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RM No. E6L31

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Source of Acquisition
CASI Acquired
Authority [illegible] Date 7-3-50
Dir., Aeron[illegible]
NACA
By [illegible] Sec 218.10-4
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RESEARCH MEMORANDUM

MINIMUM SPECIFIC FUEL CONSUMPTION OF A LIQUID-COOLED MULTICYLINDER AIRCRAFT ENGINE AS AFFECTED BY COMPRESSION RATIO AND ENGINE OPERATING CONDITIONS

By Rinaldo J. Brun, Melvin S. Feder
and Myron L. Harries

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MINIMUM SPECIFIC FUEL CONSUMPTION OF A LIQUID-COOLED MULTICYLINDER AIRCRAFT ENGINE AS AFFECTED BY COMPRESSION RATIO AND ENGINE OPERATING CONDITIONS

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SUMMARY

An investigation was conducted on a 12-cylinder V-type liquid-cooled aircraft engine of 1710-cubic-inch displacement to determine the minimum specific fuel consumption at constant cruising engine speed and compression ratios of 6.65, 7.93, and 9.68. At each compression ratio, the effect of the following variables was investigated at manifold pressures of 28, 34, 40, and 50 inches of mercury absolute: temperature of the inlet-air to the auxiliary-stage supercharger, fuel-air ratio, and spark advance. Standard sea-level atmospheric pressure was maintained at the auxiliary-stage supercharger inlet and the exhaust pressure was atmospheric.

Advancing the spark timing from 34° and 28° B.T.C. (exhaust and intake, respectively) to 42° and 36° B.T.C. at a compression ratio of 6.65 resulted in a decrease of approximately 3 percent in brake specific fuel consumption. Further decreases in brake specific fuel consumption of 10.5 to 14.1 percent (depending on power level) were observed as the compression ratio was increased from 6.65 to 9.68, maintaining at each compression ratio the spark advance required for maximum torque at a fuel-air ratio of 0.06. This increase in compression ratio with a power output of 0.585 horsepower per cubic inch required a change from a fuel blend of 6-percent triptane with 94-percent 28-R fuel at a compression ratio of 6.65 to a fuel blend of 58-percent triptane with 42-percent 28-R fuel at a compression ratio of 9.68 to provide for knock-free engine operation.

As an aid in the evaluation of engine mechanical endurance, peak cylinder pressures were measured on a single-cylinder engine at several operating conditions. Peak cylinder pressures of 1900 pounds

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per square inch can be expected at a compression ratio of 9.68 and an indicated mean effective pressure of 320 pounds per square inch. The engine durability was considerably reduced at these conditions.

INTRODUCTION

Fuel economy is one of the principle interests in long-range flight. Proper engine design and methods of engine operation for best economy have been the subjects of a large amount of research and development work. Limitations due to fuel knock or to preignition and mechanical endurance of the engine have restricted the operation and design for maximum economy. The restrictions are lessening with the development of better fuels and improved engine construction. An investigation has been conducted at the NACA Cleveland laboratory to determine the combined effects of changes in compression ratio and in some other important operating variables on fuel economy and fuel-performance requirements of a liquid-cooled aircraft engine. High-performance fuel blends of triptane and 28-R fuel were used for the suppression of knock at the engine conditions required for best economy.

The effects of a change in inlet-air temperature and in fuel-air ratio on fuel economy and on fuel-performance requirements were investigated at three compression ratios, 6.65, 7.93, and 9.68 at a constant cruising engine speed. At each compression ratio, the runs were made at two spark settings: (1) a reference spark setting, which was the same for all compression ratios, and (2) an advanced setting that gave maximum torque with constant manifold pressure and temperature at a fuel-air ratio of 0.06 at the compression ratio being tested. In order to cover a range of cruising power up to 0.760 brake horsepower per cubic inch of displacement with knock-free operation, blends of 28-R and triptane were required with a triptane content up to 75 percent for the high power and high compression ratios. All fuels were leaded with 4.6 ml TEL per gallon. Peak cylinder pressures were measured on a single-cylinder engine at several operating conditions to aid in the evaluation of engine mechanical endurance.

APPARATUS

Engine. - The experimental data were obtained with a 12-cylinder V-type liquid-cooled aircraft engine of 1710-cubic-inch displacement that had two stages of supercharging (a gear-driven engine-stage supercharger and an auxiliary-stage supercharger driven through a hydraulic coupling) with interstage carburetion. Each cylinder had two spark

plugs, one between the two exhaust valves and one between the two intake valves. All automatic engine controls were removed. Several engines of the same type were used to obtain the data.

Pistons. - Compression ratio was varied by using different pistons. An outline view of the pistons showing the difference in crown shape for the three compression ratios is given in figure 1. The compression ratios, as measured on the engine with these pistons installed, were 6.65, 7.93, and 9.68. The same type of piston ring was used with all the pistons.

Dynamometer and engine installation. - The engine was set up on a dynamometer stand with a 2500-horsepower water-cooled eddy-current dynamometer and a 600-horsepower direct-current dynamometer connected in tandem. The direct-current dynamometer was capable of developing 500 horsepower to motor the engine for friction measurements. The dynamometers were equipped with electronic controls to maintain a preset speed. Torque was measured with a balanced-diaphragm torque indicator, described in reference 1.

Special equipment and instrumentation. - Accurate manual mixture regulation was facilitated by the use of a special air-bleed valve connected across the diaphragm of the air-metering regulator of the carburetor. Vibration-type pickup units with an amplifier oscilloscope combination were used for knock detection.

A sketch of the induction system and the stations where the temperatures and pressures were measured are presented in figure 2.

Inlet-air temperature T_1 (fig. 2) was measured by five thermocouples connected in parallel and arranged in the air stream $2\frac{1}{4}$ inches from the inlet-duct surface. Temperature of the inlet air to the main-stage supercharger T_2 was measured at the interstage duct to avoid fuel-vaporization effects. (The fuel was sprayed into the engine-stage supercharger inducer.) Measured mixture temperatures T_3 were obtained by an unshielded thermocouple installed in the central manifold approximately 9 inches downstream of the flange of the engine-stage supercharger outlet or just upstream of the center-manifold venturi. The mixture temperature at this point checked closely the temperature T_4 measured by a shielded thermocouple located 3 inches downstream of the center-manifold venturi and averaged about 10° F lower than the temperature T_5 measured in the side manifolds.

The manifold-pressure tap P_3 was located in the central manifold approximately $6\frac{1}{2}$ inches downstream of the flange of the

engine-stage supercharger outlet. (The pressure at this point averaged about 0.7-in. Hg higher than the pressure P_5 at either the right or the left rear manifolds.)

Peak-cylinder-pressure equipment. - Peak cylinder pressure was measured on a multicylinder block adapted to a CUE crankcase for single-cylinder operation. A pressure pickup utilizing the balanced-pressure principle applied on a diaphragm together with an electronic instrument to determine when the cylinder pressure was equal to the applied pressure was used in the measurement of peak cylinder pressure. The balancing pressure was observed on a calibrated Bourdon gage.

CONDITIONS AND PROCEDURE

The following engine conditions were maintained during the runs:

Engine speed, rpm	2280 ±3
Outlet-coolant temperature, °F	250 ±5
Inlet-oil temperature, °F	180 ±5
Inlet-air pressure to auxiliary-stage supercharger, inches mercury absolute	29.9 ±0.1

Exhaust pressure was maintained at atmospheric pressure.

Runs were made at each of the conditions of compression ratio, spark advance, and inlet-air temperature listed in table I to determine the variation of brake specific fuel consumption and power output with fuel-air ratio. The predetermined manifold pressure was obtained by adjusting the throttle position with the auxiliary-stage supercharger operating at maximum slip in the hydraulic coupling except when the throttle was wide open and auxiliary-stage supercharging was necessary, in which case the desired manifold pressure was obtained by adjusting the speed of the auxiliary-stage supercharger.

Data were obtained at two spark settings, which will be called reference setting and advanced setting. The spark settings used are shown in the following table:

Compression ratio	Reference spark setting (deg B.T.C.)		Advanced spark setting (deg B.T.C.)	
	Exhaust	Intake	Exhaust	Intake
6.65	34	28	42	36
7.93	34	28	39	33
9.68	34	28	36	30

The reference spark setting is that recommended by the engine manufacturer for normal engine operation at a compression ratio of 6 65. The advanced spark setting, determined from single-cylinder investigations, is the spark setting that results in maximum torque at a fuel-air ratio of 0.06, a mixture temperature of 200° F, an engine speed of 2280 rpm, and a manifold pressure of 35 inches of mercury absolute.

The following fuels blended on a percentage volume basis, all containing 4.6 ml TEL per gallon, were used:

28-R
90-percent 28-R, 20-percent triptane
50-percent 28-R, 50-percent triptane
25-percent 28-R, 75-percent triptane

For each run the blend was used that contained the minimum amount of triptane to allow knock-free operation at constant manifold pressure over the range of fuel-air ratio tested.

In addition to the constant-manifold-pressure runs, data for curves of knock-limited manifold pressure plotted against fuel-air ratio were obtained for each blend of fuel with which knock occurred below a manifold pressure of 50 inches of mercury absolute at the conditions of the run.

The multicylinder engine was driven by the direct-current dynamometer to measure the motoring horsepower. The motoring horsepower was obtained with engine conditions closely simulating firing conditions; after the firing conditions had been established, the fuel and ignition were cut off and the engine was immediately automatically driven by the motoring dynamometer.

RESULTS AND DISCUSSION

The important variables affecting fuel consumption are engine speed, manifold pressure, fuel-air ratio, mixture temperature, spark setting, and compression ratio. The brake horsepower required, engine friction, and mechanical endurance of the engine usually decide the engine speed used for cruising. The engine speed chosen was that recommended by the manufacturers of the engine for operation at high cruising power; the other important variables were all investigated.

In figures 3, 4, and 5 are presented the experimental results for compression ratios of 6.65, 7.93, and 9.68, respectively. The effect of fuel-air ratio on engine performance is shown for four constant manifold pressures of 28, 34, 40, and 50 inches of mercury absolute. Knock-limited manifold-pressure curves for the fuels used in the investigation are also shown in these figures.

A number of the data curves were checked for reproducibility, in some cases by the same engine used to obtain the original curves and in others by another engine. These check data are shown on the curve sheets as tailed symbols to indicate the degree of reproducibility of the data.

Indicated horsepower is defined as the brake horsepower plus the motoring horsepower. The motoring horsepower is a measure of the losses caused by engine friction, the supercharger, the induction system, and the oil- and coolant-pumping system.

The rate of mass air flow with the engine firing was between 5 and 10 percent greater than with the engine motoring for the same values of manifold pressure, inlet-air temperature, and inlet-air pressure to the auxiliary-stage supercharger. The exhaust-gas velocity is higher during firing operation than during motoring operation; this higher velocity probably induces a greater air flow through the cylinder during the valve-overlap period. No noticeable change in air flow was measured during the motoring runs either with or without fuel passing through the engine. The measured value of motoring horsepower used to obtain indicated horsepower was corrected by adding the computed work of the supercharger caused by the difference in air flow between motoring and firing runs. As the effect of fuel-air ratio on specific fuel consumption and power output is indicated in figures 3 to 5, further consideration of the effect of engine-operating variables on engine performance will be limited to data at approximately the fuel-air ratio for minimum specific fuel consumption.

Mixture temperature. - Mixture temperature indirectly affects the engine economy in two ways: (1) The knock-limited power output decreases with increase in mixture temperature; and (2) the mass charge flow through the engine decreases with an increase in mixture temperature, thus decreasing the power output. For a given over-all supercharger pressure ratio and with constant or no intercooling of the charge, the mixture temperature is dependent on the inlet-air temperature to the supercharger.

A cross plot (fig. 6) taken from figures 3 to 4(c) shows the effects on brake specific fuel consumption and on brake horsepower of changes in mixture temperature. Curves at constant inlet-air temperatures are also shown. In order to nullify the effect of fuel-air ratio on the mixture temperature, the points in figure 6 were taken at constant fuel-air ratio near the point of minimum brake specific fuel consumption.

The effect of inlet-air temperature on engine performance was not determined for all compression ratios and spark settings used in the investigation. Performance data are available at an inlet-air temperature of 60° F for all the compression ratios and spark settings investigated; because of similarity in the trends of results, as shown in figure 6, engine performance at other inlet-air temperatures can be predicted.

Spark advance. - The economic advantage of advancing the spark timing for cruising operation, within the range of conditions used in this investigation, is shown in figure 7, which compares the data on brake specific fuel consumption obtained and the manifold pressure required for several power output levels at the reference spark setting to similar data at advanced spark setting. The figure shows that the greatest difference in brake specific fuel consumption occurs at the low compression ratio; the advanced spark setting approaches the reference spark setting as the compression ratio is increased.

Brake specific fuel consumption was decreased approximately 3 percent at a compression ratio of 6.65 by advancing the spark setting from 34° and 28° B.T.C. (exhaust and intake, respectively) to 42° and 36° B.T.C. when operation at the fuel-air ratio for minimum brake specific fuel consumption in each case is considered.

The percentage triptane in 28-R fuel required for knock-free operation is also shown in figure 7 as well as the manifold pressure required at the several power output levels. These data are cross plots at minimum brake specific fuel consumption from the data at 60° F inlet-air temperature presented in figures 3(b), 3(e), 4(b), 4(d), 5(a), and 5(b).

Compression ratio. - In view of the appreciable advantage with the low compression ratio of operating at the advanced spark setting, the advanced spark setting should be used in correlating other variables. Figure 8, obtained from the data of figures 3(e), 4(d), and 5(b), is a three-dimensional plot correlating compression ratio, manifold pressure, and brake horsepower at an inlet-air temperature

of 60° F, advanced spark setting, and minimum brake specific fuel consumption. Contour lines of minimum brake specific fuel consumption and fuel-air ratio for minimum brake specific fuel consumption are also included.

The minimum brake specific fuel consumption decreases with an increase in compression ratio or power output or both in the manner shown in figure 8. The gradient is maximum in the region of low manifold pressure and low compression ratio, which is also the region of low power output. Although the surface gradient is greater in the region of low brake horsepower, the percentage decrease in brake specific fuel consumption per unit of change in compression ratio is greater in the region of high power output. An increase in compression ratio from 6.65 to 9.68 resulted in a decrease in fuel consumption of 14.1 percent at 0.585 brake horsepower per cubic inch (1000 bhp) and 10.5 percent at 0.351brake horsepower per cubic inch (600 bhp). The minimum brake specific fuel consumption observed in the runs was 0.378 pound per brake horsepower-hour at a compression ratio of 9.68 and 0.684 brake horsepower per cubic inch (1170 bhp). The fuel-air ratio at which minimum brake specific fuel consumption is obtained increases as the power output is decreased or the compression ratio is increased.

For a given power requirement, the high compression ratio requires less manifold pressure and therefore slightly increases the allowable ceiling for the same amount of supercharging.

Knock-limited fuel requirements. - In order to take advantage of high compression ratio and of advanced spark setting for low specific fuel consumption without a reduction in power output, fuels of high antiknock quality are necessary. Triptane blended with 28-R fuel was found to have satisfactory antiknock properties through the conditions of highest compression ratio, spark advance, and power output used in this investigation. The percentage of triptane required for knock-free operation at a constant power output increased with increase in compression ratio in the manner shown in figure 7. The increase in triptane that is required for knock suppression as the spark is advanced from the reference setting to the advanced setting is also indicated in figure 7. For the 14.1-percent decrease in brake specific fuel consumption (obtained by the change in compression ratio at a power output of 0.585 bhp/cu in. with the advanced spark setting and the fuel-air ratio for minimum bsfc), an increase was required in the percentage of triptane in the fuel blends from 6-percent triptane at a compression ratio of 6.65 to 58-percent triptane at a compression ratio of 9.68. With either the reference or the advanced spark setting, knock-free operation was impossible at the compression ratio of 9.68 with 28-R fuel in the range of fuel-air ratios best for fuel economy.

Peak cylinder pressure. - Peak cylinder pressure is a principal factor in the determination of the mechanical durability of an engine. Engine durability was considerably reduced when the engine was operated at high compression ratio and high power output. Several engine failures were caused by cylinder-gas leakage into the coolant system. This gas leakage was severe enough to cause the coolant-pumping system to fail. Visual inspection showed no signs of damage to the cylinder blocks; the conclusion was made therefore that the leakage occurred between the cylinder liner and the cylinder head. These difficulties are attributed to high peak cylinder pressures.

A survey of the peak cylinder pressures that can be expected when engines are operated at the condition of the runs is presented in figure 9. The magnitudes of peak cylinder pressure that were obtained from the single-cylinder engine are shown by the solid lines, which were extrapolated to cover the range of compression ratio and of indicated mean effective pressure in which the multicylinder engine was operated. Other single-cylinder-engine data (unpublished) justify a straight-line extrapolation of peak cylinder pressures against indicated mean effective pressure. Variation in the cycles caused the peak pressure of some cycles to be higher than that of others. The peak cylinder pressures represented by the surface in figure 9 give the mean value. The data were taken at a fuel-air ratio of 0.06, a mixture temperature of 200° F, and advanced spark setting. The indicated mean effective pressure data from the single-cylinder engine were in agreement within ±2 percent with data from the multicylinder engine at the same manifold pressure.

The rate of change in peak pressure with respect to indicated mean effective pressure is greater at 9.68 than at a compression ratio of 6.65, as is shown in figure 9. Peak cylinder pressures of 1900 pounds per square inch can be expected at a compression ratio of 9.68 and an indicated mean effective pressure of 320 pounds per square inch.

Peak cylinder pressure is a maximum at a fuel-air ratio of 0.085 when indicated mean effective pressure, mixture temperature, compression ratio, and spark advance are held constant (fig. 10). These data were obtained by varying manifold pressure, as shown in the figure, to maintain indicated mean effective pressure at 200 pounds per square inch. Calculations using the thermodynamic charts show no change in peak pressure for changes in fuel-air ratio when indicated power and mixture temperature are unvaried. The calculations show no change because flame speed is not considered; flame speed is a function of fuel-air ratio and affects the observed peak cylinder pressure.

The effect of a change in the mixture temperature on peak cylinder pressure has been calculated from thermodynamic charts (reference 2). An increase in mixture temperature increases the peak cylinder pressure slightly for constant conditions of indicated mean effective pressure, fuel-air ratio, and compression ratio. An increase in mixture temperature of 100° F will increase the peak cylinder pressure by approximately 2.7 percent at a compression ratio of 6.65.

Mass air flow. - For a given compression ratio and engine speed, mass air flow is independent of fuel-air ratio and depends only on the temperature of the inlet air to the main-stage supercharger and on the manifold pressure. With constant manifold pressure, an increase in the fuel-air ratio decreased the mixture temperature (figs. 3 to 5) and increased the density of the air charge entering the cylinder during intake; however, the volume of added fuel apparently compensated for the decrease in air-charge volume. The effect of manifold pressure and air temperature at the inlet to the engine-stage supercharger on mass air flow at the three compression ratios is presented in figure 11. The inlet temperature to the engine-stage supercharger before fuel vaporization was chosen as the variable because air flow was independent of fuel-air ratio and therefore independent of any temperature affected by the fuel. Not enough data were available to locate the complete surface at the compression ratio of 9.68 from plotted points. Analytical considerations indicate, however, that if a line in space is available representing data at a compression ratio of 9.68, the surface may be drawn through that line parallel to the surfaces at compression ratios of 6.65 and 7.93 and be in error by no more than the experimental accuracy of the data at the compression ratios of 6.65 and 7.93. Line A in figure 11 represents the data available at a compression ratio of 9.68; the bottom surface was passed through this line parallel to the other two surfaces.

Within the range tested, the variation of mass air flow with respect to either variable in figure 11 was a straight line. Air flow decreased with increased compression ratio. The total volume in the cylinder when the piston is at bottom center is greater with low compression ratio than with higher compression ratio and at manifold pressures above exhaust pressure more charge can be forced into the cylinder at low compression ratio. The compensating effect of lower residual-gas temperature at the high compression ratio is small.

Within the limits of spark advance investigated, there was no change in air flow with change in spark timing.

Thermal efficiency. - Actual indicated thermal efficiency is compared in figure 12 at a fuel-air ratio of 0.06 with the ideal efficiency calculated for a constant-volume cycle with the aid of thermodynamic charts. An explanation of the basis on which actual indicated thermal efficiency was determined is presented in the appendix.

Indicated thermal efficiency is inappreciably affected by inlet conditions of mixture temperature and manifold pressure; there was no measurable change in thermal efficiency for a mixture temperature change of 100° F. Calculations based on the thermodynamic charts show a change of 0.6 percent for a 320° F change in mixture temperature; this change is caused by chemical dissociation of the products of combustion. The calculations also show no change in thermal efficiency when the manifold pressure is varied between 30 and 120 inches of mercury absolute. This statement is substantiated in the data of figures 3(a) and 3(b) for manifold pressures between 28 and 50 inches of mercury absolute.

At a fuel-air ratio of 0.06, which corresponds to the point of minimum indicated specific fuel consumption, the indicated thermal efficiency increased from 37.1 percent at a compression ratio of 6.65 and a spark setting of 42° and 36° B.T.C. (exhaust and intake, respectively) to 41.4 percent at a compression ratio of 9.68 and a spark setting of 36° and 30° B.T.C. (fig. 12).

The curve for actual indicated thermal efficiency (fig. 12) diverges from that for the ideal indicated thermal efficiency as the compression ratio is increased. The reason for this behavior is unknown; however, the change in the shape of the combustion chamber as a result of the change in the shape of the piston crown when the compression ratio was changed should be considered.

Consideration given to valve timing and to combustion-chamber design may lead to higher indicated thermal efficiencies at all compression ratios studied. The engine was not redesigned to obtain the ultimate advantages possible at high compression ratios.

SUMMARY OF RESULTS

The following results were obtained on a 12-cylinder V-type liquid-cooled aircraft engine of 1710-cubic-inch displacement from an investigation to determine the fuel-economy and fuel-performance requirements at compression ratios of 6.65, 7.93, and 9.68 at the engine speed recommended for cruising:

1. Brake specific fuel consumption was decreased approximately 3 percent at a compression ratio of 6.65 by advancing the spark timing from 34° and 28° B.T.C. (exhaust and intake, respectively) to 42° and 36° B.T.C., when operation at the fuel-air ratio for minimum brake specific fuel consumption is considered in each case.

2. An increase in compression ratio from 6.65 to 9.68 with the spark timing required for maximum torque at a fuel-air ratio of 0.06 and fuel-air ratios for minimum brake specific fuel consumption resulted in decreases in fuel consumption of 14.1 percent at 0.585 brake horsepower per cubic inch of engine displacement and 10.5 percent at 0.351 brake horsepower per cubic inch. The minimum brake specific fuel consumption observed in the runs was 0.378 pound per brake horsepower-hour at a compression ratio of 9.68 and 0.684 brake horsepower per cubic inch.

3. Fuels with high antiknock properties were required to operate at high power and high compression ratio; at 0.585 brake horsepower per cubic inch, compression ratio of 9.68, spark advance of 36° and 30° B.T.C. (exhaust and intake, respectively), and fuel-air ratio for minimum brake specific fuel consumption, a fuel blend of 58-percent triptane in 28-R fuel was required for knock-free operation. At a compression ratio of 6.65, a fuel blend of 6-percent triptane in 28-R fuel was required for knock-free operations.

4. Peak cylinder pressures of 1900 pounds per square inch can be expected at a compression ratio of 9.68 and an indicated mean effective pressure of 320 pounds per square inch. The engine durability was considerably reduced at conditions of high compression ratio and high mean effective pressure.

5. When engine speed and compression ratio were held constant, the mass air flow through the engine was a linear function of manifold pressure and of temperature of the inlet air to the main-stage supercharger and was independent of fuel-air ratio.

6. At a fuel-air ratio of 0.06, which corresponds to the point of minimum indicated specific fuel consumption, the indicated thermal

efficiency increased from 37.1 percent at a compression ratio of 6.65 and a spark advance of 42° and 36° B.T.C. (exhaust and intake, respectively) to 41.4 percent at a compression ratio of 9.68 and a spark advance of 36° and 30° B.T.C.

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APPENDIX - INDICATED THERMAL EFFICIENCY

The basis for determining the indicated data presented has followed the usual relation that indicated horsepower is equal to the brake horsepower plus the motoring horsepower. For a supercharged engine of the type used in this investigation, the value of indicated horsepower is affected by the work of compression in the supercharger and the flow work of the working substance. For a clear understanding of the manner in which the actual indicated thermal efficiency is compared in figure 12 with the ideal efficiency calculated for a constant-volume combustion cycle, it is necessary to know the components of the over-all cycle that are compared and how they are influenced by the other components. A pressure-volume diagram of an ideal constant-volume combustion cycle with atmospheric exhaust and a diagram for the supercharger cycle, with parts of the cycles denoted as in equations (1) and (2), are shown in figure 13. The following relations more clearly show the terms involved in the measured values presented:

$$B = N + P - S_c - S_f - F \tag{1}$$

$$M = F + S_c + S_f - P \tag{2}$$

$$I = B + M \tag{3}$$

where

B brake work measured by dynamometer when engine is firing

N net work of working substance, proportional to area on pressure-volume diagram encompassed by compression, firing, and expansion portions of over-all cycle (fig. 13)

P engine pumping work, proportional to area encompassed by exhaust and intake strokes. Algebraic signs of P in equations (1) and (2) are correct when manifold pressure is higher than exhaust pressure (conditions shown in fig. 13). When manifold pressure is lower than exhaust pressure, opposite signs must be used in equations (1) and (2).

S_c work done by superchargers in compressing work substance

S_f flow work of working substance leaving engine-stage supercharger

F work required to overcome rubbing friction, resistance in oil- and coolant-pumping systems, and resistance of mechanical accessories

M work required to motor the engine with inlet conditions of pressure and temperature to auxiliary-stage supercharger and manifold pressure equal to those when B was measured

I indicated work

From equations (1), (2), and (3) and figure 13, the term I is seen to equal N if the terms P, S_c, S_f, and F are the same during motoring conditions as during firing conditions. In the ideal cycle, I is equal to N therefore N is determined and the value used for indicated work in the ideal case. In the actual cycle, I is slightly different from N because of slight differences in the values of P, S_c, S_f, and F between motoring and firing conditions. As was previously explained, when the engine was firing the mass air flow was higher than when the engine was motoring; for the value of M used to determine I, the supercharger work ($S_f + S_c$) was corrected for the difference in air flow between motoring and firing conditions. Other differences in P, S_c, S_f, and F between motoring and firing cannot be readily corrected.

Over-all cycle efficiency is defined as the ratio of the energy output by the machine in the form of useful work to the total energy input to the machine. For a determination of energy output by the cycle, the term S_c (fig. 13) should be charged against N. In the actual case, the term S_c was included in both the motoring and the firing runs (equations (1) and (2)) and could not readily be evaluated separately; S_c was therefore not charged against N in the determination of net work of the over-all cycle in either the actual or the ideal case. The indicated thermal efficiencies in figure 12 are therefore not over-all cycle efficiencies.

In the calculations of thermal efficiency, a heating value of 18,800 Btu per pound was used for all the fuel blends because the difference in heating value between 28-R fuel and a blend of 25-percent 28-R and 75-percent triptane is within the usual experimental error of measuring the heating value.

REFERENCES

1. Moore, Charles S., Biermann, Arnold E., and Voss, Fred: The NACA Balanced-Diaphragm Dynamometer-Torque Indicator. NACA RB No. 4C28, 1944.

2. Hershey, R. L., Eberhardt, J. E., and Hottle, H. C.: Thermodynamic Properties of the Working Fluid in Internal-Combustion Engines. SAE Jour. (Trans.), vol. 39, no. 4, Oct. 1936, pp. 409-424.

TABLE I - OPERATING CONDITIONS AT WHICH DATA WERE OBTAINED

[Data were obtained at manifold pressures of 28, 34, 40, and 50 in. Hg absolute, and engine speed of 2280 rpm.]

Compression ratio	Spark advance (deg B.T.C.)		Inlet-air temperature (°F)	Figure
	Exhaust	Inlet		
6.65	34	28	120	3(a)
			60	3(b)
			0	3(c)
	42	36	[a]120	3(d)
			60	3(e)
			0	3(f)
7.93	34	28	120	4(a)
			60	4(b)
			0	4(c)
	39	33	60	4(d)
9.68	34	28	60	5(a)
	36	30	60	5(b)

[a]No data were obtained at a manifold pressure of 50 in. Hg absolute at these conditions.

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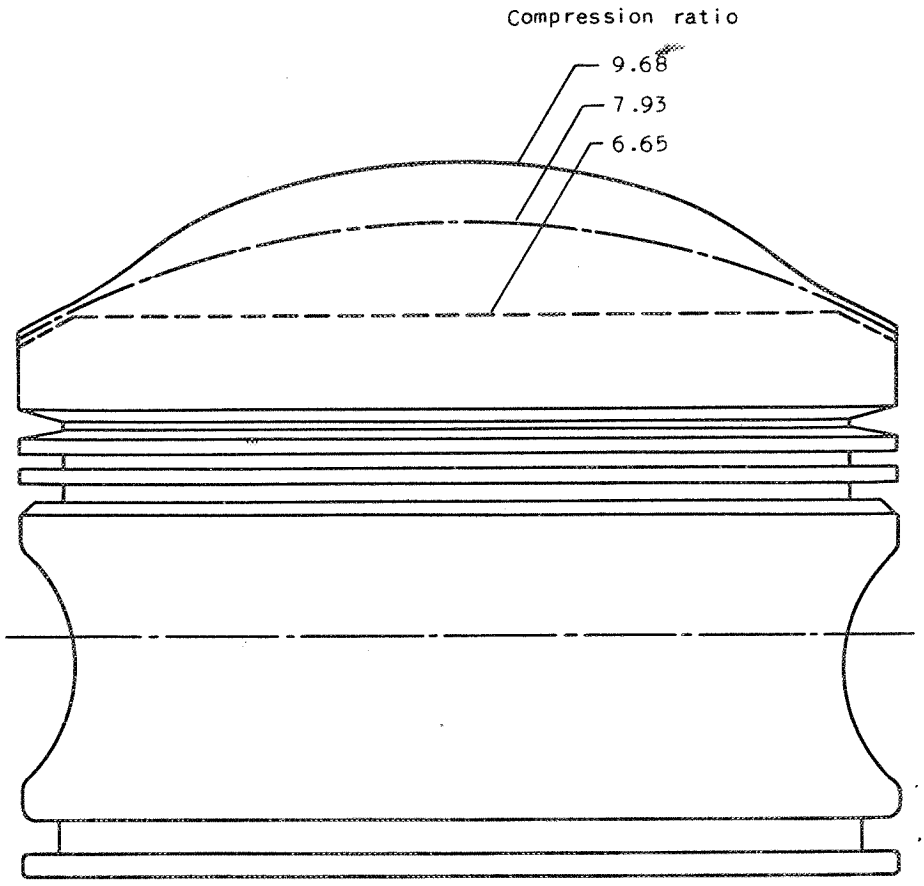

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Figure 1. - Outline view of pistons comparing crown shapes of pistons used for compression ratios of 6.65, 7.93, and 9.68.

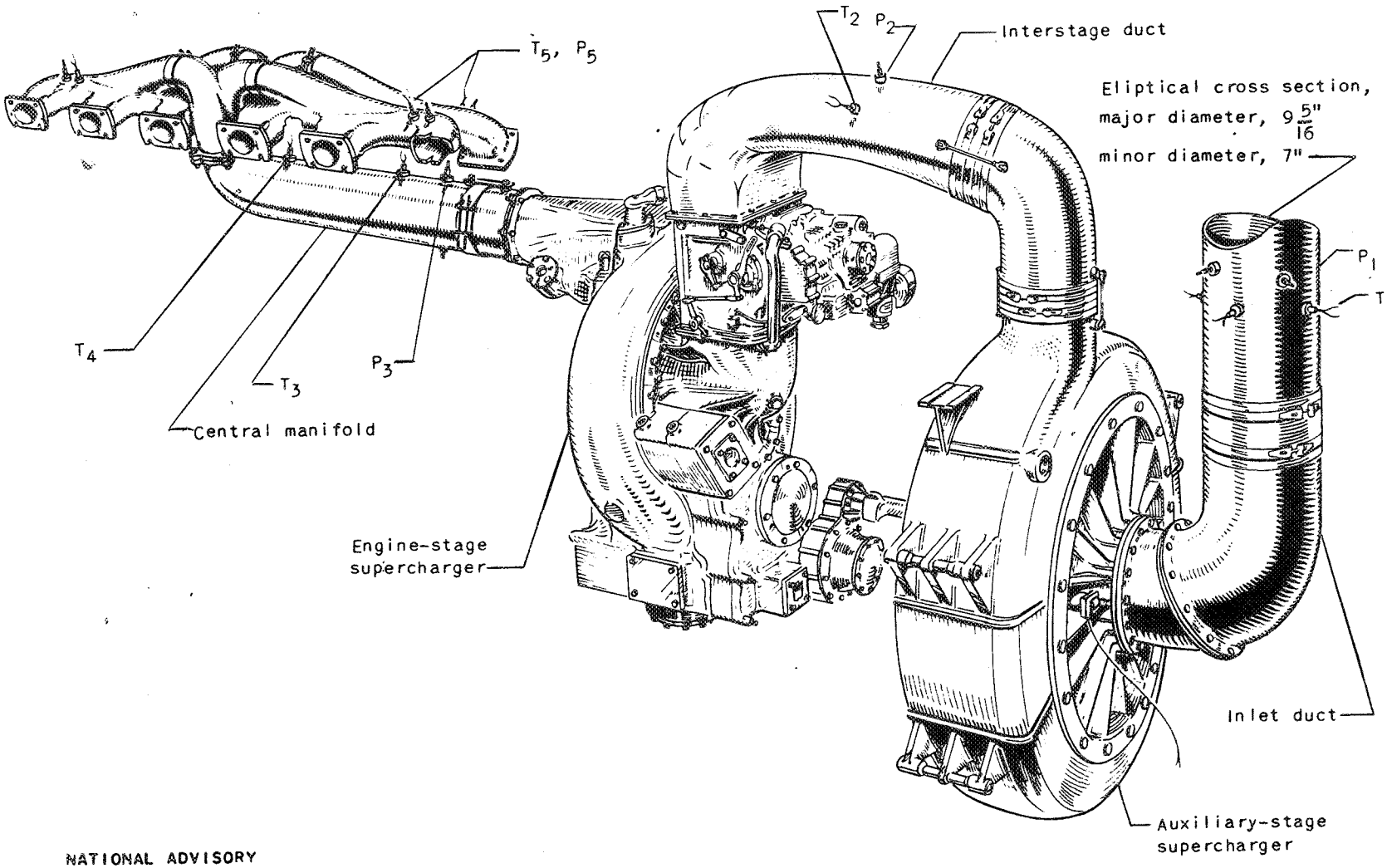

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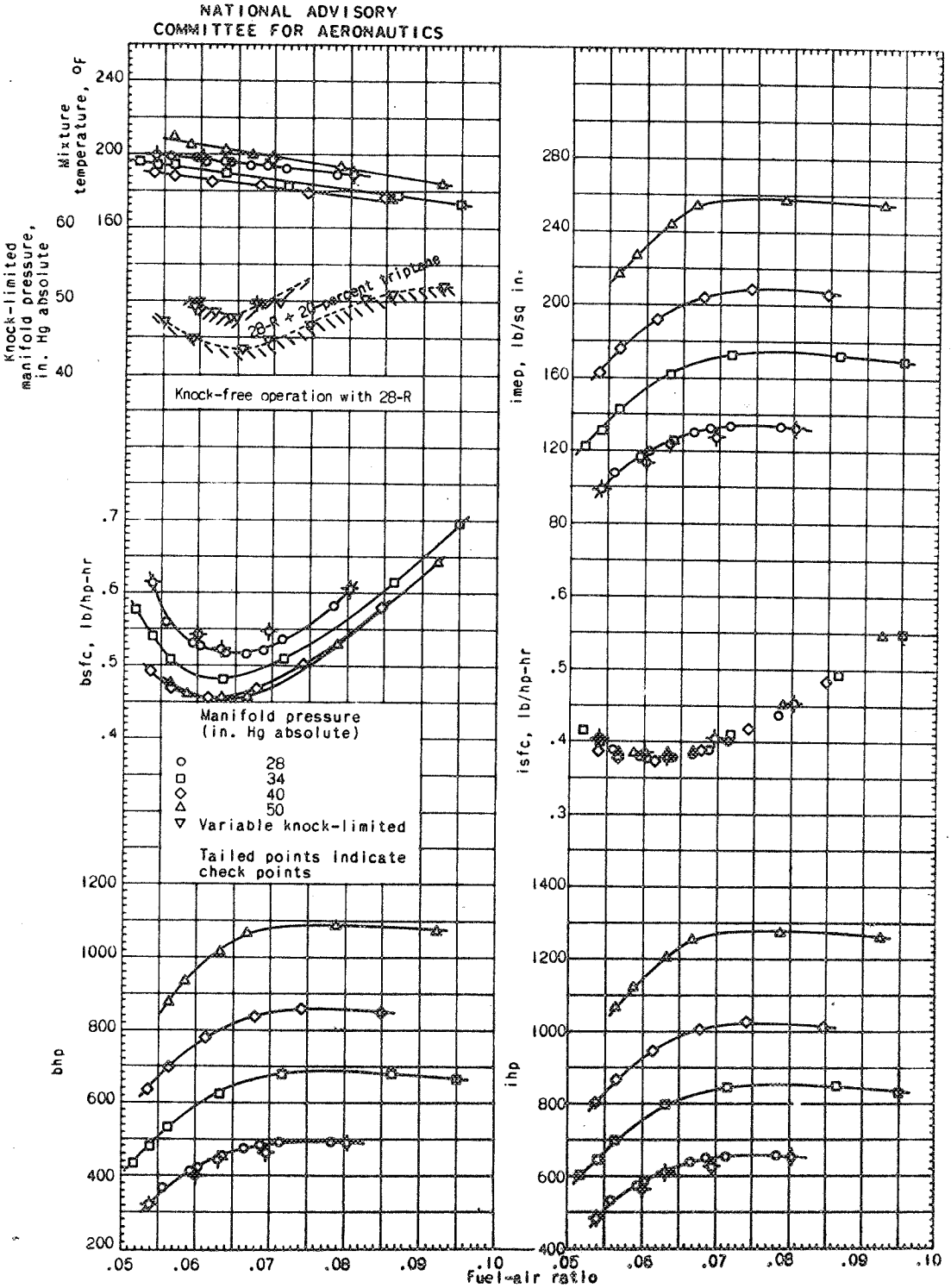
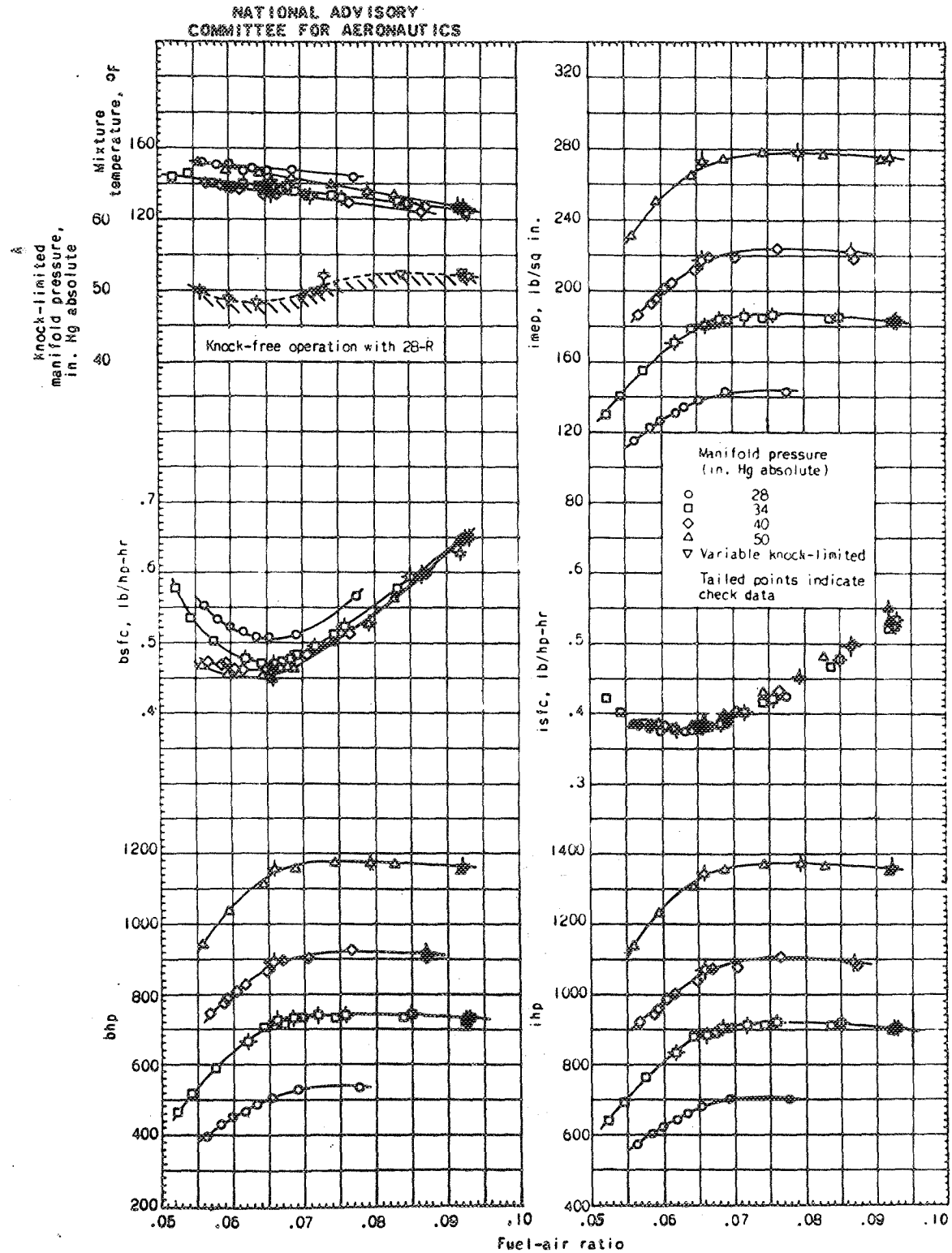
Figure 2. - Induction system of engine.

Fig. 2



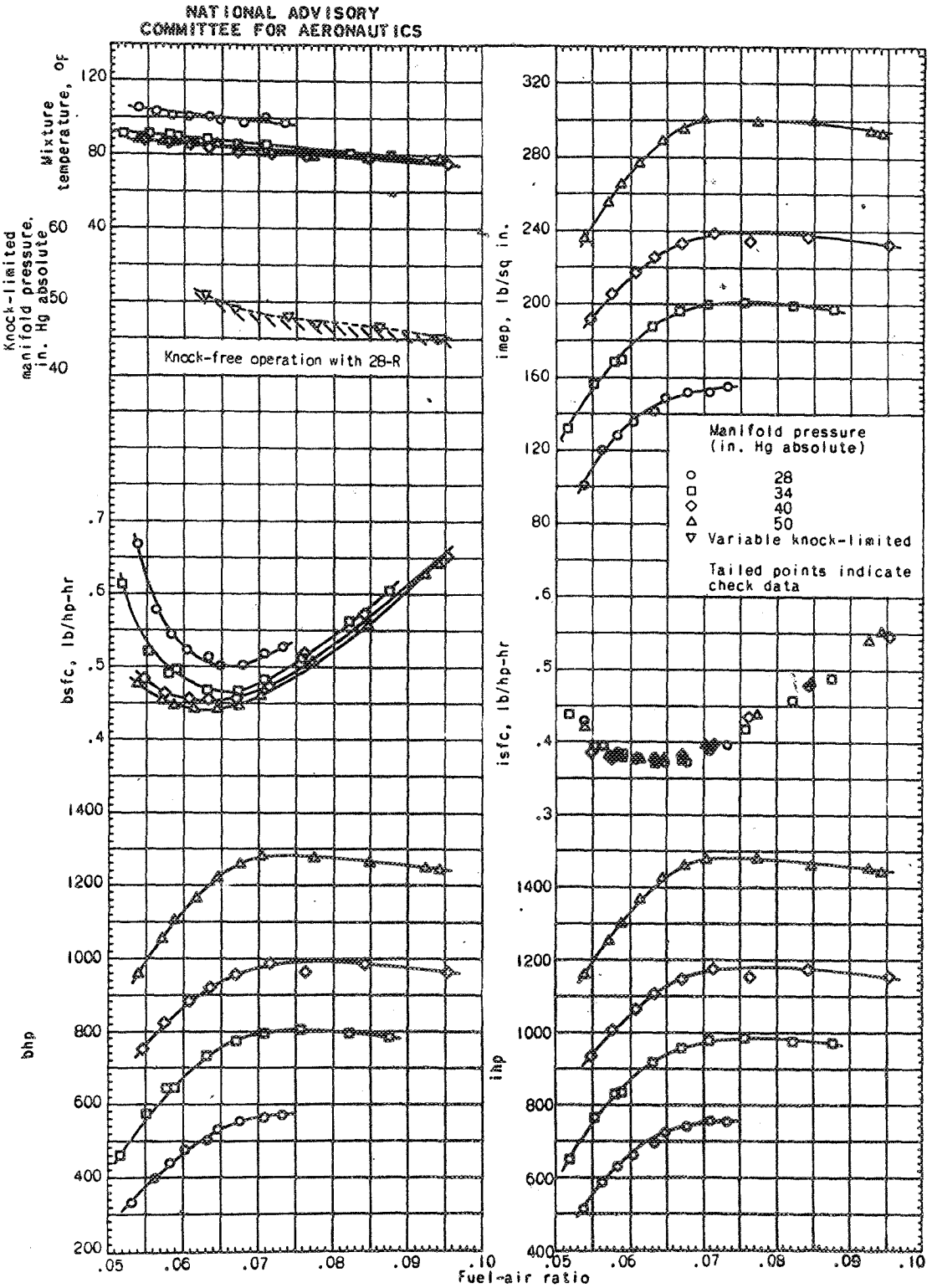
(a) Inlet-air temperature, 120° F; reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

Figure 3. - Cruising performance at compression ratio of 6.65. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



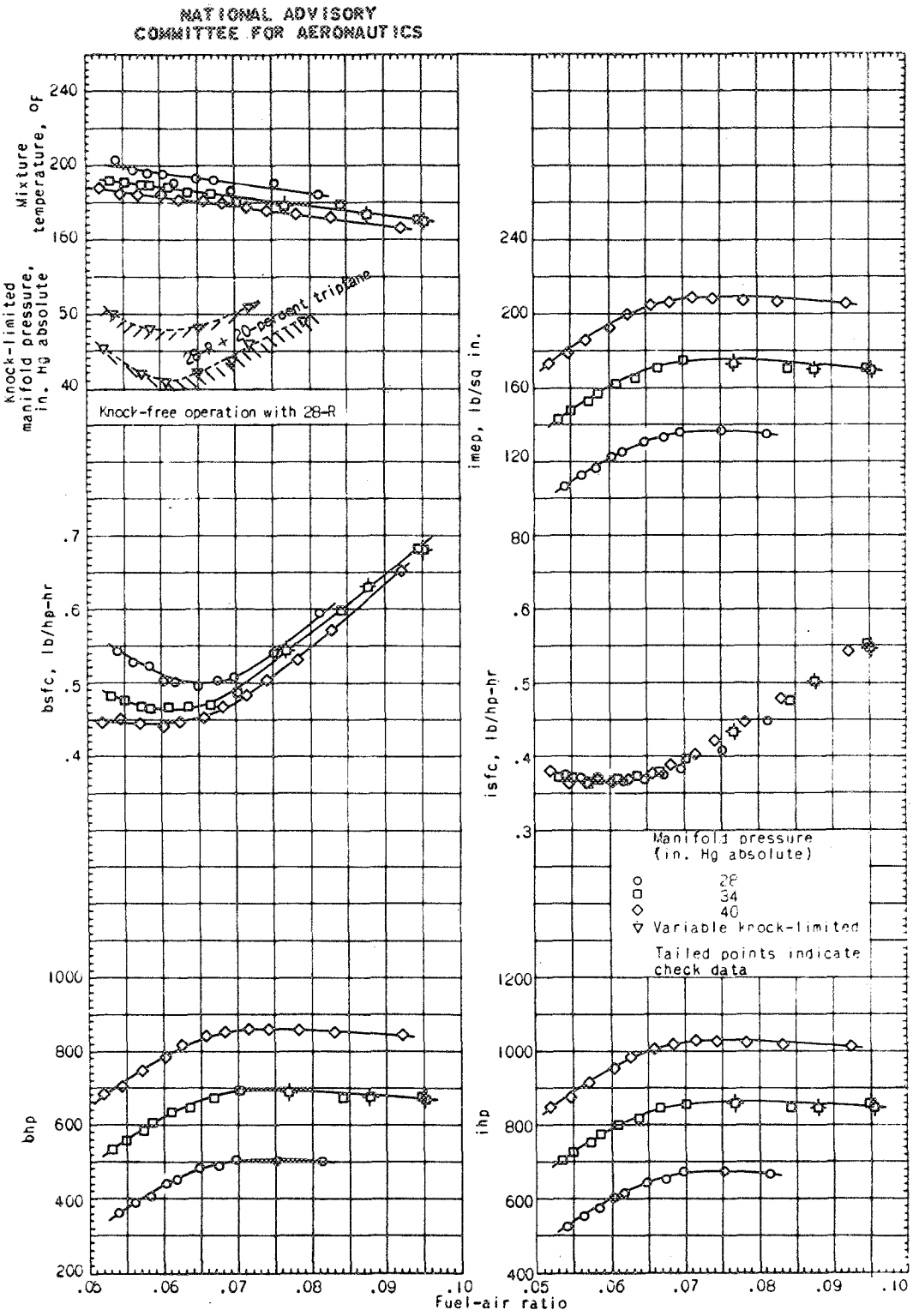
(b) Inlet-air temperature, 60° F; reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

Figure 3. - Continued. Cruising performance at compression ratio of 6.65. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



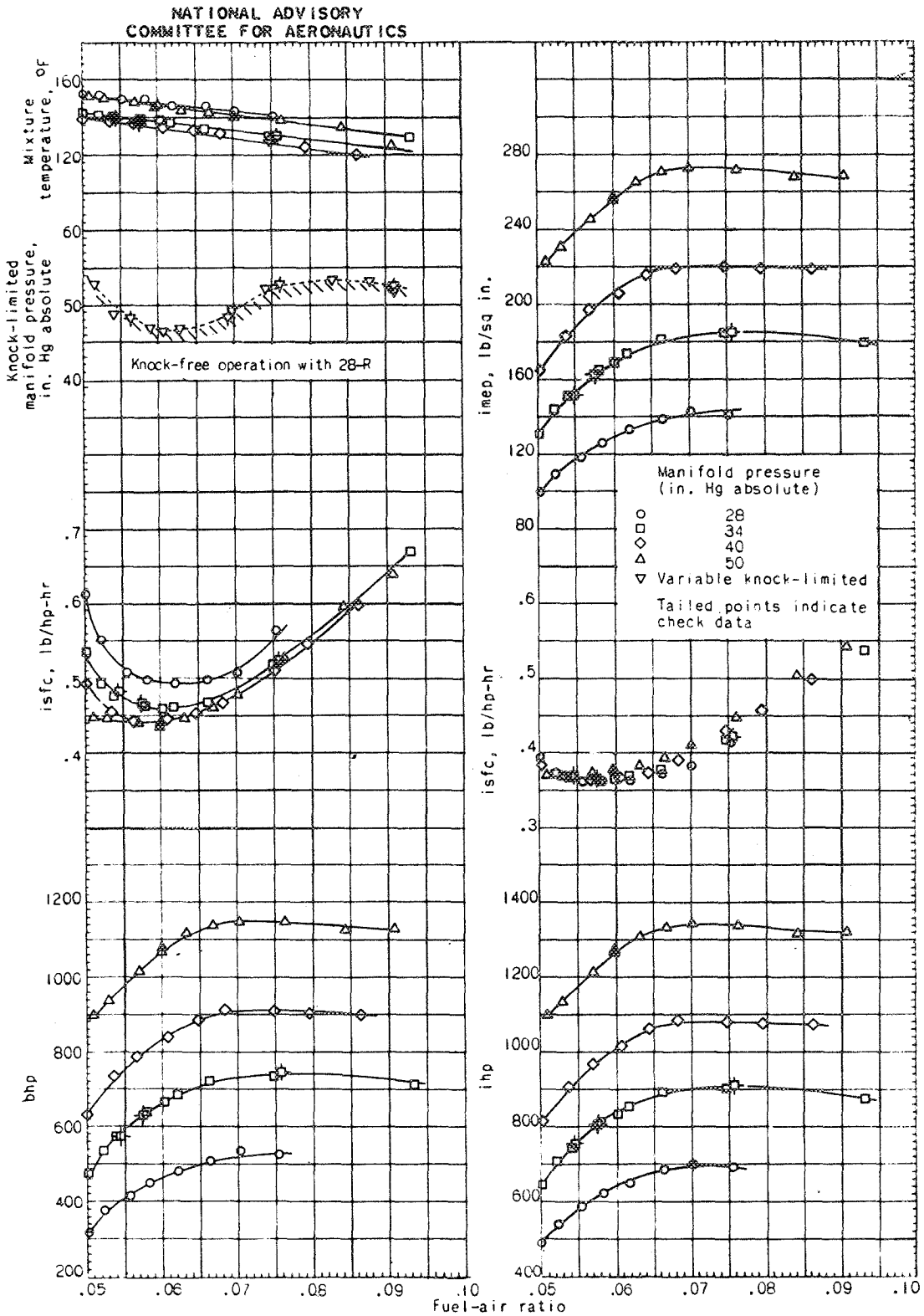
(c) Inlet-air temperature, 0° F; reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

Figure 3. - Continued. Cruising performance at compression ratio of 6.65. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



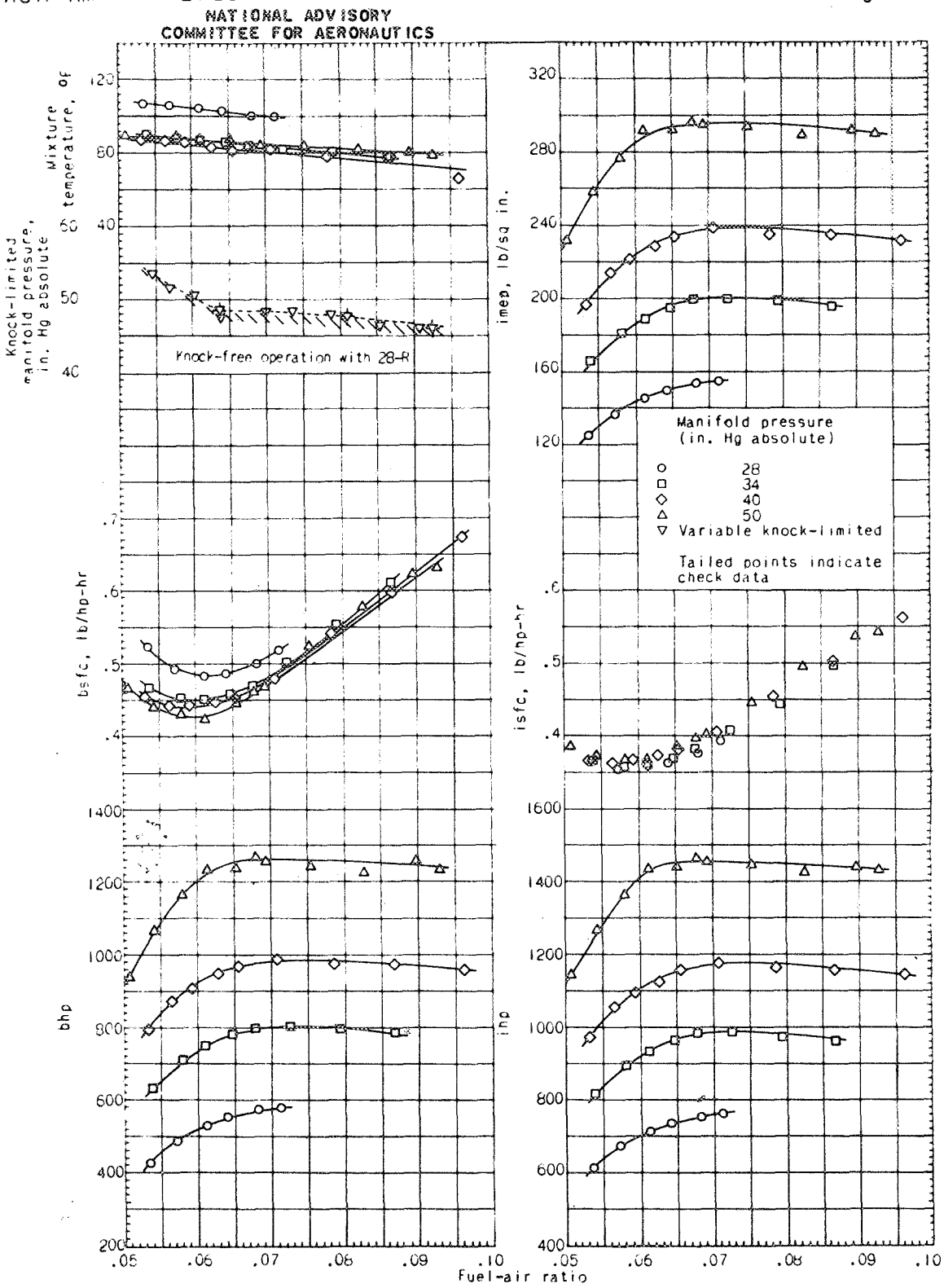
(d) Inlet-air temperature, 120° F; advanced spark timing: exhaust, 42° B.T.C.; intake, 36° B.T.C.

Figure 3. - Continued. Cruising performance at compression ratio of 6.65. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



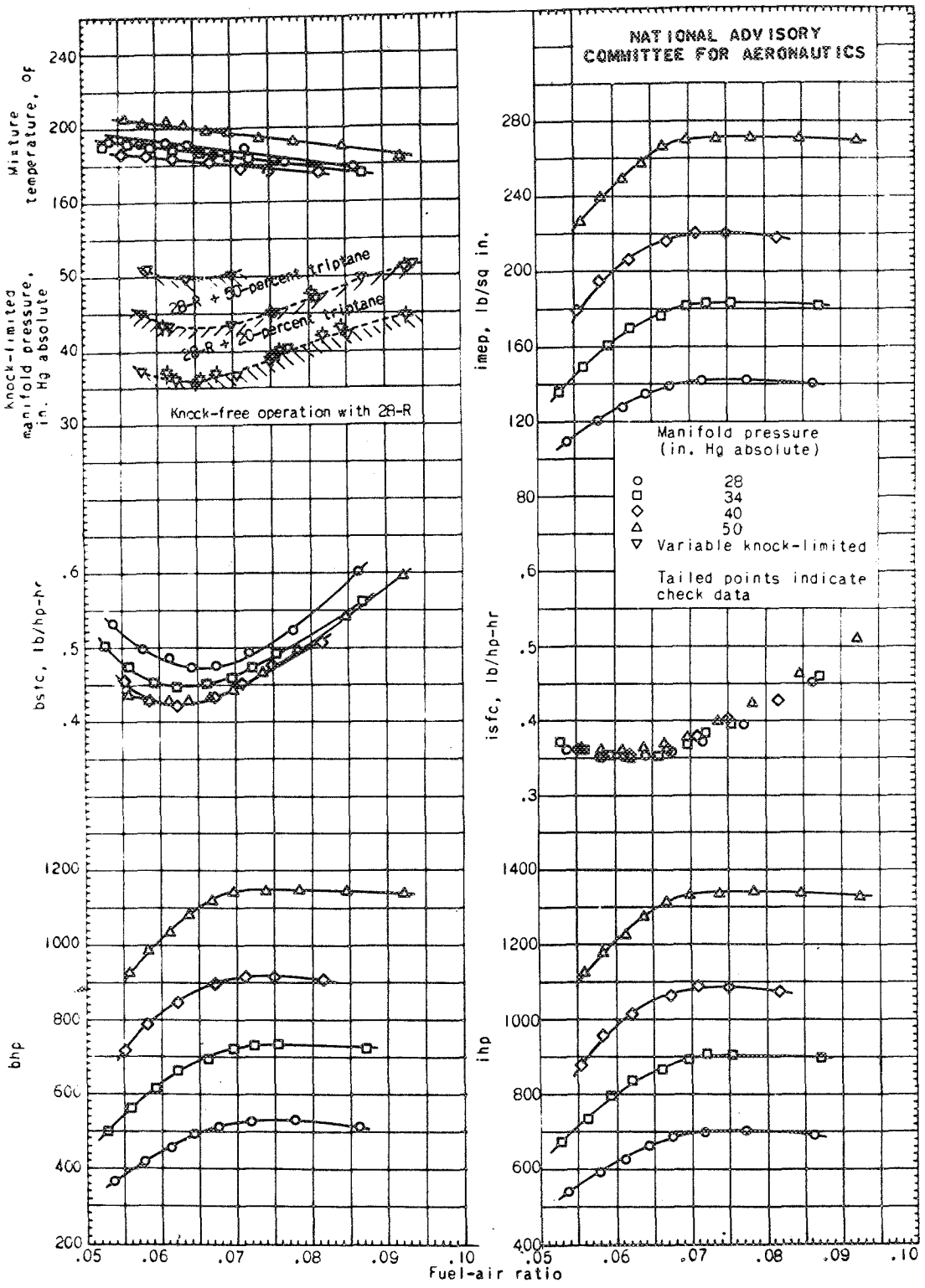
(e) Inlet-air temperature, 60° F; advanced spark timing: exhaust, 42° B.T.C; intake, 36° B.T.C.

Figure 3. - Continued. Cruising performance at compression ratio of 6.65. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



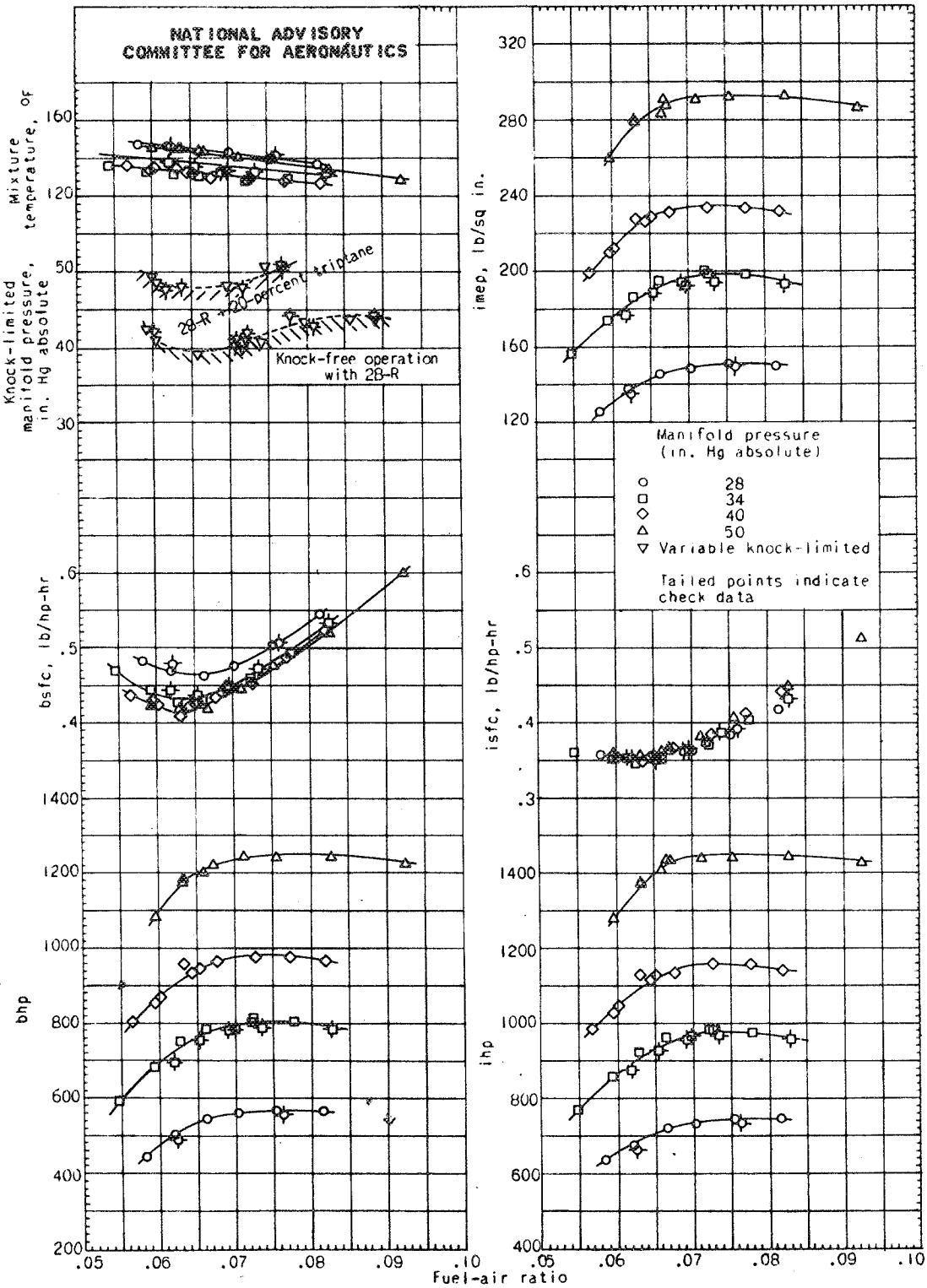
(f) Inlet-air temperature, 0° F; advanced spark timing: exhaust, 42° B.T.C.; intake, 36° B.T.C.

Figure 3. - Concluded. Cruising performance at compression ratio of 6.65. Engine displacement, 1710 cubic inches; engine speed, 2260 rpm; standard sea-level inlet and exhaust pressures.



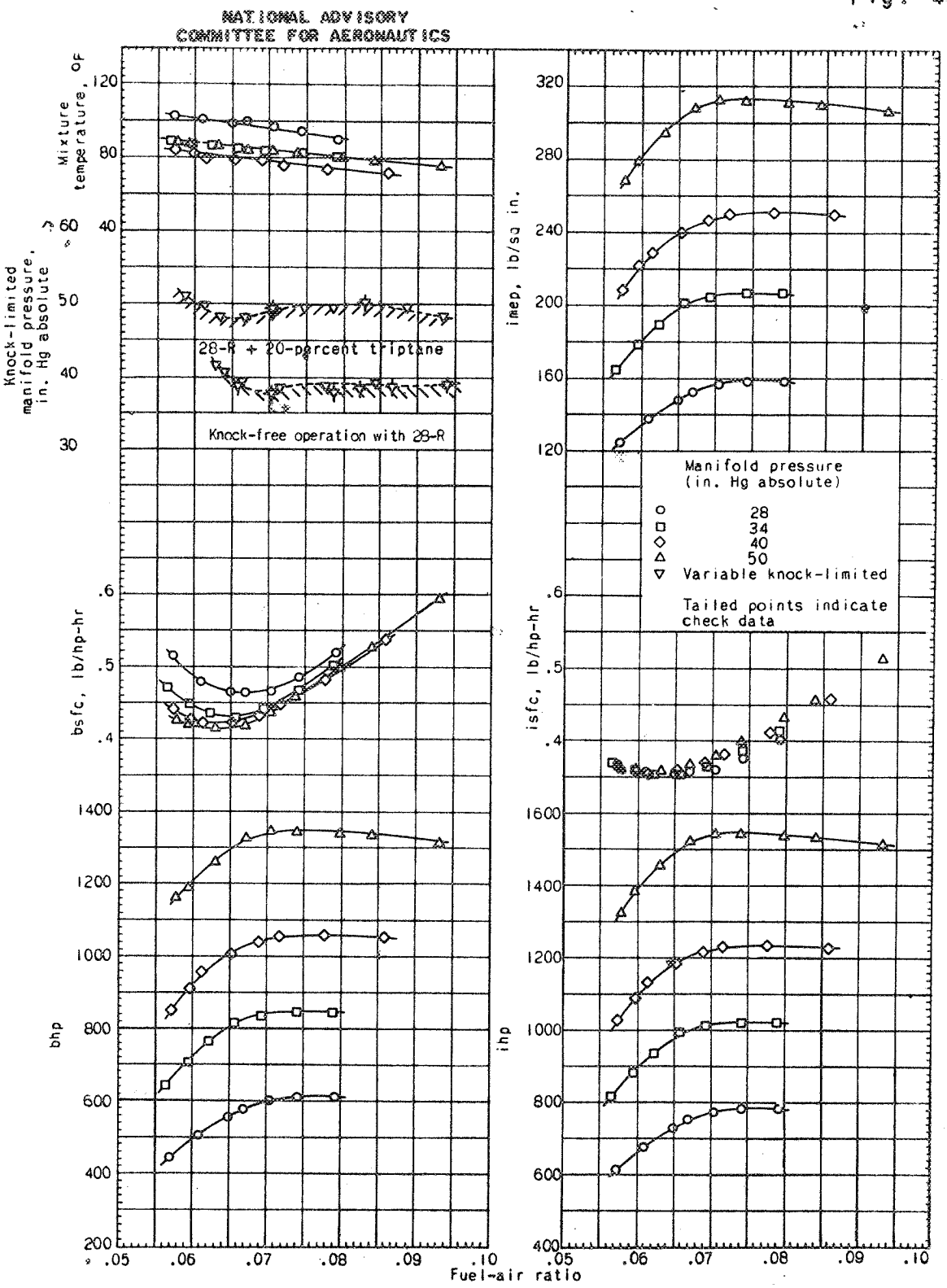
(a) Inlet-air temperature, 120° F; reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

Figure 4. - Cruising performance at compression ratio of 7.93. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



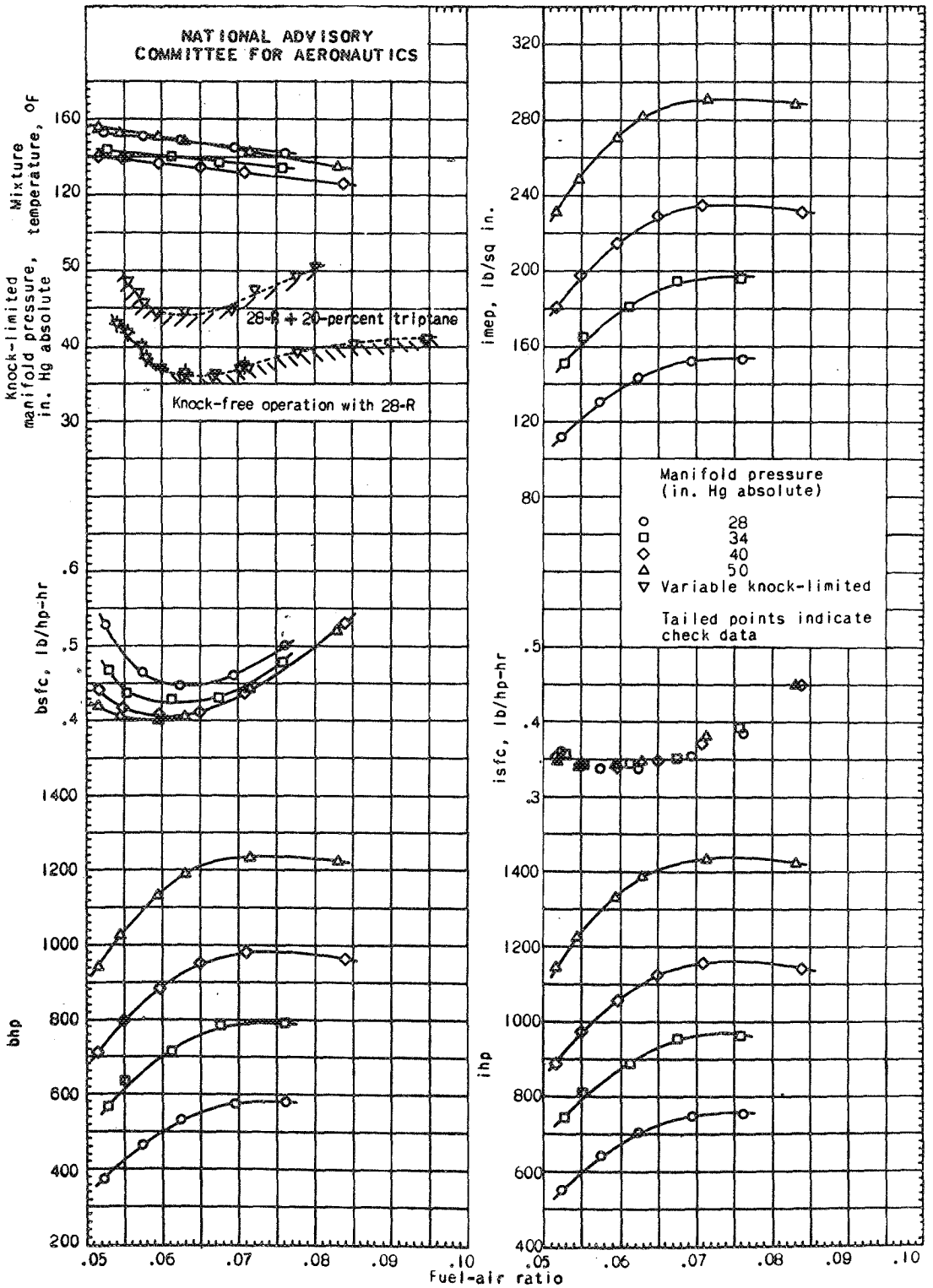
(b) Inlet-air temperature, 60° F; reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

Figure 4. - Continued. Cruising performance at compression ratio of 7.93. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



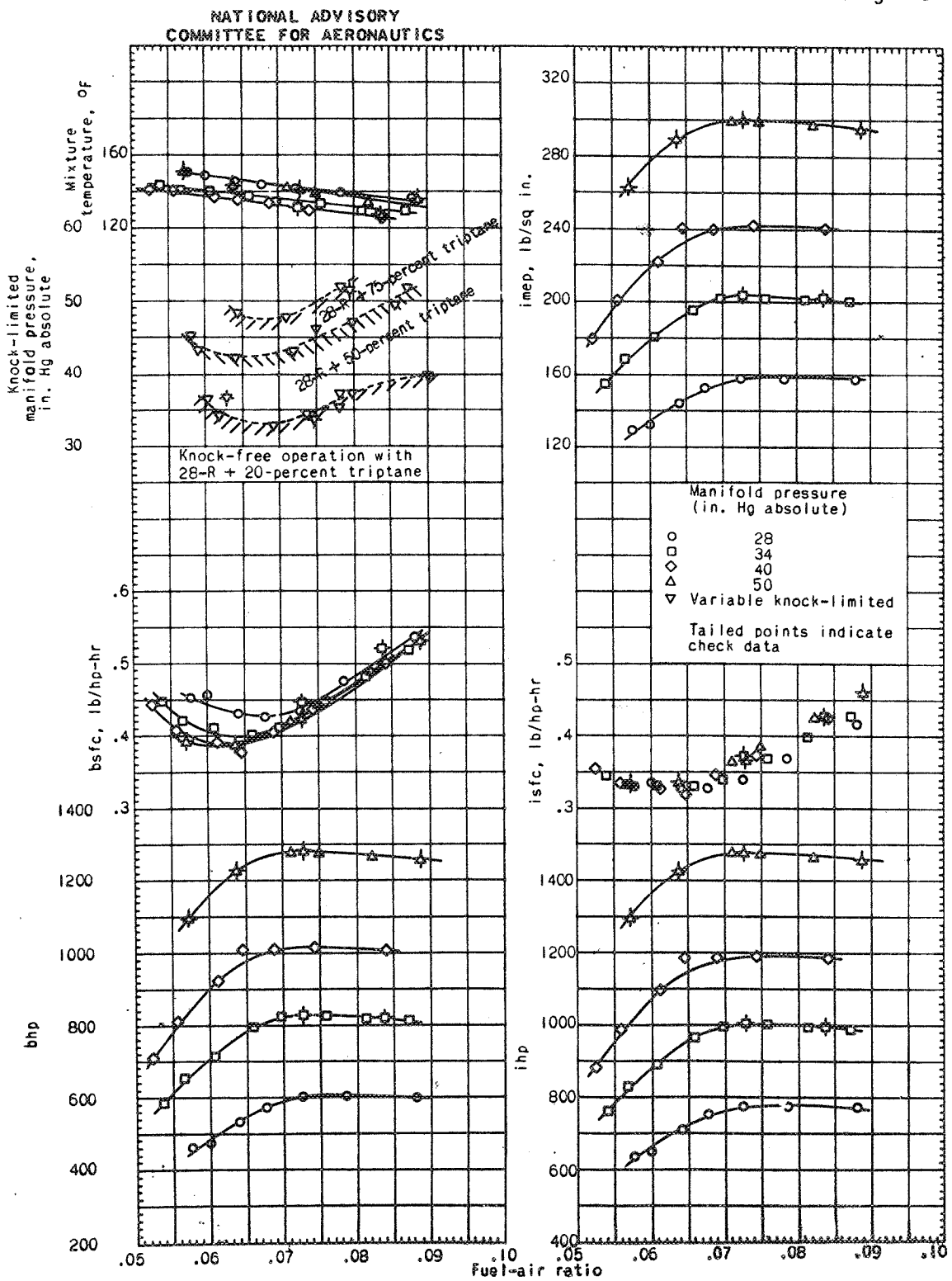
(c) Inlet-air temperature, 0° F; reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

Figure 4. - Continued. Cruising performance at compression ratio of 7.93. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



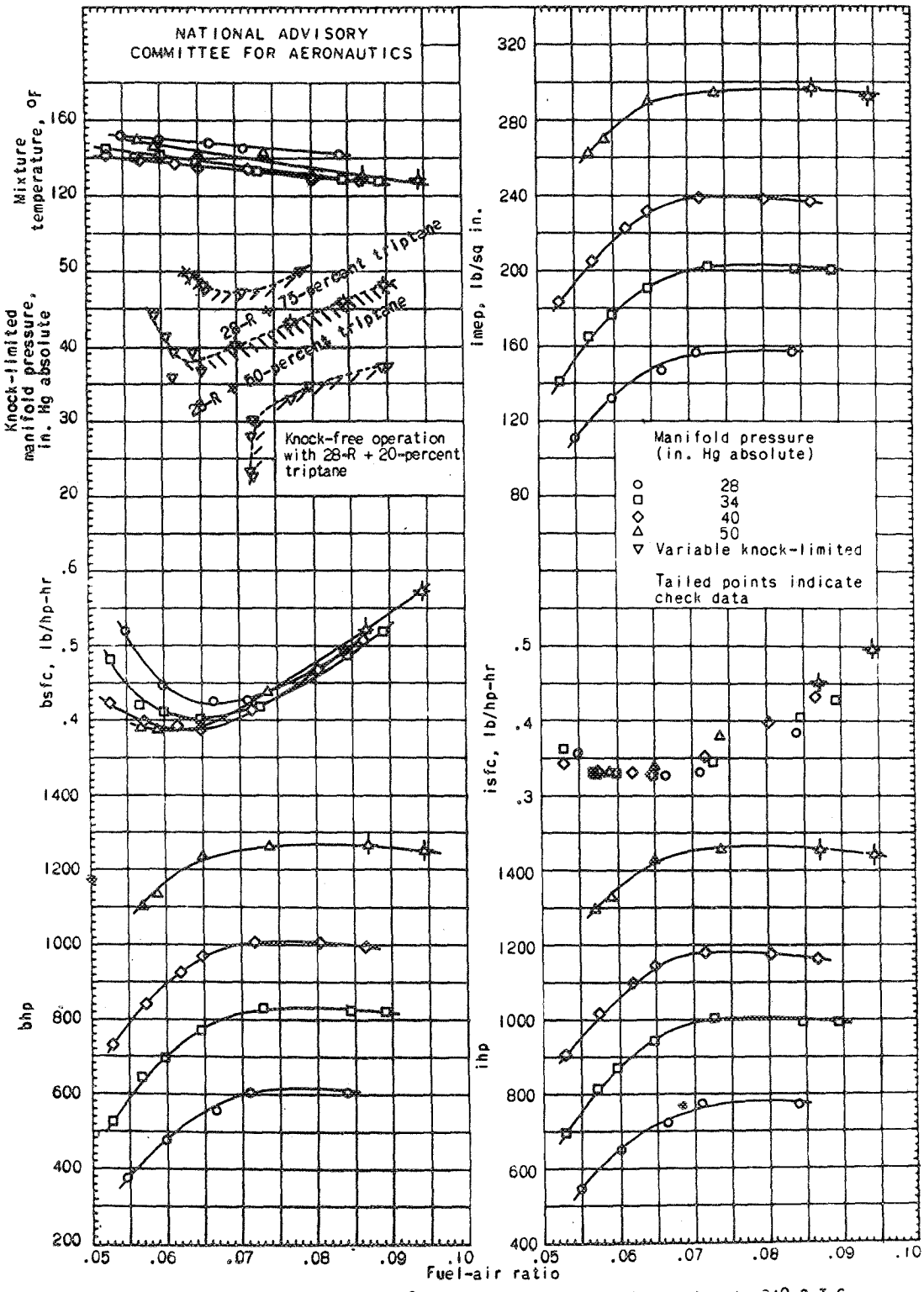
(d) Inlet-air temperature, 60° F; advanced spark timing: exhaust, 39° B.T.C.; intake, 33° B.T.C.

Figure 4. - Concluded. Cruising performance at compression ratio of 7.83. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



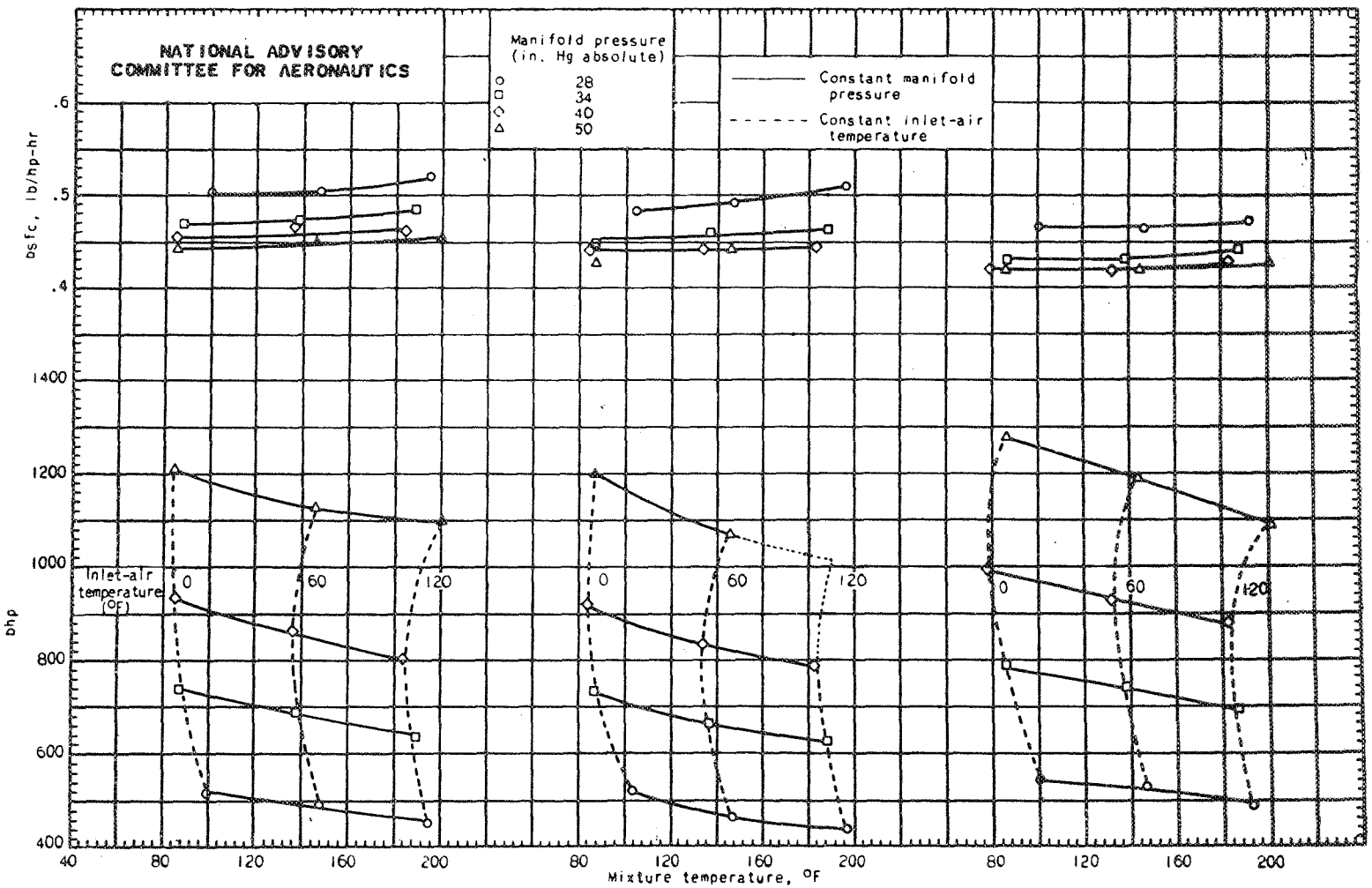
(a) Inlet-air temperature, 60° F; reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

Figure 5. - Cruising performance at compression ratio of 9.68. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



(b) Inlet-air temperature, 60° F; advanced spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

Figure 5. - Concluded. Cruising performance at compression ratio of 9.68. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.



(a) Compression ratio, 6.65; fuel-air ratio, 0.064; reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

(b) Compression ratio, 6.65; fuel-air ratio, 0.060; advanced spark timing: exhaust, 42° B.T.C.; intake, 36° B.T.C.

(c) Compression ratio, 7.93; fuel-air ratio, 0.064; reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.

Figure 6. - Effect of mixture temperature on brake specific fuel consumption and brake horsepower at four manifold pressures. Curves at constant inlet-air temperatures are also shown. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures. (Cross-plotted from figs. 3 to 4(c).)

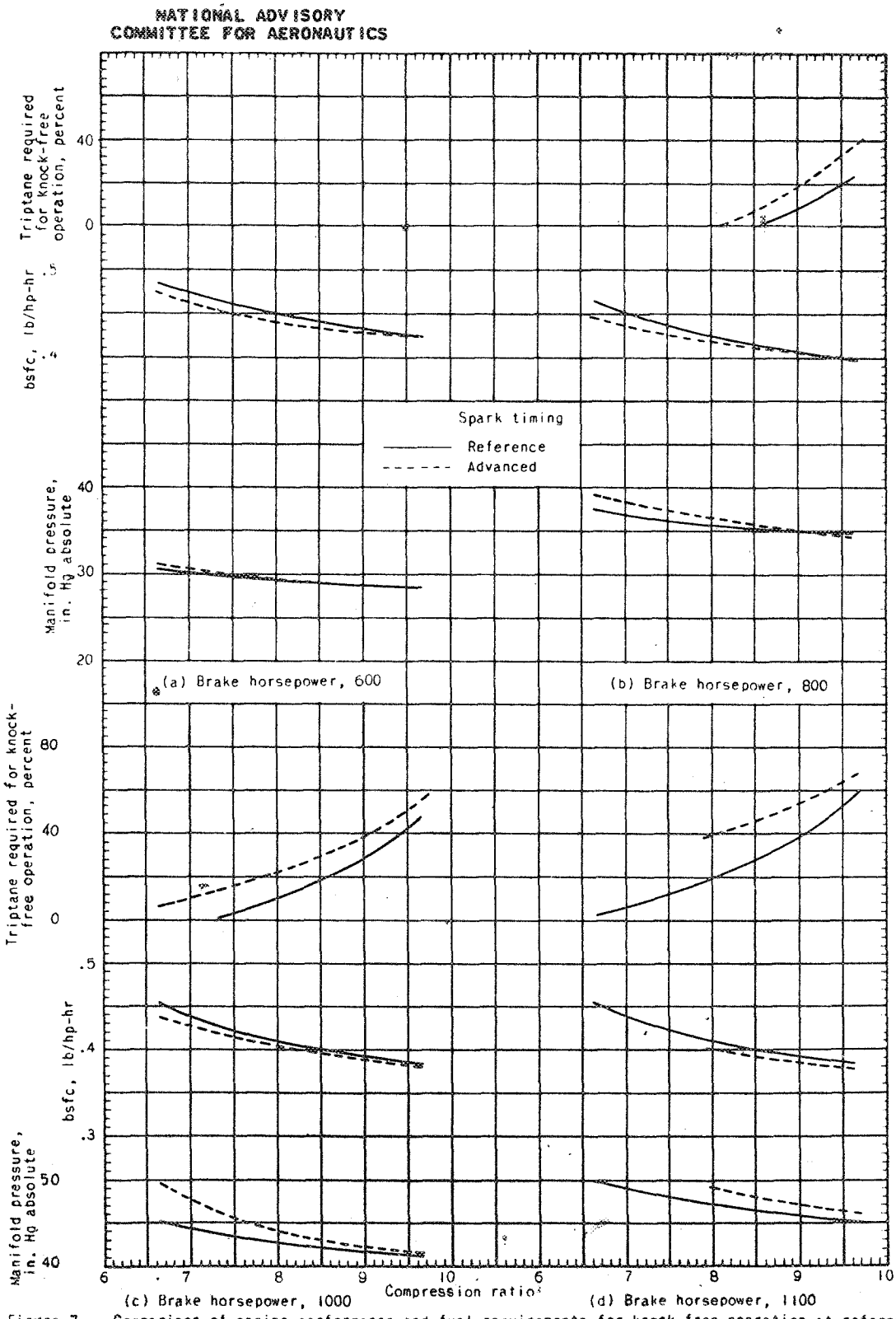


Figure 7. - Comparison of engine performance and fuel requirements for knock-free operation at reference and advanced spark timings. Inlet-air temperature, 60° F; engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures. (Cross-plotted from figs. 3(b), 3(e), 4(b), 4(d), 5(a), and 5(b) at fuel-air ratio for minimum brake specific fuel consumption.)

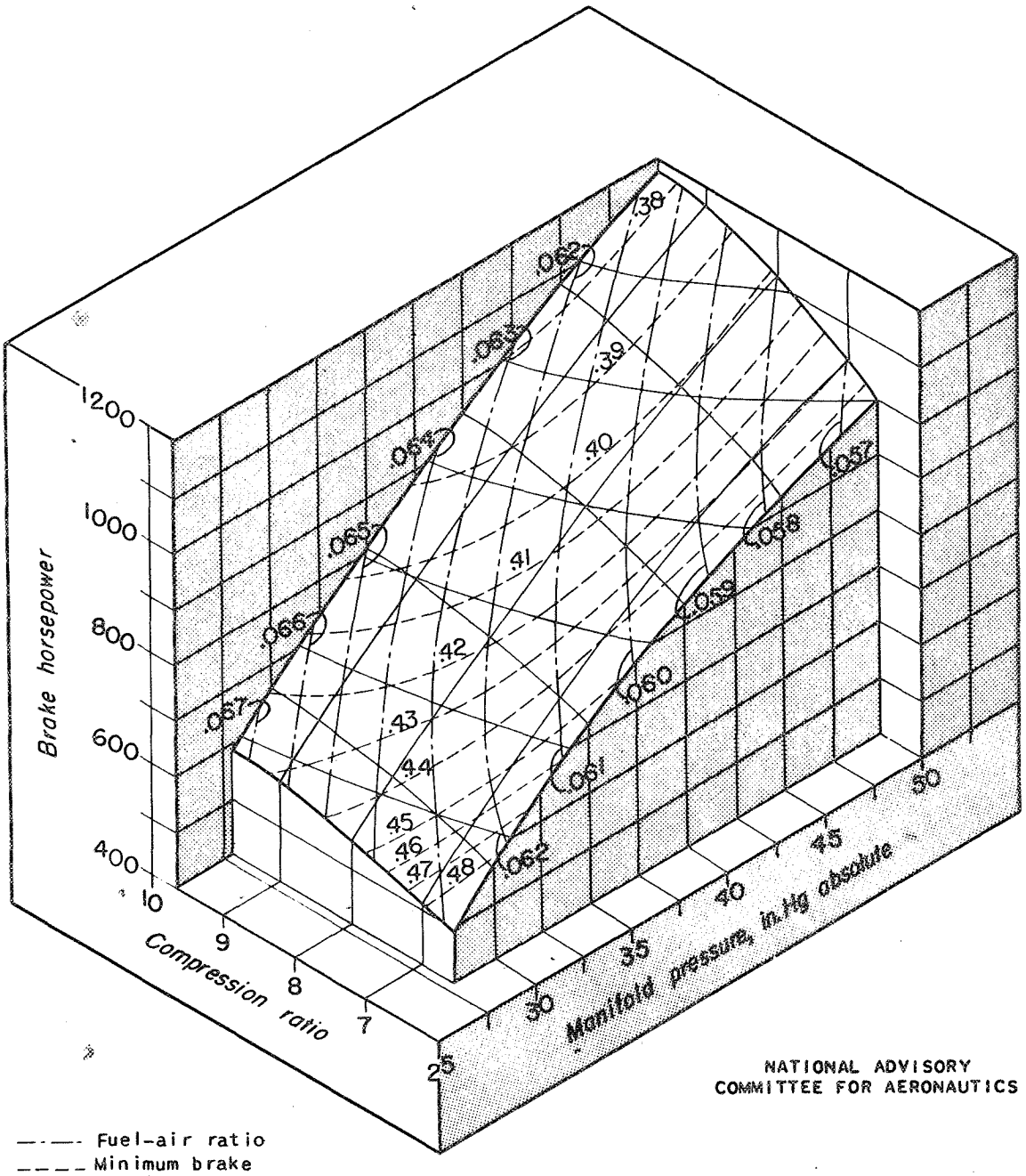


Figure 8. - Three-dimensional plot showing effect of compression ratio and manifold pressure on power output. Advanced spark timing for each compression ratio; fuel-air ratio at minimum brake specific fuel consumption; brake horsepower at minimum brake specific fuel consumption; inlet-air temperature, 60° F; engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures. (Cross plot from figs. 3(e), 4(d), and 5(b).)

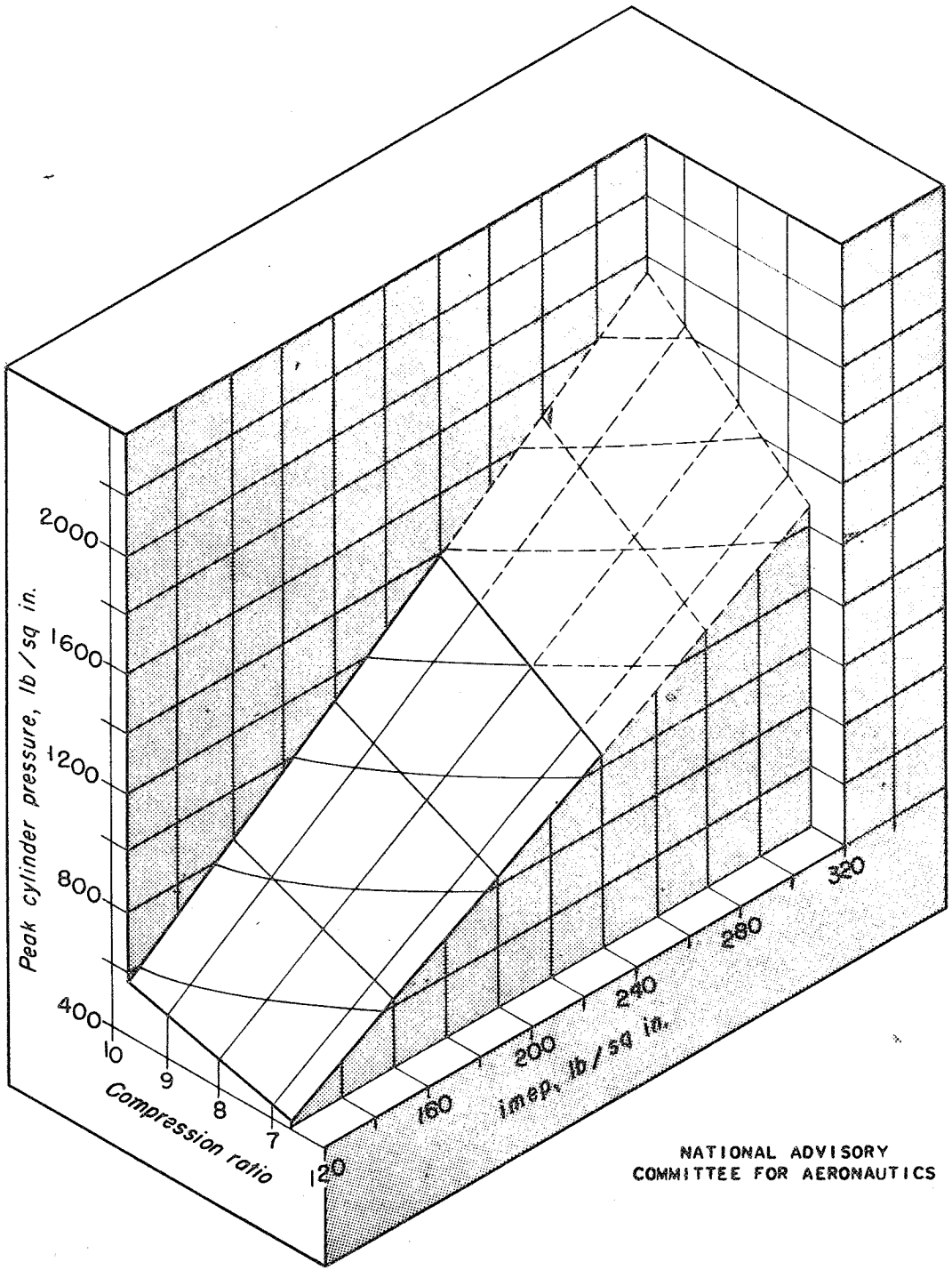


Figure 9. - Peak cylinder pressures as affected by compression ratio and indicated mean effective pressure. Single-cylinder adaptation of multicylinder block to CUE crankcase; advanced spark timing for all compression ratios; fuel-air ratio, 0.06; mixture temperature, 200° F; engine speed, 2280 rpm.

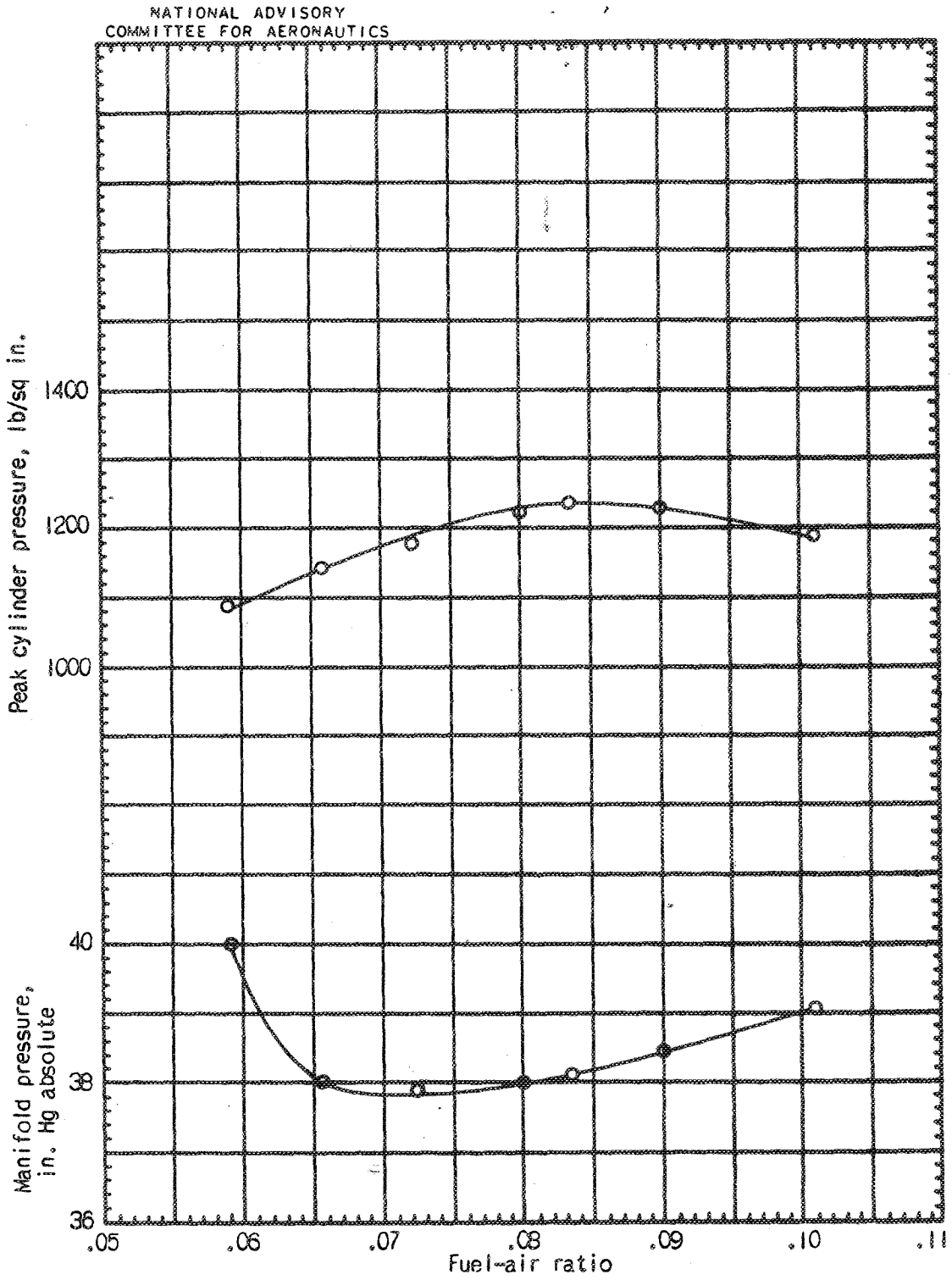


Figure 10. - Variation of peak cylinder pressure and manifold pressure with fuel-air ratio at constant indicated mean effective pressure of 200 pounds per square inch. Single-cylinder adaptation of multicylinder block to CUE crankcase; compression ratio, 9.68; advanced spark timing: exhaust, 36° B.T.C.; intake, 30° B.T.C.; mixture temperature, 200° F; engine speed, 2280 rpm.

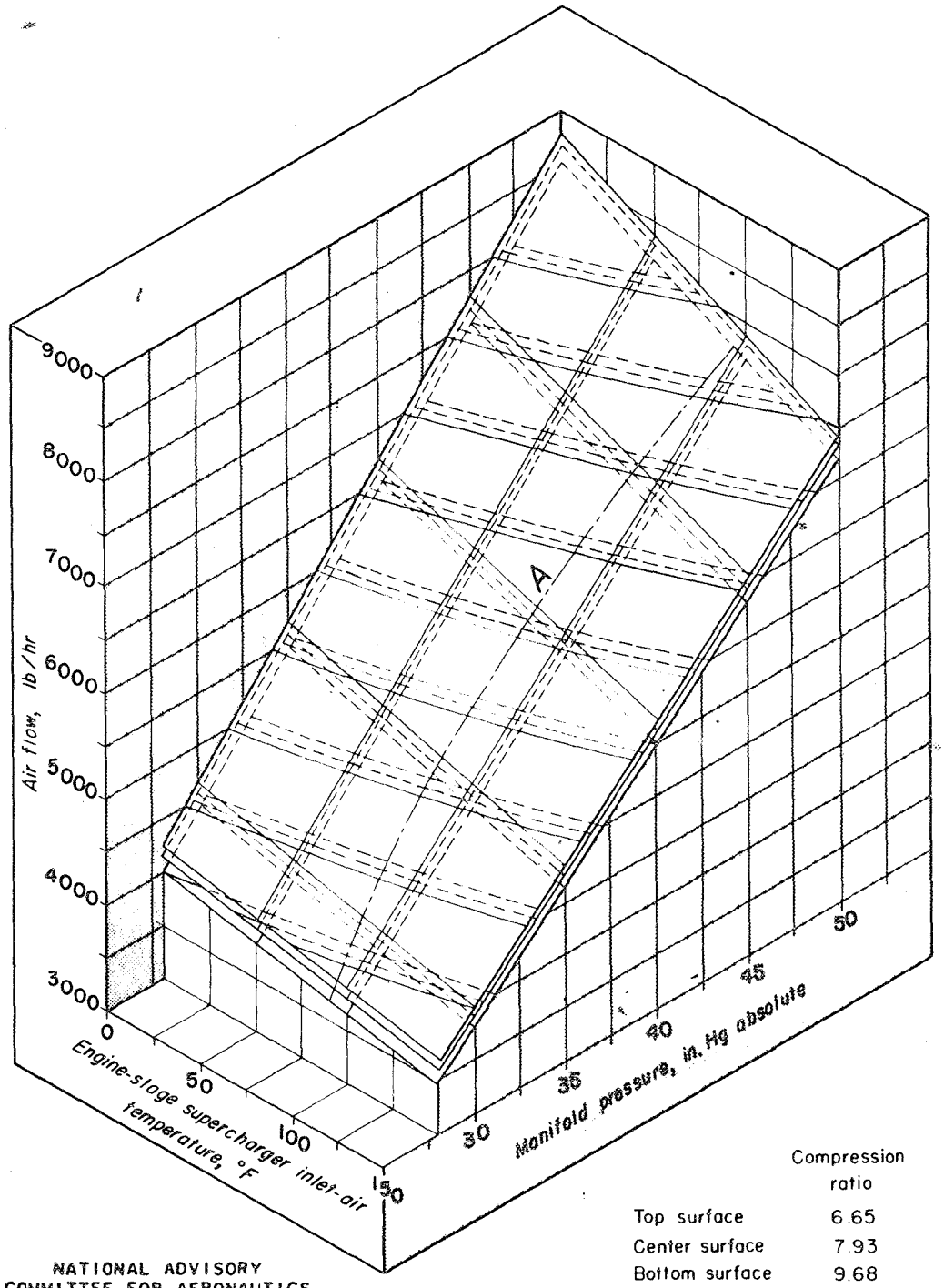


Figure 11.- Mass air flow as affected by temperature of inlet air to engine-stage supercharger and by manifold pressure. Reference spark timing: exhaust, 34° B.T.C.; intake, 28° B.T.C.; engine displacement, 1710 cubic inches; engine speed, 2280 rpm; standard sea-level inlet and exhaust pressures.

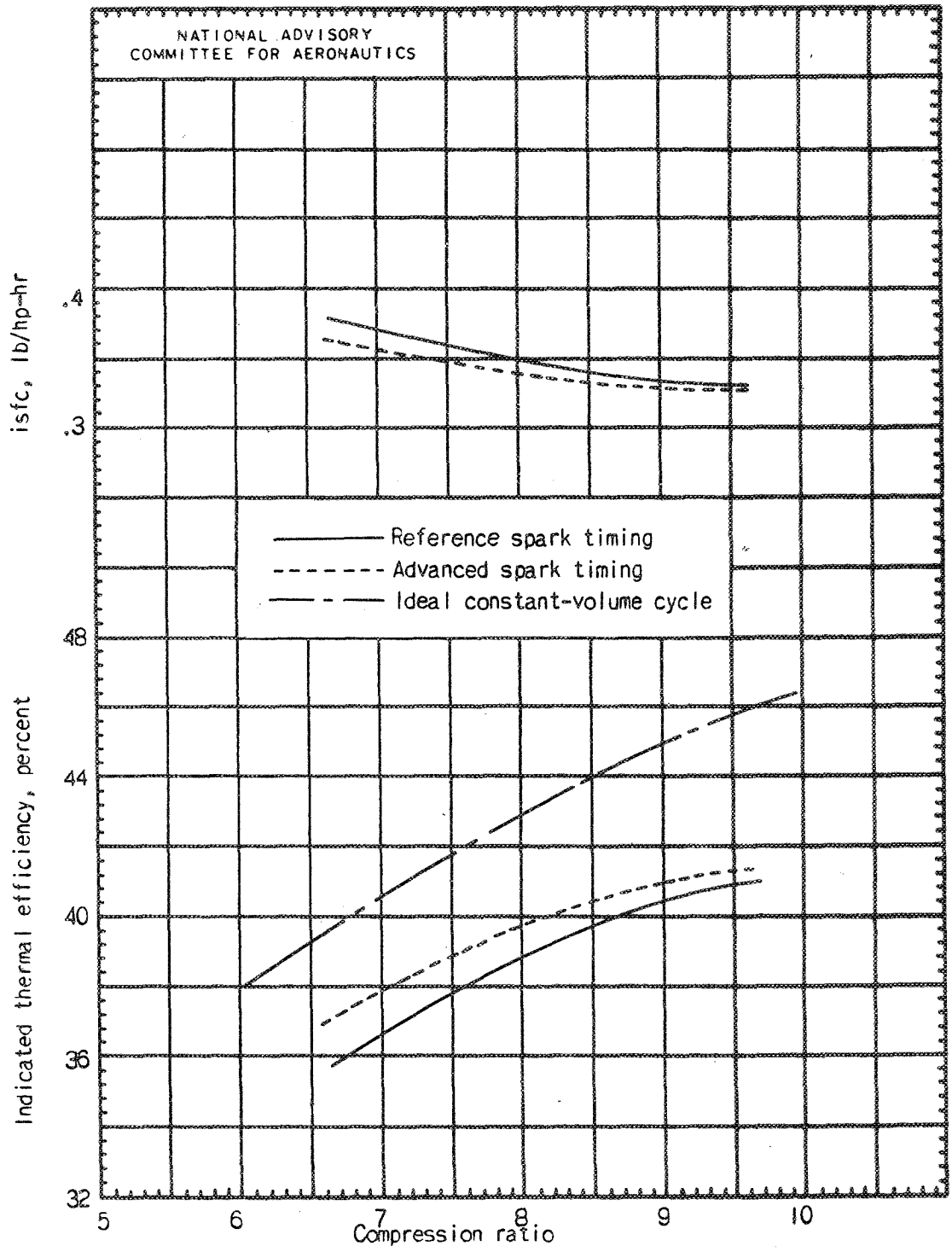


Figure 12. - Comparison of indicated thermal efficiencies with advanced and reference spark timings to thermal efficiency of ideal constant-volume cycle and variation of indicated specific fuel consumption with compression ratio at both spark timings. Engine displacement, 1710 cubic inches; engine speed, 2280 rpm; fuel-air ratio, 0.06.

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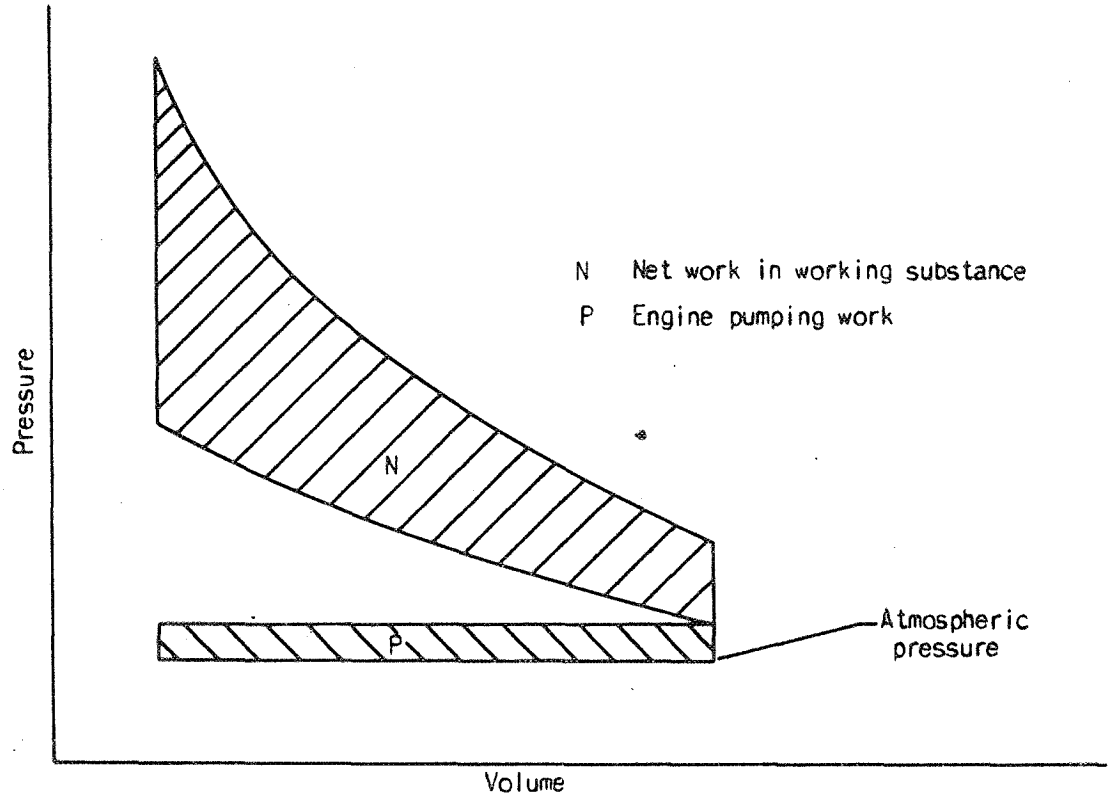
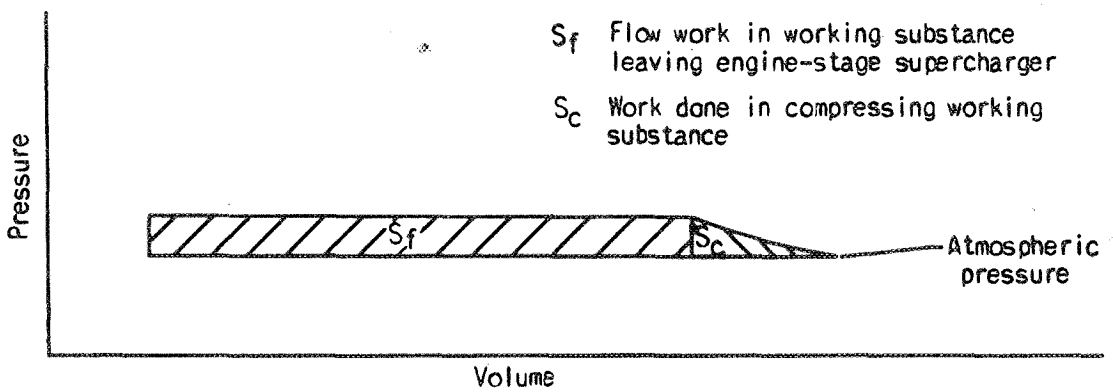


(a) Cycle of working substance in engine cylinder.



(b) Cycle of working substance in supercharger.

Figure 13. - Relation of pressure to volume of ideal constant-volume combustion cycle and supercharger cycle.