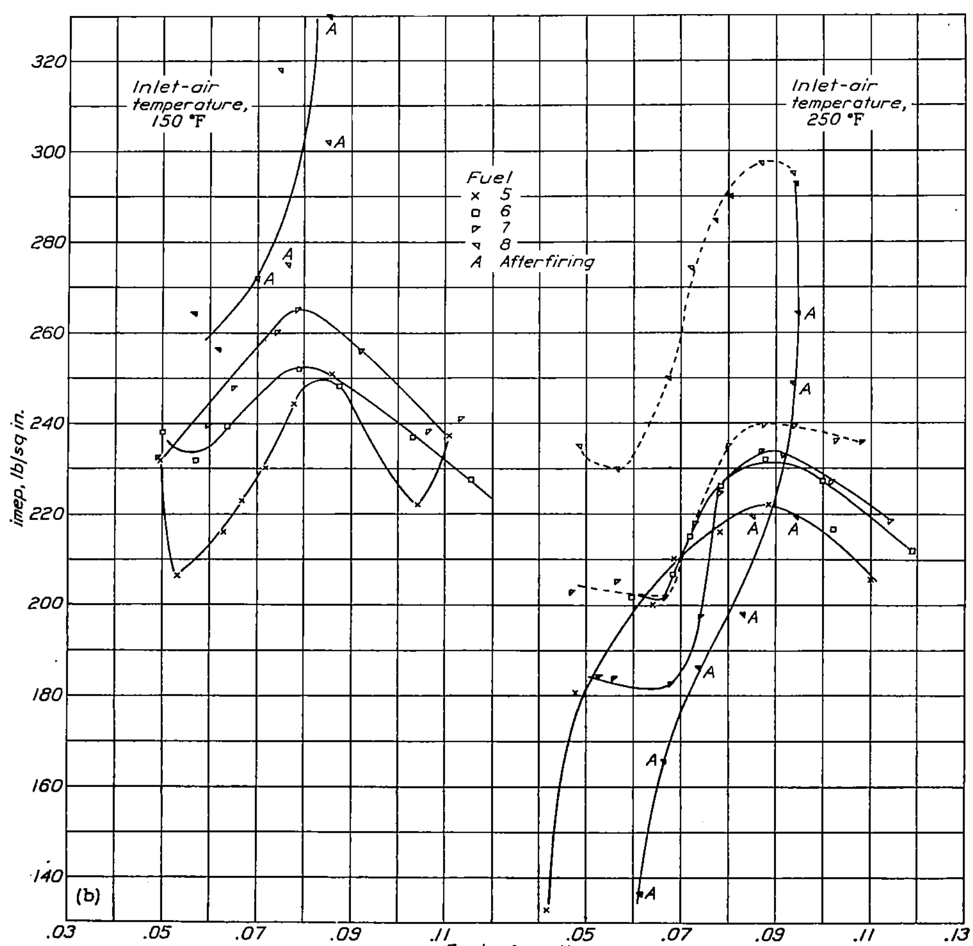


Figure 20.- Average relative indicated mean effective pressure with respect to S-1 for NACA fuels and S-1 plus tetraethyl lead.



(a) NACA fuels 1, 2, 3, and 4.



(b) NACA fuels 5, 6, 7, and 8.

Figure 7 – Effect of inlet-air temperature on relation between fuel-air ratio and maximum permissible indicated mean effective pressure. Lycoming O-1230 cylinder; engine speed, 2000 rpm; spark advance, 27°; coolant inlet temperature, 250°; compression ratio, 7.0.

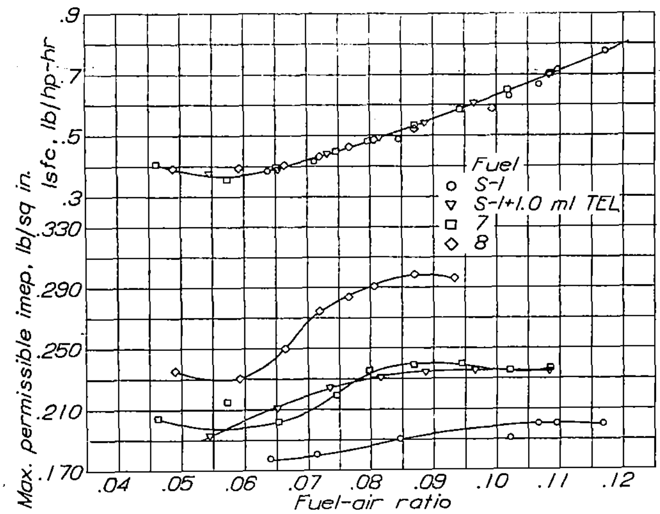
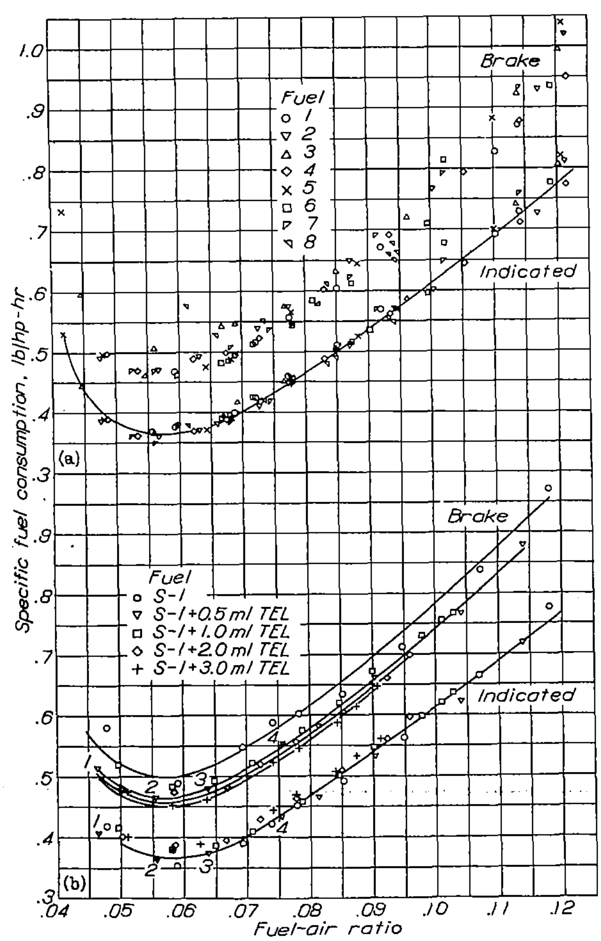
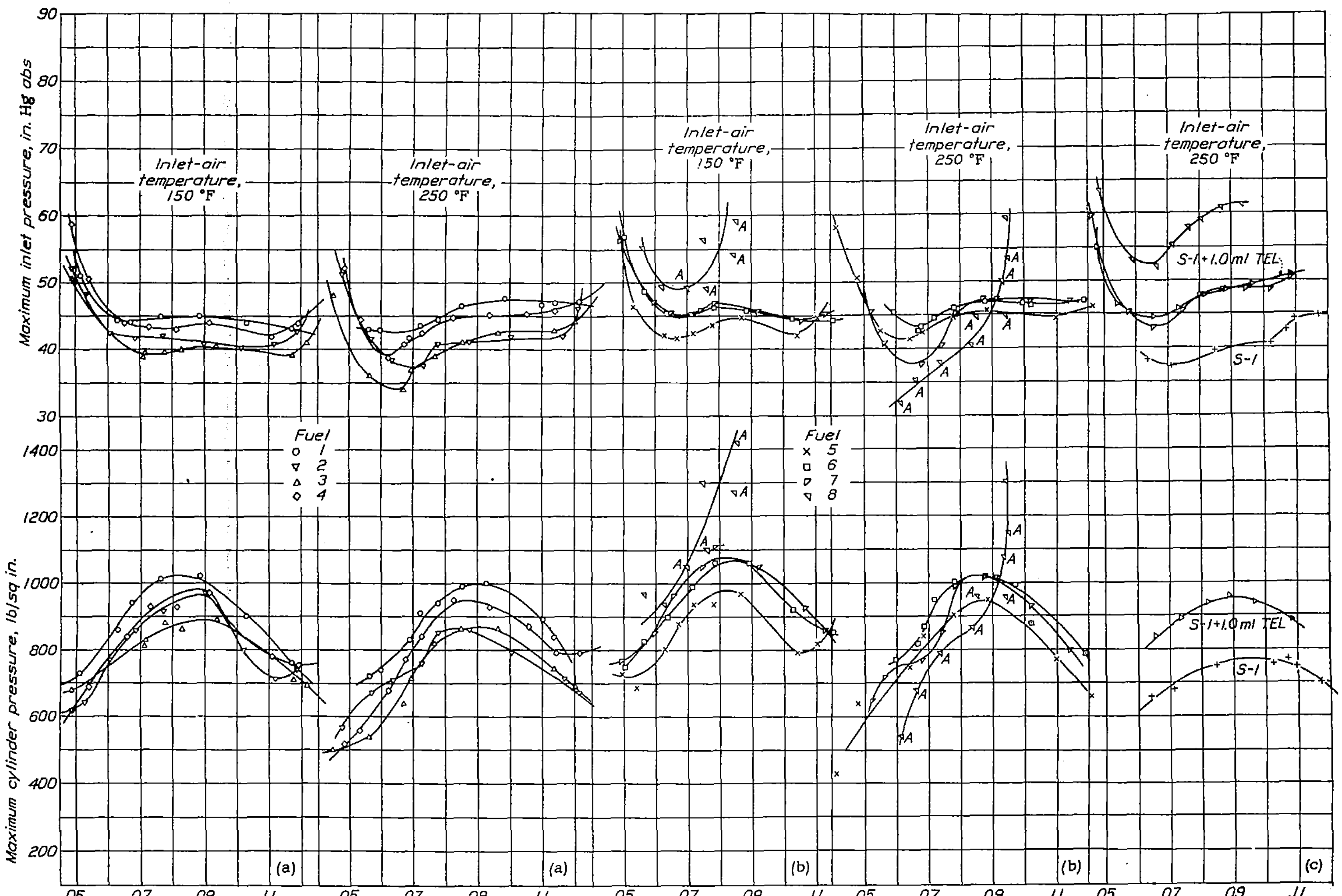


Figure 8.-Effect of fuel-air ratio on the maximum permissible performance of fuels 7,8, S-1, and S-1+ 1 ml TEL.Lycoming 0-1230 cylinder;engine speed, 2000 rpm;spark advance,27°; coolant temperature,250°F; compression ratio,7.0;inlet-air temperature,250°F.



(a) NACA fuels 1 to 8.
(b) S-1 and S-1 plus teeraethyl lead.

Figure 10.-Relation between fuel-air ratio and specific fuel consumption for different fuels. Lycoming 0-1230 cylinder; engine speed,2000 rpm;spark advance,27°;compression ratio,7.0;inlet-air temperature,250°F;coolant inlet temperature,250°F.



(a) Fuels 1,2,3,and 4. (b) Fuels 5,6,7,and 8. (c) Second series of runs of fuels 7 and 8 compared with S-1 and S-1 + 1.0 ml TEL.

Figure 9.- Relation between fuel-air ratio and maximum permissible inlet pressure and between fuel-air ratio and maximum cylinder pressure at this inlet pressure for NACA fuels. Lycoming 0-1230 cylinder;engine speed,2000 rpm;spark advance,27°;coolant inlet temperature,250°F;compression ratio,7.0.

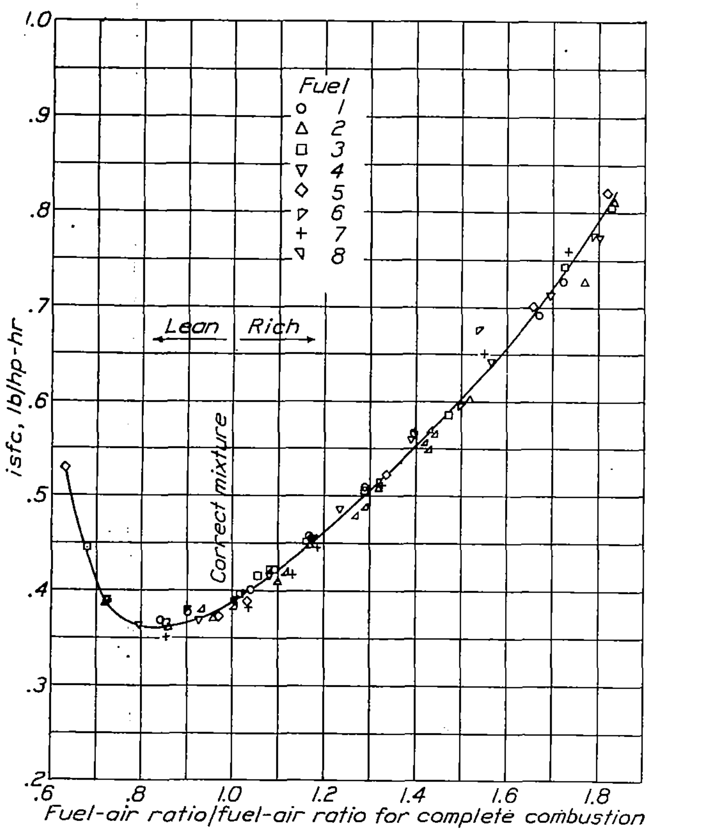


Figure 11.- Relation between relative mixture and indicated specific fuel consumption for NACA fuels 1 to 8. Lycoming O-1230 cylinder; engine speed, 2000 rpm; spark advance, 27°; coolant inlet temperature, 250°F; compression ratio, 7.0; inlet-air temperature, 250°F.

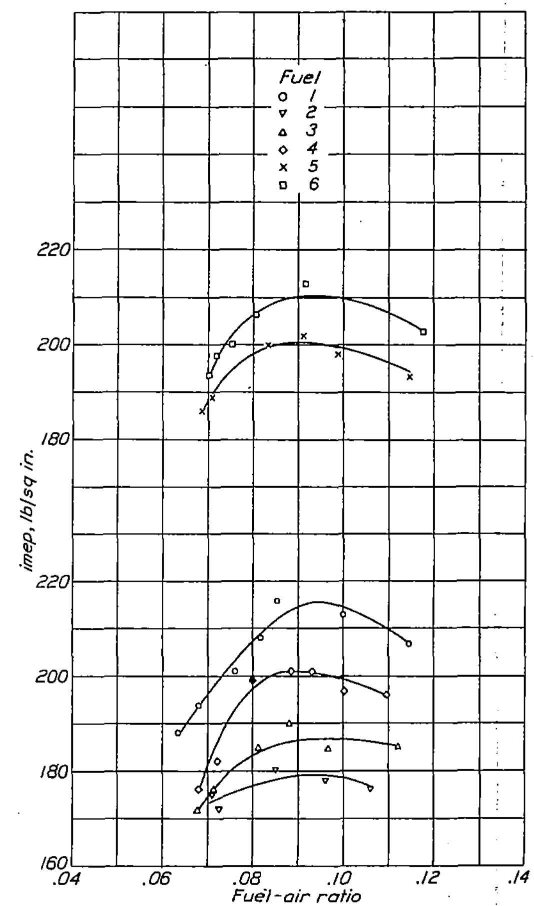


Figure 12.- Data showing relation between fuel-air ratio and maximum permissible indicated mean effective pressure for NACA fuels 1 to 6 in C.F.R. engine. (Data from Standard Oil Development Co.) Engine speed, 1800rpm; spark advance 30°; inlet-air temperature, 110°F; jacket temperature, 350°F; piston bore 2 5/8 inches; compression ratio, 6.5; engine displacement, 24.3 cubic inches.

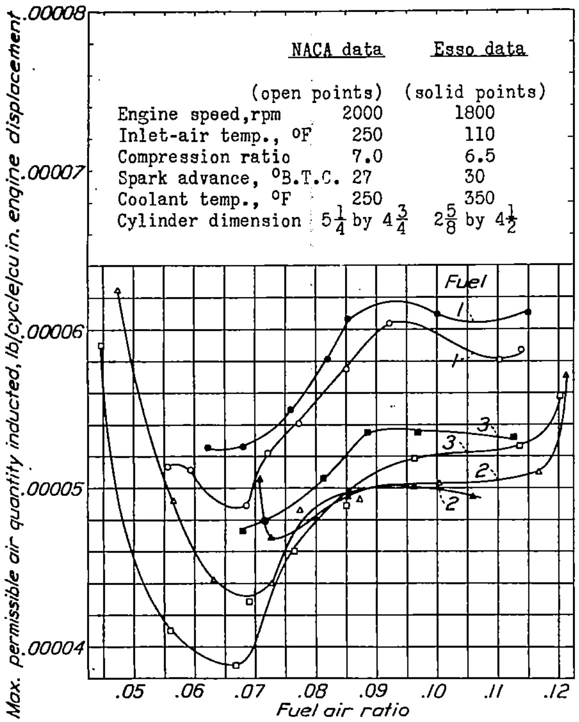


Figure 13.- Comparison of effect of fuel-air ratio on maximum permissible air quantity inducted per cubic inch of engine displacement for NACA fuels 1, 2, and 3 tested in Lycoming 0-1230 cylinder and in C.F.R.* cylinder.

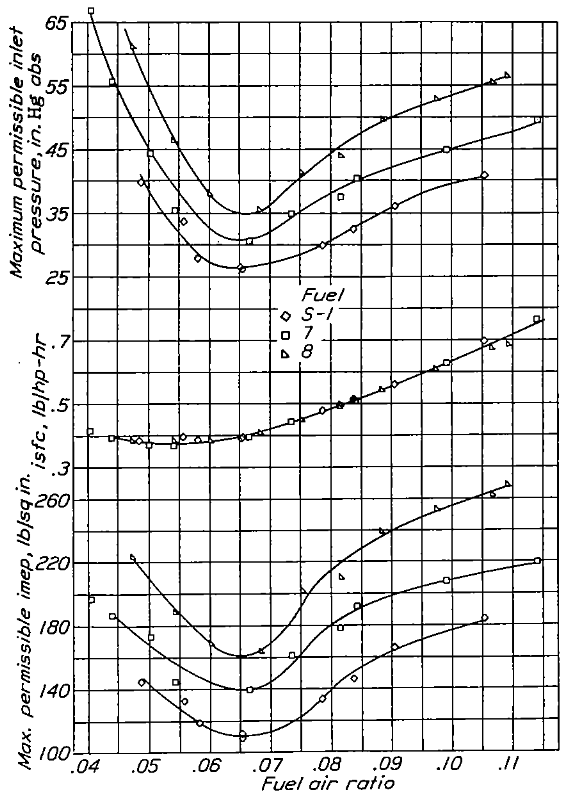


Figure 14.- Effect of fuel air ratio on maximum permissible performance of NACA fuels 7 and 8 and S-1 in Wright G-200 cylinder. Engine speed, 2000 rpm; spark advance, 20°; rear spark-plug boss temperature, 400°F; compression ratio, 7.0; inlet-air temperature, 250 °F.

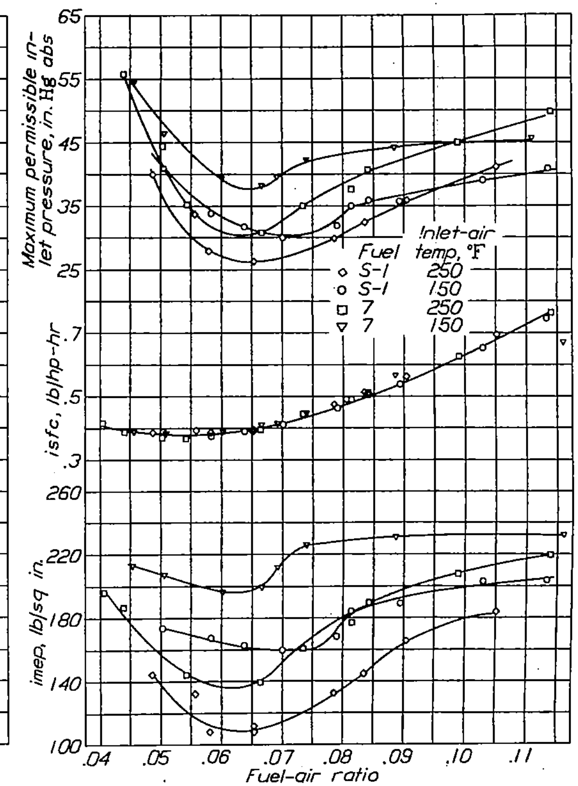


Figure 15.- Effect of fuel-air ratio on maximum permissible performance of NACA fuel 7 and S-1 in Wright G-200 cylinder at two inlet-air temperatures. Engine speed, 2000 rpm; spark advance, 20° B.T.C.; compression ratio, 7.0, rear spark-plug boss temperature, 400 °F.

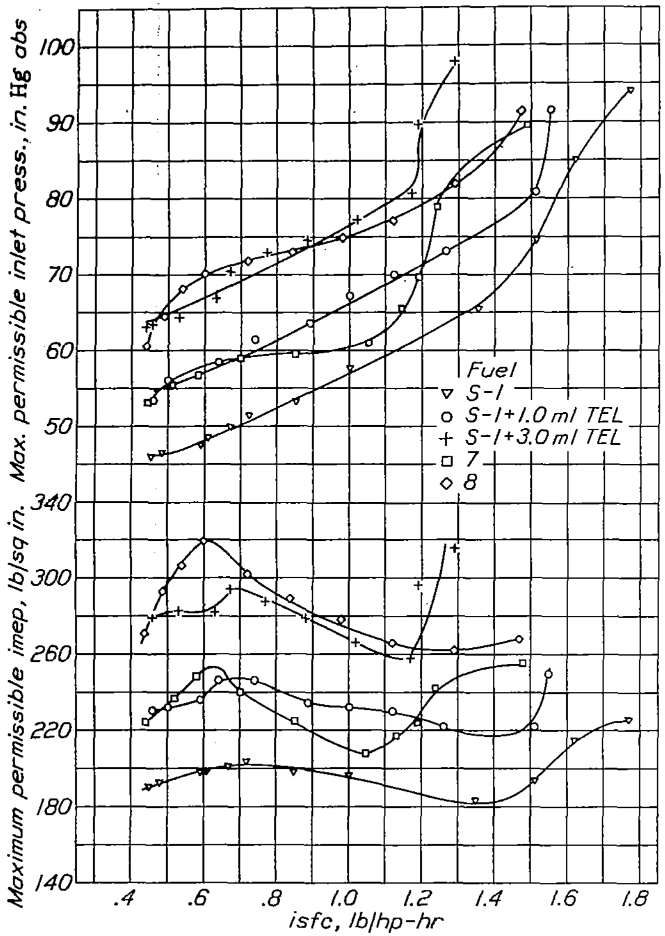


Figure 16.-Relation between indicated specific fuel consumption and maximum permissible imep and maximum permissible inlet pressure for S-1, S-1+ 1.0 ml tetraethyl lead, S-1 + 3.0 ml tetraethyl lead, and NACA fuels 7 and 8 in E.G.C. 17.6 cylinder. Engine speed, 2700 rpm; spark advance, 20°; inlet-air temperature, 225°F; compression ratio, 7.7. (Data from the Ethyl Gasoline Corporation), inlet coolant temperature, 240°F.

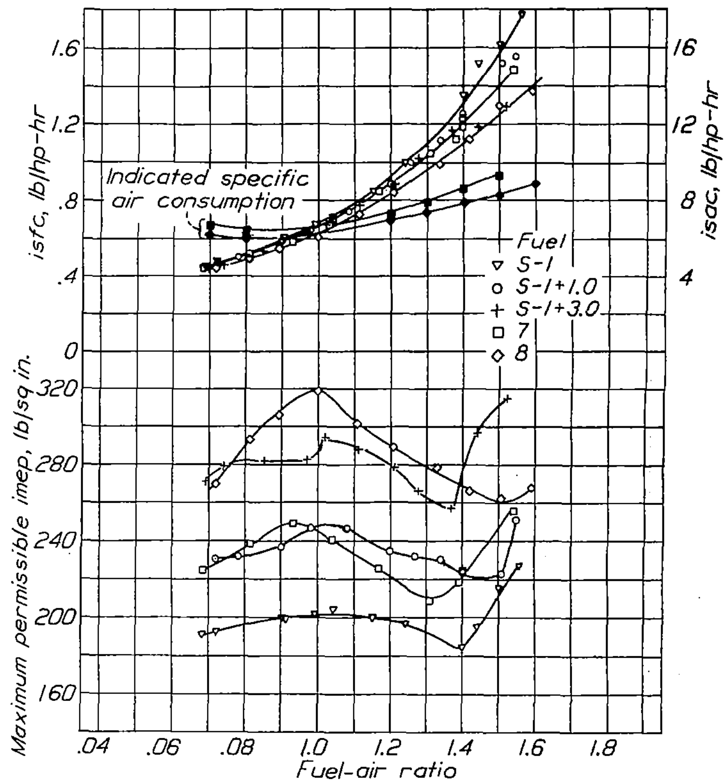


Figure 17.-Relation between estimated fuel-air ratio, maximum permissible imep, indicated specific fuel consumption, and indicated specific air consumption for S-1, S-1 + 1.0 ml tetraethyl lead, S-1 + 3.0 ml tetraethyl lead, and NACA fuels 7 and 8 in E.G.C. 17.6 cylinder. Engine speed, 2700 rpm; spark advance, 20°; inlet air temperature, 225°F; inlet coolant temperature, 240°F; compression ratio, 7.7. (Data from Ethyl Gasoline Corporation)

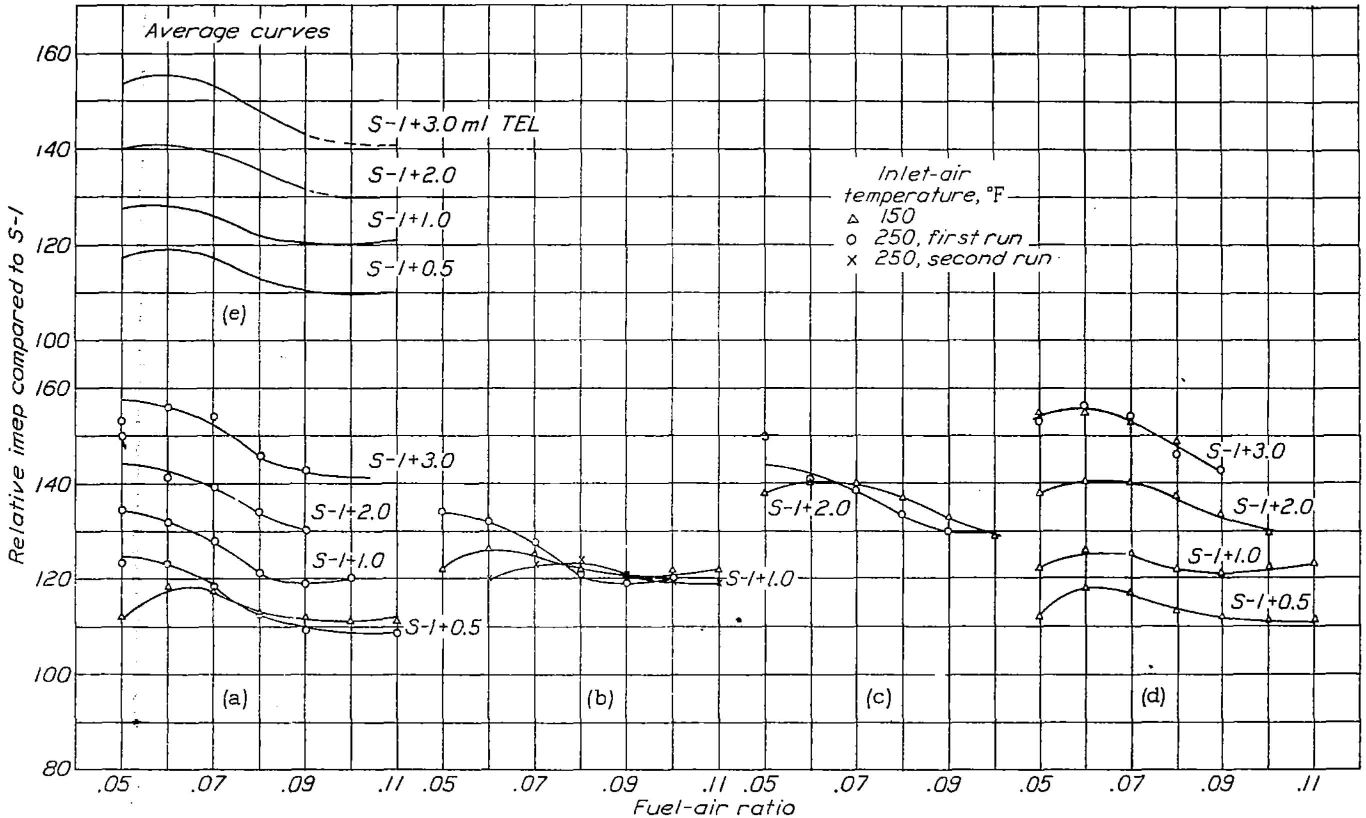


Figure 18.-Relation between fuel-air ratio and relative indicated mean effective pressure with respect to S-1 for S-1 plus tetraethyl lead when tested at different inlet-air temperatures. Lycoming O-1230 cylinder. Engine speed, 2000 rpm; spark advance, 27° B.T.C.; coolant temperature, 250°F; compression ratio, 7.0.

	△	○	◇	□	x	▽
Cylinder	O-1230	O-1230	O-1230	G-200	G-200	IGC 17.6
Engine speed, rpm	2000	2000	2000	2000	2000	2700
Inlet-air temp., °F	150	250	250	250	150	225
Spark advance, °B.T.C.	27	27	27	20	20	20
Compression ratio	7.0	7.0	7.0	7.0	7.0	7.7
Coolant temp., °F	250	250	250	-	-	240
Rear spark-plug temp., °F.	-	-	-	400	400	-

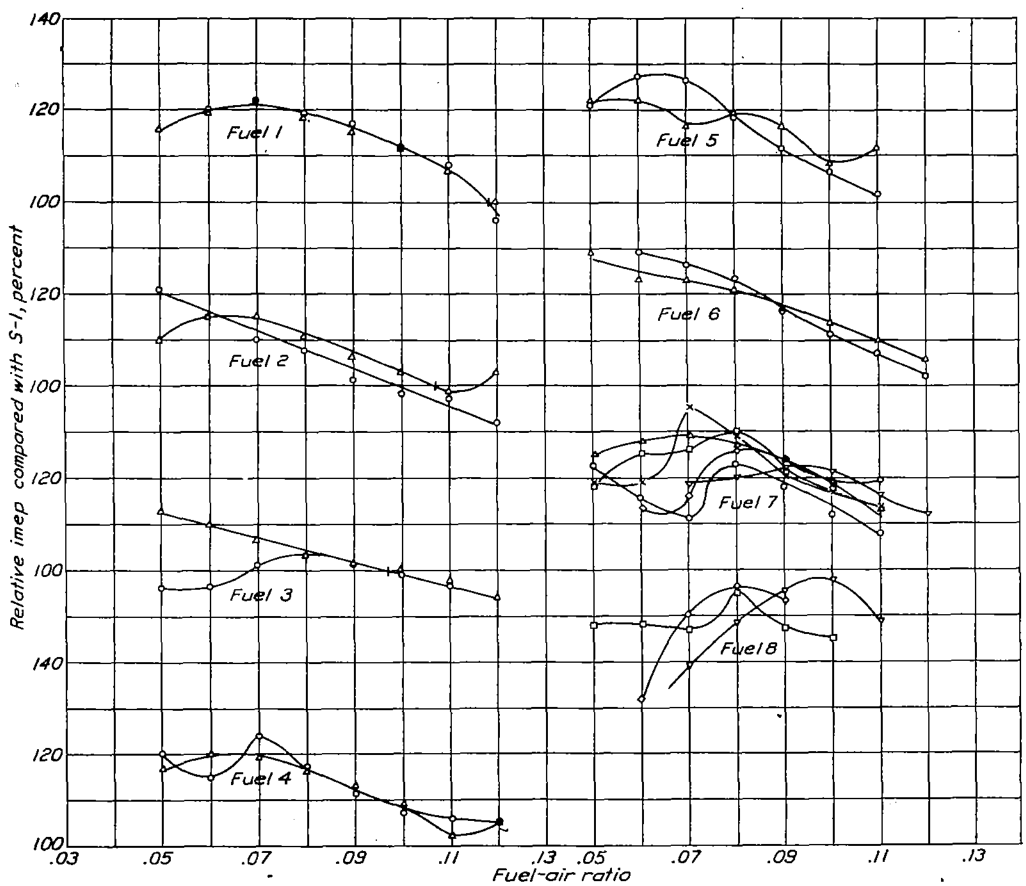


Figure 19.-Relation between fuel-air ratio and relative indicated mean effective pressure with respect to S-1 for NACA fuels 1 to 8 when tested in different engine cylinders and at different inlet-air temperatures.