MR No. E5H04

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

August 1945 as
Memorandum Report E5H04

FLIGHT AND TEST-STAND INVESTIGATION OF HIGH-PERFORMANCE FUELS IN MODIFIED DOUBLE-ROW RADIAL AIR-COOLED ENGINES

II - FLIGHT KNOCK DATA AND COMPARISON OF FUEL KNOCK LIMITS WITH ENGINE COOLING LIMITS IN FLIGHT

By H. Jack White, Philip C. Pragliola
and Calvin C. Blackman

Aircraft Engine Research Laboratory
Cleveland, Ohio

NACA

WASHINGTON

E-262

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MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

FLIGHT AND TEST-STAND INVESTIGATION OF HIGH-PERFORMANCE FUELS IN MODIFIED DOUBLE-ROW RADIAL AIR-COOLED ENGINES

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SUMMARY

A comparison has been made in flight of the antiknock characteristics of triptane and a temperature-sensitive fuel component (xylidines) with a reference fuel (28-R) and of flight fuel knock limits with engine cooling limits. The knock limits of the three fuels – 28-R, 80 percent 28-R plus 20 percent triptane (leaded to 4.5 ml TEL/gal), and 97 percent 28-R plus 3 percent xylidines (leaded to 6.0 ml TEL/gal) – were investigated in a modified 14-cylinder double-row radial air-cooled engine installed in a four-engine airplane. Tests were conducted at engine speeds of 1800 and 2250 rpm, at high and low blower ratios, spark settings of 25° and 32° B.T.C., and the carburetor-air temperature was maintained at approximately 85° F. All tests for a given engine speed were made with approximately constant cooling-air pressure drop; consequently, engine-temperature levels were higher with the higher performance blends.

A brief survey of the knock-limited performance characteristics of the two fuel blends relative to 28-R follows:

RATIOS OF KNOCK-LIMITED BRAKE HORSEPOWER OF TEST

FUELS RELATIVE TO 28-R

Engine speed, rpm		1800				2250			
Carburetor-air temperature, °F		85				85			
Blower ratio		Low		High		Low		High	
Fuel blend (volume)	F/A	Spark advance, deg B.T.C.							
		25	32	25	32	25	32	25	32
80% 28-R plus 20% triptane leaded to 4.5 ml TEL/gal	0.065	1.15		1.11	1.20	1.21	1.15	1.25	1.13
	.080	1.20		1.20	1.18	1.19	1.17	1.19	1.27
	.090	1.24		1.20	1.19	1.24		1.21	1.27
97% 28-R plus 3% xylidines leaded to 6.0 ml TEL/gal	0.065			1.21	1.17	1.23	1.10	1.21	1.13
	.080			1.27	1.21	1.24	1.20	1.20	1.17
	.090			1.27	1.21	1.26		1.25	

Estimates were made of temperature-limited engine performance at several typical flight and engine conditions. Based on these relations it appears that, if the cooling requirements of the engine are to be governed by the manufacturer's specified maximum rear-spark-plug-gasket temperatures, engine operation at or near fuel knock limits in the economical range of fuel-air ratio may cause these temperatures to be exceeded, particularly at the higher engine speed of 2250 rpm. If it were considered possible to operate with average rear-spark-plug-boss temperatures approaching those experienced with the original model engine (corresponding to maximum rear-spark-plug-gasket temperatures specified for those engines), the cooling limits of the modified engine would be raised and would apparently permit engine operation at or near fuel knock limits under many conditions.

INTRODUCTION

The tests reported herein are an extension of a general investigation to evaluate triptane and other high-performance fuels as antiknock components of aviation fuels. This work is being conducted at the NACA Cleveland laboratory at the request of the Air Technical

Service Command, Army Air Forces. The scope of these tests, which have included single-cylinder and multicylinder work, has been briefly described in reference 1. This reference presents the results of flight knock tests made with the original test engine; the flight cooling characteristics and a comparison between test-stand and flight cooling characteristics of the original test engine are presented in references 2 and 3, respectively.

In order to parallel the procedure used in the presentation of flight data taken with the original engine, knock data for the current series of flight tests with modified engine are being reported in the same order. The cooling characteristics of the modified engine in flight are given in reference 4, which is part I of the present series of reports. The engine-cooling data of reference 4 are used in this report to compare fuel knock limits with the estimated cooling-limit relations for the same engine installed in a four-engine airplane.

TEST FUELS

The knock data obtained with the modified engines in flight for 28-R fuel, a blend of 80 percent 28-R and 20 percent triptane (plus 4.5 ml TEL/gal), and a blend of 97 percent 28-R and 3 percent xylidines (leaded to 6.0 ml TEL/gal) are compiled and discussed herein. Fuels were blended, as for previous tests, on a volume basis. These fuels will hereinafter be designated 28-R, triptane blend, and xylidine blend. The xylidine blend was chosen because it represents a temperature-sensitive fuel that bridges the gap in performance numbers between the lean rating of 28-R and the rich rating of the triptane blend. The knock ratings of the test fuels, obtained at the Cleveland laboratory, are as follows:

Fuel	Army-Navy performance number	
	F-3 rating (lean)	F-4 rating (rich)
28-R	100	130
Triptane blend	109	147
Xylidine blend	100	150

EQUIPMENT AND INSTRUMENTATION

Obtaining fuel knock ratings of the mixture-response type involves the following measurements: engine manifold pressure, brake horsepower, fuel flow, charge-air flow, and inlet-charge temperatures. Measurements of various cylinder temperatures were made to supplement these data because fuel knock characteristics may be affected to a certain extent by engine temperature levels. In tests of this type, the determination of the intensity and distribution of knock among the cylinders is necessary.

For most of the tests reported herein, a modified 14-cylinder double-row radial air-cooled engine (R-1830-94) was used, and the installation of this engine was (as for the original test engine, R-1830-90C) at the left inboard position in a B-24D airplane. Data for flights subsequent to number 47 were obtained with another engine of the same model. The equipment and instrumentation for these tests were very nearly the same as were used in tests with the R-1830-90C engine. The chief difference in the instrumentation of the two types of engine was a set of 14 thermocouples installed at the rear of the cylinder hold-down flanges for the first modified engine, which was not installed on the original engine. This position was selected because the manufacturer's temperature limits for cylinder "barrels" are based on flange temperatures. (See reference 5.)

The original test engine was equipped with a set of shallow-type, rear-spark-plug-boss thermocouples, embedded 1/8 inch, in addition to the standard installation, embedded 3/8 inch. The shallow embedded thermocouples were previously discussed only in reference 3 where it was necessary to use a measurement that would duplicate the test-stand installation. The modified engines do not have shallow-type thermocouples.

A fairly comprehensive description of the equipment and instrumentation used with the modified test engines is given in the appendix of reference 4, which presents a written and pictorial description of all the important instrumentation including thermocouples, cooling-air pressure tubes, knock pickups and harness, fuel-flow meters, special controls, control-position indicators, the exhaust-gas oxidizing furnace, and other research equipment used in these tests. Much of this equipment was used for tests with both the original and the modified test engines.

As was the case in former tests with the original engine, a PD-12F2-16 carburetor was used for the modified test engines. This carburetor permitted a wider range of fuel-air ratio at cruising engine speeds than would be possible with the PD-12F7 carburetor, which is standard for the modified engine. The special mixture-control plate described in reference 1 was used for the sensitive control of fuel flow in the lean-mixture range with this carburetor.

TEST PROCEDURE AND CONDITIONS

Procedure. - A technique similar to that employed for the original engine (reference 1) was used for obtaining knock data with the modified engines. The carburetor-air temperature was maintained constant by adjusting the intercooler shutter opening and, in some cases, by bucking the turbosupercharger output with the engine throttle (part-throttling).

As in tests with the original engine, knock data were recorded when four, five, or six cylinders showed light or occasional knock. The procedure for cooling the engine during knock tests was to maintain approximately constant indicated airspeed and constant cowl-flap setting. This procedure, which was used for the earlier knock tests, is explained in more detail under PROCEDURE in reference 1. One departure from the practice of holding a constant cooling-air pressure drop was made: Instead of maintaining an indicated airspeed of approximately 200 mph for all the knock runs, as in reference 1, the tests at 1800 rpm were made with an airspeed of approximately 180 mph whereas those at 2250 rpm were made at approximately 200 mph. A cowl-flap setting of full open was held throughout the tests for the original and the modified test engines.

The maintenance of an approximately constant cooling-air $\sigma\Delta p$ resulted, of course, in a variation of engine temperatures, both for the different fuels and for changes in fuel-air ratio, the primary test variable. A special investigation was made to determine the extent by which the two methods of test-engine cooling – constant cooling-air pressure drop (customarily used) and constant head temperature – affect the shape or position of a knock curve at a given set of engine conditions. At the engine conditions used for this investigation no appreciable difference in knock limits was observed for the two methods; a tentative justification was thus obtained for the method used. (See appendix A.)

Test conditions. - The following table lists the engine-operating conditions at which the various fuels were tested. Values of carburetor-air temperature given are those indicated by the resistance-bulb thermometer unit in the carburetor elbow. This unit closely simulates the standard airplane installation. The actual carburetor calibration was based upon a screen thermocouple temperature T_c, which was employed in analyzing all data and was found to indicate temperatures approximately 5° F higher than the resistance bulb.

Fuel	Engine speed (rpm)	Blower ratio	Spark setting (deg B.T.C.)	Approximate carburetor-air temperature (°F)
Xylidine blend	1800	High	25 and 32	85
	2250	High and low	25	85
Triptane blend	1800	Low	25	85
	1800	High	25 and 32	85
	2250	Low and high	25	85
28-R	1800	Low	25	85
	1800	High	25 and 32	85
	2250	Low and high	25	85
	2230	High	25	100

The engine conditions pertaining to the various groups of knock curves and the numbers of the flights from which the various knock curves or check points were obtained are given on the figures. Table I lists flight conditions and recorded free-air temperatures according to flight number. Variation in free-air temperature was, of course, due to atmospheric conditions and could not be avoided.

RESULTS AND DISCUSSION

Knock-Limited Performance

Presentation of knock data. - Results of the flight knock tests are plotted in basic form in figures 1 through 8 and are arranged, as nearly as possible, in the order of increasing severity of engine conditions (for example, fig. 1: 1800 rpm, low blower ratio, low spark setting; fig. 2: 1800 rpm, high blower ratio, low spark setting; fig. 3: 1800 rpm, high blower ratio, high spark setting). The (a) sheet of each figure shows knock-limited manifold pressure, knock-limited brake horsepower, fuel flow, brake specific fuel consumption, and average mixture temperature; the (b) sheet shows knock-limited brake mean effective pressure, knock-limited charge-air flow, exhaust pressure, and average cooling-air pressure drop for heads and barrels; and the (c) sheet presents carburetor-air temperature (screen thermocouple) and average and maximum values of three cylinder temperatures.

Check points on the knock curves are represented by tailed symbols. Check data were obtained for nearly all the curves. In some instances, scatter of the data for certain of the variables such as average mixture temperature, brake specific fuel consumption, carburetor-air temperature, and average cooling-air pressure drop made differentiation between fuels difficult, therefore a single average curve was faired through the test points. In most cases, however, separate curves for all three fuels will be found.

Discussion of knock-test data. - The knock curves in figures 1 and 2 show little variation of knock-limited manifold pressure over the range of fuel-air ratio between 0.06 and 0.10. Flat knock curves are frequently noted when engine conditions are very mild with regard to fuel knock. In figure 1, consequently, the knock-limited brake-horsepower curves approximate the relation that usually exists for the variation of brake horsepower with fuel-air ratio at constant manifold pressure. The knock limit of the triptane blend falls considerably higher than that of 28-R over the entire range of fuel-air ratio in figures 1 and 2. The knock limits of the xylidine blend exceed those of the triptane blend by a definite margin. (See fig. 2.)

The knock data in figure 3, which were obtained at more severe engine conditions (high spark advance and high blower ratio) than those of figures 1 and 2, show the xylidine blend to be depreciated, relative to the triptane blend, by the change in engine conditions. Both fuels, however, exhibit a definite improvement in knock limit over 28-R. The knock limits of all three of the fuels were lowered to some extent by the higher spark advance. (Cf. figs. 2 and 3.) No apparent improvement in brake specific fuel consumption was noted at the higher spark advance within the range of the data, but it is emphasized that tests were not run primarily to investigate the effect of spark advance on specific fuel consumption. Knock data for the three fuels at an engine speed of 2250 rpm are shown in figures 4 and 5. At low blower ratio and low spark setting (fig. 4) the xylidine blend nearly equaled the triptane blend in knock-limited performance at the rich and lean extremes and exhibited slightly higher knock limits at intermediate mixtures. A relatively flat mixture-response curve was again obtained with 28-R at these conditions. At high blower ratio and low spark setting (fig. 6) the increase in severity of engine conditions again effected a slight depreciation of the knock limits of the xylidine blend relative to the triptane blend in the lean region. The high spark setting at 2250 rpm effected a decrease in knock limits for all three fuels and decreased the performance both of the triptane and xylidine blends relative to 28-R. This effect is to be observed both for low and for high blower ratios. (Cf. figs. 4 and 5 and figs. 6 and 7.)

The data obtained in these tests show that the xylidine blend consistently decreased more in knock limit than the triptane blend or the 28-R fuel as the engine conditions became more severe. This effect is accounted for by the greater temperature sensitivity of the fuel, as noted in reference 1.

Figure 8 presents knock data obtained with 28-R fuel at a carburetor-air temperature approximately 15° F higher than was maintained for the other tests of this report. In order to check the knock limits of the modified engine against those of the original, similar conditions were used to test the fuel. These data, however, do not permit a fair comparison because of the necessity of maintaining an unusually high exhaust pressure to obtain the desired carburetor-air temperature by bucking the turbosupercharger output with the throttle. (The tests with the modified engine were conducted in much colder weather than those with the original.) Because of the possible effects of exhaust pressure on the knock limits, these data may not be completely comparable with the rest of the tests.

For all plots (figs. 1 through 7) data for brake specific fuel consumption with the three test fuels at a given set of engine conditions define nearly the same curve, despite a difference in knock-limited power level (and over-all mechanical efficiency). The lack of separation between these data may be attributed to the increased use of the turbosupercharger (increased exhaust pressures) at the higher powers and the added loss of power in the engine-stage supercharger resulting from the increased rates of charge-air flow. Appreciable differences in exhaust-pressure data between the three fuels at various conditions are again the result of operation of the turbosupercharger. Whether these differences in exhaust pressure have affected the knock data to any appreciable extent has not been determined. (See reference 6.) The same effects, however, pertain to the data of reference 1, although the values of exhaust pressure were not given in that report. The increased exhaust pressures were apparently not effective, of themselves, in appreciably raising engine temperatures because all the temperature data recorded during the knock tests, at both high and low exhaust pressures, were satisfactorily correlated (reference 4) by means of the NACA cooling correlation, which does not take the effects of exhaust pressure upon engine temperatures into account.

<u>Cross plots of knock data.</u> - An effort was made to determine to what extent all the knock data in figures 1 through 6 could be correlated without differentiating between various engine speeds and blower ratios. This concept is in agreement with the correlation principles set forth in reference 7 although the coordinate scales

herein bear different labels. Essentially, figure 9 presents plots of knock-limited charge-air flow per cycle against average mixture temperature for the three test fuels. These data were obtained by cross-plotting at certain fuel-air ratios the average mixture-temperature data on the (a) sheet and the knock-limited charge-air flow data on the (b) sheet of figures 1 through 8. In order to reduce all the data (at various engine speeds) to a single plot, the knock-limited total charge-air flow was converted to knock-limited charge-air flow per cycle (roughly equivalent to a comparison on the basis of knock-limited manifold pressure).

The data in figure 9 show fairly consistent trends of variation in knock-limited performance with mixture temperature for the various engine speeds, blower ratios, and fuel blends. The data at a spark advance of 32° B.T.C. usually fall lower than the data at a spark advance of 25° B.T.C. The slopes of the curves in figure 9 indicate the degree of severity of engine conditions imposed upon the fuels. The progressive reduction in the slope of the curves with increasing fuel-air ratio in the low mixture-temperature range (going from fig. 9(a) to (c) and from (d) to (f)) shows that, for low mixture temperatures and rich mixtures, the engine conditions imposed upon the fuels were very mild.

Engine cooling during knock tests. - Approximately constant indicated airspeed, cowl-flap setting, pressure altitude, (and consequent cooling-air $\sigma\Delta p$) were maintained for all the knock tests; this method resulted in uniformly higher engine temperatures for the high-performance fuels than for 28-R. A description of a side investigation to determine the effect of engine cooling on the knock data and a tentative justification for the procedure used are given in appendix A. This justification is based on the fact that at the conditions investigated, a change of 85° F in head temperature did not alter the knock limits appreciably.

Data from inlet-charge thermocouple. - Good correlation is shown between the measured, inlet-charge (so-called mixture) temperatures and the computed charge temperatures. A comparison of these temperatures is given in appendix B. A brief derivation of the equations used in these thermodynamic calculations is also presented.

Temperature-Limited Performance

Method of determining temperature-limited performance. - In order to compare the knock-limited performance of the different fuel blends with the engine-cooling limits, calculations were made to estimate the cooling-limited performance of this engine installed in the airplane. The cooling equation for the modified engine developed in reference 4 and the plot of effective gas temperature T_{g_e} against fuel-air ratio presented therein were used in these calculations, supplemented by the manufacturer's cruising-control chart from the flight manual (reference 8). These temperature-limited performance curves are shown in figures 10 and 11. The knock-limited performance curves also shown in these figures were replotted from figures 1(a) and 4(a).

Cooling-limited engine performance was determined for two criterions of temperature limits: (1) the engine manufacturer's specified maximum rear-spark-plug-gasket temperatures for continuous operation of 450° F (maximum recommended value) and 400° F (desired operating value) and (2) temperatures higher than the rear-spark-plug-gasket temperature specified by the manufacturer in order to permit a direct comparison between the modified and the older type engines. The following assumptions were made in both cases:

(a) Airplane gross weight, 50,000 pounds

(b) Flight at 7000-foot pressure altitude

(c) Cooling-air stagnation temperature, 60° F

(d) Carburetor-air temperature, 85° F

(e) Airplane equipped with four double-row radial air-cooled engines, all operating at the same conditions and having the same cooling characteristics as the modified test engine

(f) Approximately constant propeller efficiency in the high-power range with changes in pitch and airspeed

(g) Variation of true airspeed as a linear function of the cube root of engine power

(h) Variation of brake horsepower as a linear function of manifold pressure within the rich range of fuel-air ratio

Criterion 1, based on specified rear-spark-plug-gasket temperature limits. - Temperature-limited performance curves were calculated for cruising with a maximum temperature at the rear-spark-plug gasket of 450° F; these curves were determined at cowl-flap positions of 1/3 open and closed for engine speeds of both 1800 and 2250 rpm. Cowl-flap settings of 1/3 open and closed are approximately 7° and $2\frac{1}{2}$° open, respectively. Similar curves were determined using 400° F for the maximum gasket temperature; these relations are plotted as dashed curves in figures 10(a) and 11(a).

Because the cooling equation for cylinder heads was developed using an average value of the temperatures measured at the embedded rear-spark-plug-boss thermocouple, a conversion was made from the initially assumed maximum (of 14 cylinders) rear-spark-plug-gasket temperature to average rear-spark-plug-boss temperatures. (See figs. 6 and 9, reference 4.)

In order to determine engine cooling limits as the fuel-air ratio varied, corrections had to be made to the engine cooling-air pressure drop as the airspeed varied with changes in engine power. The cruise-control chart given in reference 8 was used throughout these calculations in determining the airspeed from the engine power; thus, it can be seen that the cooling limits of the engine are partly a function of the airplane-performance characteristics.

Figure 10(a) shows that at an engine speed of 1800 rpm the knock curves for both 28-R fuel and the triptane blend fall below the highest temperature-limit curve when the specified rear-gasket temperature is the criterion. These knock curves, however, exceed the manufacturer's desired operating conditions (400° F maximum rear-gasket temperature with cowl flaps closed). At an engine speed of 2250 rpm (fig. 11(a)) the triptane blend and xylidine blend knock curves exceed all the temperature-limit curves, whereas the 28-R knock curve is lower than the highest temperature-limit curve at fuel-air ratios higher than 0.084. For these assumed temperature limits at an engine speed of 1800 rpm the engine is either knock limited or cooling limited (fig. 10(a)) depending upon the temperature-limit criterion, but at 2250 rpm it is predominantly cooling limited, particularly in the lean-mixture range (fig. 11(a)).

Criterion 2, based on increased rear-spark-plug-boss temperatures. - Because the original test engine was found to operate with higher average boss temperatures than the modified engine although the same maximum gasket temperature was maintained in both cases, it was decided to recompute the cooling-limited performance relations for the modified engine by using the average rear-spark-plug-boss temperature limits obtained with the original engine for comparison with the standard values obtained with the modified engine. The new relations based on elevated temperatures are plotted as dashed curves in figures 10(b) and 11(b).

Figure 12 shows a comparison of the conversions from average rear-spark-plug-boss temperature to maximum rear-spark-plug-gasket temperature for both engines. (The curve for the modified engine is a replot of figs. 6 and 9 of reference 4 and the original test engine curve is taken from fig. 10 of reference 2.) At the manufacturer's specified limit of 450° F maximum gasket temperature, the modified engine had an average rear-boss temperature of 429° F whereas the original engine showed an average rear-boss temperature of 461° F. (See fig. 12.) Similarly, for the manufacturer's recommended maximum gasket temperature of 400° F, the modified engine showed an average rear-boss temperature of 386° F and the original engine had an average rear-boss temperature of 411° F. The cooling-limited performance relations were therefore recalculated for the modified engine based on average rear-boss temperatures of 411° and 461° F.

A comparison of figures 10(b) and 11(b) with figures 10(a) and 11(a) shows that by using the average rear-boss temperatures corresponding to original engine operating values as cooling limits, the temperature-limited performance of the modified engine is increased by at least 20 percent. In figure 10(b) for an engine speed of 1800 rpm, the 28-R knock curve just touches the cooling-limit curve for an average rear-boss temperature of 411° F, cowl flaps 1/3 open, at the minimum point; and, in figure 11(b) for 2250 rpm the 28-R knock curve touches the cooling-limit curve for an average rear-boss temperature of 461° F, cowl flaps closed, near its minimum point. Based on the cooling criterion of figures 10(b) and 11(b), the knock limits of 28-R are well within the operating cooling-limit range. The knock limits of both the triptane and the xylidine blend exceed the highest cooling-limit curve over part of the fuel-air-ratio range in figure 11(b).

An interpolation between the minimum points of the highest and the lowest cooling-limit curves in figure 10(b) reveals that the 28-R knock limit is approximately one-third of the distance above the lowest. This knock limit may then be considered to be the equivalent of a cooling limit of approximately 430° F (average rear boss) with cowl flaps closed. A similar interpolation may be applied to many of the other knock curves in figures 10 and 11.

Maximum barrel temperatures. - The maximum rear middle-barrel and rear-hold-down-flange temperatures, corresponding to the assumed constant maximum rear-spark-plug-gasket temperatures of 400° and 450° F in figures 10(a) and 11(a), are plotted in figure 13. The data for these curves were obtained by means of the cooling equation for rear middle barrels presented in reference 4 and apply for both the 1/3 open and the closed cowl-flap settings. Conversions from average barrel temperature to maximum barrel and maximum flange temperatures were made with the aid of plots shown in reference 4. These conversions were obtained from engine data taken during flight tests. The highest rear-flange temperatures predicted for any of the eight sets of conditions are seen to be in the neighborhood of the manufacturer's maximum specified value of 335° F. (See reference 5.) It will be observed that the maximum barrel temperatures generally fall 30° to 40° F lower than the corresponding maximum flange temperatures at the same conditions.

Maximum barrel and flange temperatures, corresponding to the assumed constant average rear-spark-plug-boss temperatures of 411° and 461° F in figures 10(b) and 11(b), are plotted in figure 14. The data shown again apply for both the 1/3 open and the closed cowl-flap positions. These temperatures, in comparison with those for figure 13, are uniformly higher, as would be expected. Maximum barrel temperatures again fall roughly 30° to 40° F lower than the corresponding maximum flange temperatures.

Specific operating instructions and carburetor-metering characteristics. - The knock and cooling limits just presented will next be compared with the carburetor-metering characteristics and with the conditions specified in the operating instructions of the engine manufacturer. The average metering characteristics of the carburetor, which is standard for the modified engine, have been plotted in figures 10 and 11 for comparison with the fuel-knock and estimated engine cooling limits. These carburetor-metering data were obtained and converted from flow-bench test data.

The operating instructions for this engine (reference 5) do not list a specific manifold pressure for an 1800 rpm cruise; however, manifold pressures of 32.6 and 32.5 inches of mercury was specified for 1400 and 2000 rpm, respectively, at low blower ratio and in automatic-lean mixture-control setting. In reference to figure 10(a) a similar manifold pressure at 1800 rpm falls a little below the intersection of the automatic-lean carburetor-metering curve with the lowest cooling-limit curve. A Bureau of Aeronautics calibration of the modified engine (reference 9) lists an operating condition at 1800 rpm at low blower ratio with a manifold pressure of 34 inches of mercury. This setting (fig. 10(a)) lies almost exactly at the intersection of the automatic-lean carburetor-metering curve with the lowest cooling-limit curve (which satisfies both the engine manufacturer's desired operating temperature of 400° F and the airplane manufacturer's desired closed cowl-flap setting).

The operating instructions (reference 5) specify a manifold pressure of 31.2 inches of mercury for an engine speed of 2250 rpm at low blower ratio with the automatic-lean carburetor setting. With relation to the curves in figure 11(a), this setting falls at the intersection of the automatic-lean carburetor-metering curve and the lowest cooling-limit curve (again satisfying both manufacturers' desired operating conditions).

SUMMARY OF RESULTS

Tests of a modified 14-cylinder double-row radial air-cooled engine installed in a four-engine airplane with 28-R, triptane blend, and xylidine blend fuels, at engine speeds of 1800 and 2250 rpm, high and low blower, and spark advance of 25° and 32° B.T.C. gave the following results:

1. Based on brake-horsepower measurements, the blend of 20 percent triptane and 80 percent 28-R, leaded to 4.5 ml TEL per gallon, had a knock limit from 11 to 27 percent higher than that of 28-R. The improvement was about the same for both blower ratios and at both values of spark advance.

2. Based on brake-horsepower measurements, the blend of 3 percent xylidines and 97 percent 28-R, leaded to 6.0 ml TEL per gallon, had a knock limit from 10 to 27 percent higher than that of 28-R. The improvement was, on the average, somewhat greater than that found for the triptane blend. Within the range of these investigations, the temperature sensitivity of the xylidine blend did not cause it to rate appreciably lower than the triptane blend from a standpoint of actual knock-limited performance, although increasing the severity of engine conditions depreciated the lean-mixture antiknock characteristics of the xylidine blend to a greater extent than was found to apply for the triptane blend.

3. A fair degree of correlation was obtained by plotting, for the three test fuels at various fuel-air ratios, knock-limited charge-air flow per cycle against (observed) mixture temperature.

4. For 28-R fuel at the higher engine speed and blower ratio and with a spark advance of 25° B.T.C., a change of head temperature from 485° to 400° F did not alter the knock limit of the fuel to an appreciable extent.

5. Good correlation was obtained between average (of 14 cylinders) observed mixture temperature and values of mixture temperature calculated from a theoretical equation.

6. Estimated temperature-limited performance relations for this engine based on the manufacturer's specified maximum rear-spark-plug-gasket temperatures may be exceeded when operating at the knock limits of all three fuels at 2250 rpm. Operation at or near knock limits of 28-R or of the higher-performance fuel blends, however, may be possible at 1800 rpm under certain conditions without exceeding these temperature limits.

7. If the operating temperature limits specified for the modified engine could be raised to the equivalent of a rear-spark-plug-boss temperature that corresponds to normal operating conditions for the earlier model engines, the cooling-limited performance of this engine could be considerably increased and fuel knock rather than cooling would become the limit with 28-R fuel at the conditions investigated, particularly at 1800 rpm.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 4, 1945.

APPENDIX A

DISCUSSION OF PROCEDURE FOR ENGINE COOLING DURING KNOCK TESTS

The maintenance of approximately constant cooling-air $\sigma\Delta p$ in running the knock tests resulted (as for the tests reported in reference 1) in uniformly higher engine temperatures for the high-performance fuels than for 28-R. The effect of engine temperatures (cooling procedure) on the knock data has been repeatedly questioned because knock tests are often run maintaining constant head temperatures. Therefore, two separate investigations were made in addition to the customary knock tests.

For a particular set of engine conditions, a knock curve was first obtained following the customary cooling procedure; namely, maintaining approximately constant indicated airspeed (cooling-air pressure drop) for all the knock points (over the range of fuel-air ratio). This practice, of course, resulted in a considerable variation in engine temperatures. (See figs. 1(c) through 8(c).) Such variation is primarily the result of fuel-air ratio and secondarily of knock-limited power.

A second set of data was then obtained with the same fuel and the same engine conditions, except that the engine cooling-air pressure drop was so varied that the maximum rear-spark-plug-boss temperature was maintained essentially constant (over the range of fuel-air ratio). This constant temperature, as shown in figure 15, was chosen as the highest temperature obtained in running the conventional knock curve. The curves of figure 15 and of figure 6 (fig. 6 includes all the data from fig. 15 with additional curves) show that, for these conditions, little if any difference is produced in the knock curves when using either constant head temperature or constant $\sigma\Delta p$. (This statement does not imply that under other operating conditions cylinder-head temperature does not affect knock limits.)

A similar investigation was made with a carburetor-air temperature of 100° F (fig. 8). Because of the method used to obtain this elevated carburetor-air temperature for the data of figure 8 (bucking the turbosupercharger output with the throttle) the range in fuel-air ratio obtainable was somewhat restricted. These data, however, again demonstrate that the knock limits under both conditions of engine cooling are, in general, within the customary band of experimental scatter of such data. Engine conditions, as affecting fuel-knock limits, were quite severe (f. figs. 1 through 8) for the tests in which the effect of the additional variable — engine cooling — was studied.

In the light of the small effect of head temperatures upon knock limits found in these tests, it was felt that the added difficulty involved in maintaining constant temperatures was not warranted; furthermore, the maintenance of constant head temperature implies that the highest head temperature experienced for any of the test conditions is the one to be held constant. This procedure decidedly shortens the life of the cylinder barrels and the piston rings.

APPENDIX B

DATA FROM INLET-CHARGE THERMOCOUPLE

Inasmuch as inlet-charge (so-called mixture) temperature is one of the most important engine variables in its effect on fuel-knock limits, correct evaluation of this parameter is necessary. These data were experimentally obtained with 14 bare thermocouples located at the centers of the various intake stacks. This installation is described in more detail in the appendix of reference 4. The data plotted as average mixture temperatures in figures 1(a) through 8(a) are the average temperatures for the 14 thermocouples. The maximum deviation of an individual measurement from the average (of 14) was, in general, less than 5° F.

A comparison of the average observed mixture temperature with the theoretically determined charge temperature is of interest. A brief résumé of the method of calculation follows. The symbols used are:

T_m final charge temperature, °F

T_c carburetor-air temperature (screen thermocouple), °F

ΔT_s temperature rise across supercharger, °F

ΔT_v temperature drop due to fuel vaporization, °F

N engine speed, rpm

R impeller gear ratio

d impeller diameter, in.

k constant

The final mixture temperature is equal to the sum of the carburetor-air temperature plus the temperature rise due to compression in the supercharger less the temperature drop due to fuel vaporization.

Thus

$$T_m = T_c + \Delta T_s - \Delta T_v \qquad (1)$$

From a familiar equation given in a number of engineering texts

$$\Delta T_s = k \frac{(\text{blower tip speed})^2}{778\ c_p\ g} \qquad (2)$$

where blower tip speed is in feet per second, 778 is the mechanical equivalent of heat in foot-pounds per Btu, c_p is the specific heat of air at constant pressure (usually taken as 0.243 Btu/lb/°F) and g is the acceleration due to gravity (taken as 32.2 ft/sec^2). Equation (2) requires modification to account for the physical characteristics of the actual impeller and diffuser. Correcting for the pressure coefficient q_{ad} and the adiabatic temperature-rise efficiency η, equation (2) becomes

$$\Delta T_s = \frac{(\text{blower tip speed})^2}{6090} \times \frac{q_{ad}}{\eta}$$

Assuming an average ratio of coefficients of 0.90 for conventional superchargers

$$\Delta T_s = \frac{(\text{blower tip speed})^2}{6090} \times 0.90 \qquad (3)$$

However, blower tip speed = $\frac{N \times R \times d \times 3.14}{60 \times 12}$

For the modified engine with an 11.3-inch-diameter impeller at low impeller gear ratio (7.15:1) equation (3) may be expressed as

$$\Delta T_s = 1.83 \times 10^{-5} \times N^2$$

and at high impeller gear ratio (8.47:1) this equation becomes

$$\Delta T_s = 2.58 \times 10^{-5} \times N^2$$

The temperature drop due to fuel vaporization for charge thermocouples, as installed for these tests, is represented with fair accuracy by

$$\Delta T_v = 390 \times (\text{fuel-air ratio})$$

Equation (1) may finally be expressed as

Low blower

$$T_m = T_c + 1.83 \times 10^{-5} \times N^2 - 390 \times F/A \qquad (4)$$

High blower

$$T_m = T_c + 2.58 \times 10^{-5} \times N^2 - 390 \times F/A \qquad (5)$$

Equations (4) and (5) have been repeated in figure 16 and were used to obtain the curves plotted therein. With the aid of these figures it is possible to determine, usually with $\pm 5^\circ$ F, the average manifold mixture temperature of the modified engine. Separate curves for each of three fuel-air ratios were constructed at each individual value of carburetor-air temperature. Thus, rapid identification of the average mixture temperature at a given set of engine conditions may be made because all pertinent variables are given in the plot.

It is of interest to observe the degree of correlation that exists between values of the average observed mixture temperature (of the 14 thermocouples) and the calculated values. In figure 17 are shown data from all the knock tests taken from figures 1 through 8. Cross plots were made of the average mixture temperature values (observed from test results) at three fuel-air ratios whereas the calculated relations were based on values of carburetor-air temperature indicated by the screen thermocouple. The 45° dashed line shown on this figure represents the ideal relation that would exist between observed and calculated values if the calculations exactly predicted the observed results.

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TABLE I - FLIGHT CONDITIONS AND FREE-AIR TEMPERATURE

Flight	Fuel	Pressure altitude (ft)		Free-air temperature (°F)		Indicated airspeed (mph)	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
25	28-R	4920	4980	46	53	137	180
26	Triptane blend	7050	7050	50	53	192	202
27	28-R	7010	7060	44	46	190	193
	Xylidine blend	6970	7030	46	47	196	200
28	28-R	7410	7410	43	45	187	192
	Triptane blend	7390	7410	48	49	192	196
	Xylidine blend	7390	7420	45	48	193	197
29	28-R	7466	7466	50	51	190	193
	Triptane blend	7466	7466	50	51	195	197
	Triptane blend	9970	9970	48	48	195	195
30	28-R	6960	7000	50	52	187	194
	Triptane blend	6960	7000	50	52	192	199
	Xylidine blend	6960	7000	50	53	193	200
31	28-R	7140	7220	45	47	197	206
	Triptane blend	7140	7220	45	48	198	210
	Xylidine blend	7120	7220	45	48	198	211
32	28-R	7000	7040	57	59	199	201
34	28-R	6970	7110	50	53	138	203
35	28-R	6930	7020	49	50	177	183
	Triptane blend	7020	7020	50	51	181	185
	Xylidine blend	7020	7020	50	51	179	185
36	28-R	7060	7110	42	44	198	207
	Triptane blend	7110	7110	43	43	210	210
37	28-R	3970	4010	55	56	146	167
	Triptane blend	7010	7060	43	44	199	210
	Xylidine blend	6980	7040	42	43	202	209
38	28-R	7030	7060	44	45	201	207
	Triptane blend	7030	7060	42	46	201	213
	Xylidine blend	7050	7100	42	43	204	212
50	28-R	7075	7140	43	48	191	200
	Triptane blend	7090	7120	43	47	192	208
51	28-R	8190	8260	46	49	194	204
	Triptane blend	8130	8220	48	49	200	210
52	28-R	7050	7100	47	49	194	202
	Triptane blend	7000	7080	48	50	197	205
	Xylidine blend	6860	7110	47	49	196	207
55	28-R	7090	7100	31	31	197	204
56	28-R	6940	7030	49	50	198	203

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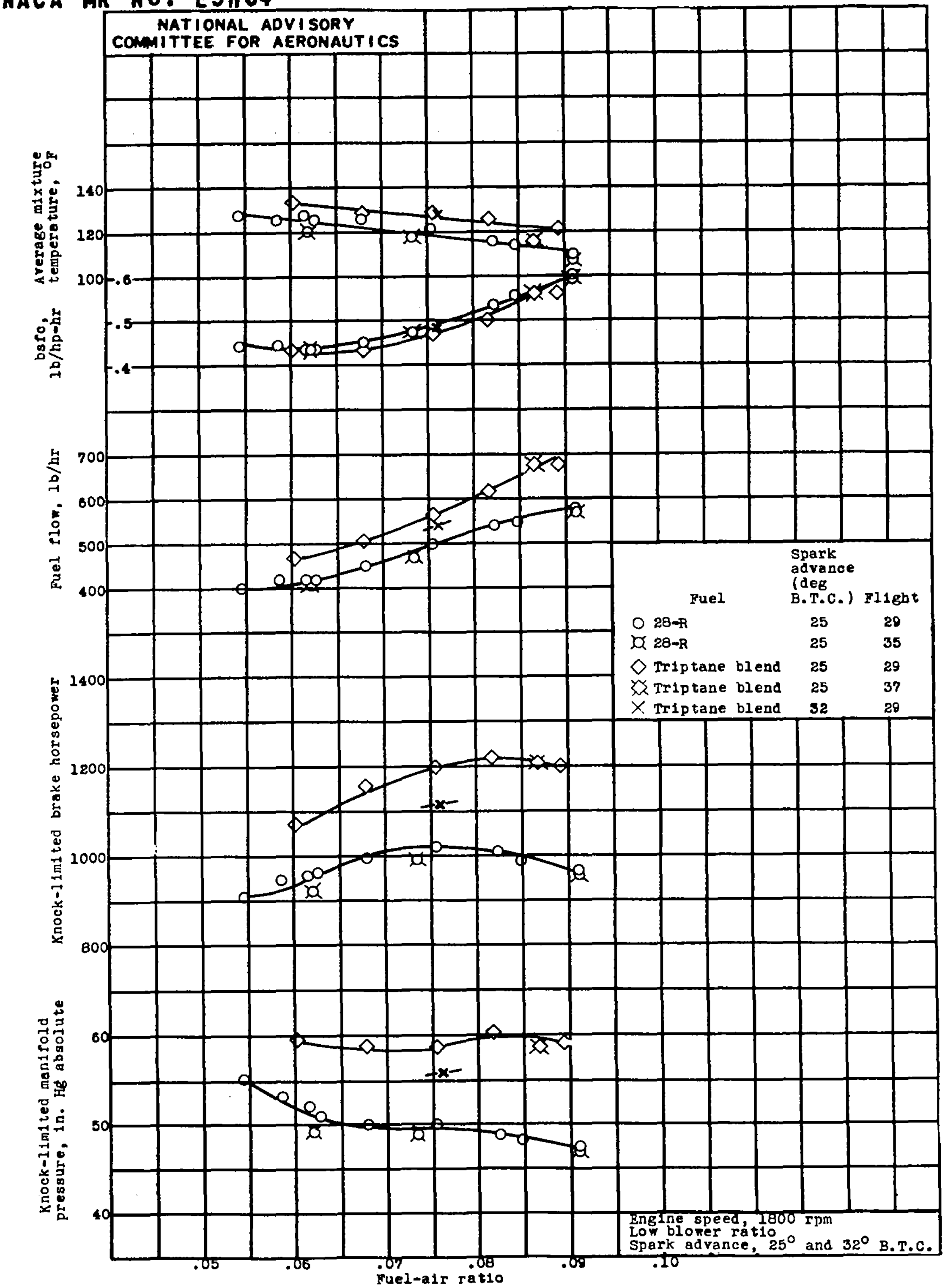
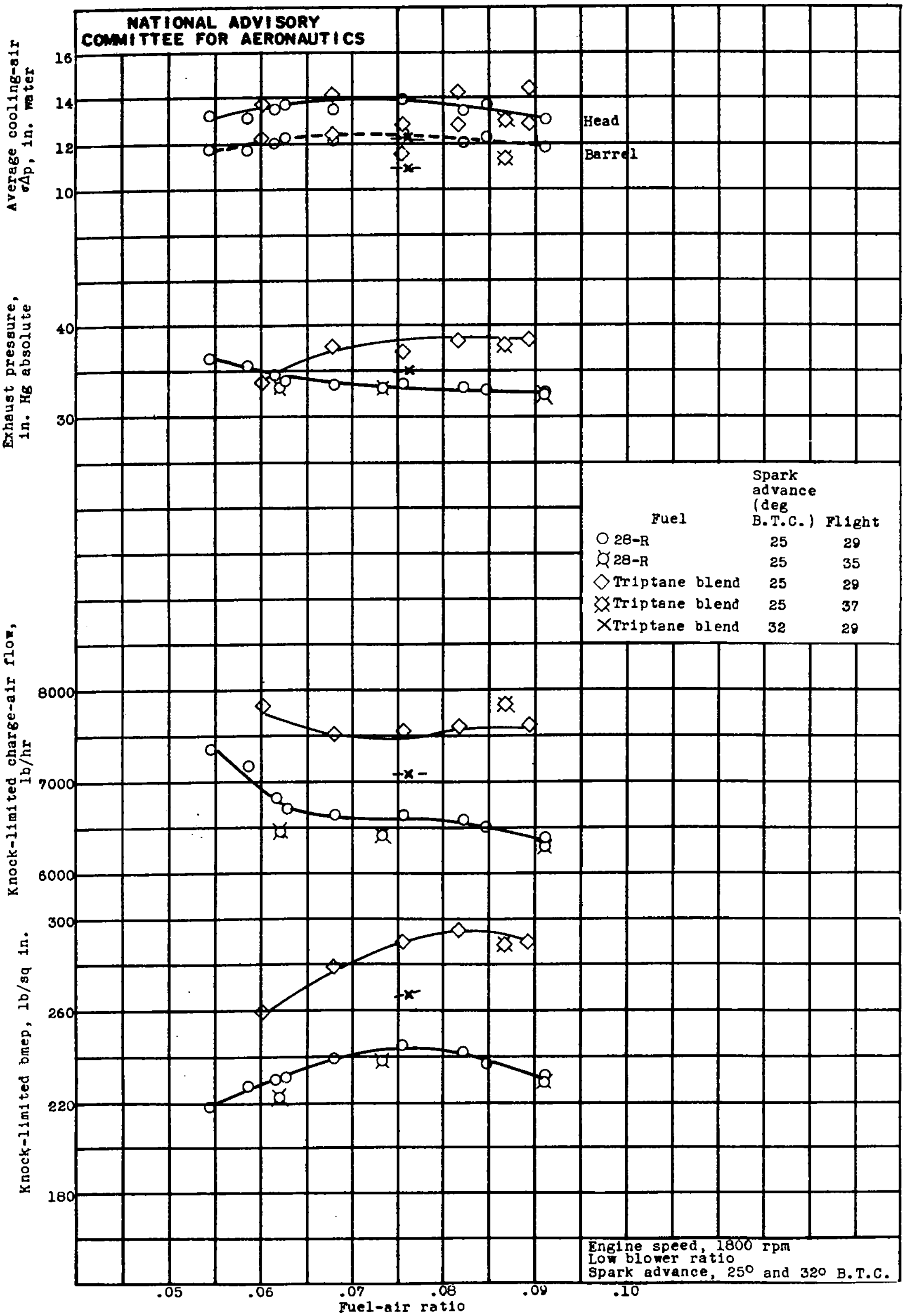


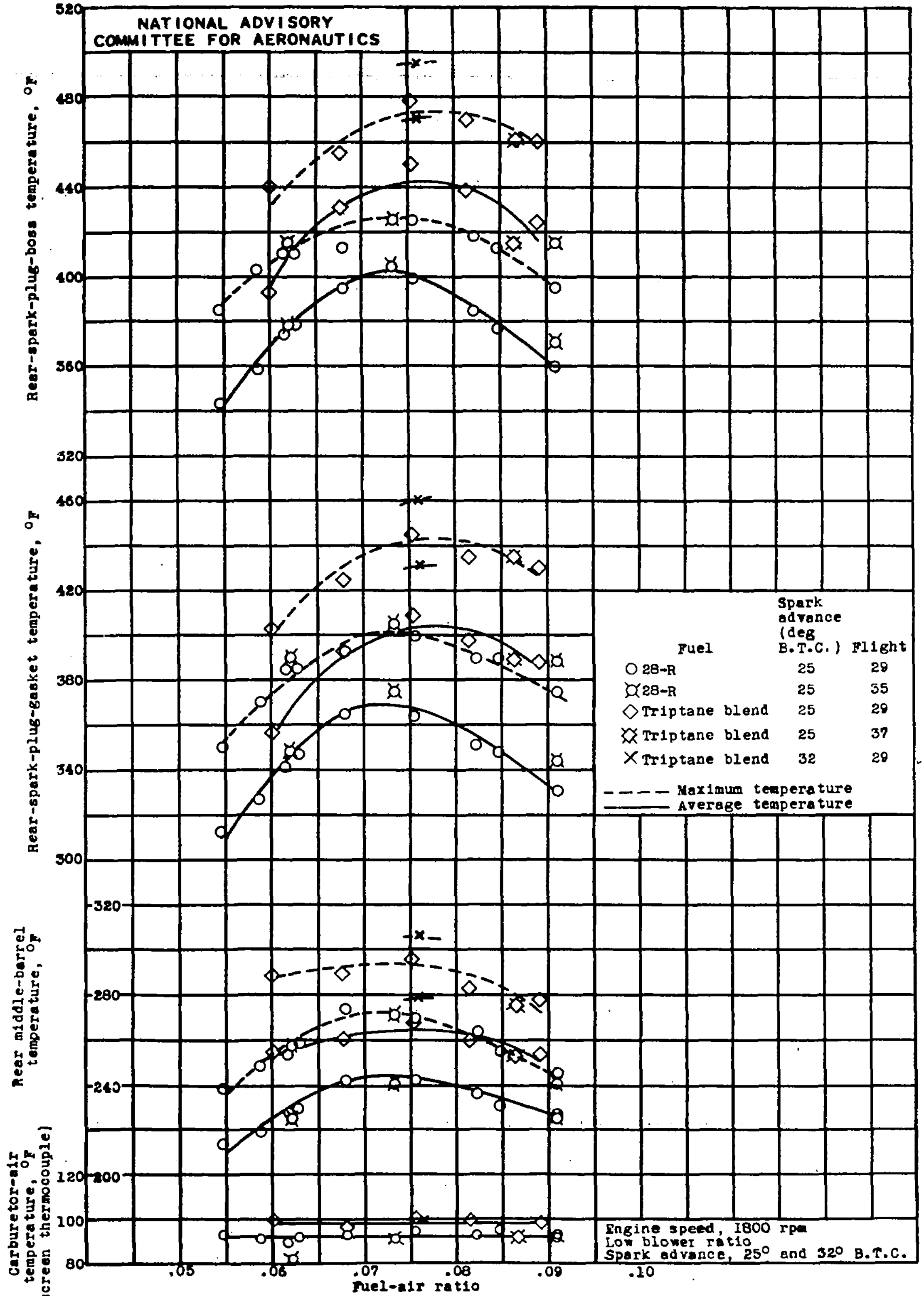
(a) Engine-performance variables.

Figure 1. - Performance of modified engine as limited by the knock characteristics of two fuels; engine speed, 1800 rpm; low blower ratio (7.15:1); spark advance, 25° and 32° B.T.C.; carburetor -air temperature (bulb), approximately 85° F; four-engine airplane.



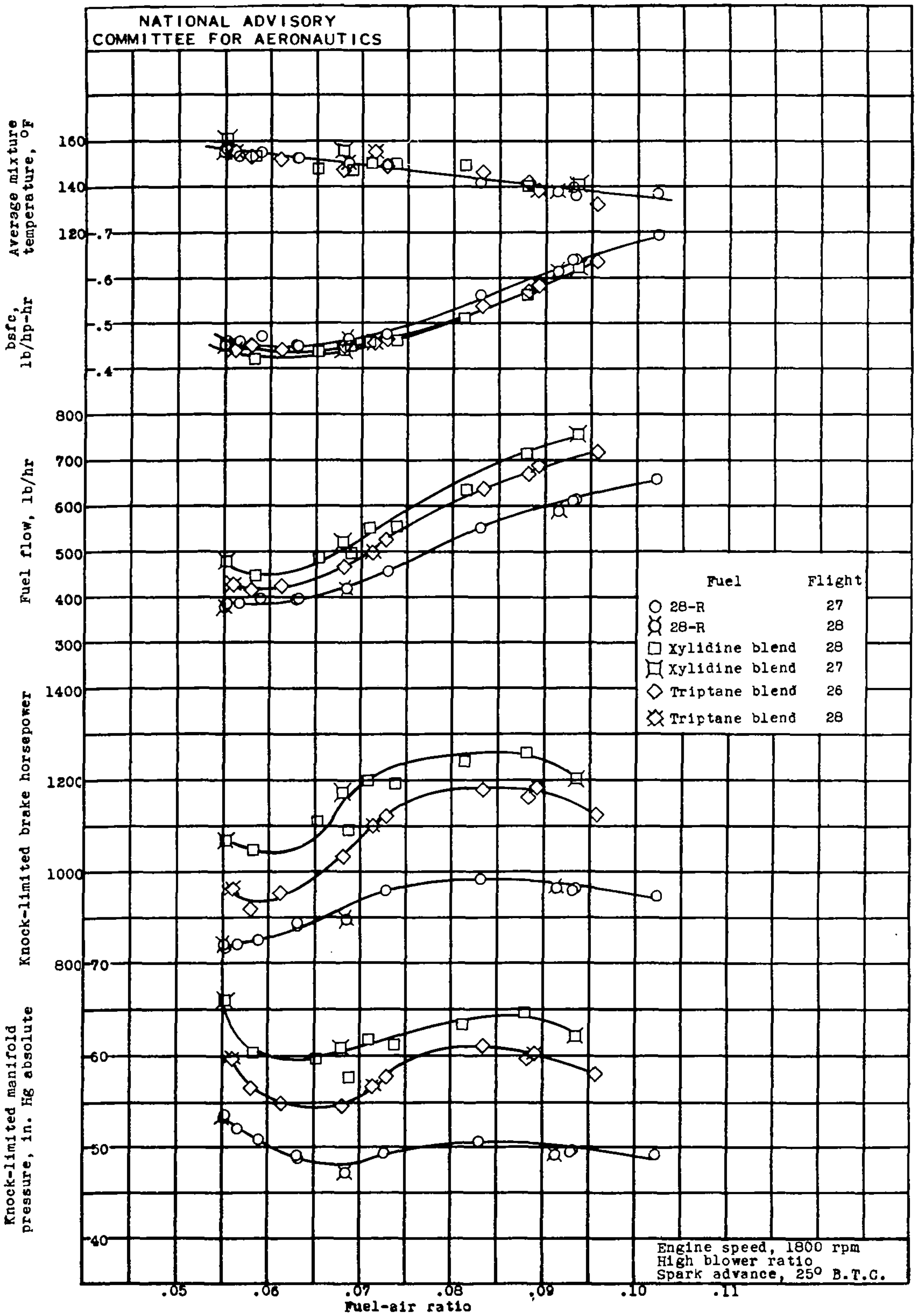
(b) Additional performance variables.

Figure 1. - Continued.



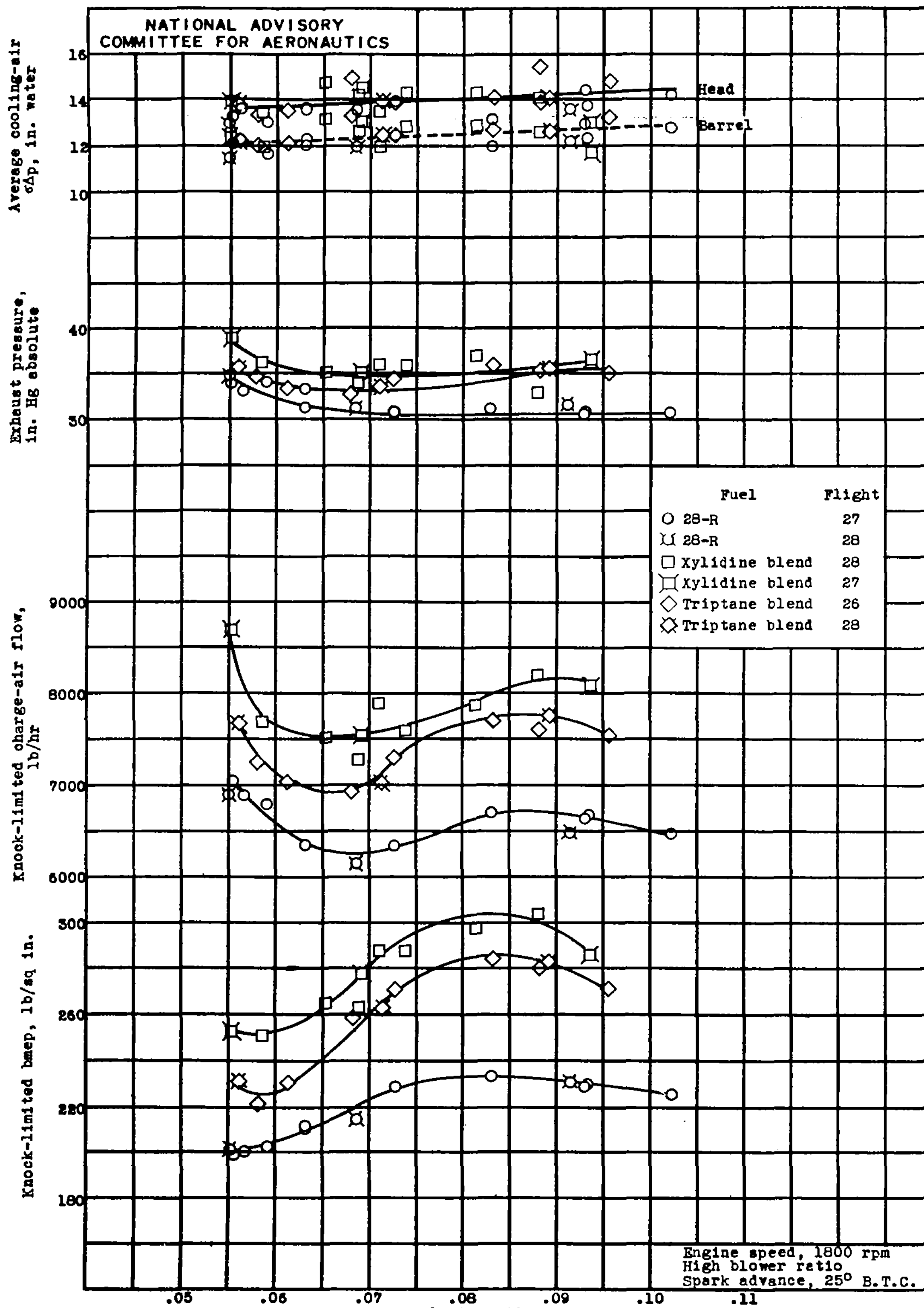
(c) Temperatures.

Figure 1. Concluded.



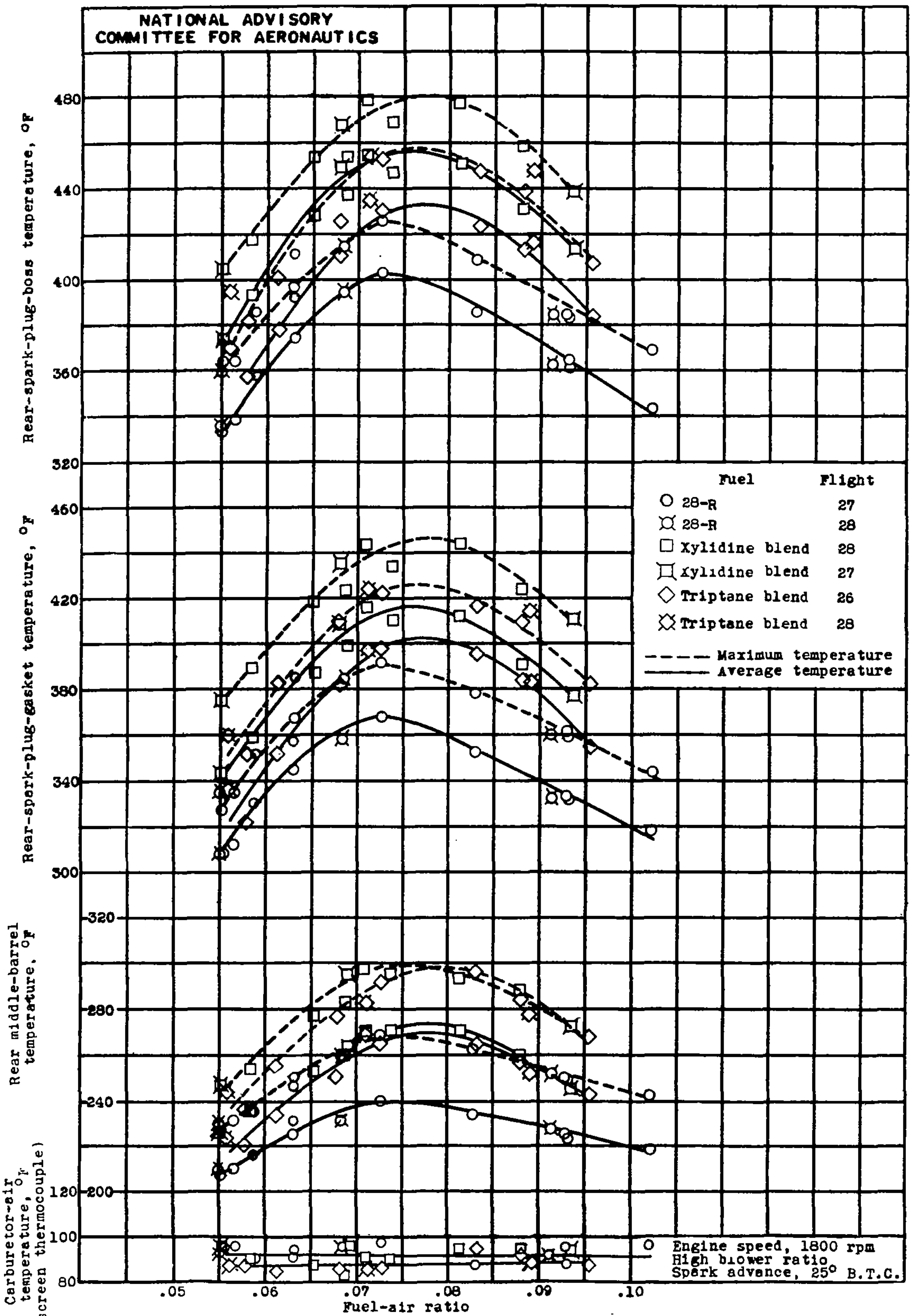
(a) Engine-performance variables.

Figure 2. - Performance of modified engine as limited by the knock characteristics of three fuels; engine speed, 1800 rpm; high blower ratio (8.47:1); spark advance, 25° B.T.C.; carburetor-air temperature (bulb), approximately 85° F; four-engine airplane.



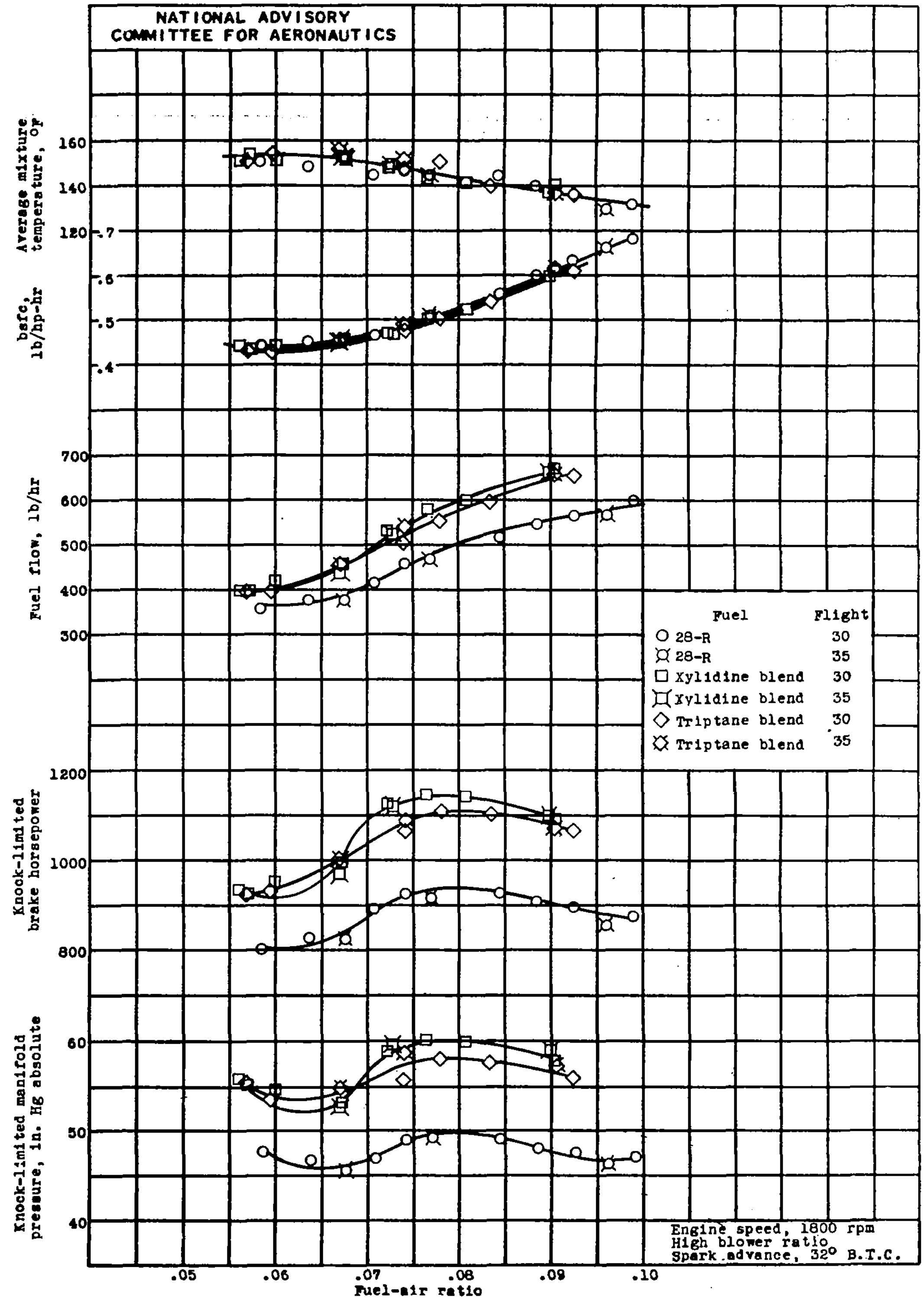
(b) Additional performance variables.

Figure 2. - Continued.



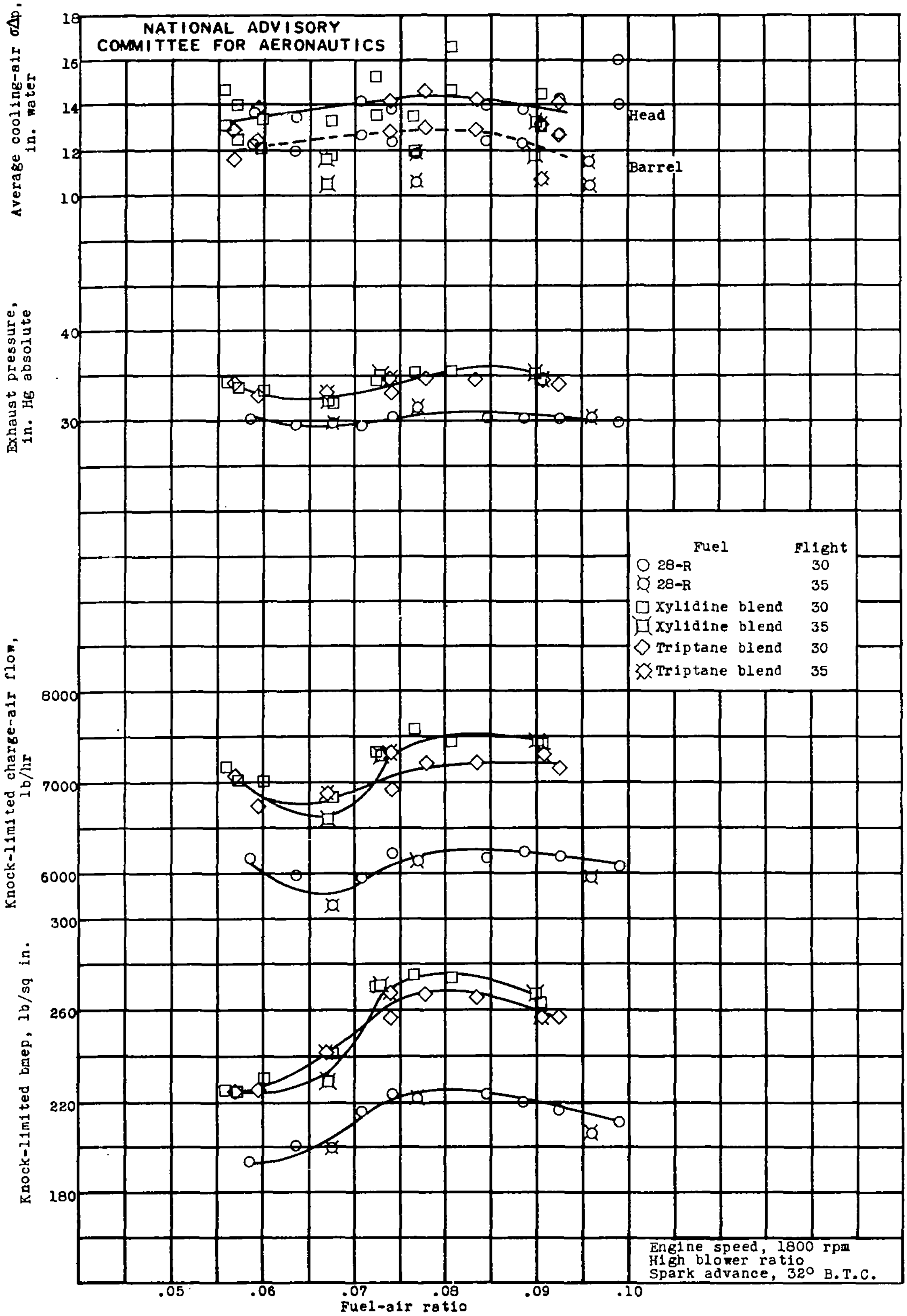
(c) Temperatures.

Figure 2. - Concluded.



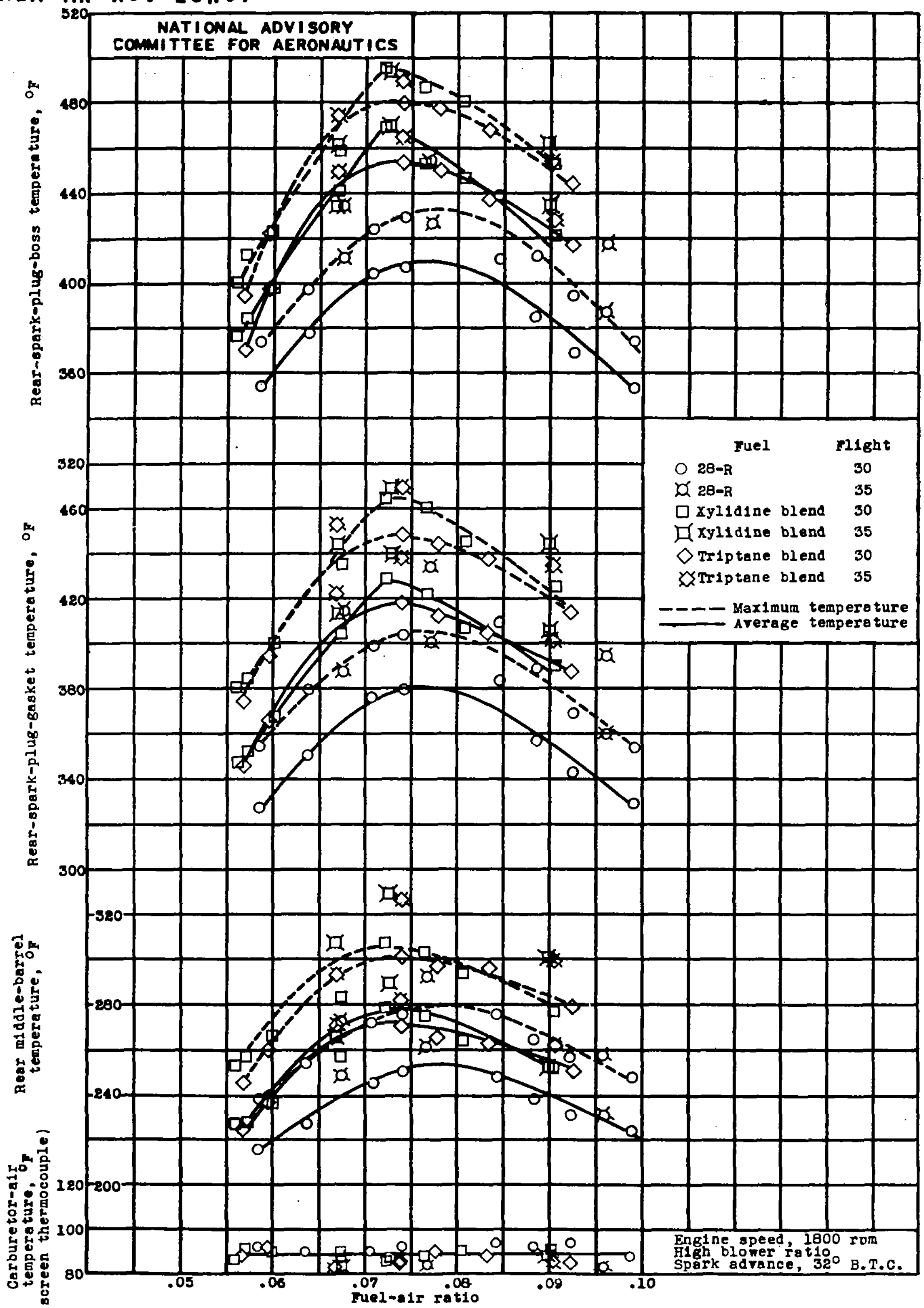
(a) Engine-performance variables.

Figure 3. - Performance of modified engine as limited by the knock characteristics of three fuels; engine speed, 1800 rpm; high blower ratio (8.47:1); spark advance, 32° B.T.C.; carburetor-air temperature (bulb), approximately 85° F; four-engine airplane.



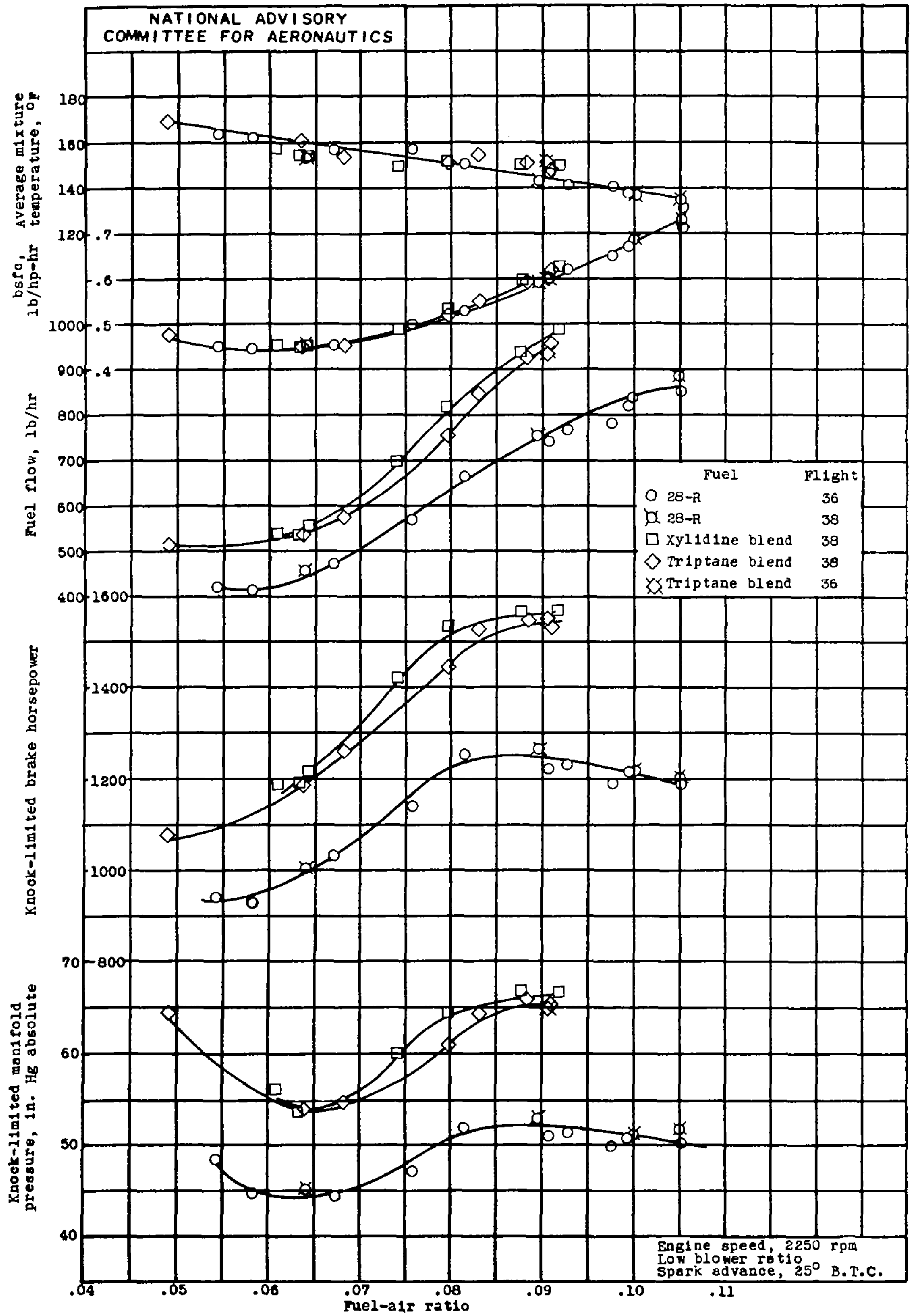
(b) Additional performance variables.

Figure 3. - Continued.



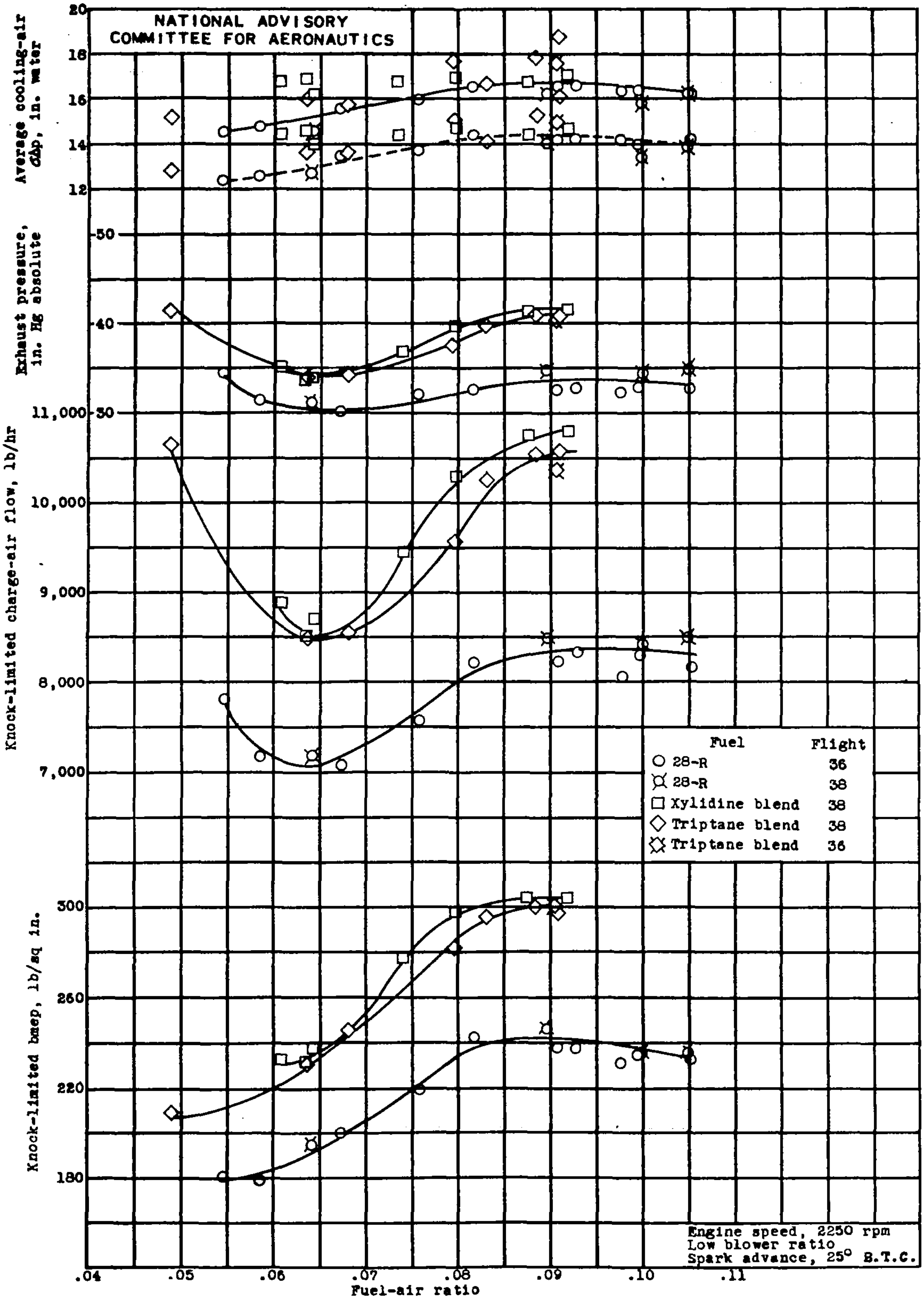
(c) Temperatures.

Figure 3. - Concluded.



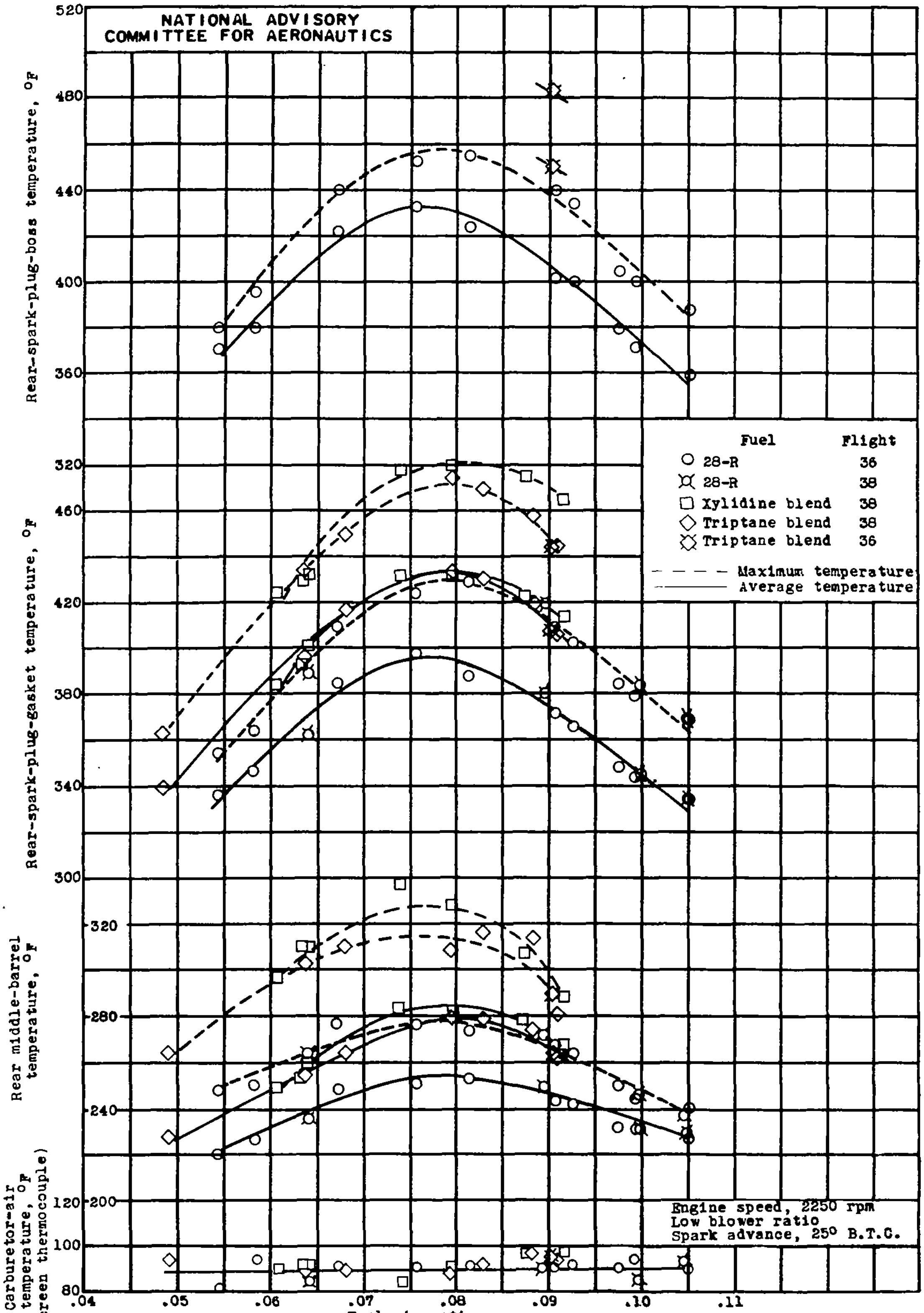
(a) Engine-performance variables.

Figure 4. - Performance of modified engine as limited by the knock characteristics of three fuels; engine speed, 2250 rpm; low blower ratio (7.15:1); spark advance, 25° B.T.C.; carburetor-air temperature (bulb), approximately 85° F; four-engine airplane.



(b) Additional performance variables.

Figure 4. - Continued.



(c) Temperatures.

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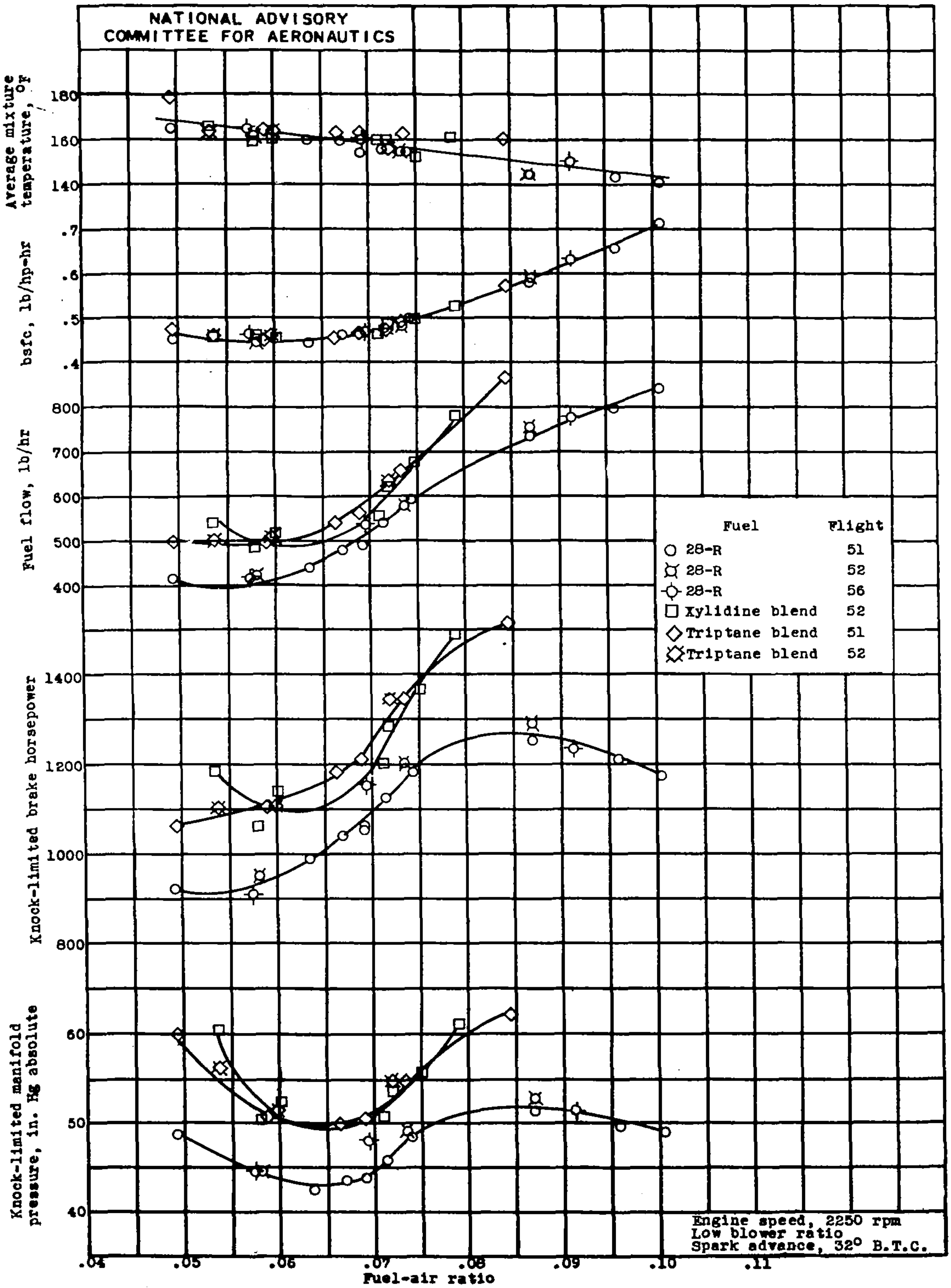
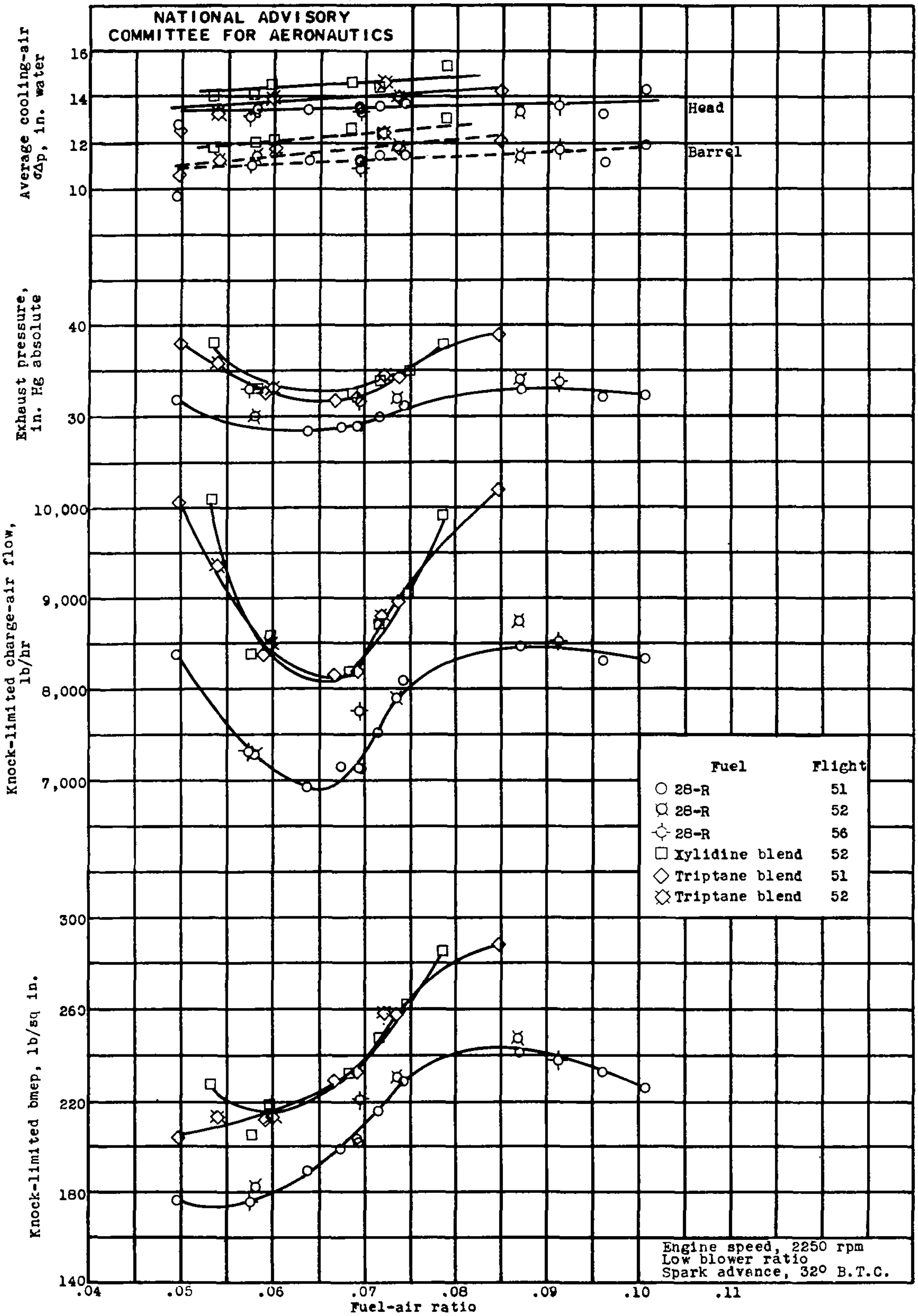


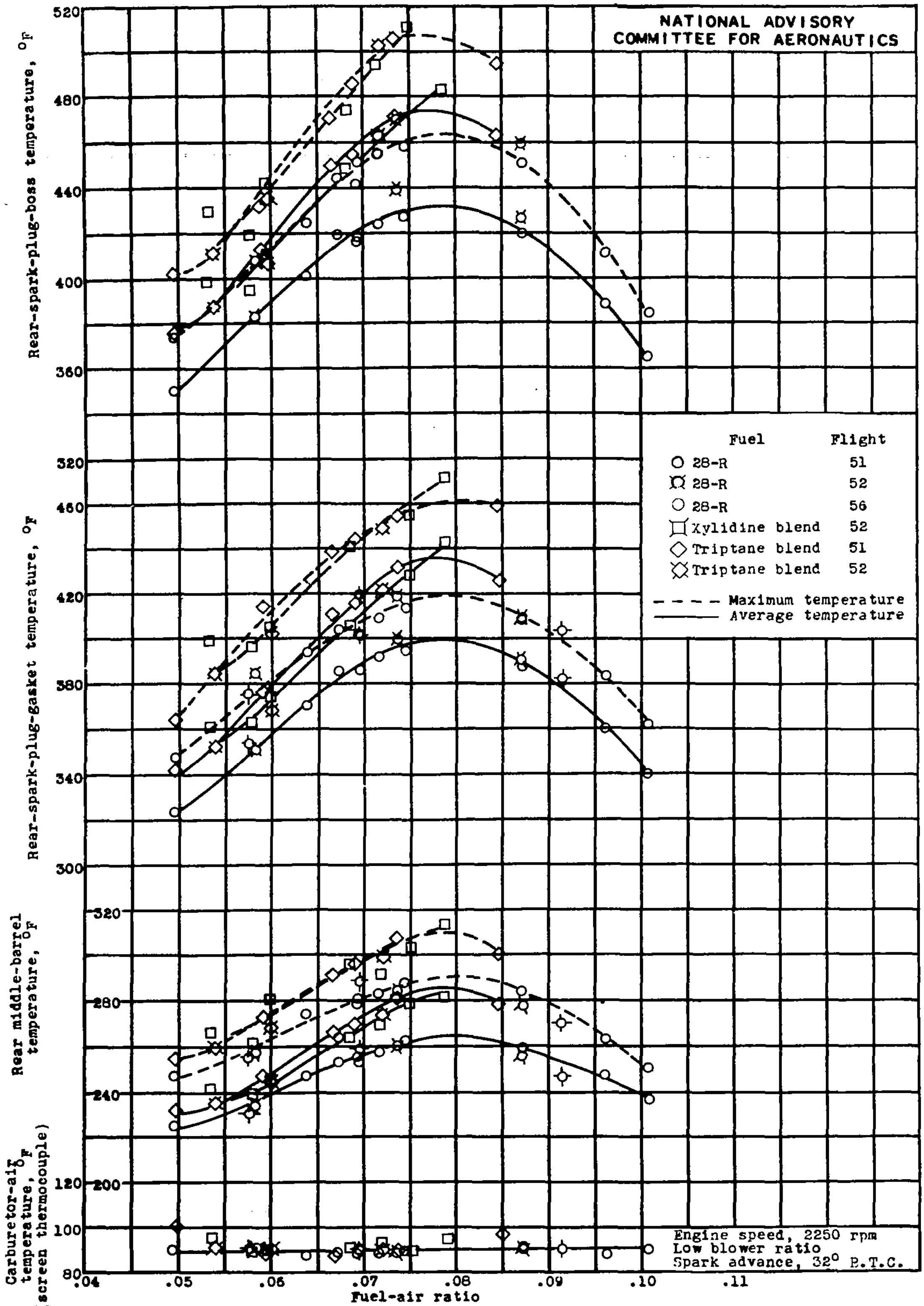
(a) Engine-performance variables.

Figure 5. - Performance of modified engine as limited by the knock characteristics of three fuels; engine speed, 2250 rpm; low blower ratio (7.15:1); spark advance, 32° B.T.C.; carburetor-air temperature (bulb), approximately 85° F; four-engine airplane.



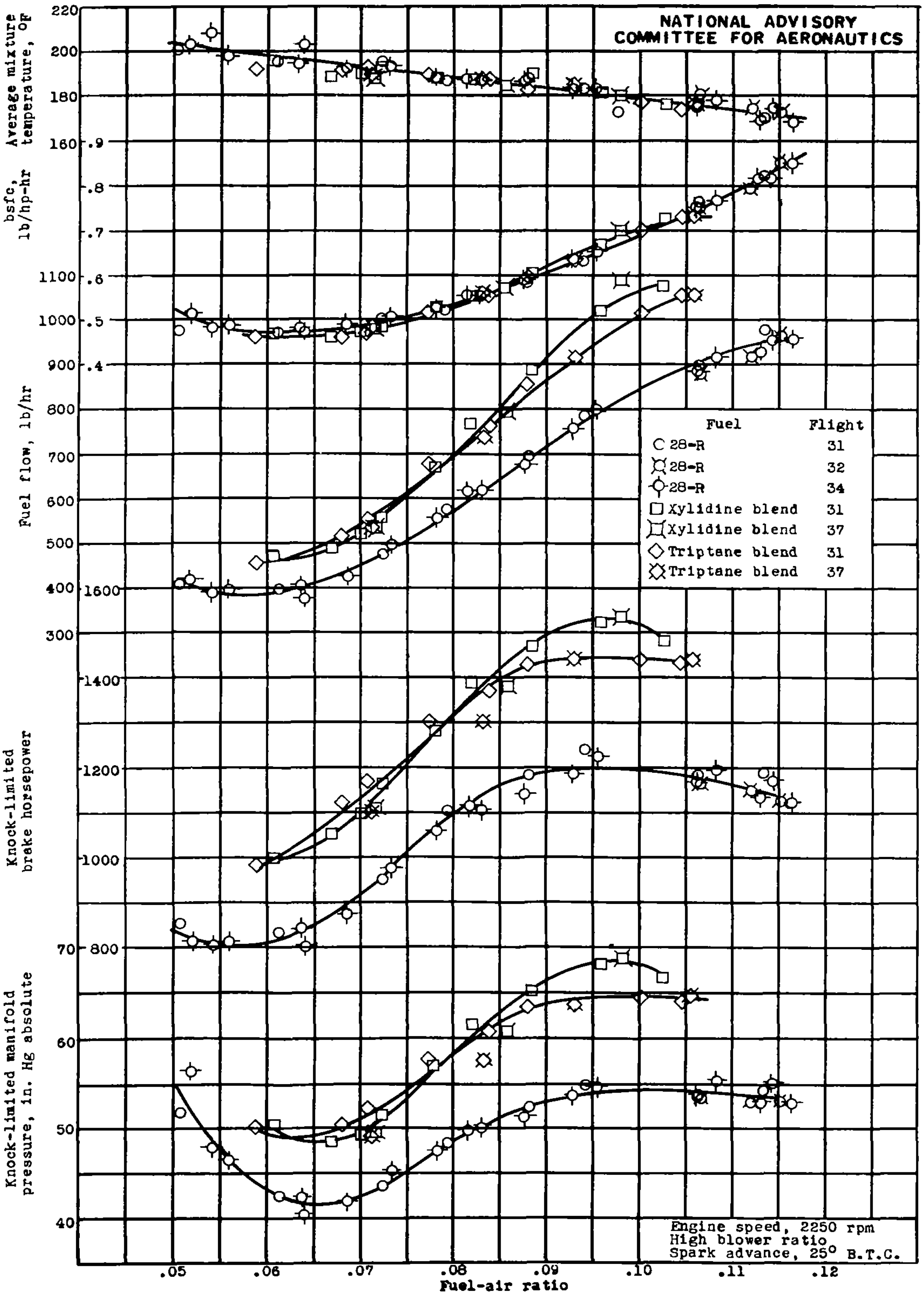
(b) Additional performance variables.

Figure 5. - Continued.



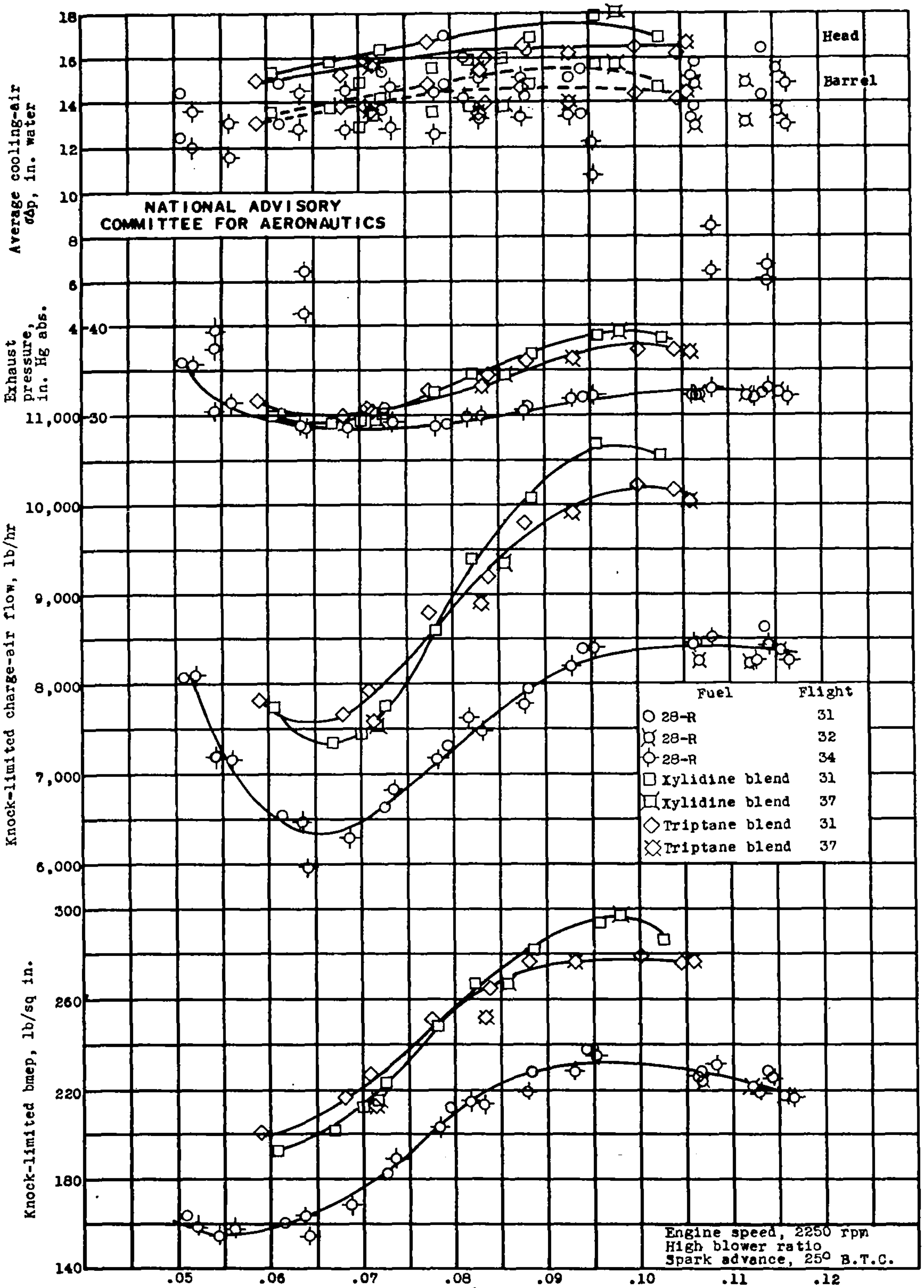
(c) Temperatures.

Figure 5. - Concluded.



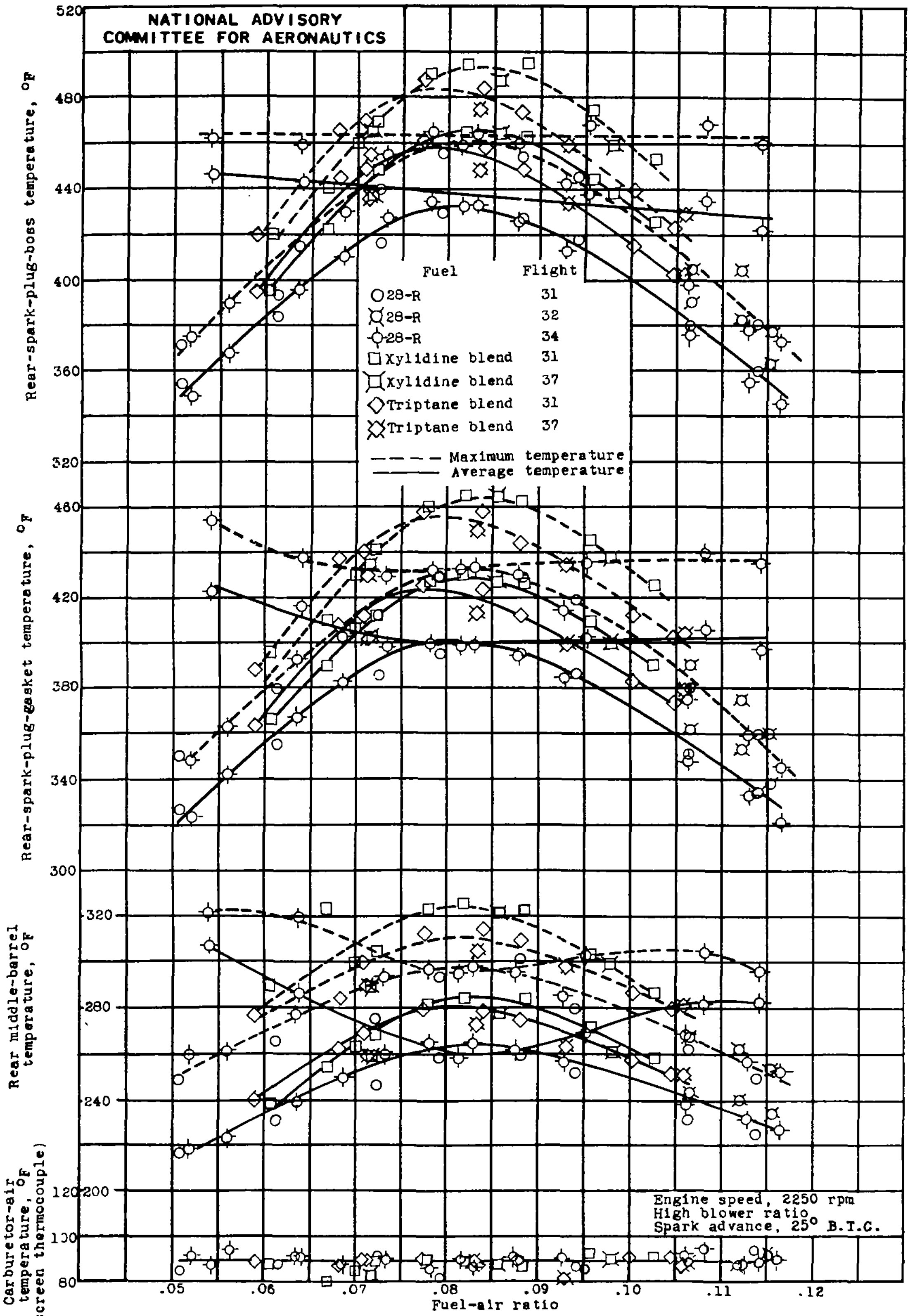
(a) Engine-performance variables.,

Figure 6. - Performance of modified engine as limited by the knock characteristics of three fuels; engine speed, 2250 rpm; high blower ratio (8.47:1); spark advance, 25° B.T.C.; carburetor-air temperature (bulb), approximately 85° F; four-engine airplane.



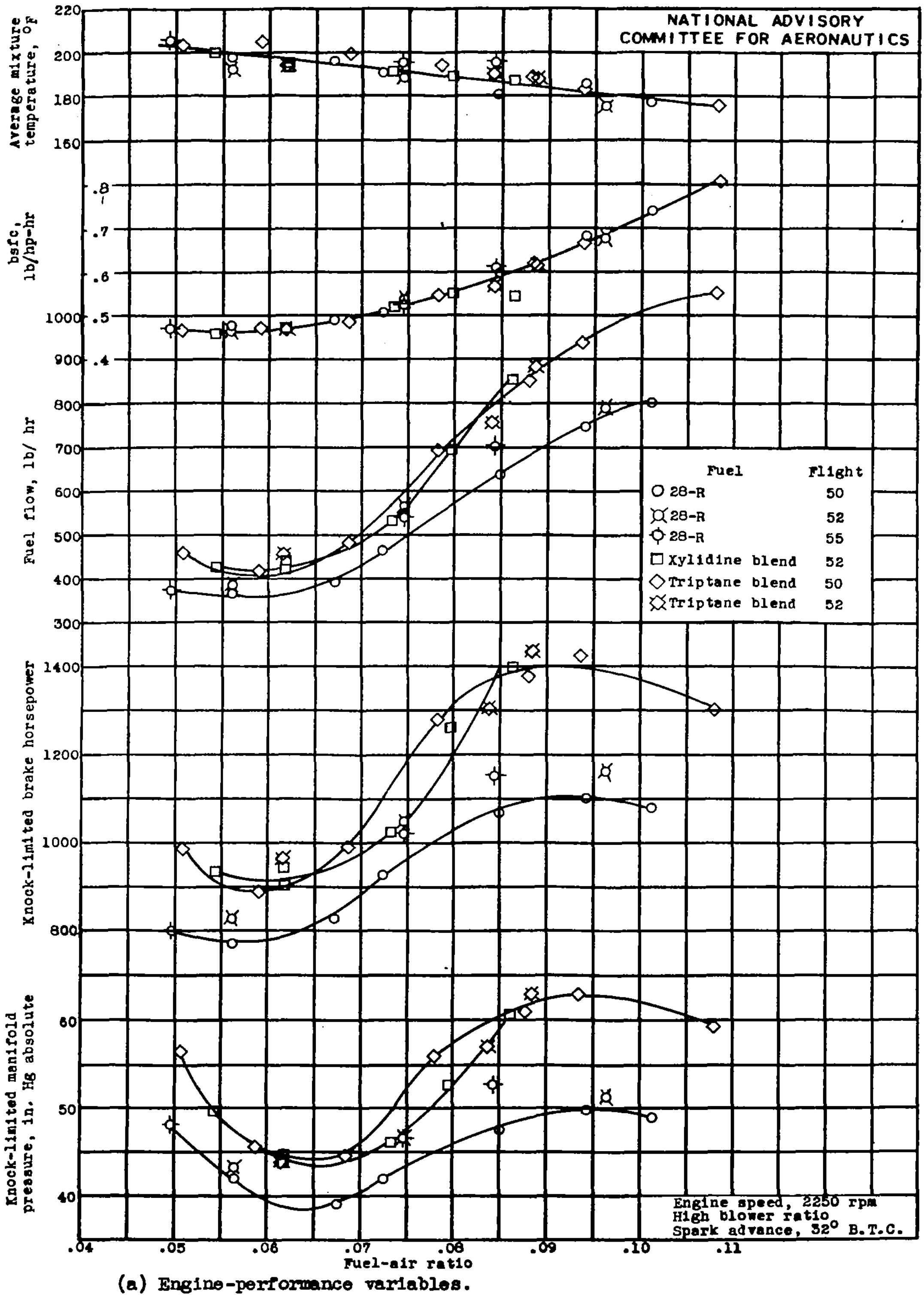
(b) Additional performance variables.

Figure 6. - Continued.



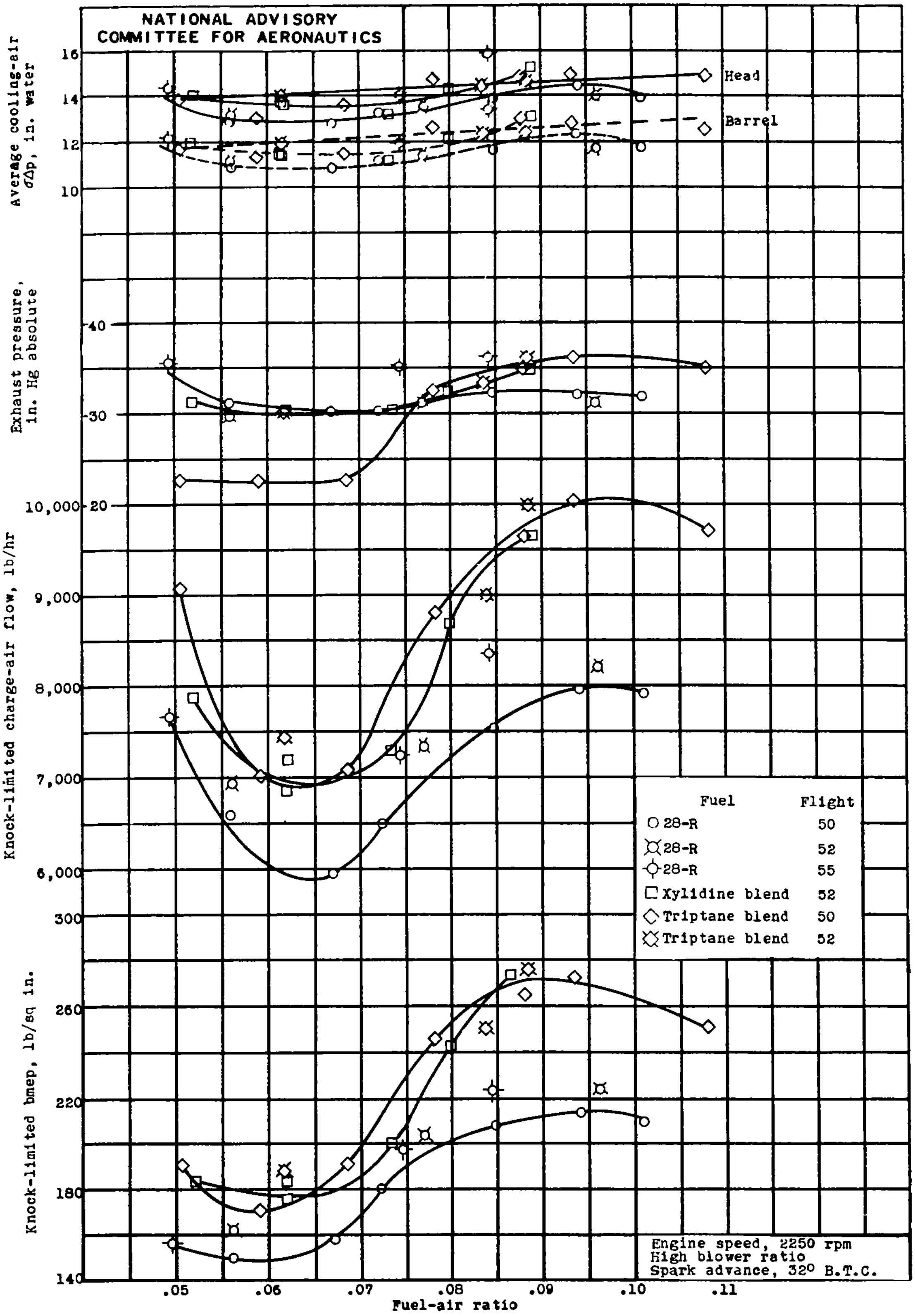
(c) Temperatures.

Figure 6. - Concluded.



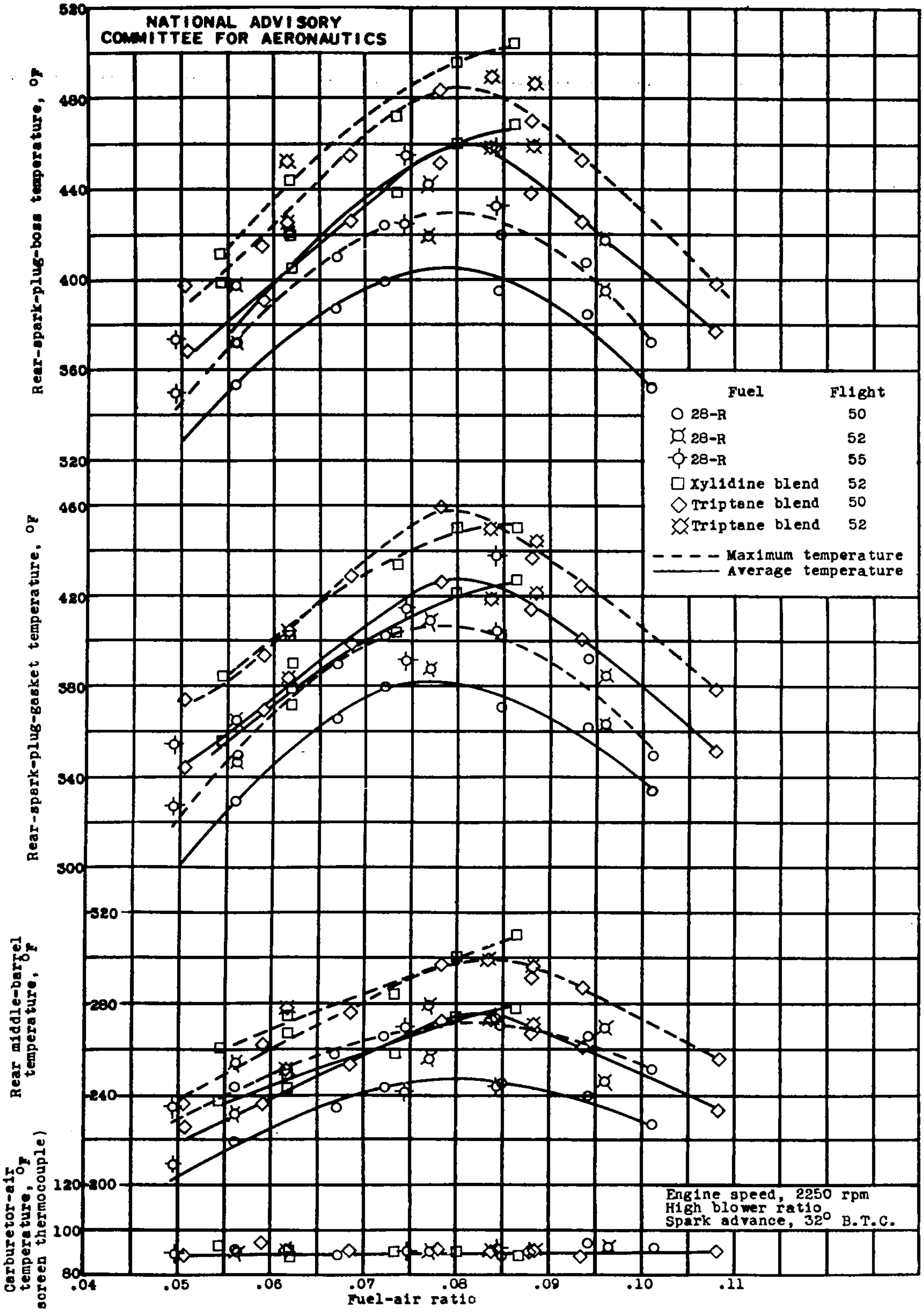
(a) Engine-performance variables.

Figure 7. - Performance of modified engine as limited by the knock characteristics of three fuels; engine speed, 2250 rpm; high blower ratio (8.47:1); spark advance, 32° B.T.C.; carburetor-air temperature (bulb), approximately 85° F; four-engine airplane.



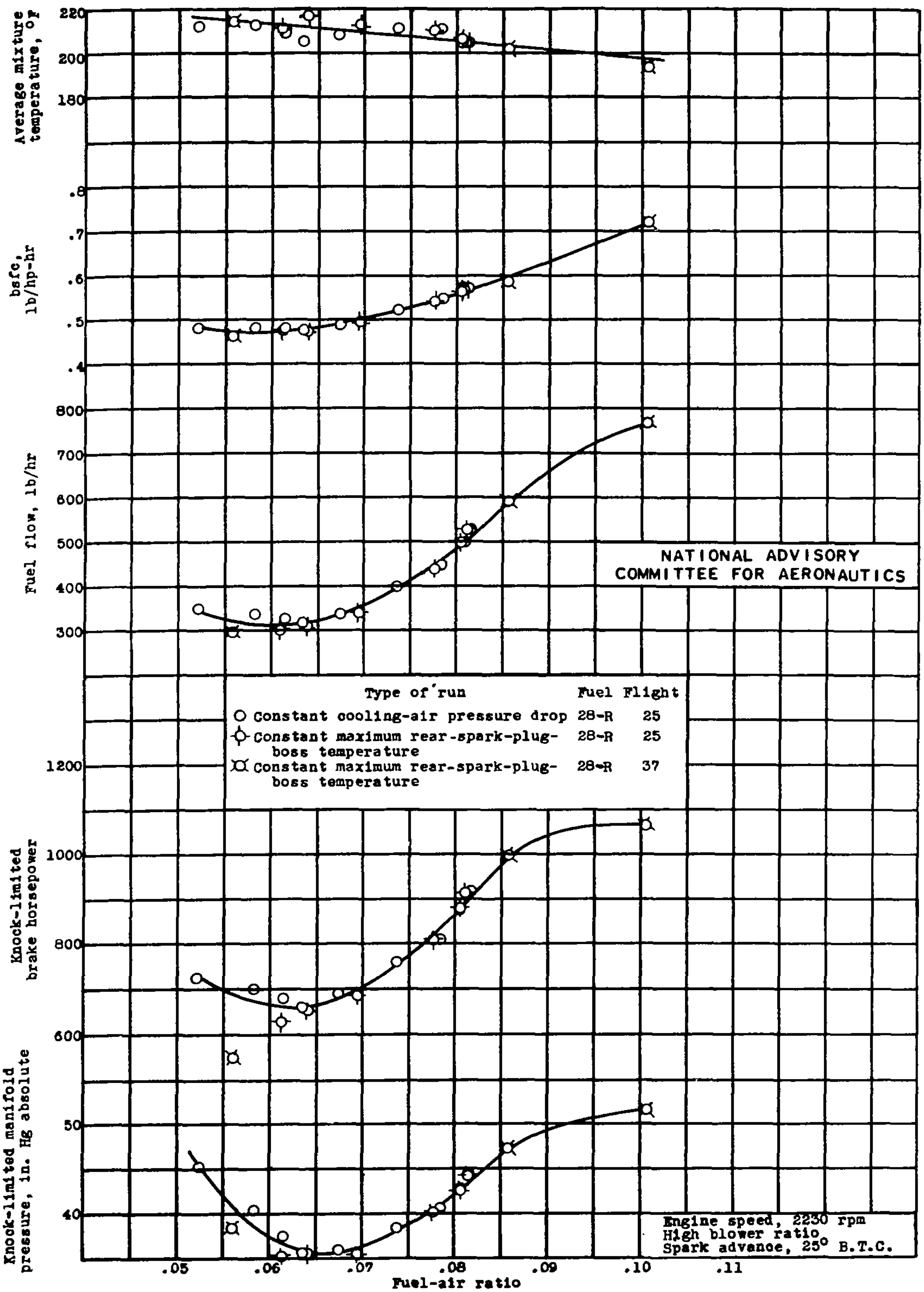
(b) Additional performance variables.

Figure 7. - Continued.



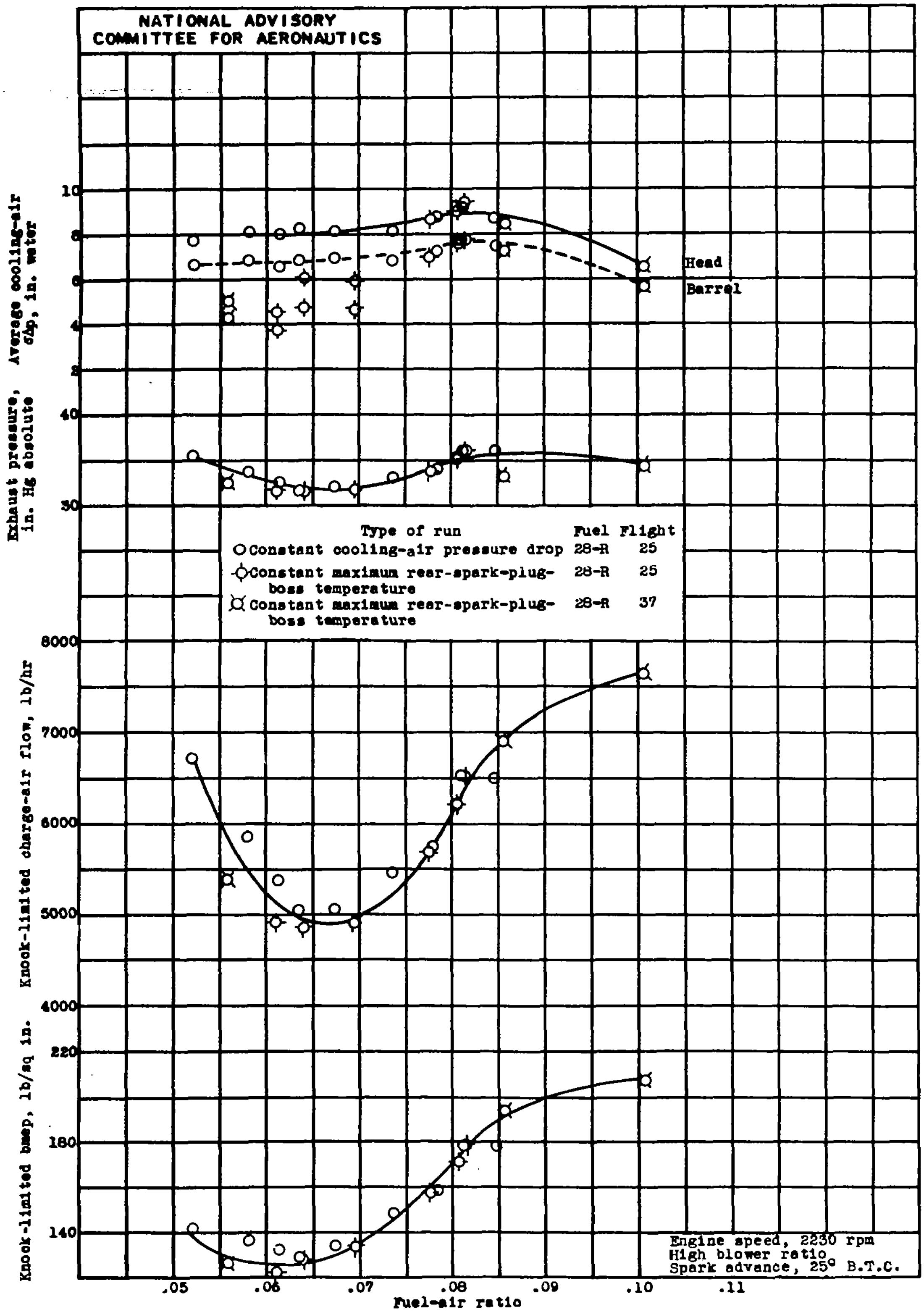
(c) Temperatures.

Figure 7. - Concluded.



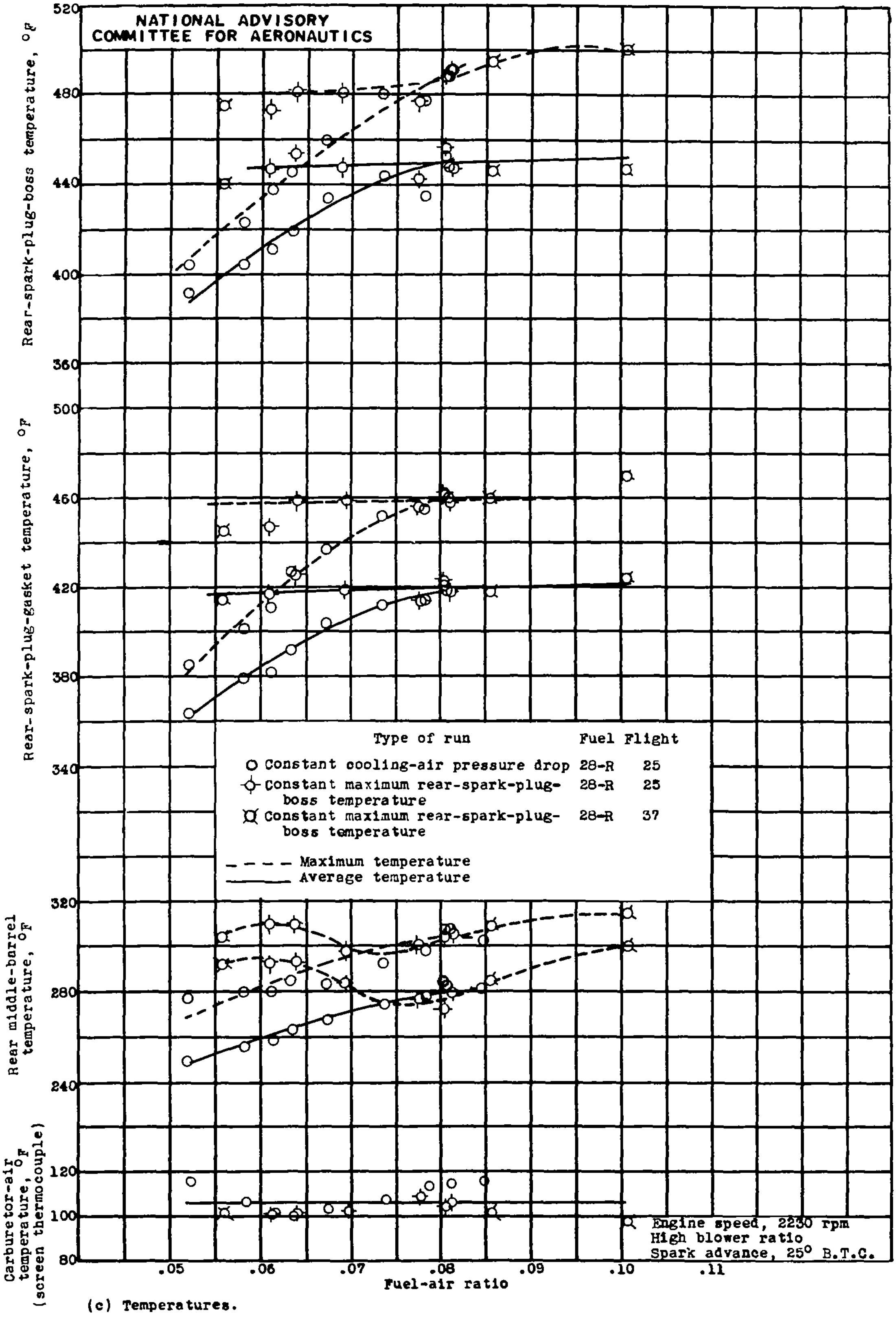
(a) Engine-performance variables.

Figure 8. - Performance of modified engine as limited by the knock characteristics of 28-R fuel; engine speed, 2230 rpm; high blower ratio (8.47:1); spark advance, 25° B.T.C.; carburetor-air temperature (bulb), approximately 100° F; four-engine airplane.



(b) Additional performance variables.

Figure 8. - Continued.



(c) Temperatures.

Figure 8. - Concluded.

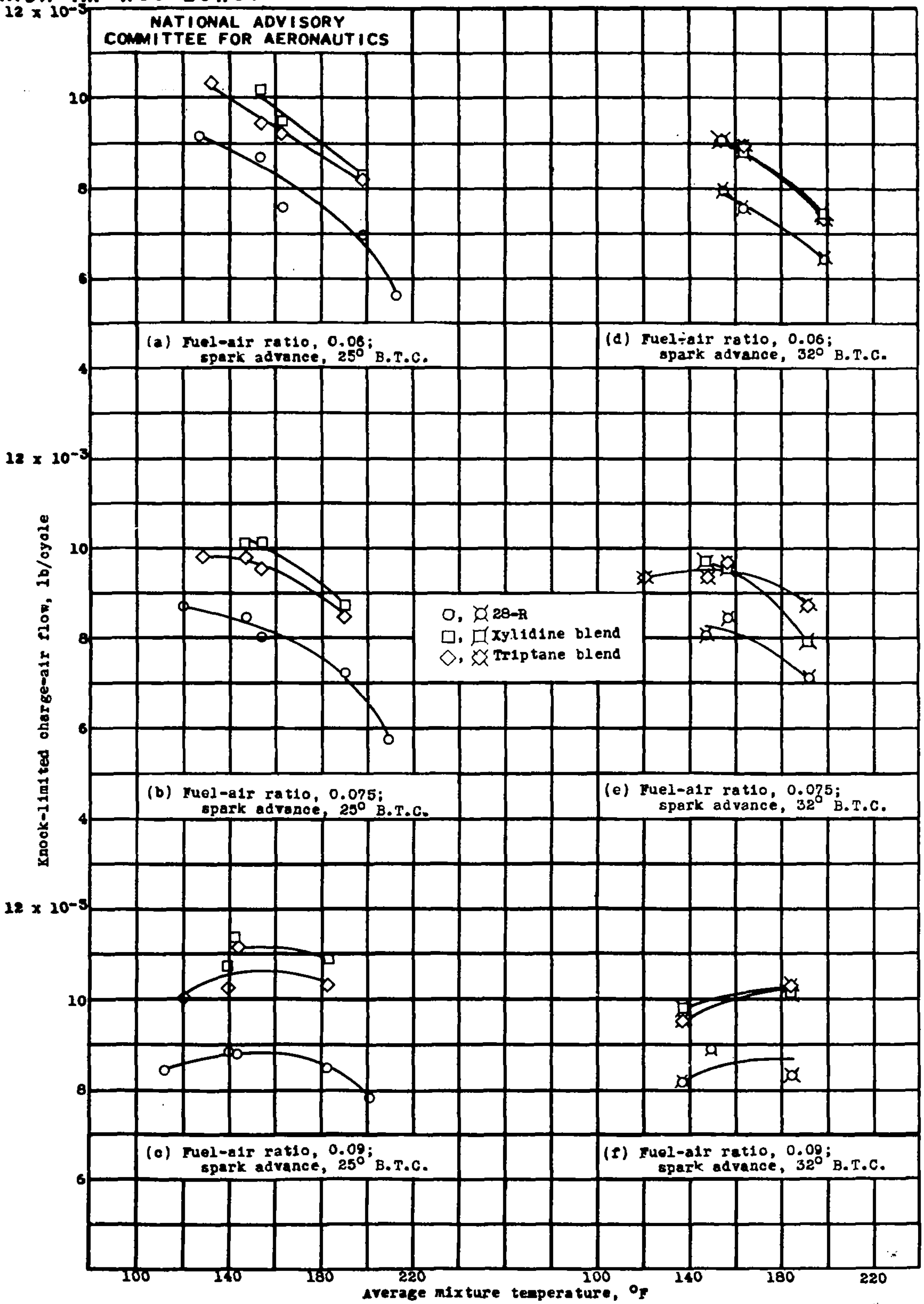
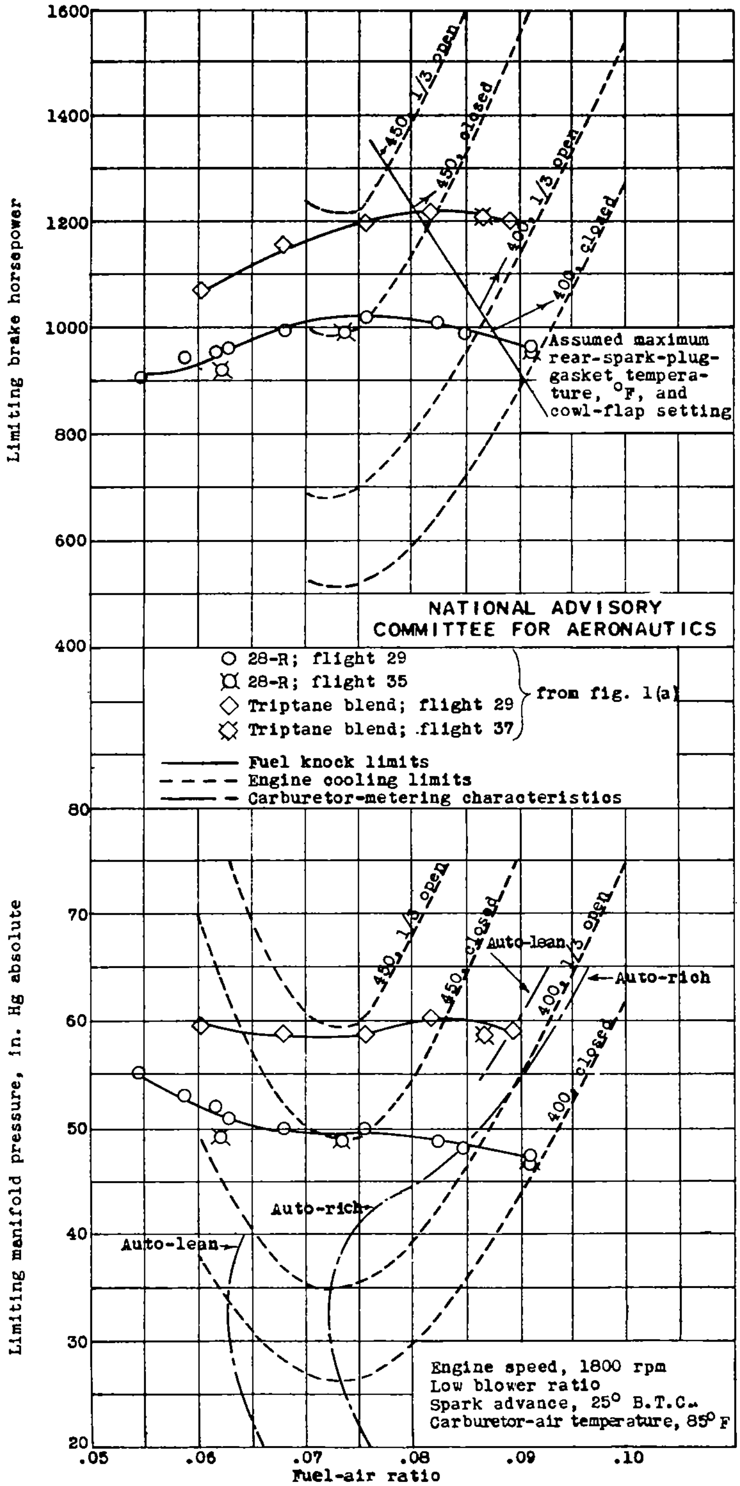
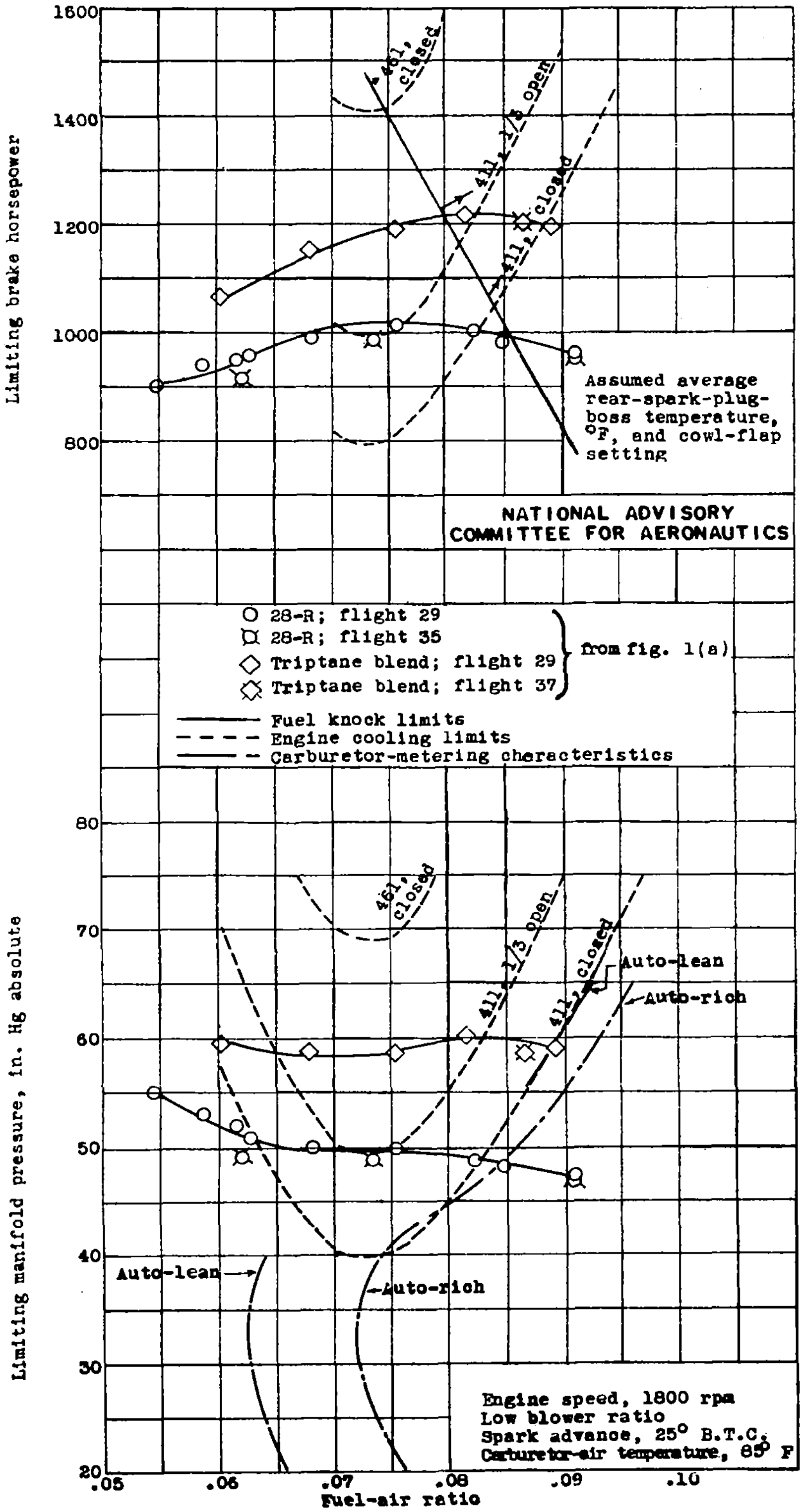


Figure 9. - Variation of knock-limited charge-air flow per cycle with average mixture temperature. Modified engine installed in a four-engine airplane. Data obtained by cross-plotting figures 1 through 8.



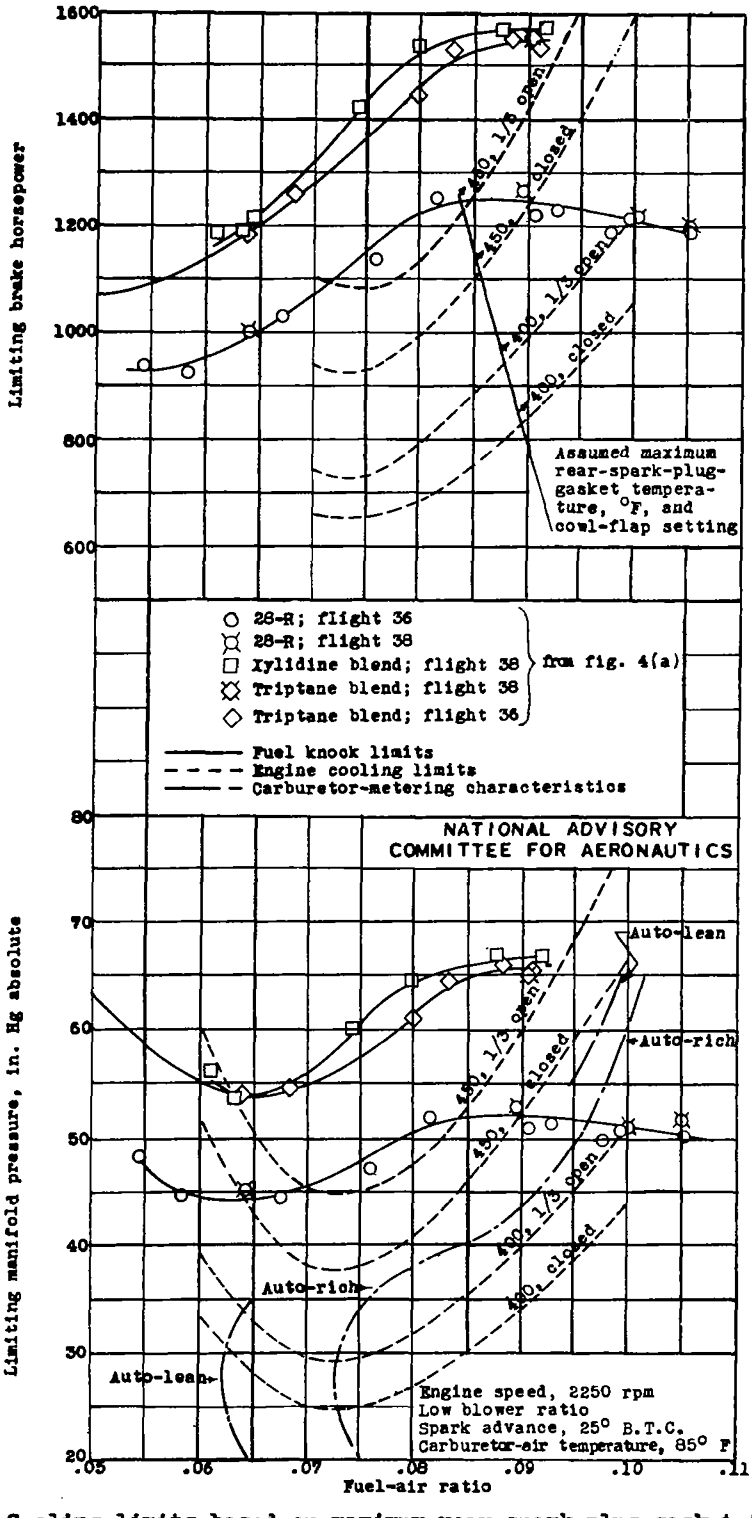
(a) Cooling limits based on maximum rear-spark-plug-gasket temperatures.

Figure 10. - Comparison of fuel knock limits, engine cooling limits, and carburetor-metering characteristics for modified engine installed in four-engine airplane at an engine speed of 1800 rpm. (Engine cooling-limit data based on cooling equation for this engine. Airplane assumed equipped with four modified engines, all operating at temperature-limited power. Assumed conditions: airplane gross weight, 50,000 lb; cooling-air temperature, 60° F; pressure altitude, 7000 ft.)



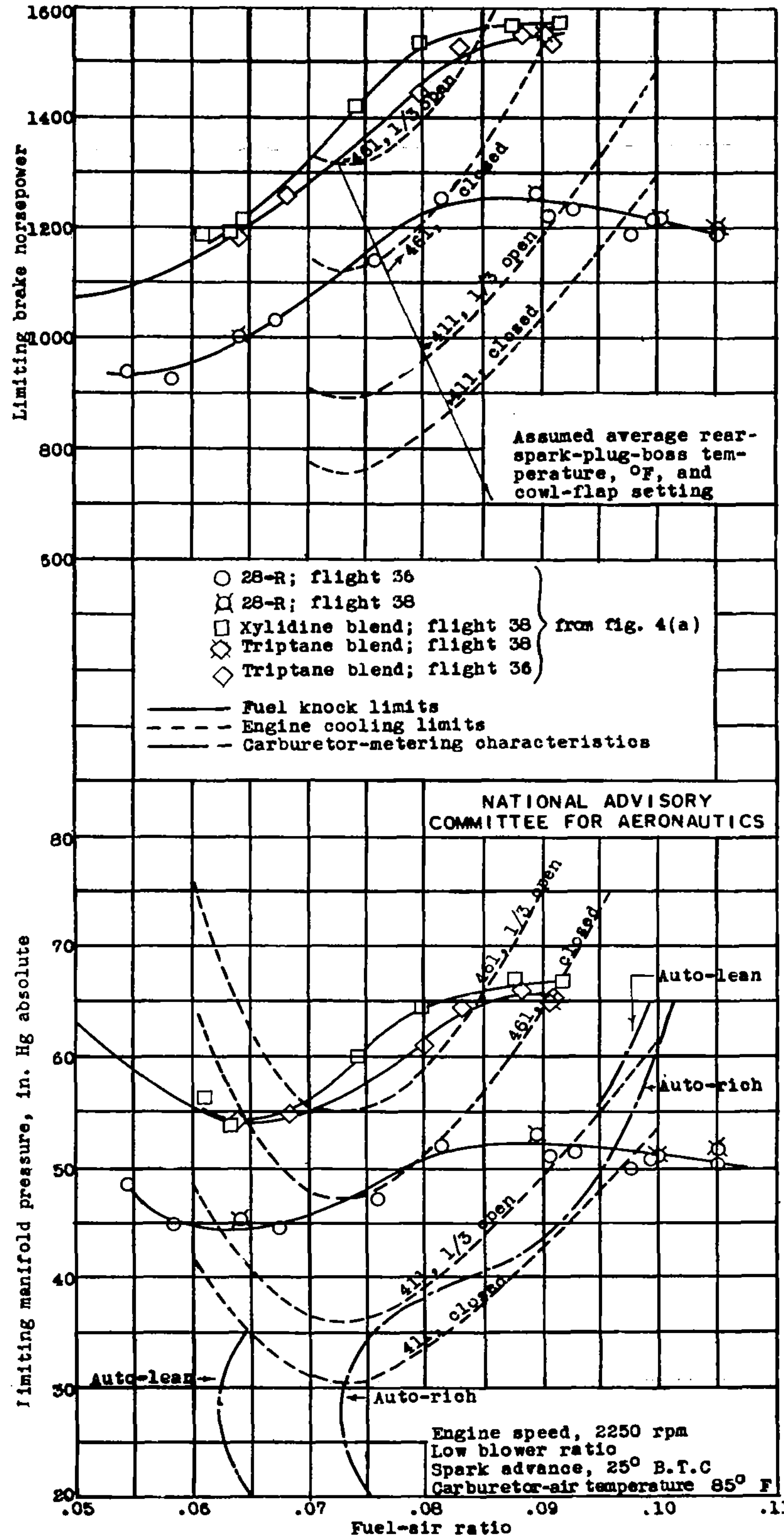
(b) Cooling limits based on average rear-spark-plug-boss temperatures.

Figure 10. - Concluded.



(a) Cooling limits based on maximum rear-spark-plug-gasket temperatures.

Figure 11. - Comparison of fuel knock limits, engine cooling limits, and carburetor-metering characteristics for modified engine installed in a four-engine airplane at an engine speed of 2250 rpm. (Engine cooling-limit data based on cooling equation for this engine. Airplane assumed equipped with four modified engines, all operating at temperature-limited power. Assumed conditions: airplane gross weight, 50,000 lb; cooling-air temperature, 60° F; pressure altitude, 7000 ft.)



(b) Cooling limits based on average rear-spark-plug-boss temperatures.

Figure 11. - Concluded.

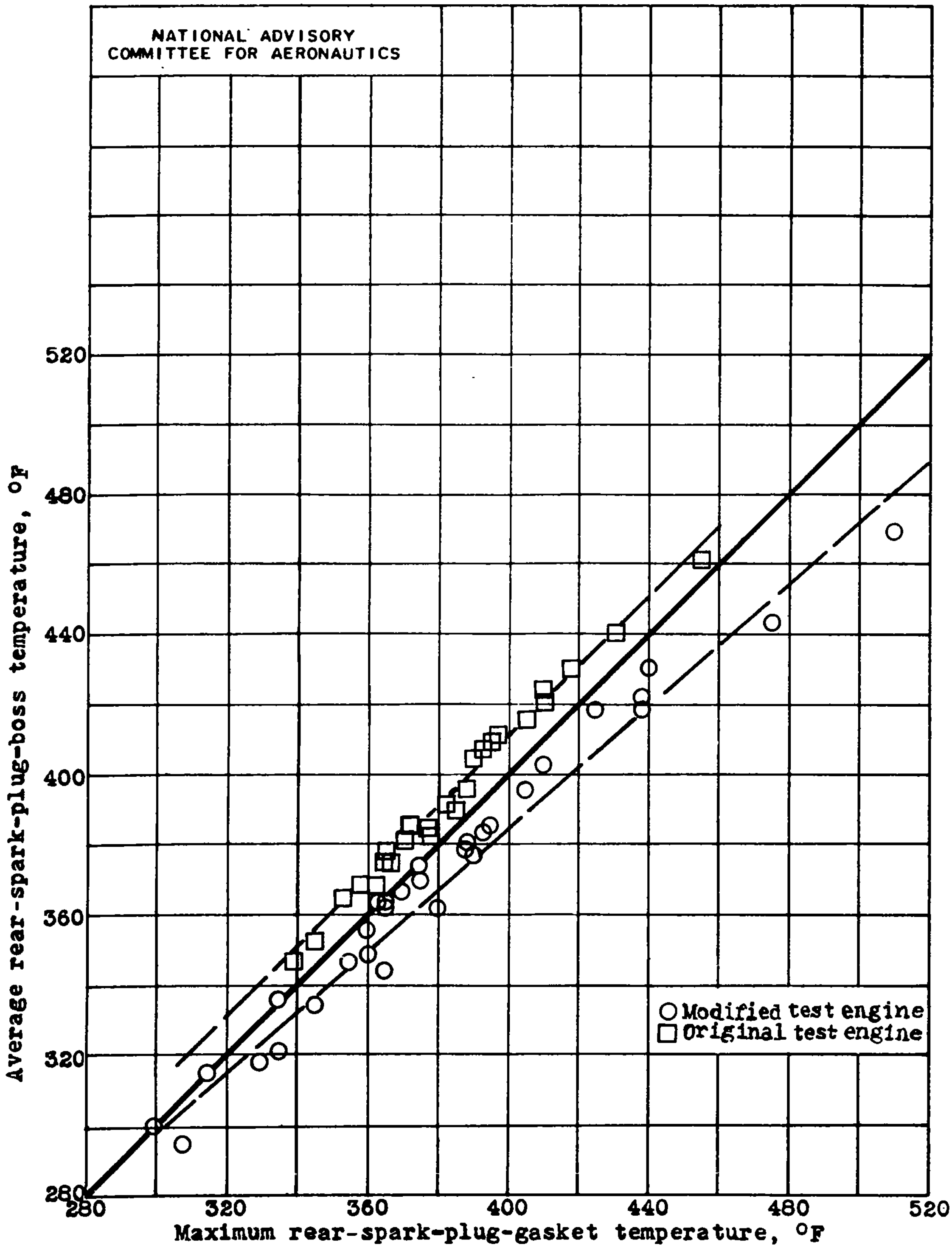


Figure 12. - Comparison of average rear-spark-plug-boss temperature, measured by embedded thermocouples, with maximum rear-spark-plug-gasket temperature.

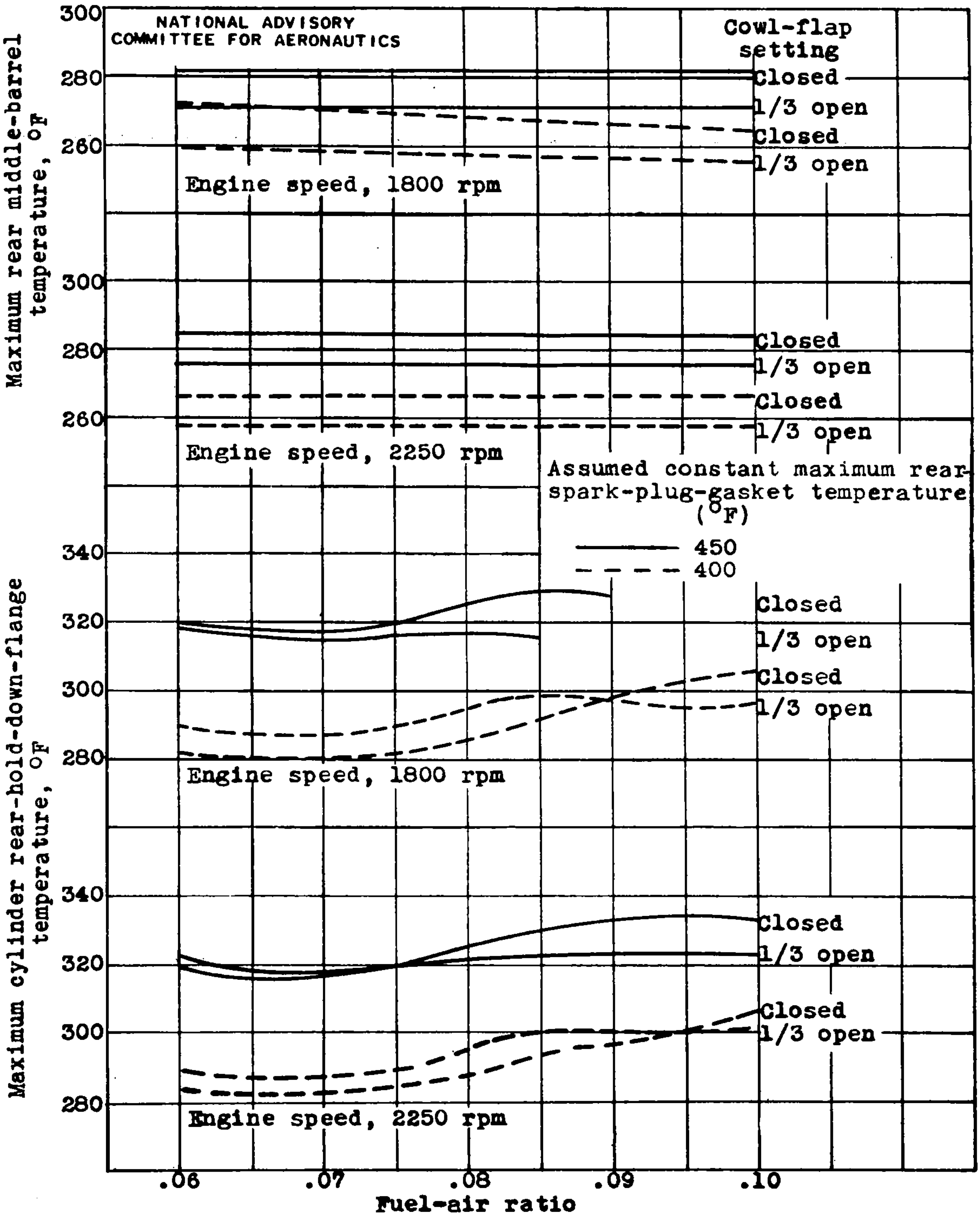


Figure 13. - Variation of maximum rear middle-barrel and maximum cylinder rear-hold-down-flange temperature with fuel-air ratio for two assumed constant maximum rear-spark-plug-gasket temperatures. (Curves correspond to respective temperature-limited performance curves in figs. 10(a) and 11(a) for 1/3 open and closed cowl-flap settings.)

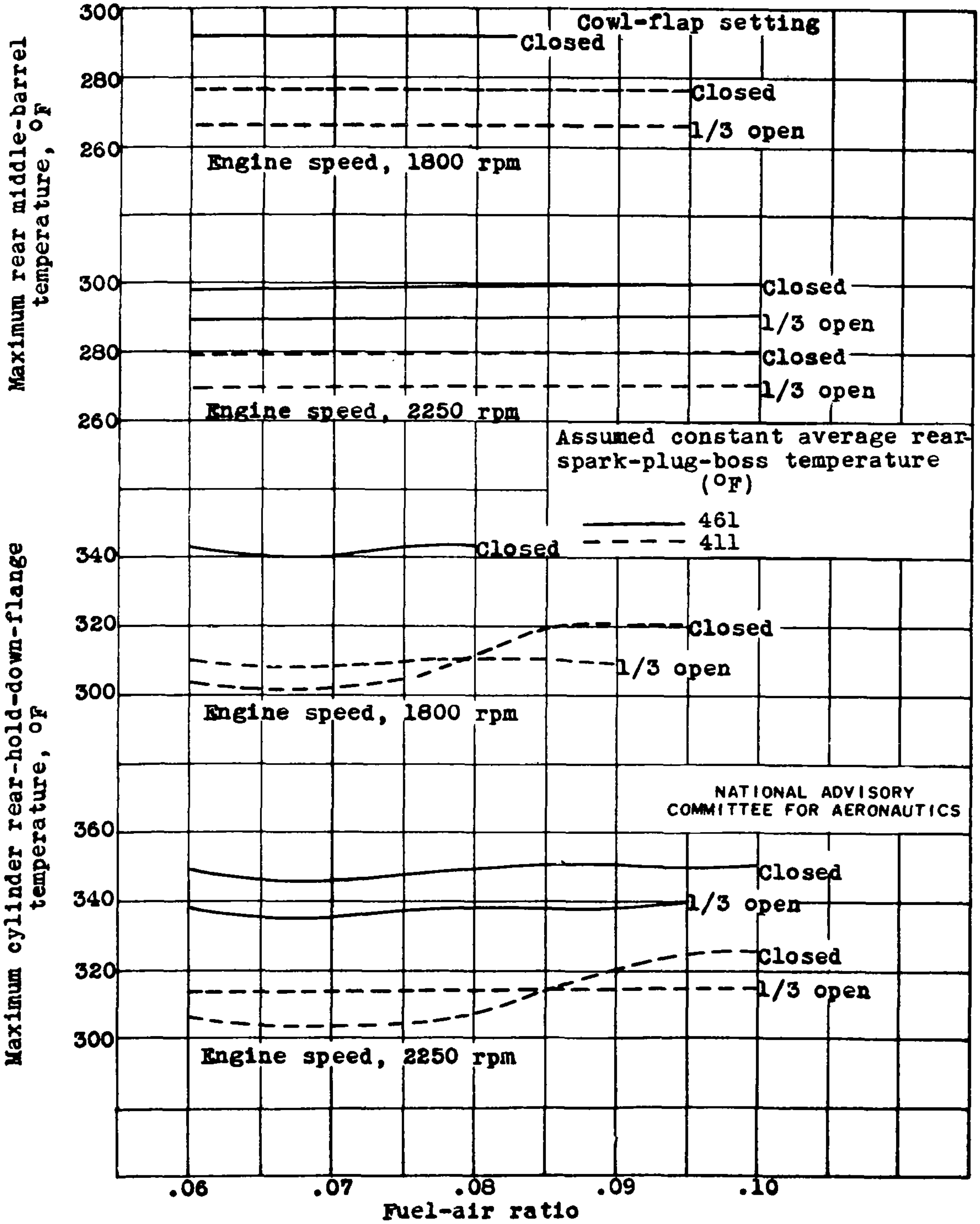
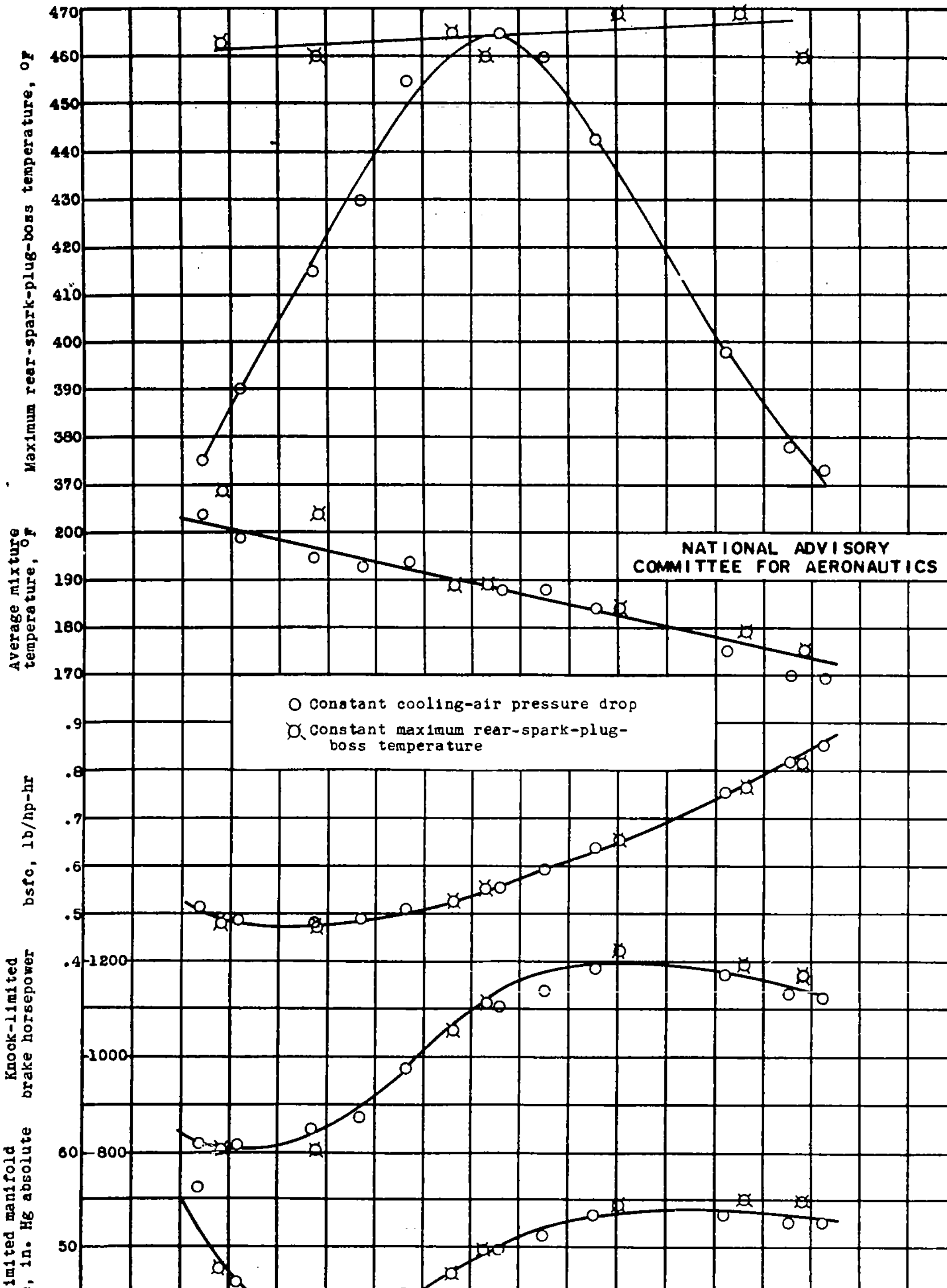
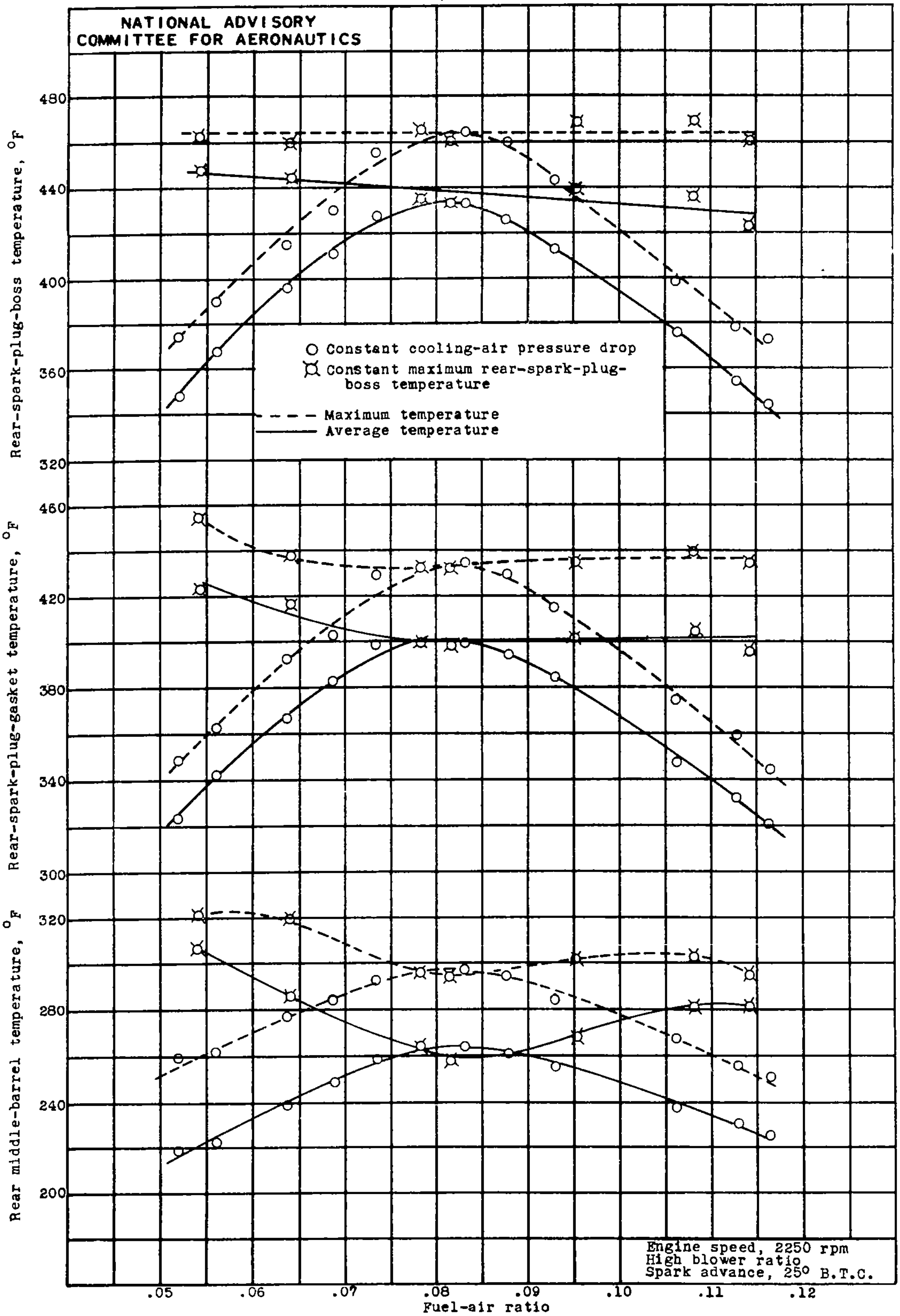


Figure 14. - Variation of maximum rear middle-barrel and maximum cylinder rear-hold-down-flange temperature with fuel-air ratio for two assumed constant average rear-spark-plug-boss temperatures. (Curves correspond to respective temperature-limited performance curves in figs. 10(b) and 11(b) for 1/3 open and closed cowl-flap settings.)



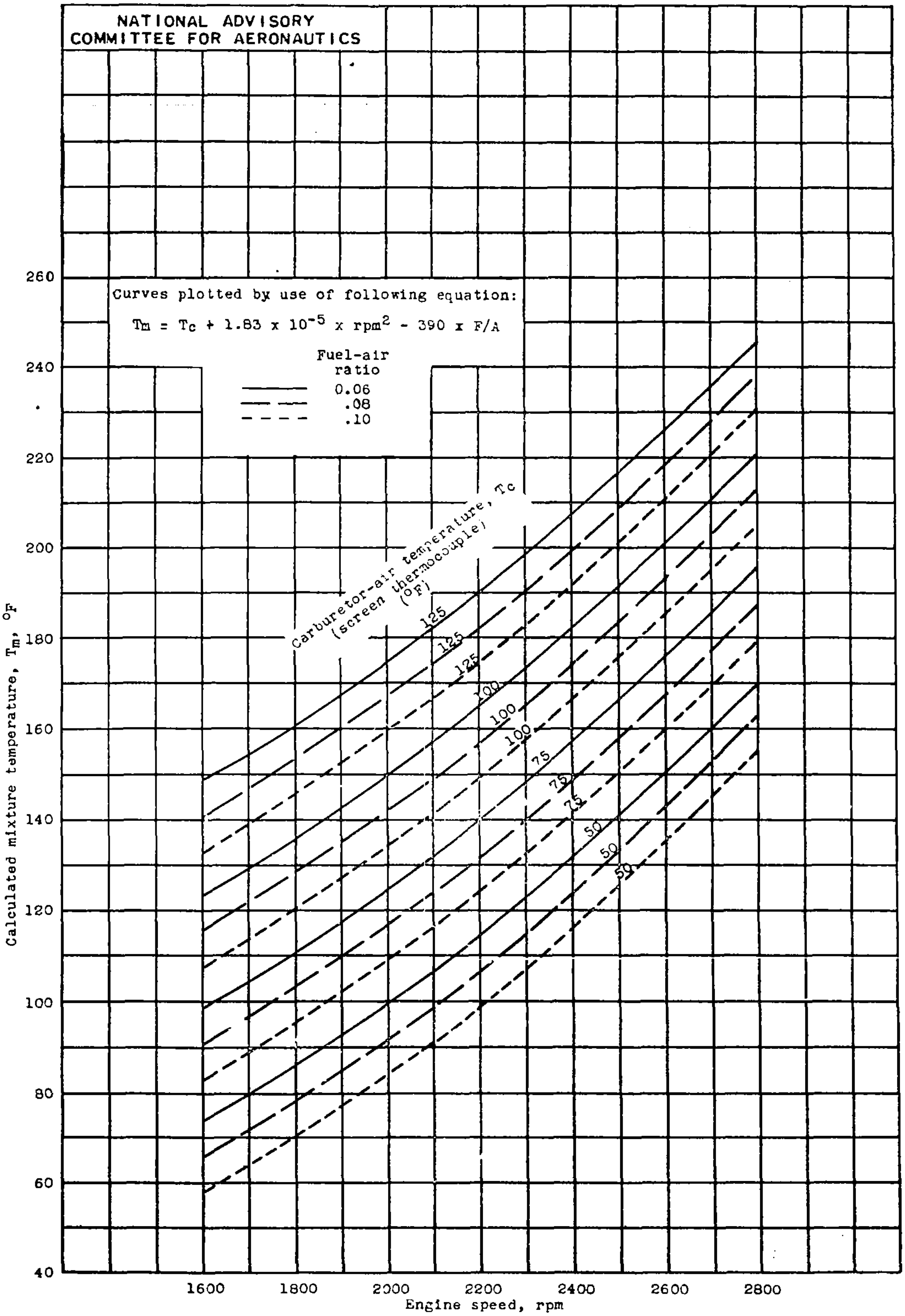
(a) Engine-performance variables and maximum rear-spark-plug-boss temperature.

Figure 15. - Comparison of knock data obtained at constant cooling-air pressure drop with data obtained at constant maximum rear-spark-plug-boss temperature; 28-R fuel; carburetor-air temperature (bulb), approximately 85° F; flight 34.



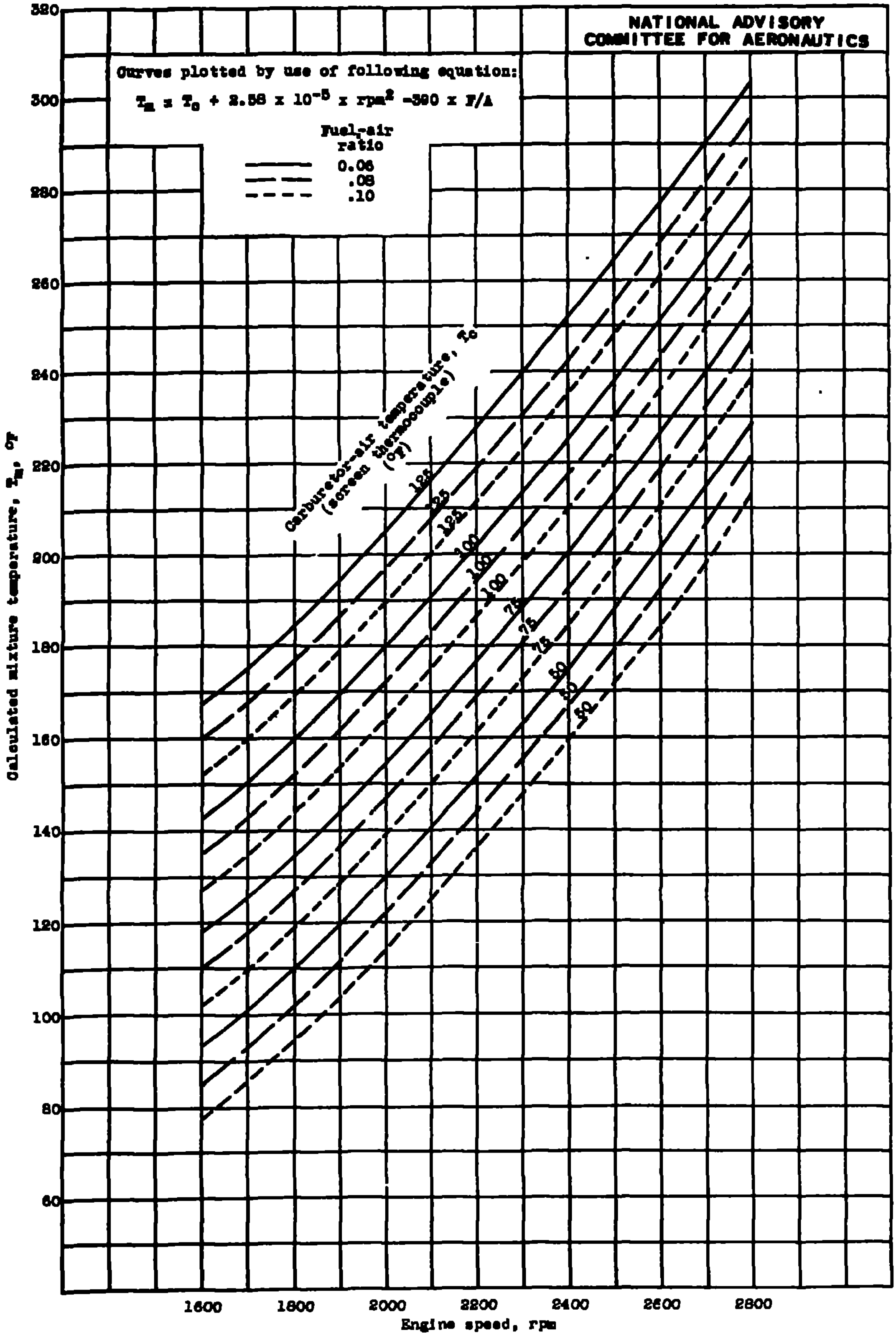
(b) Engine temperatures.

Figure 15. - Concluded.



(a) Low blower (7.15:1).

Figure 16. - Calculated relation between engine speed, carburetor-air temperature, fuel-air ratio, and mixture temperature. Modified engine; impeller diameter, 11.3 inches; low blower ratio.



(b) High blower (8.47:1).

Figure 16. - Concluded.

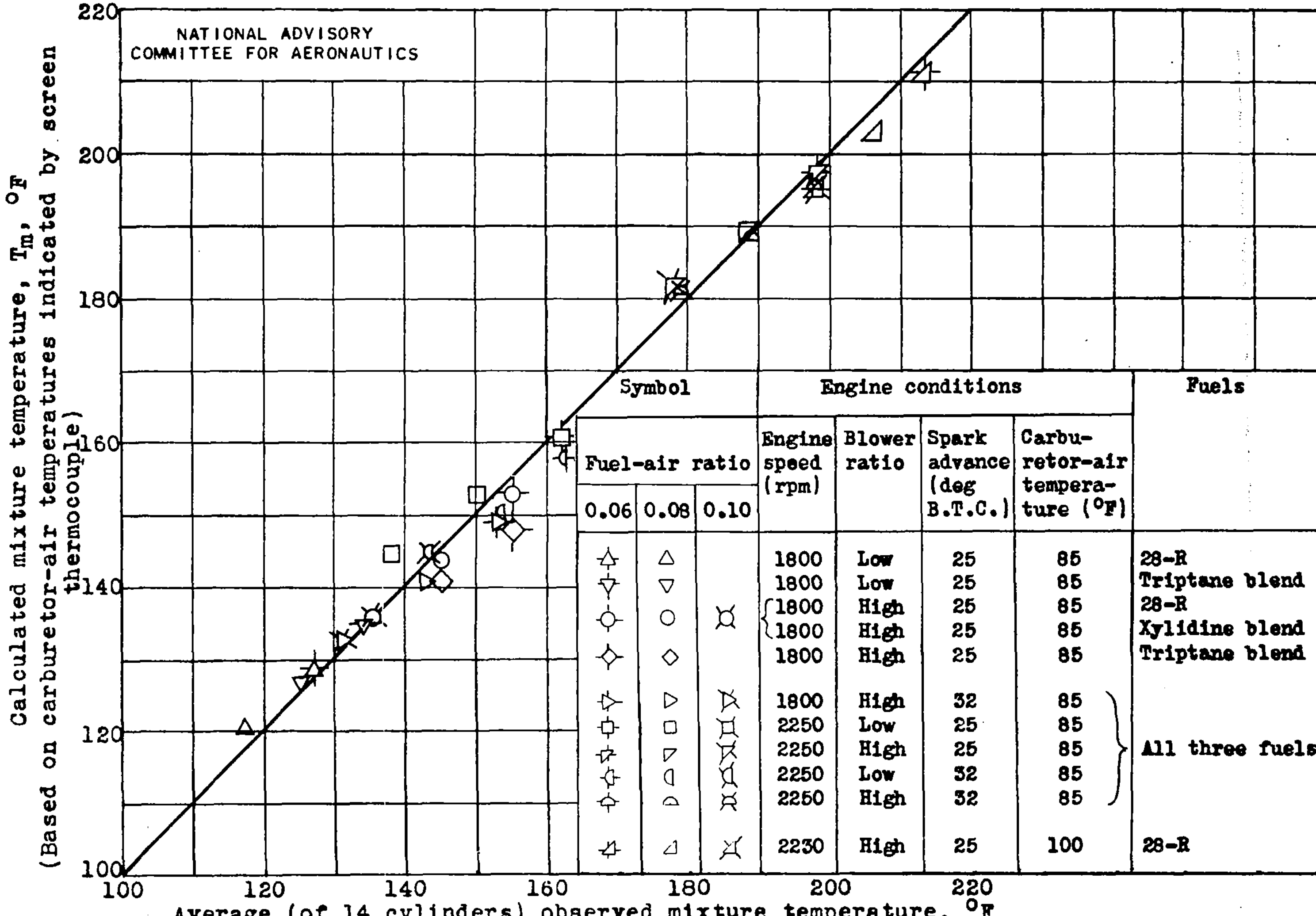


Figure 17. - Relation between calculated and average observed mixture temperatures. Modified engine installed in four-engine airplane.