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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 772

ANALYSIS OF CYLINDER-PRESSURE-INDICATOR DIAGRAMS SHOWING
EFFECTS OF MIXTURE STRENGTH AND SPARK TIMING

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SUMMARY

An investigation was made to determine the effect of mixture strength and of normal as well as optimum spark timing on the combustion, on the cylinder temperature, and on the performance characteristics of an engine. A single-cylinder test unit utilizing an air-cooled cylinder and a carburetor and operating with gasoline having an octane rating of 92 was used. The investigation covered a range of fuel-air ratios from 0.053 to 0.118. Indicator diagrams and engine-performance data were taken for each change in engine conditions.

Examination of the indicator diagrams shows that for fuel-air ratios less than and greater than 0.082 the rate and the amount of effective fuel burned decreased. For a fuel-air ratio of 0.118 the combustion efficiency was only 58 percent. Advancing the spark timing increased the rate of pressure rise. This effect was more pronounced with leaner mixtures.

INTRODUCTION

The maximum power of aircraft engines is required only for a take-off or in an emergency. For cruising, the engine power is normally only 50 to 70 percent of maximum power. The power is usually decreased by throttling the intake, that is, by reducing the manifold pressure. The power may also be reduced by leaning the mixture inducted by the engine. Leaning the mixture with constant engine speed has the advantage of reduced specific fuel consumption, although the range of power reduction is considerably less than that obtained by throttling.

The time of occurrence of ignition should have an

important influence on engine performance with both ultra-rich and ultralean mixtures. Such mixtures are slow burning. Earlier starting of combustion, obtained by advancing the spark timing, is essential to realize the greatest returns in both engine power and fuel consumption.

This investigation was made in the summer of 1937 to evaluate the effect of mixture strength and spark timing on the rate and the completeness of combustion, on the engine performance, and on the cylinder temperature throughout the available range of mixtures producing stable engine operation.

APPARATUS

The single-cylinder test unit (fig. 1) for this investigation utilized a Wright 1820-G air-cooled cylinder and piston. The engine has a bore of $6\frac{1}{8}$ inches and a stroke of 7 inches, giving a displacement of 206 cubic inches. The compression ratio was 7.4. The engine is equipped with a Stromberg NAL-5 carburetor and a fuel-injection pump, but in these tests only the carburetor was used. The air-cooled cylinder was enclosed in a sheet-metal jacket open at the front and the rear. A centrifugal blower provided the necessary cooling air for the cylinder. An electric dynamometer was used for measuring the torque of the engine and an electrically operated revolution counter and a stop watch were used for determining the engine speed. A gasometer was used to measure the combustion air and a scale, to measure the fuel. The fuel was a gasoline that complied with Army specification 2-92 Grade 92.

Iron-constantan thermocouples were peened in the cylinder head and spot-welded to the cylinder barrel at the representative positions shown in reference 1. A potentiometer was used to obtain the temperature readings.

Cylinder-pressure-indicator diagrams were taken with a modified Farnboro indicator, the pressure element being inserted in an auxiliary hole in the cylinder head.

METHOD

With a constant throttle setting and an engine speed of 1500 rpm, tests were made for a range of fuel-air ratios from 0.053 to 0.118. These fuel-air ratios were determined from the measurement of the air and the fuel entering the engine cylinder. For each mixture strength, both normal and optimum spark timing were used. Normal spark timing, which is the setting for the maximum power with the maximum-power mixture, was a constant advance of 16° B.T.C. Optimum spark timing is the setting for maximum power. The usual power, friction, fuel consumption, and air-consumption data were taken. The indicated mean effective pressure was obtained by adding the friction determined by motoring to the brake mean effective pressure. The average head temperature was determined from readings of 21 thermocouples and the average barrel temperature from readings of 8 thermocouples.

Curves showing the amount of effective fuel burned were computed by converting into weight of fuel the enthalpy changes determined from a thermodynamic analysis of the indicator diagram. These changes in enthalpy are determined for various crank-angle positions during the combustion and the expansion processes. The thermal energy is computed from the temperature, the weight, and the specific heat of the gaseous mixture. The temperature is computed from the gas law by using the pressure from the indicator diagram, the volume corresponding to the crank angle, and the weight and the gas constant of the mixture in the engine cylinder. The changes in weight, gas constant, and specific heat of the mixture as combustion proceeds are calculated on the assumption that the increment of fuel which causes the changes in enthalpy at each position is completely burned. The work done is computed by assuming straight-line pressure variation between increments of volume changes. The change in enthalpy divided by the heating value of the fuel is the amount of effective fuel burned.

RESULTS AND DISCUSSION

Indicator-card analysis.- The indicator diagrams obtained during this investigation with normal spark timing are compared at a reduced scale in figure 2. A decrease

in the fuel-air ratio from 0.082, which is approximately the condition for maximum power, decreases the rate of pressure rise and thus reduces the magnitude and delays the occurrence of maximum cylinder pressure. Figure 2 also shows that an increase in the fuel-air ratio beyond 0.082 has the same effect. The diagram taken at a fuel-air ratio of 0.118 closely resembles that taken at a fuel-air ratio of 0.064.

The scatter of the points on the indicator diagrams between top center and the position of maximum cylinder pressure indicates the cyclic variation in combustion, which is probably due in part to the variation in the mixture strength. The cyclic variations are more noticeable for both ultrarich and ultralean mixtures than for the mixture giving maximum power, indicating the importance of mixture strength on reaction velocity.

The faired curves from these indicator diagrams with their corresponding curves of effective fuel burned are shown superimposed in figure 3. The regularity of increasing changes in the indicator diagrams and the curves of effective fuel burned is broken by those taken at a fuel-air ratio of 0.118. The fuel-burned curves show that, for fuel-air ratios less than and greater than 0.082, the rate of burning and the amount of effective fuel burned decrease. The reduction in the total effective fuel burned for lean mixtures is due to the fact that less fuel is available for combustion; whereas, for rich mixtures, the reduction is due to incomplete combustion. For instance, the combustion efficiencies (ratio of effective fuel burned to fuel inducted) for lean mixtures were 100 percent; whereas, for mixtures having fuel-air ratios of 0.118, 0.082, and 0.073, they were 58, 88, and 98 percent, respectively. For all fuel-air ratios, the maximum effective fuel burned occurred between 30° and 40° A.T.C. This position is the end of effective fuel burning because any later burning produces less heat than that lost to the cylinder walls.

Figure 4 shows faired curves from indicator diagrams taken with both normal and optimum spark timing and with various mixture strengths. Each of the fuel-air ratios given on the figure is an average of the mixture used with normal and optimum spark timing. The greatest deviation from any average fuel-air-ratio value was 0.003. The results show that advancing the spark timing advances the time of occurrence of maximum cylinder pressure and increases

its magnitude. The rate of pressure rise also increases. This increase in the rate of combustion should result in improved cycle efficiency although the increased amount of negative work during the early stages of combustion will somewhat reduce the efficiency. Figure 4 shows that control of the spark timing increases in importance as the mixture is leaned.

Engine performance.- The effect of fuel-air ratio and spark timing on engine performance is shown in figure 5. As indicated by the relative areas of the indicator diagrams (fig. 2), maximum power occurred at a fuel-air ratio of 0.082. With normal spark timing, 77 percent of maximum power was produced at a fuel-air ratio of 0.056. This reduced power is sufficient, without change in the throttle, for cruising operation under some flight conditions.

Specific fuel consumption is a function of thermal efficiency, which, in turn, is a function of combustion and cycle efficiencies. Cycle efficiency is indicated by the rate of pressure rise on the indicator diagram. Reference to the indicator diagrams (fig. 2) shows that the cycle efficiency for normal spark timing decreases as the mixture is made leaner or richer than the optimum fuel-air ratio of 0.082. Figure 5 shows that, for normal spark timing, the fuel consumption decreased with leaning of the mixture to a fuel-air ratio of 0.064. The loss in cycle efficiency was therefore more than offset by the increase in combustion efficiency. For mixtures having a fuel-air ratio of less than 0.064, the combustion was complete and the fuel consumption should therefore increase because of the decrease in the cycle efficiency. For rich mixtures, the poorer cycle and combustion efficiencies combine to give a much larger specific fuel consumption.

Advancing the spark timing was shown in figure 4 to increase the rate of combustion and the power output. The fuel consumption should therefore be less than with normal spark timing. This conclusion is borne out by the lower specific fuel consumption shown in figure 5. It will also be seen that 77 percent of maximum power and minimum fuel consumption occurred at lower fuel-air ratios than for normal spark timing. The earlier ignition of the mixture increased the power output, decreased the specific fuel consumption with constant mixture strength, and increased the leanness of the mixture at which the engine would operate consistently. This reduction in fuel consumption is more clearly shown in figure 6.

The indicated power obtained at a fuel-air ratio of 0.118 is about equal to that obtained at a fuel-air ratio of 0.066. The fuel consumption, however, is about double. These facts are further substantiated by examination of the indicator diagrams and the curves of effective fuel burned (fig. 3) and by the knowledge that about twice as much fuel was used for the rich as for the lean mixture.

Cylinder temperature.- Figure 7 shows the average cylinder-head and cylinder-barrel temperatures recorded during this investigation. The maximum temperature with normal spark timing occurred at a fuel-air ratio of 0.072. This value is in agreement with the values found by Rabezzana and Kalmar (reference 2) and by Swan and Morley (reference 3). With both richer and leaner mixtures, the temperature rapidly decreased.

Figures 5 and 7 show that, for lean mixtures, the cylinder temperature is approximately proportional to the power output. Maximum cylinder temperature, however, does not occur at the fuel-air ratio giving maximum power.

The decrease in cylinder temperature from the maximum with increase in mixture strength up to the occurrence of maximum power is due to the presence of unburned combustibles, which have a high thermal capacity. The effect would have been much more pronounced if the power had not increased. Further enriching of the mixture resulted in a greater amount of unburned combustibles with an attendant loss in power, which caused further reduction in the cylinder temperature. For mixtures leaner than that giving maximum cylinder temperature, the decrease in cylinder temperature is due to both the increase in the quantity of unburned air present and the decrease in the amount of fuel burned. (See fig. 3.) It appears that, if the power had been maintained constant irrespective of the mixture strength, curves similar to those shown in figure 7 would have been obtained. The cylinder temperature would have increased to a maximum value and then decreased; the maximum value would have occurred at approximately the theoretically correct mixture strength.

It should be noted that the same power output may be obtained for mixtures leaner as well as richer than that giving maximum power, but at the expense of higher cylinder temperature. Operation at these leaner mixtures would be advantageous when fuel consumption is an important item and the power required is such as to produce cylinder temperatures less than the maximum allowed.

CONCLUSIONS

The following conclusions are based on the results obtained from a single-cylinder engine using a carburetor fuel system.

A study of the cylinder-pressure-indicator diagrams and their thermodynamic analysis shows that, for fuel-air ratios less than and greater than 0.082, the rate of pressure rise was decreased, the pressure magnitude was decreased, and the occurrence of maximum cylinder pressure was delayed. The rate of fuel burned decreased and the amount of effective fuel burned also decreased. For a fuel-air ratio of 0.118, the combustion efficiency was only 58 percent. The end of effective fuel burned occurred between 30° and 40° A.T.C. Advancing the spark timing up to the optimum timing increased the rate of pressure rise, increased the pressure magnitude, and advanced the occurrence of the maximum cylinder pressure. These effects were more pronounced with leaner mixtures.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 24, 1940.

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2. Rabezzana, Hector, and Kalmar, Stephen: Mixture Distribution in Cylinder Studied by Measuring Spark Plug Temperature. Auto. Ind., vol. 66, no. 12, March 19, 1932, pp. 450-454; and vol. 66, no. 13, March 26, 1932, pp. 486-491.
3. Swan, J., and Morley, A. W.: Tests of a Nine Cylinder Radial Engine at Reduced Mixture Strength and with Variable Ignition Timing. R.&M. No. 1485, British A.R.C., 1932.

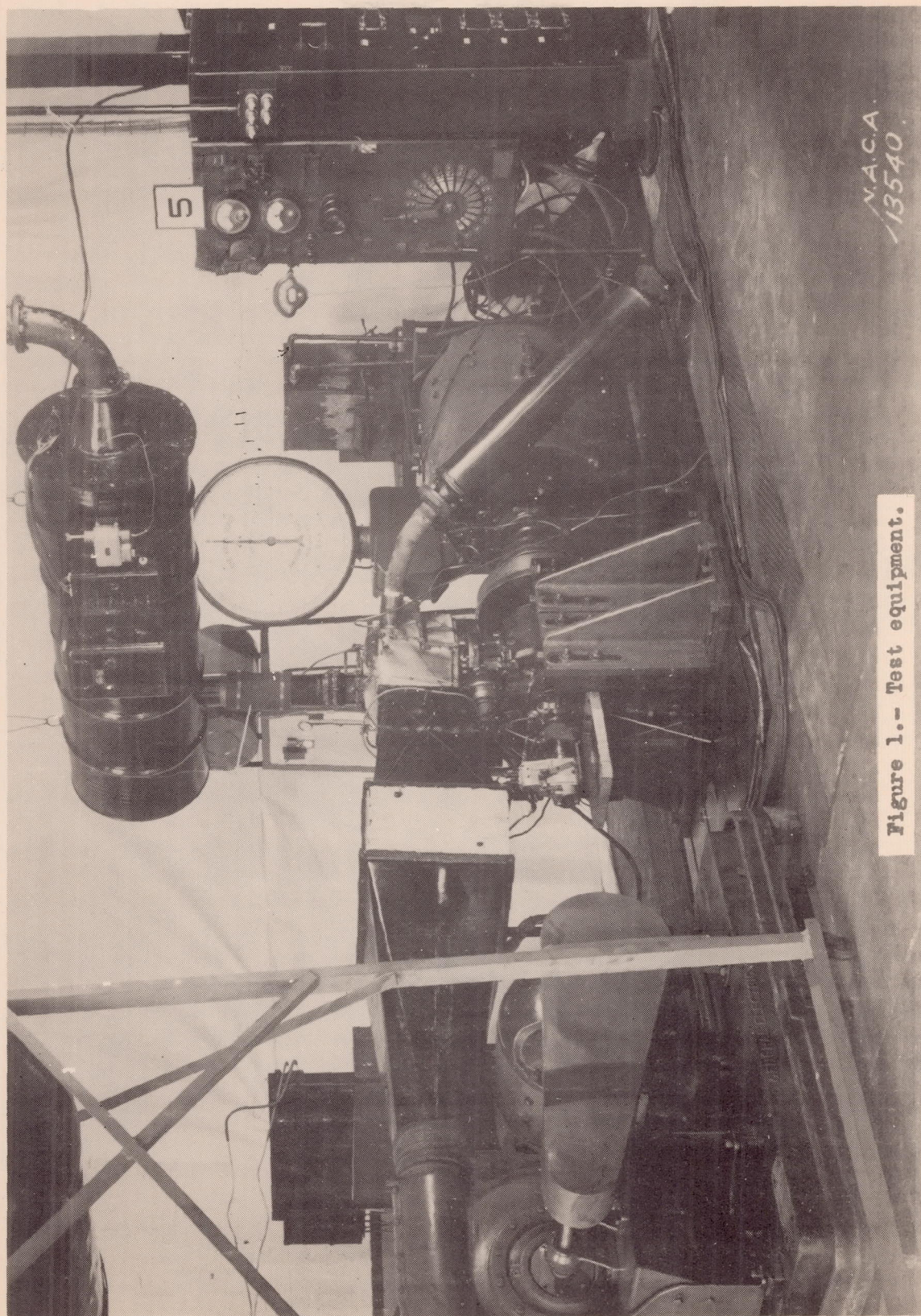


Figure 1.- Test equipment.

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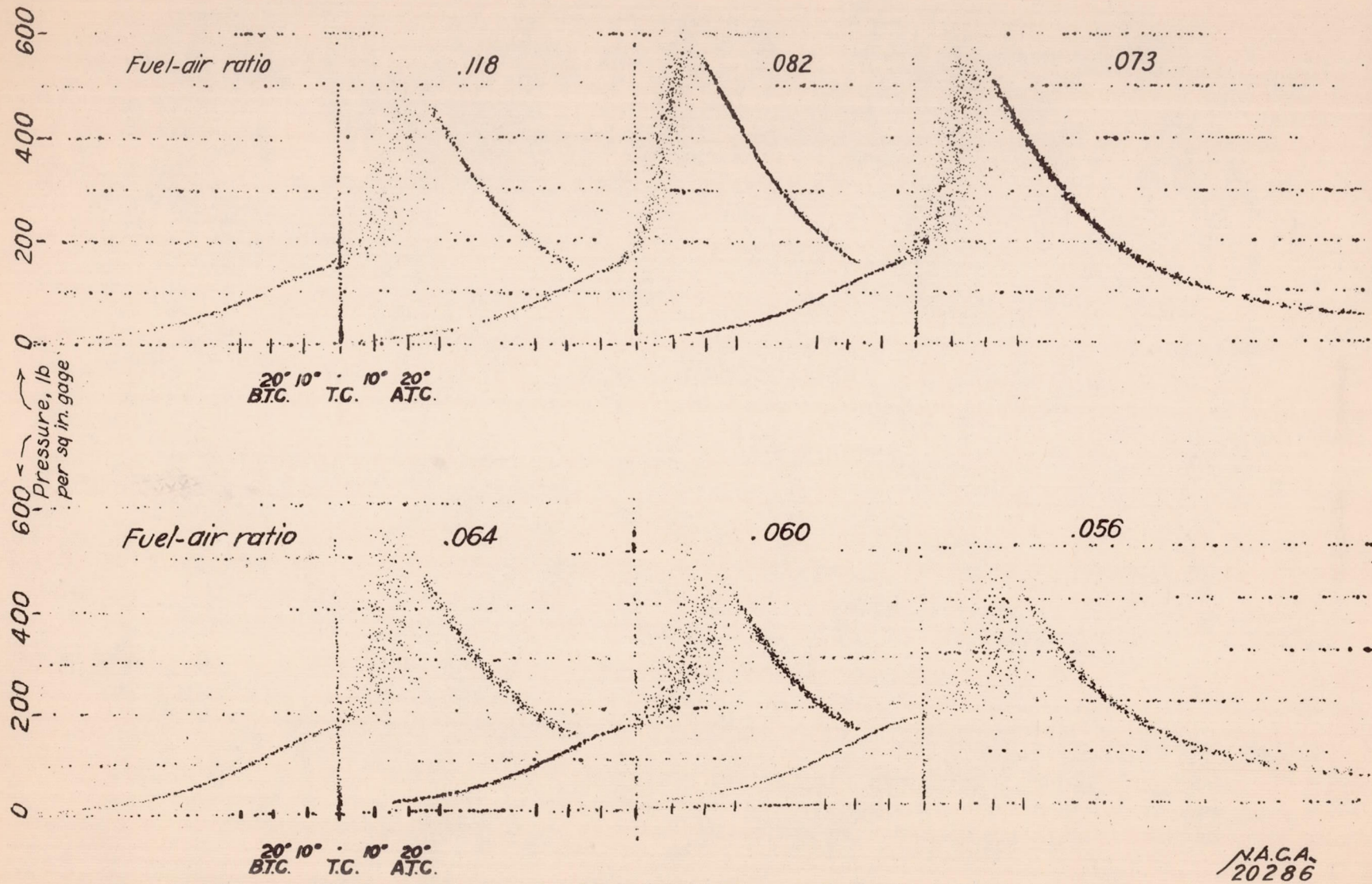


Figure 2.- Farnboro indicator diagrams obtained for different fuel-air ratios.
Engine speed, 1500 rpm, compression ratio, 7.4, spark timing, 16 crank degrees B.T.C.

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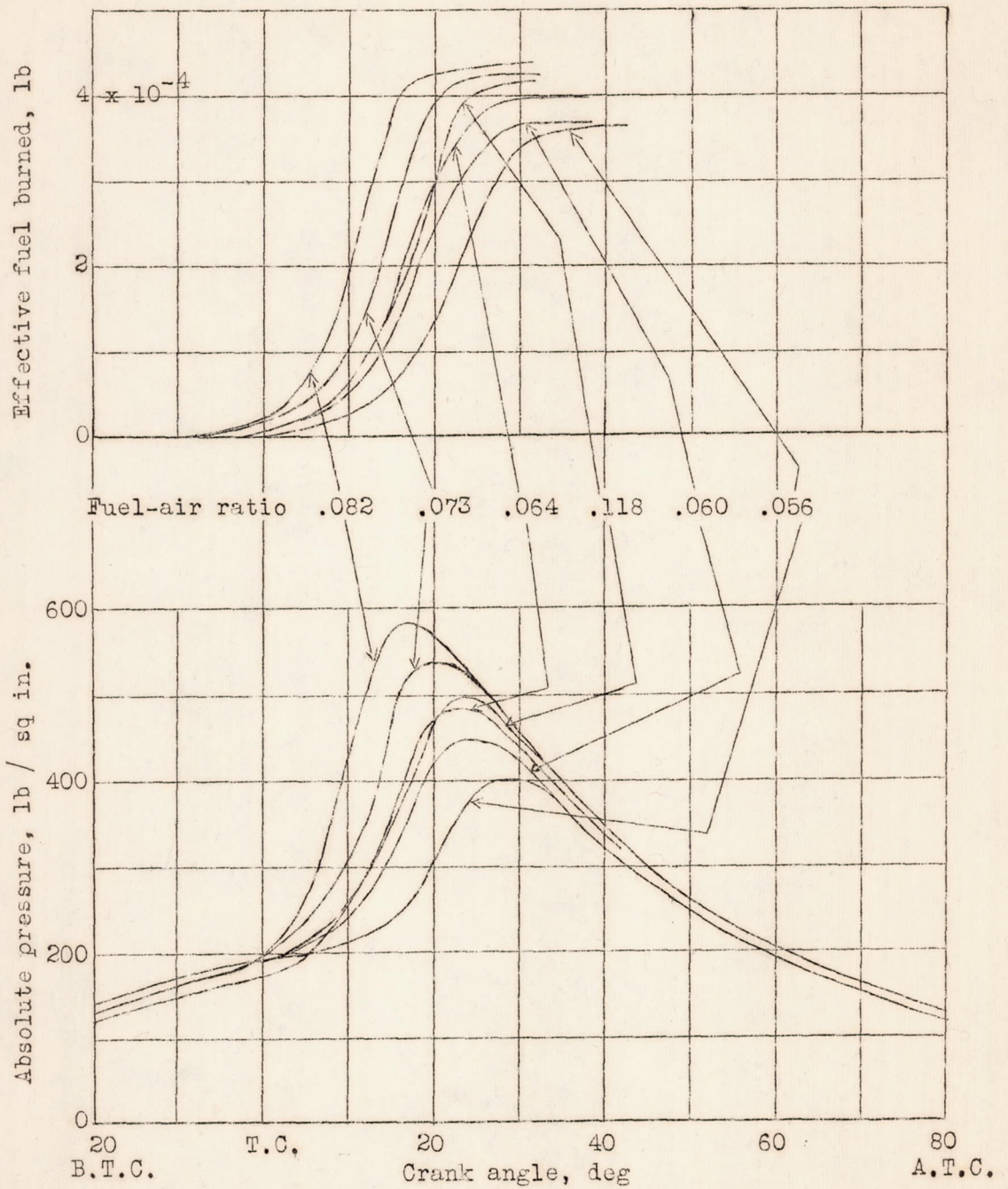


Figure 3.- Effect of mixture strength on indicator cards. Spark timing, 16 crank degrees B.T.C.

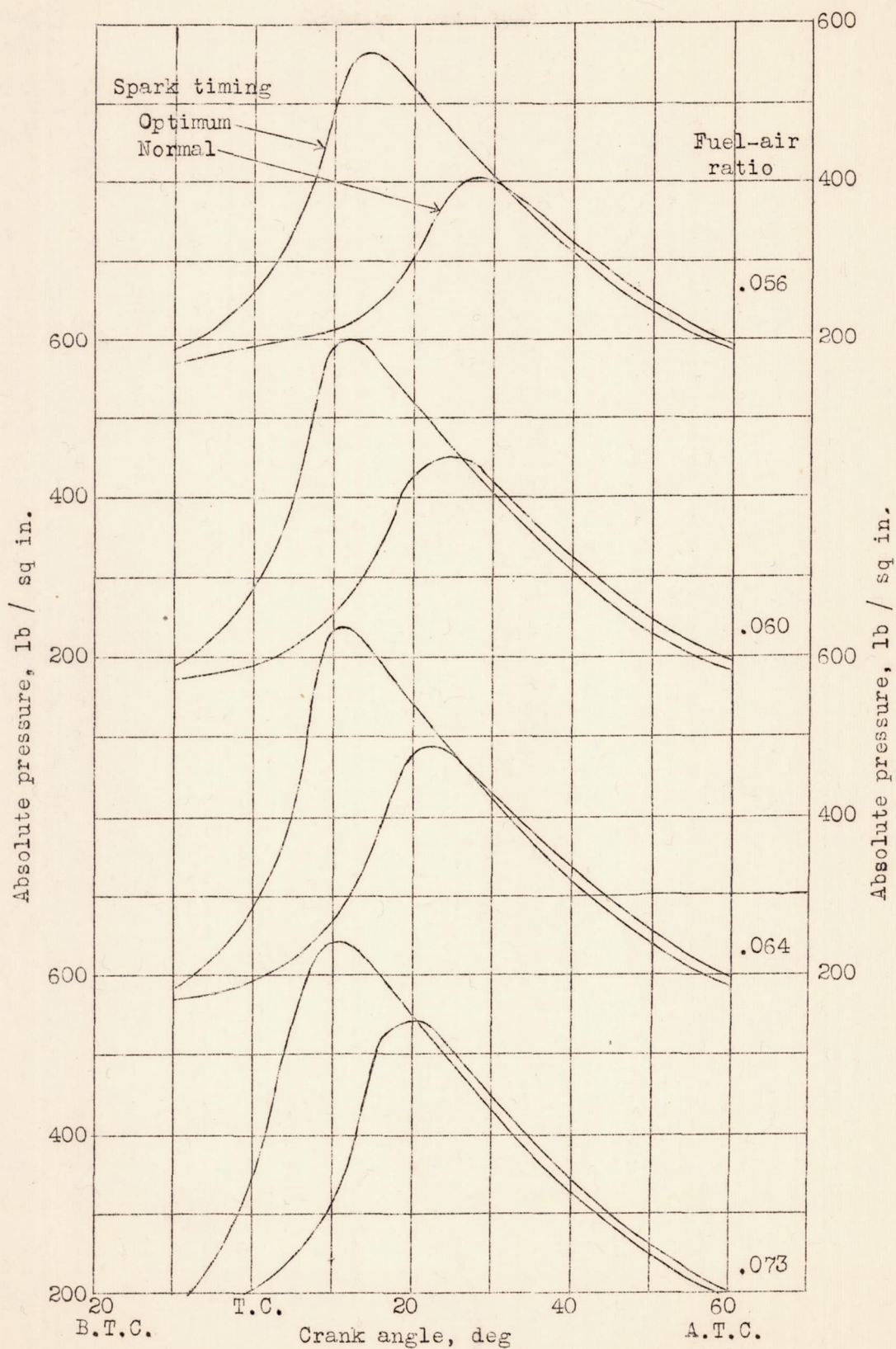


Figure 4.- Effect of mixture strength and spark timing on indicator-card shape.

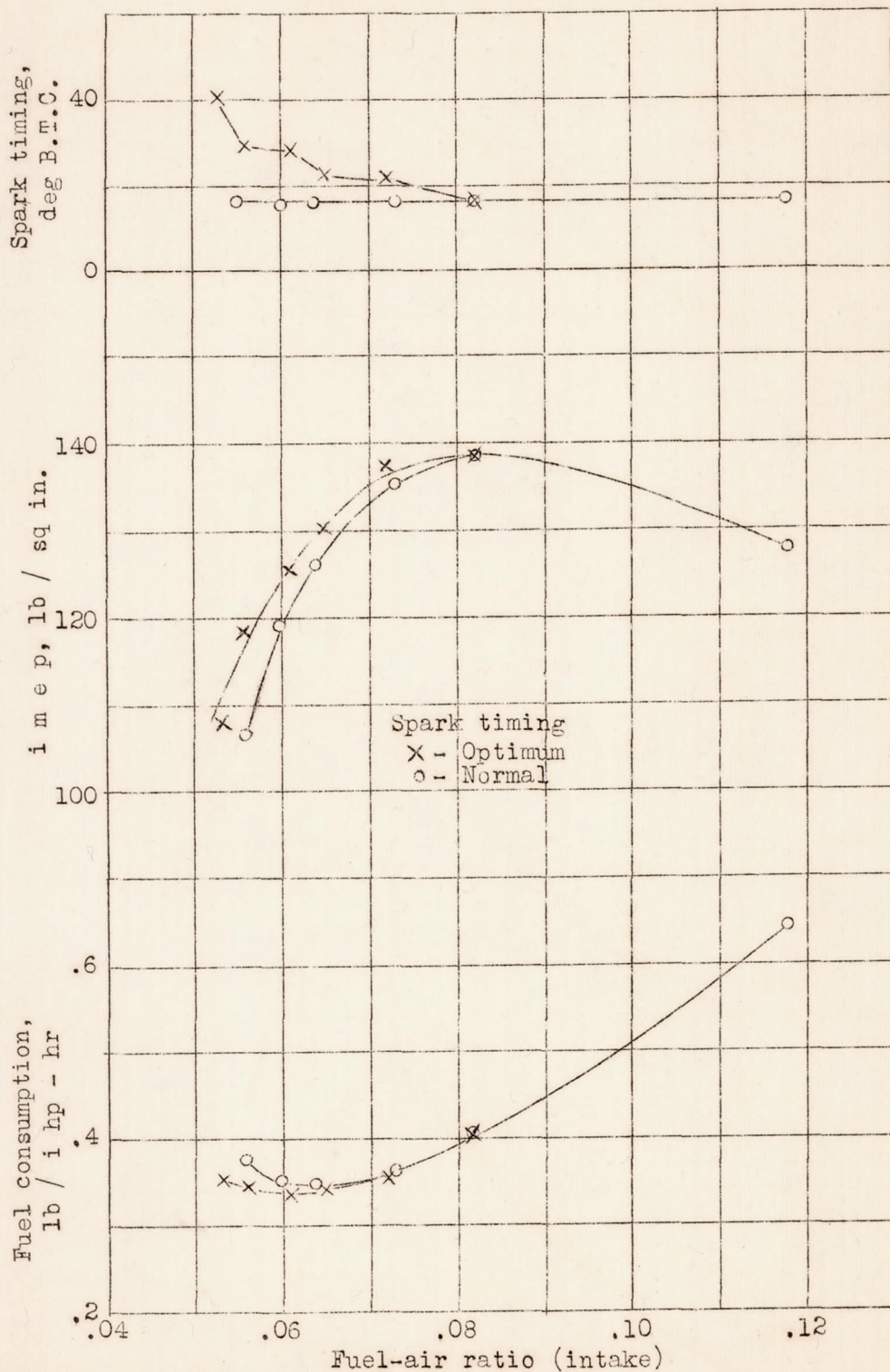


Figure 5.- Effect of mixture strength and spark timing on engine performance.

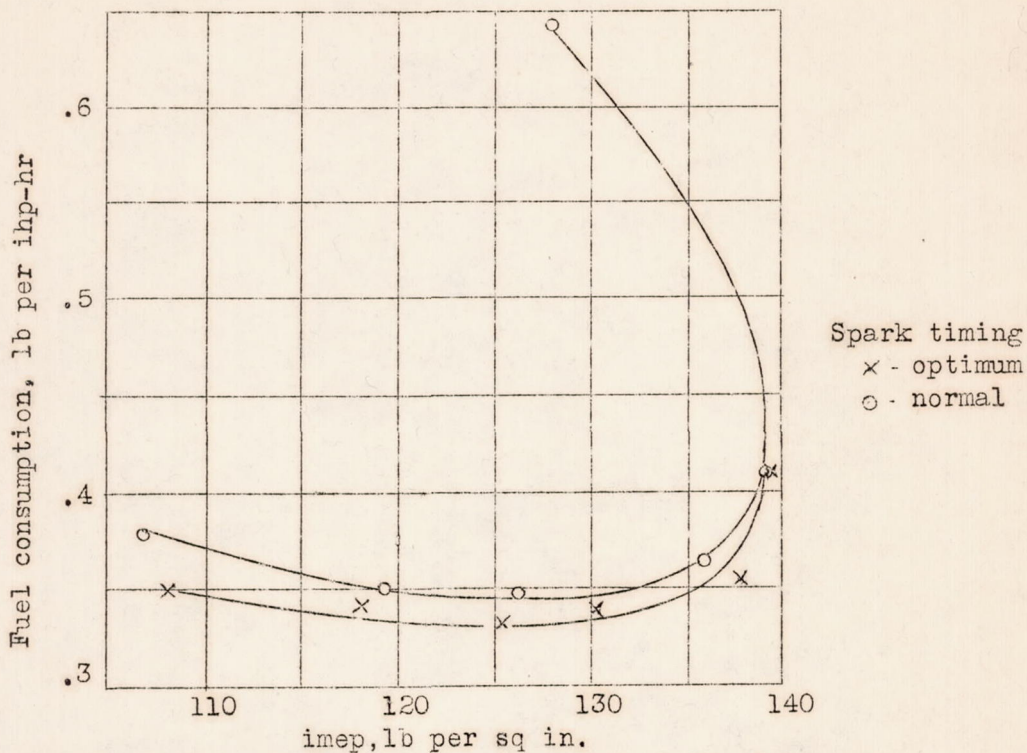


Figure 6.- Variation of fuel consumption with indicated mean effective pressure (mixture control run).

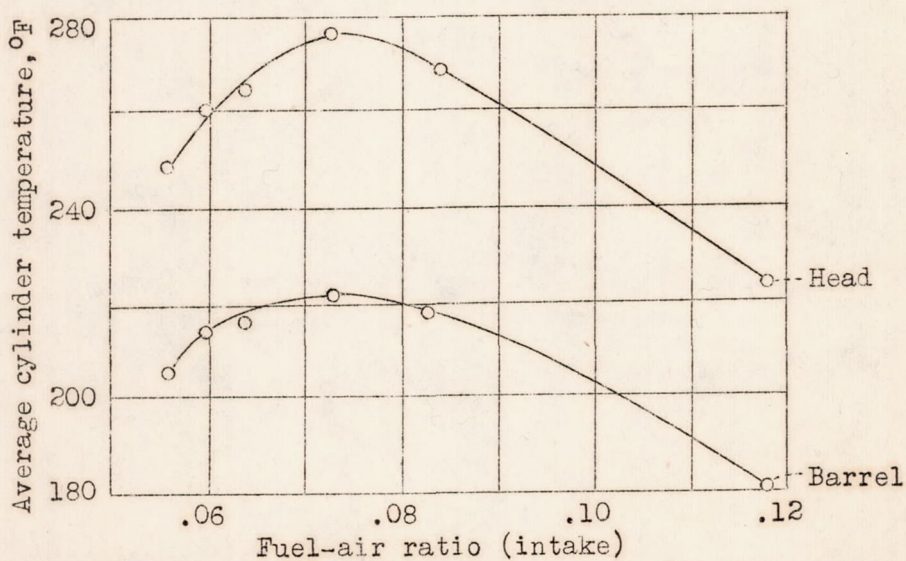


Figure 7.- Effect of mixture strength on cylinder temperatures. Spark timing, 16 crank degrees B.T.C.