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A CORRELATION OF THE EFFECTS OF COMPRESSION RATIO AND INLET-AIR TEMPERATURE ON THE KNOCK LIMITS OF AVIATION FUELS IN A CFR ENGINE - I

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A CORRELATION OF THE EFFECTS OF COMPRESSION RATIO AND INLET-AIR TEMPERATURE ON THE KNOCK LIMITS OF AVIATION FUELS IN A CFR ENGINE - I

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SUMMARY

A method of correlating the effects of compression ratio and inlet-air temperature on the knock limits of aviation fuels is presented. The knock-limited compression-air density when the piston is at top center is plotted against the compression temperature. Knock-limited performance tests of S-2 reference fuel, 28-R fuel, and a blend containing 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel in CFR engines were run to check the method; a description of these tests and the data obtained are included.

INTRODUCTION

In order to evaluate the knock-limited performance characteristics of a fuel in a spark-ignition engine, many different engine variables, such as inlet-air temperature and pressure, spark advance, compression ratio, and engine speed, should be considered. In conventional engines all of the aforementioned variables except compression ratio can usually be varied at the discretion of the testing engineer. Even in laboratory engines specially equipped for varying the compression ratio, fuel tests are often limited in number or length by engine operating time or by an insufficient fuel quantity. If basic relations between the effects of the various engine variables could be determined, predicting the knock-limited performance over a wide range of engine operating conditions from data obtained over a relatively limited range would be possible.

A correlation involving end-gas density and temperature was suggested in reference 1 as a means of indicating the knocking tendency of a fuel in an internal-combustion engine. Equations for calculating approximate values of end-gas density and temperature are given in references 1 and 2. In reference 1 it was also suggested that a simplified density factor might serve in place of the end-gas density and that the inlet-air temperature might serve in place of the end-gas temperature. Tests conducted at the Massachusetts Institute of Technology over a limited range of engine operating conditions, described and analyzed in reference 3, showed that a smooth curve resulted when the knock-limited density factor was plotted against the compression ratio.

In each of the foregoing correlations, the density and the temperature of the combustion gases in the knocking zone were considered to be functions of the density and the temperature of the charge in the intake manifold. If the characteristics of the induction system - upon which the relation of the factors involved are dependent - could be eliminated when the correlation method is applied, a more satisfactory correlation of engine operating variables would result.

A simple and practical method of correlating the effects of compression ratio and inlet-air temperature upon the knock limit of a fuel in a CFR engine was developed at the Cleveland laboratory of the NACA during August 1944 and is described herein. The knock-limited compression-air density when the piston is at top center is plotted against the compression temperature, as calculated by adiabatic-compression formulas. The method has been checked by CFR engine tests of S-2 reference fuel, 28-R fuel, and a blend containing 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel.

CORRELATION METHOD

The threshold of knocking combustion is probably controlled by the density and the temperature of the combustion gases in the knocking zone (reference 1), but the knocking reaction should not indicate whether changes in end-gas density and temperature are due to variations in compression ratio or to equivalent changes in the inlet-charge density and temperature. In a given engine operating at constant speed and fuel-air ratio, the end-gas density and temperature may be considered as functions of the compression-charge density and temperature. In view of this consideration, compression density and temperature may be used in place of end-gas density and temperature when correlating the effects of engine variables on the knock limits of a fuel.

The compression-air density, as used hereinafter, is calculated by dividing the air flow to the cylinder per intake cycle by the clearance volume. In terms of cylinder displacement volume and compression ratio:

$$\rho = \frac{A}{nv_c} = \frac{A(r-1)}{nv_d} \qquad (1)$$

where

ρ	compression-air density, pounds per cubic inch
A	intake-air flow, pounds per minute
n	intake cycles per minute
v_c	engine clearance volume, cubic inches
r	compression ratio
v_d	engine displacement volume, cubic inches

Other partial densities (the counterparts to partial pressures) can be applied in place of compression-air density with equal accuracy. Partial densities involving fuel flow, air flow, or simple sums of the two can be converted from one to the other provided that the fuel-air ratio is held constant.

The effects of engine operating characteristics, such as fuel vaporization, heat transfer to the cylinder walls, fuel-air ratio, and preflame reactions, should be considered in order to give an accurate calculation of compression temperature. Because these considerations would probably prove unnecessary in practice, however, an adiabatic-compression formula is suggested:

$$T = T_o r^{(\gamma-1)} \qquad (2)$$

where

T	compression-air temperature, °R
T_o	intake-air temperature, °R
γ	ratio of specific heat of charge at constant pressure to that at constant volume

In order to illustrate the correlation method, the knock-limited compression-air density at constant fuel-air ratio (calculated from equation (1)) is plotted against compression temperature (calculated from equation (2)). If the correlation method is satisfactory, a reproducible curve should result when either inlet-air temperature, compression ratio, or both are varied.

Equation (1) required air-flow data. Because engine data are usually reported in terms of indicated mean effective pressure, indicated specific fuel consumption, and fuel-air ratio, the following well-known identity can be applied:

$$\frac{A}{nv_d} = \frac{\text{imep} \times \text{isfc}}{(F/A) \times 2.376 \times 10^7} \qquad (3)$$

where F is the rate of fuel flow, pounds per minute.

If the knock-limited data are given in terms of inlet-air pressure and fuel-air ratio, an equation that expresses air flow as a function of inlet-air pressure must be determined. If the intake-valve arrangement of the engine offers no resistance to the incoming charge and if the exhaust residuals are isothermally compressed by the incoming charge, the air flow may be approximated as follows:

$$\frac{A}{nv_d} \approx \frac{M}{R(r - 1)}\left(\frac{pr - p_e}{T_o}\right) \qquad (4)$$

where

M	average molecular weight of air
R	gas constant
p	inlet-air pressure
p_e	effective exhaust-back pressure

When the value of the air flow from expression (4) is substituted into equation (1), the compression-air density becomes:

$$\rho \approx \frac{M}{R}\left(\frac{pr - p_e}{T_o}\right) \qquad (5)$$

Either with or without the correction for exhaust back pressure p_e, the expression $(pr - p_e)/T_o$ will be hereinafter called the approximate density factor. Without the small exhaust-pressure correction, this approximate density factor is the same as the simplified density factor RP_1/T_1 (pr/T_o in the notation of this paper) suggested in references 1 and 3. (For engines with valve overlap adjusted to give 100-percent scavenging of exhaust residuals, p_e is 0.)

It is emphasized that expression (4) contains approximations that may not conform to experimental results. Expressions (4) and (5) should therefore be considered unreliable until they are adequately checked by tests with a given engine.

PRESENTATION OF DATA

For the purpose of verifying the correlation method presented herein, three sets of knock-limited performance data were obtained with supercharged CFR engines run at various compression ratios and inlet-air temperatures. Series I and III were run with CFR engines equipped with four-hole cylinders, dual ignition, and fuel-and-air metering systems similar to the one described in reference 4. Series II was run with a CFR engine equipped with a two-hole cylinder, single ignition, and auxiliary equipment similar to that used on an F-4 engine. The fuels tested and the engine operating conditions for the three series of tests are given in the following table:

Series	Fuel	Compression ratio	Inlet-air temperature (°F)	Engine speed (rpm)	Spark advance (deg B.T.C.)	Coolant temperature (°F)	Oil temperature (°F)
I	S-2	6, 8, 10	150, 200, 250	2000	35	250	175
II	28-R	6, 8, 10	150, 250	1800	30	250	165
III	50 percent triptane + 4.53 ml TEL/gal and 50 percent 28-R	5, 6, 7, 7.5, 9, 10.5	250	[a]1800	30	250	165
		8	100, 150 200, 250, 300, 350				

[a]Because this engine was coupled to an induction-current dynamometer, the speed increased somewhat at high power outputs.

The data obtained during series I and II are plotted in figures 1 and 2, respectively. Data from series III are shown in figures 3 and 4.

EXPERIMENTAL CHECK OF THE METHOD

The data in figure 1 were substituted in equations (1) and (2) to show the effect of compression temperature on the knock-limited compression-air density (fig. 5). The ordinate was calculated by means of equations (1) and (3) and the abscissa by equation (2). Although γ may be affected by fuel-air ratio, fuel vaporization, preflame reactions, engine design, and other engine variables, a γ value of 1.41 (the approximate value for air at atmospheric conditions) was selected as a first approximation and was found to be satisfactory for a CFR engine. The points plotted in figure 5 are calculated points and are shown to indicate the accuracy of the correlation.

Figure 6 presents the correlation curve for the 28-R fuel data presented in figure 2. Figures 5 and 6 indicate that the correlation method will apply to current aviation fuels within the accuracy of the experimental data.

The correlation curves for the triptane fuel-blend data taken over a broad range of compression ratios and inlet-air temperatures (figs. 3 and 4) are plotted in figure 7. The correlation method proved quite satisfactory in this case because the same curve apparently resulted when either inlet-air temperature or compression ratio was varied.

The correlation curves of compression-air density and temperature for the triptane blend (fig. 7) are steeper than the corresponding curves for 28-R fuel (fig. 6). The knock-limited performance of triptane would therefore be expected to be more sensitive to changes of either compression ratio or inlet-air temperature than 28-R fuel.

The extent to which approximate rather than measured compression-air densities may influence the accuracy of the correlation can be roughly estimated from the data of figures 3 and 4. Curves of the approximate density factor (from expression (5)) - with and without the correction for exhaust back pressure p_e - against compression temperature are shown in figures 8 and 9, respectively. From an inspection of the curves it is evident that the approximate density factor with or without the correction for exhaust-back pressure can be used only when a very rough correlation over a limited range of compression ratios and inlet-air temperatures is desired.

Whether a correlation involving curves of the simplified knock-limited density factor pr/T_0 against either the inlet-air temperature or the compression ratio (the methods described in references 1 and 3) might be satisfactorily applied to the CFR engine data presented herein was also considered. Figures 10 and 11 demonstrate that neither of the simplified methods is applicable to the triptane data presented in figures 3 and 4.

SUMMARY OF RESULTS

A satisfactory correlation of the effects of compression ratio and inlet-air temperature on the knock limits of S-2 reference fuel, 28-R fuel, and a blend containing 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel in CFR engines was obtained by plotting the variation of knock-limited compression-air density with compression temperature.

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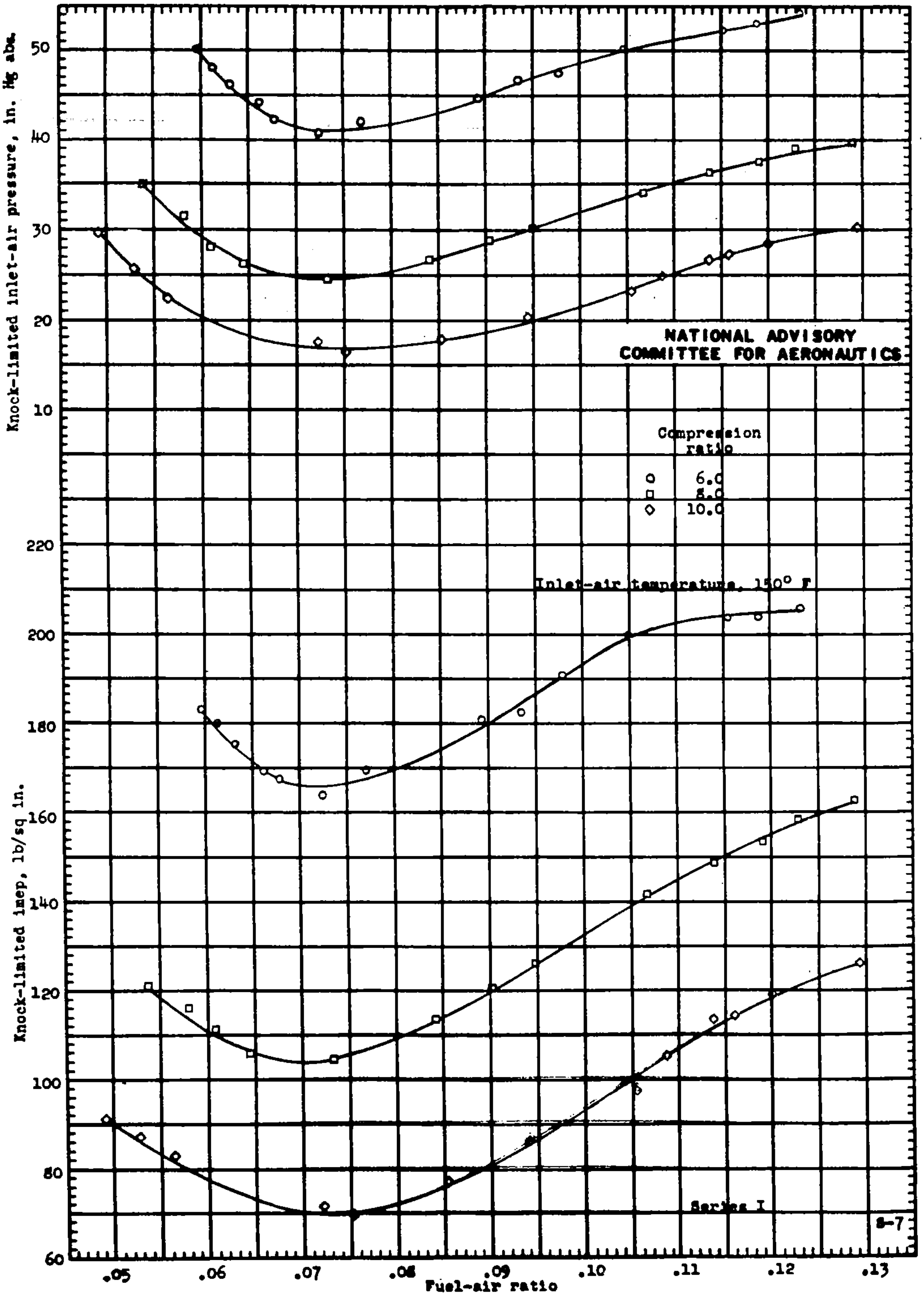
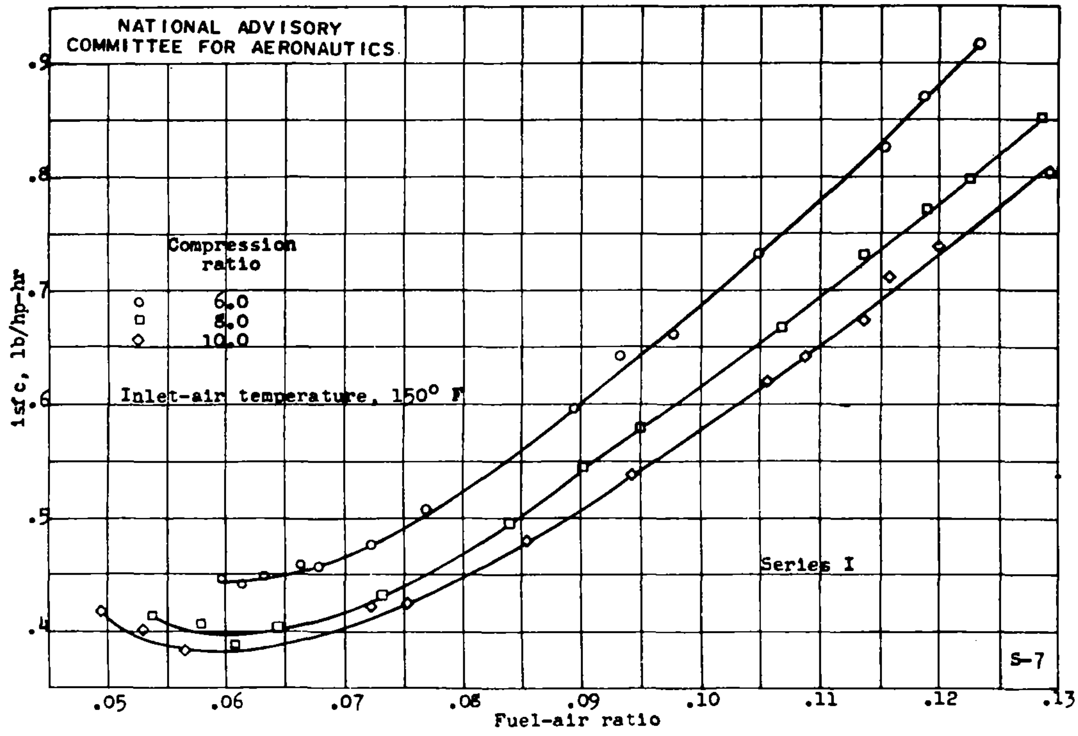
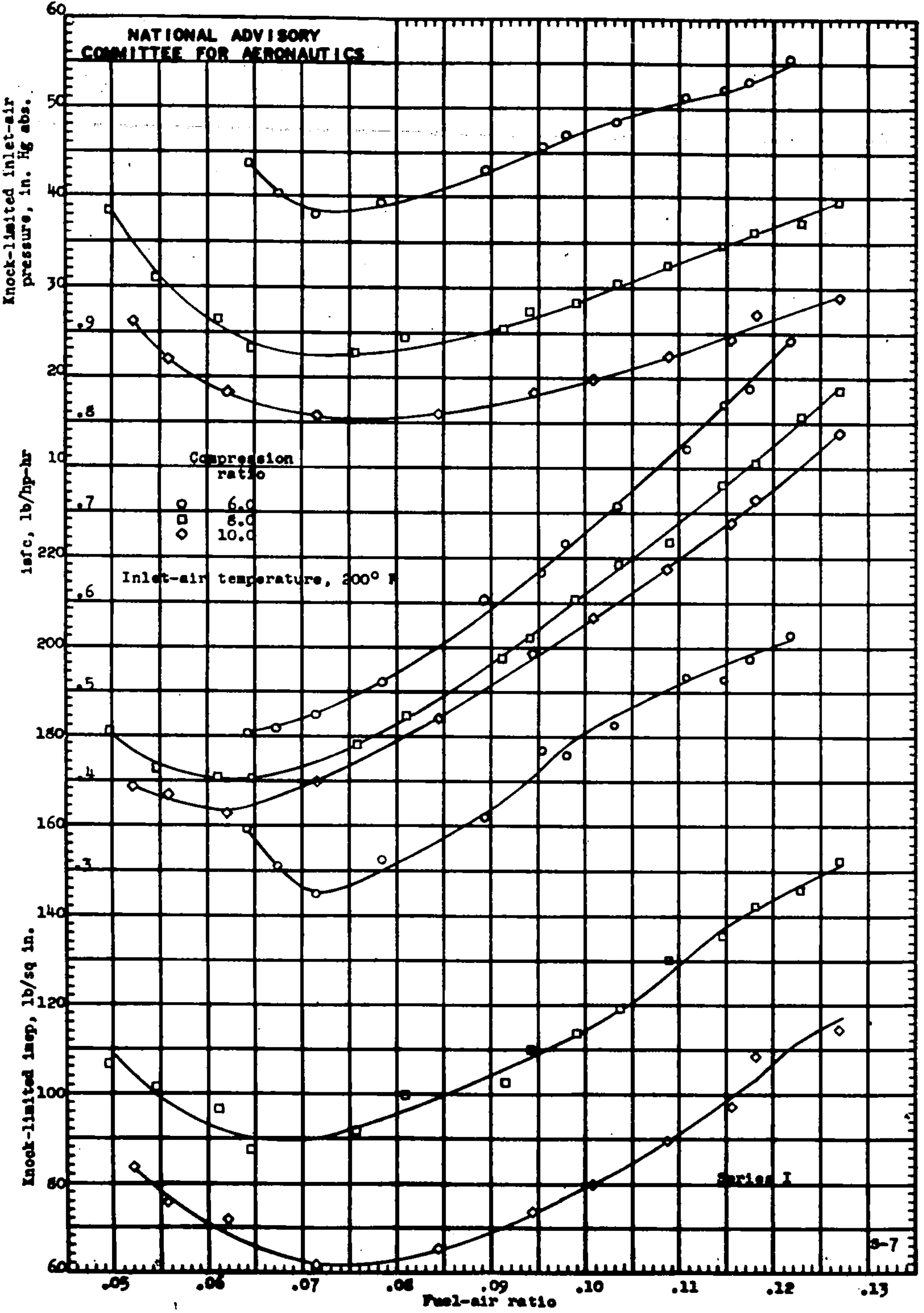


(a) Inlet-air temperature, 150° F.

Figure 1. - Effect of compression ratio on knock-limited performance of S-2 fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 35° B.T.C.; coolant temperature, 250° F; engine speed, 2000 rpm.

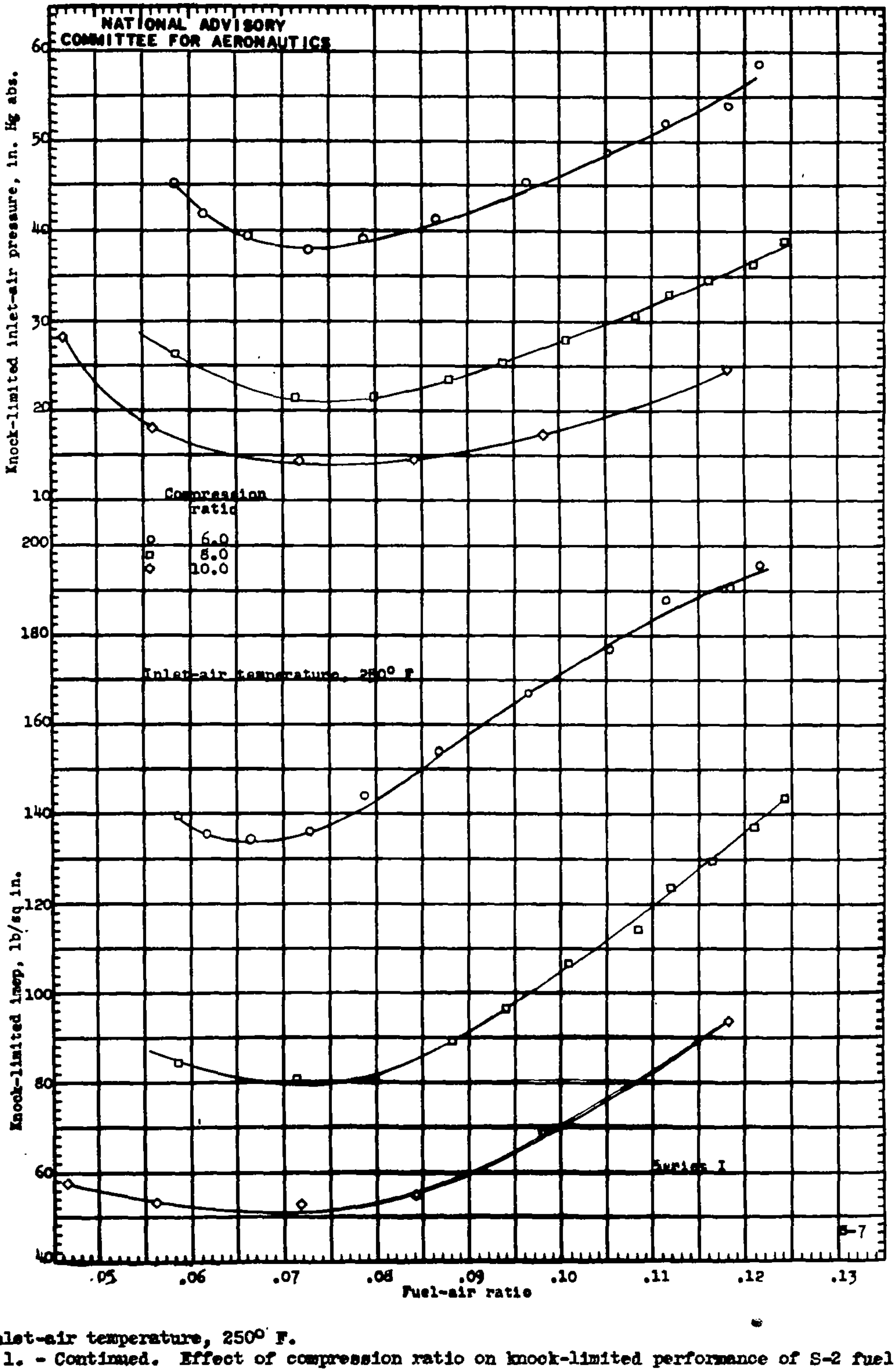


(a) Concluded. Inlet-air temperature, 150° F.
Figure 1. - Continued. Effect of compression ratio on knock-limited performance of S-2 fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 35° B.T.C.; coolant temperature, 250° F; engine speed, 2000 rpm.



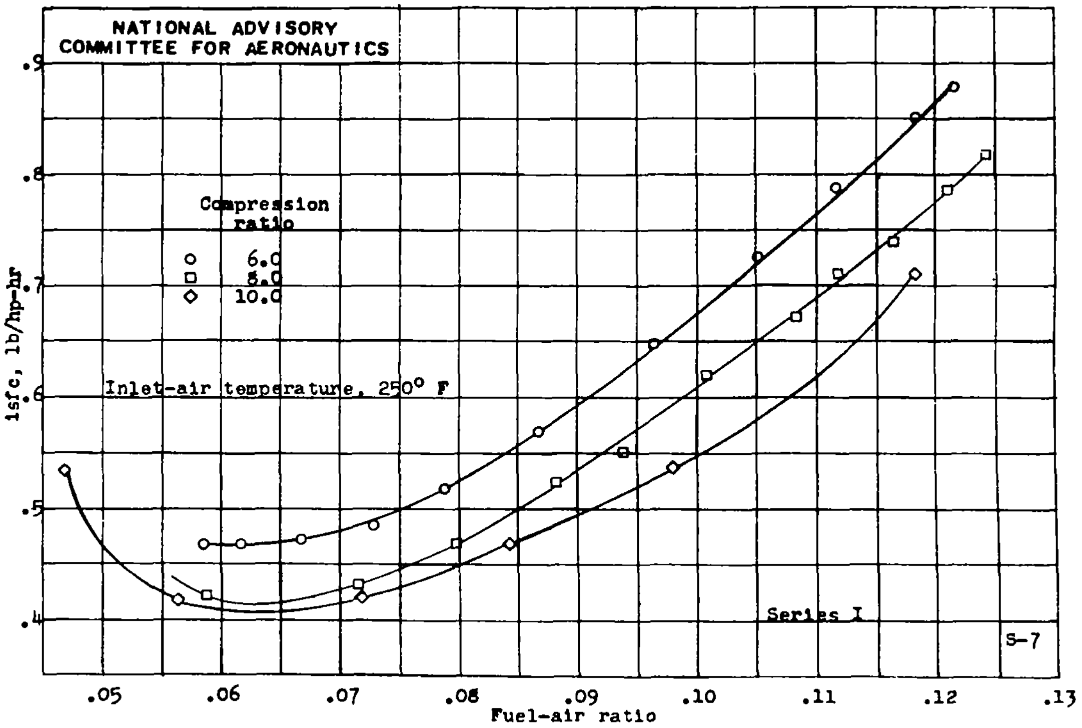
(b) Inlet-air temperature, 200° F.

Figure 1. - Continued. Effect of compression ratio on knock-limited performance of S-2 fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 35° B.T.C.; coolant temperature, 250° F; engine speed, 2000 rpm.



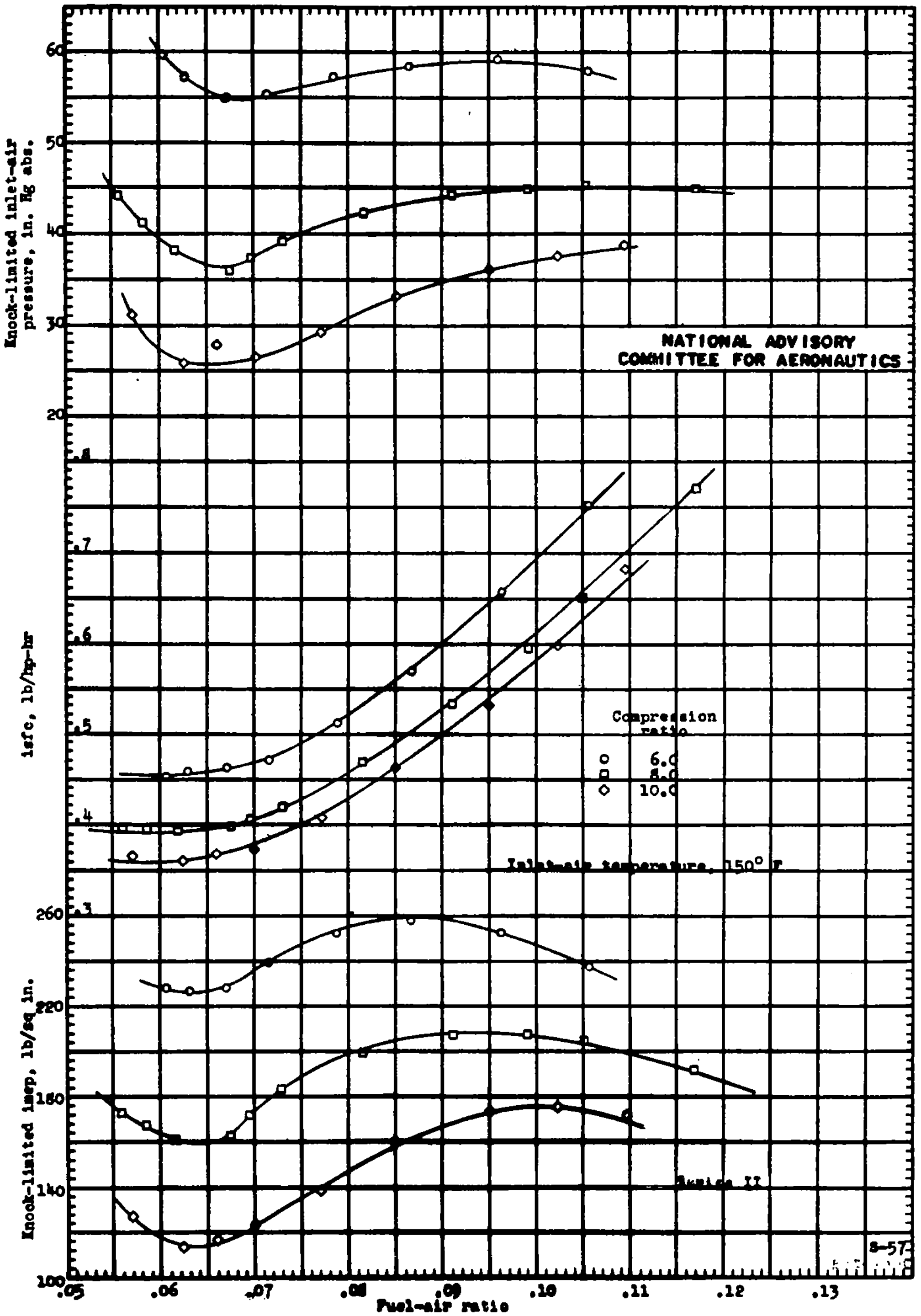
(c) Inlet-air temperature, 250° F.

Figure 1. - Continued. Effect of compression ratio on knock-limited performance of S-2 fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 35° B.T.C.; coolant temperature, 250° F; engine speed, 2000 rpm.



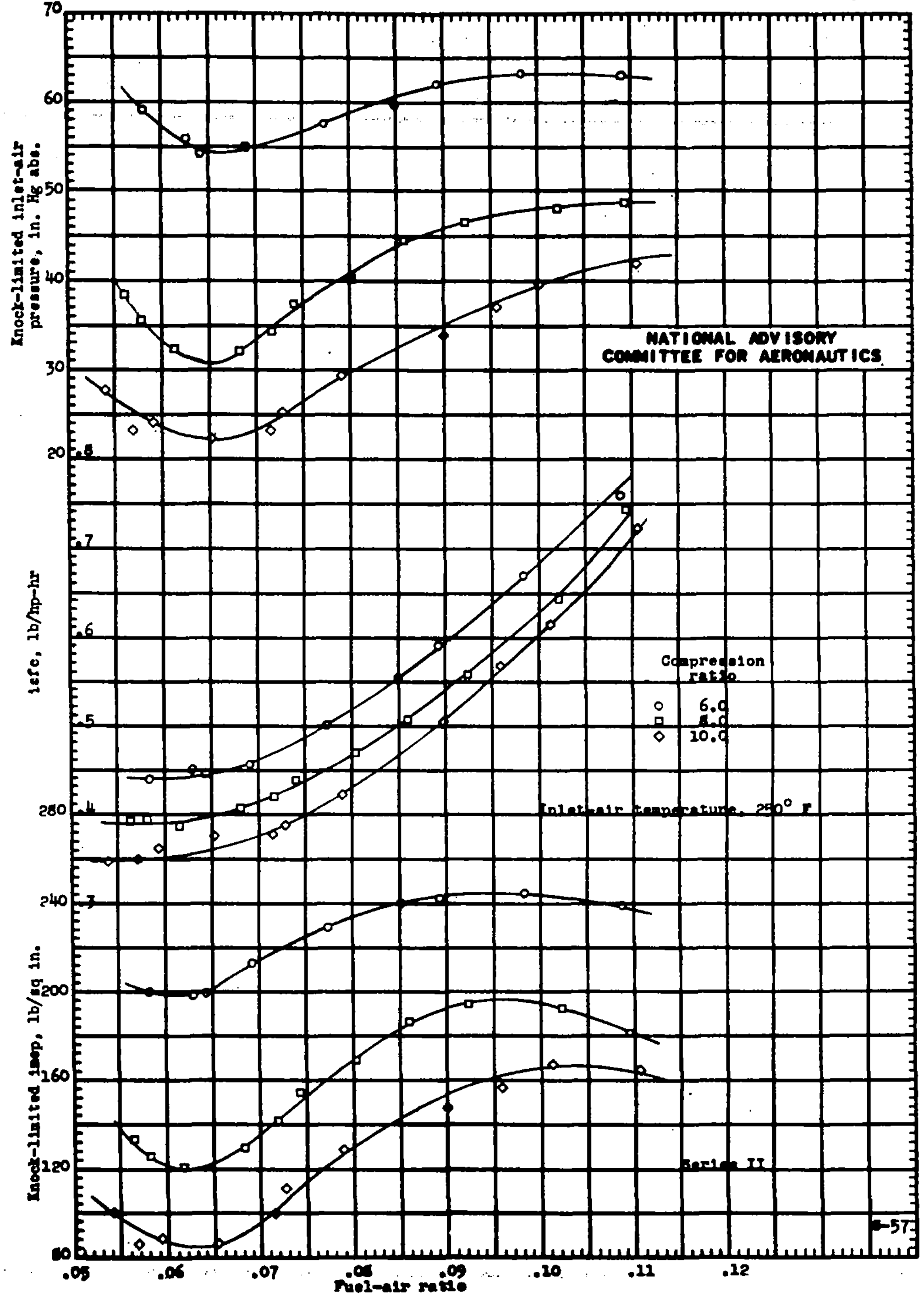
(c) Concluded. Inlet-air temperature, 250° F.

Figure 1. - Concluded. Effect of compression ratio on knock-limited performance of S-2 fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 35° B.T.C.; coolant temperature, 250° F; engine speed, 2000 rpm.



(a) Inlet-air temperature, 150° F.

Figure 2. - Effect of compression ratio on knock-limited performance of 28-R fuel. CFR engine; two-hole cylinder, single ignition; spark advance, 30° B.T.C.; coolant temperature, 250° F; engine speed, 1800 rpm.



(b) Inlet-air temperature, 250° F.

Figure 2. - Concluded. Effect of compression ratio on knock-limited performance of 28-R fuel. CFR engine; two-hole cylinder, single ignition; spark advance, 30° B.T.C.; coolant temperature, 250° F; engine speed, 1800 rpm.

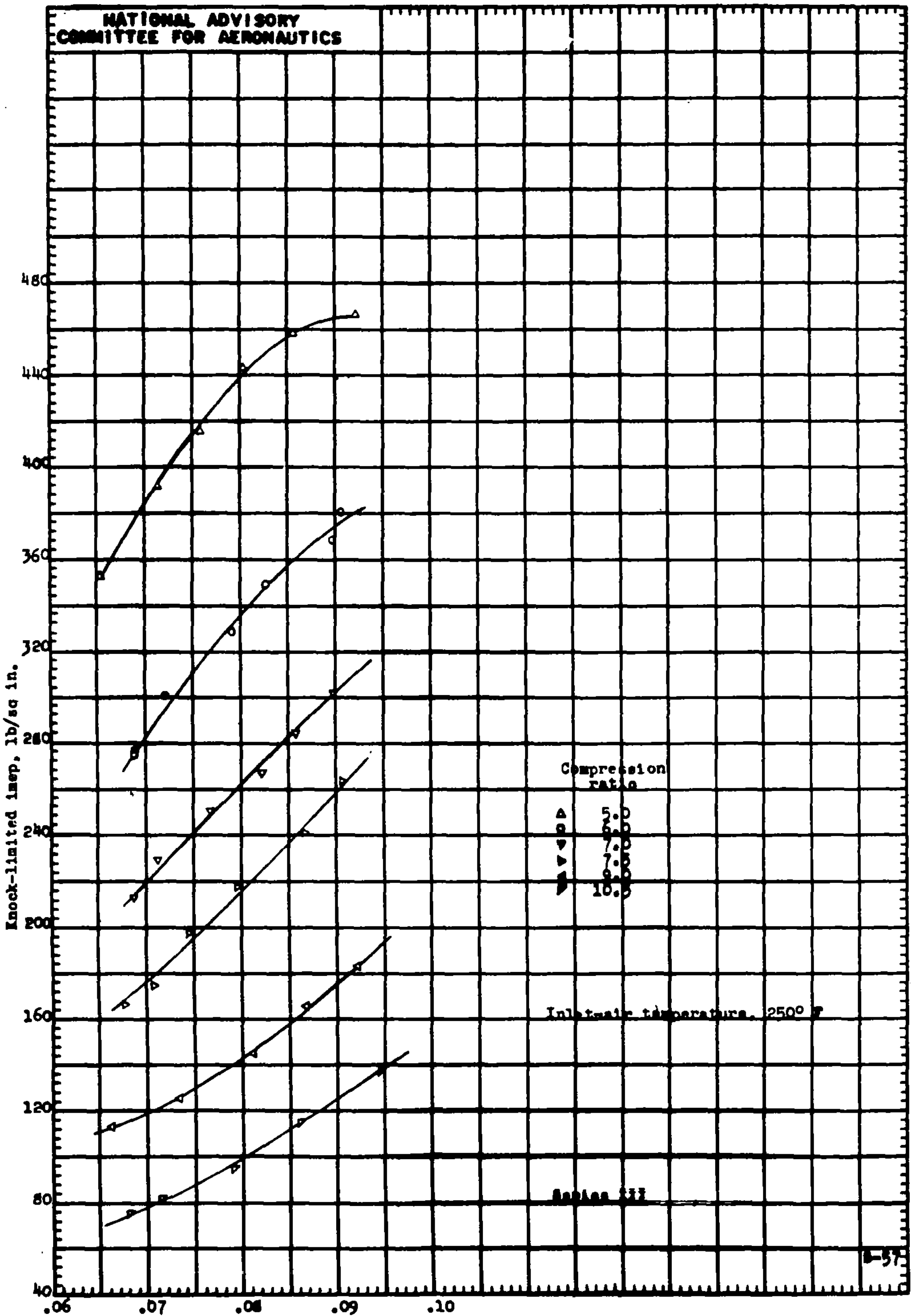


Figure 3. - Effect of compression ratio on knock-limited performance of a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 30° B.T.C.; coolant temperature, 250° F; engine speed, 1800 rpm.

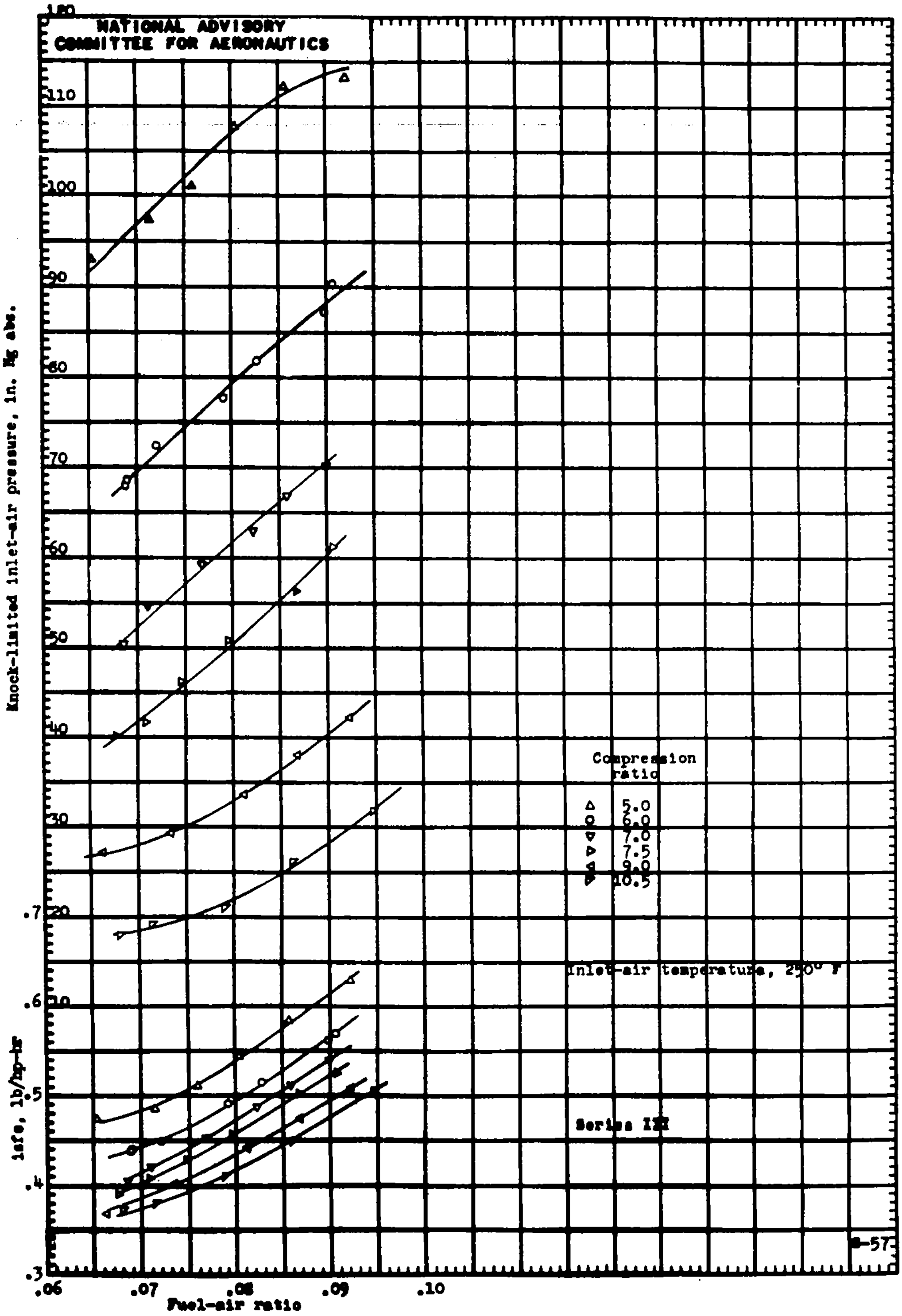
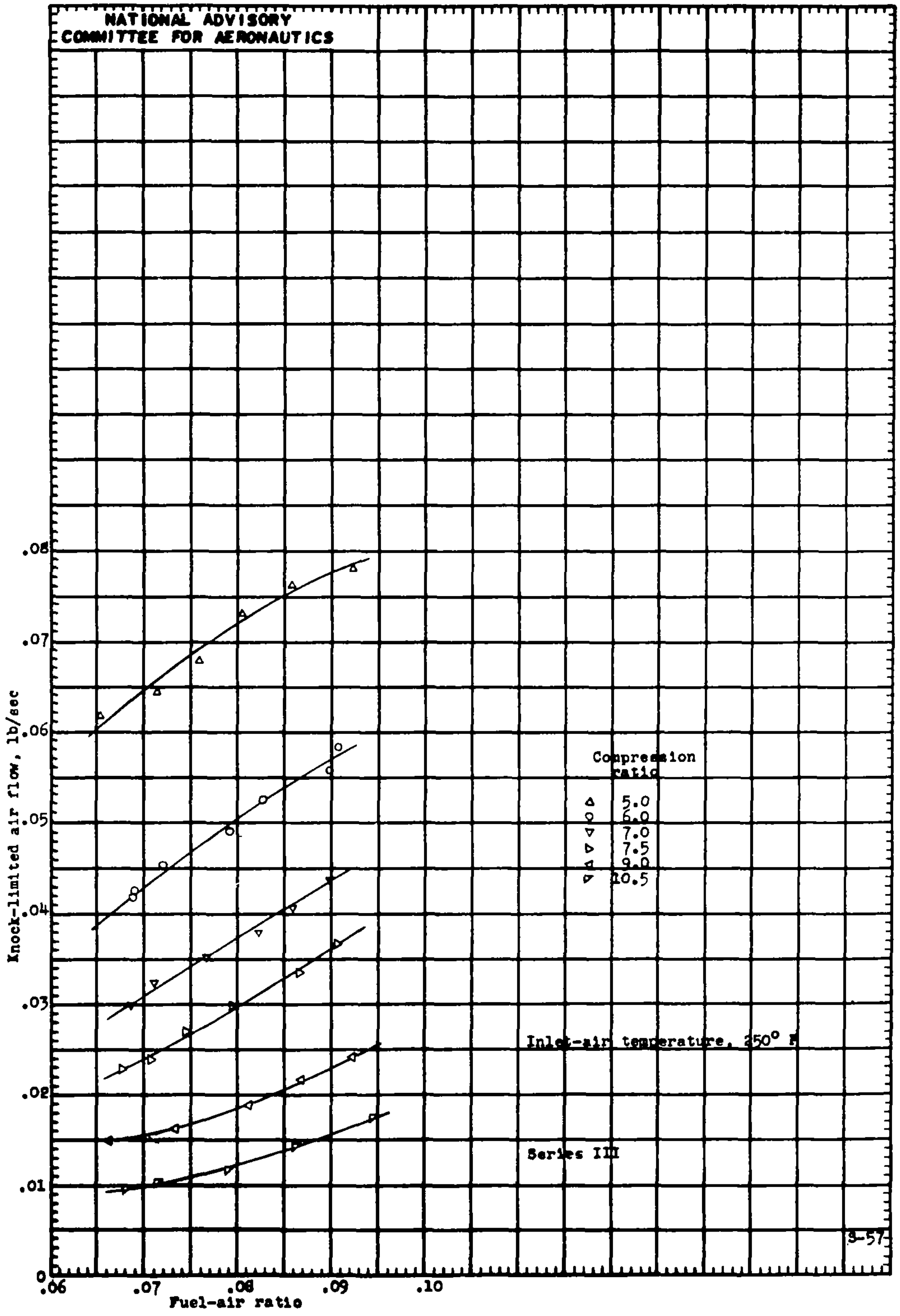


Figure 3. - Continued. Effect of compression ratio on knock-limited performance of a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 30° B.T.C.: coolant temperature, 250° F; engine speed, 1800 rpm.



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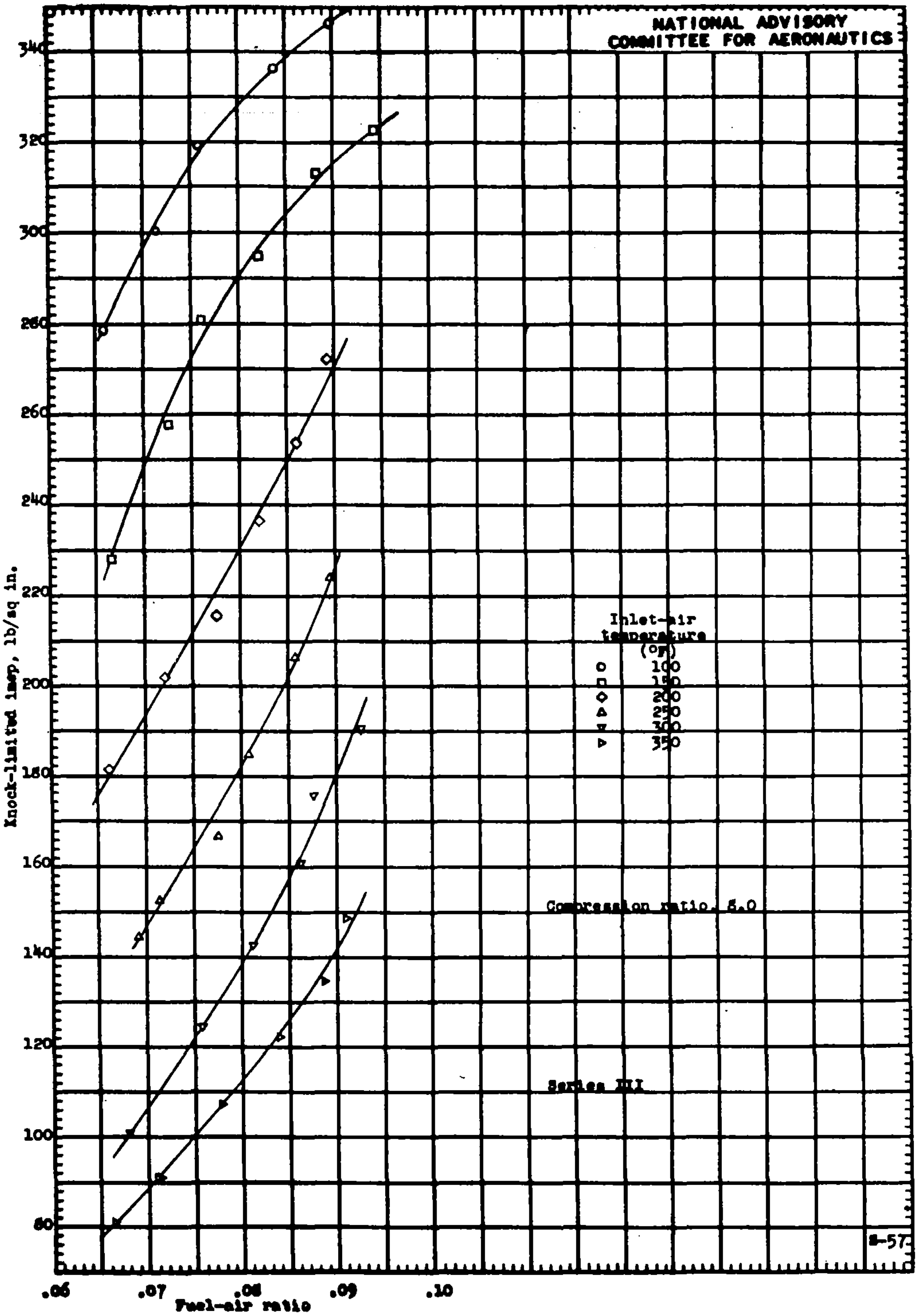

Figure 4. - Effect of inlet-air temperature on knock-limited performance of a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 30° B.T.C.; coolant temperature, 250° F; engine speed, 1800 rpm.

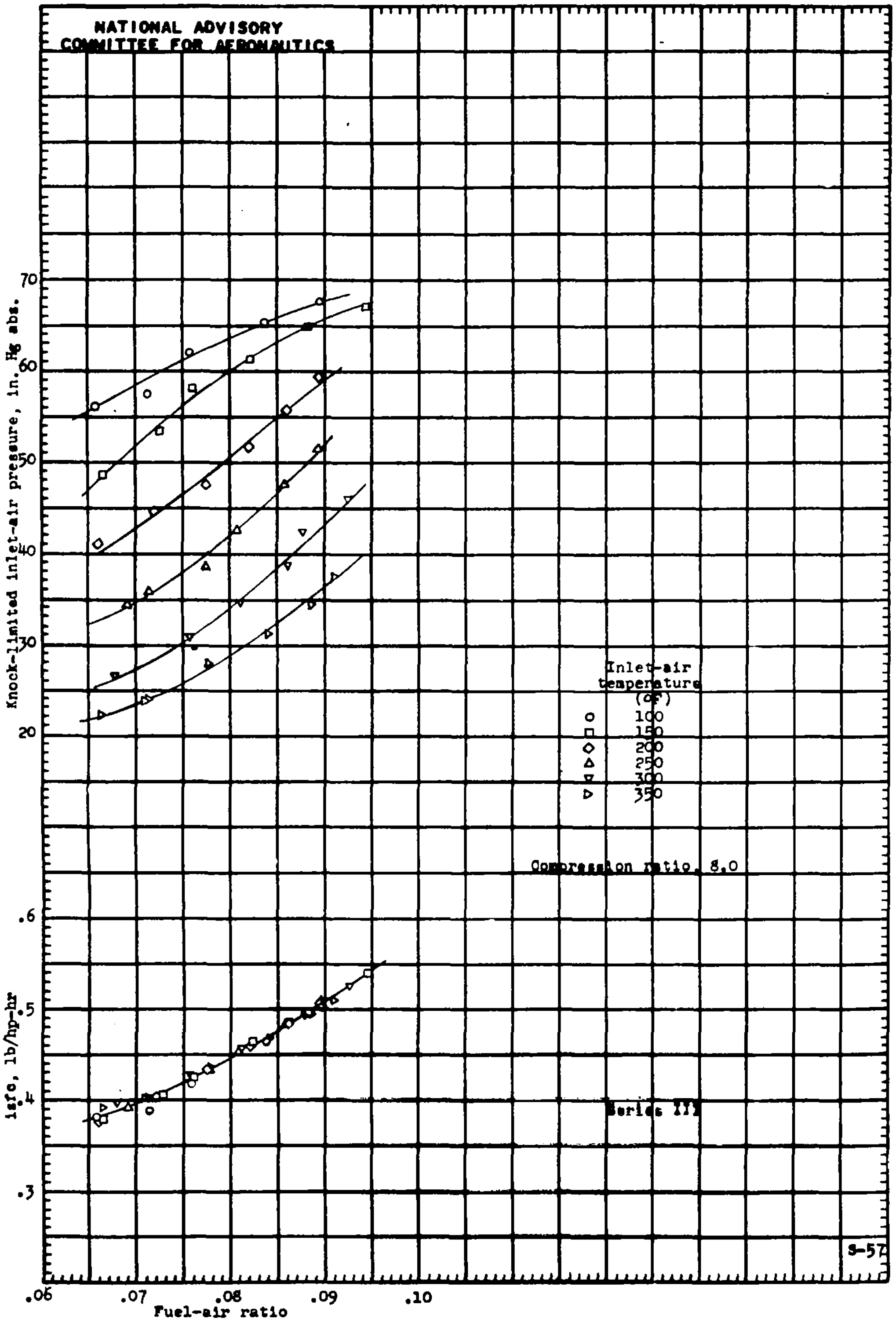

Figure 4. - Continued. Effect of inlet-air temperature on knock-limited performance of a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 30° B.T.C.; coolant temperature, 250° F; engine speed, 1800 rpm.

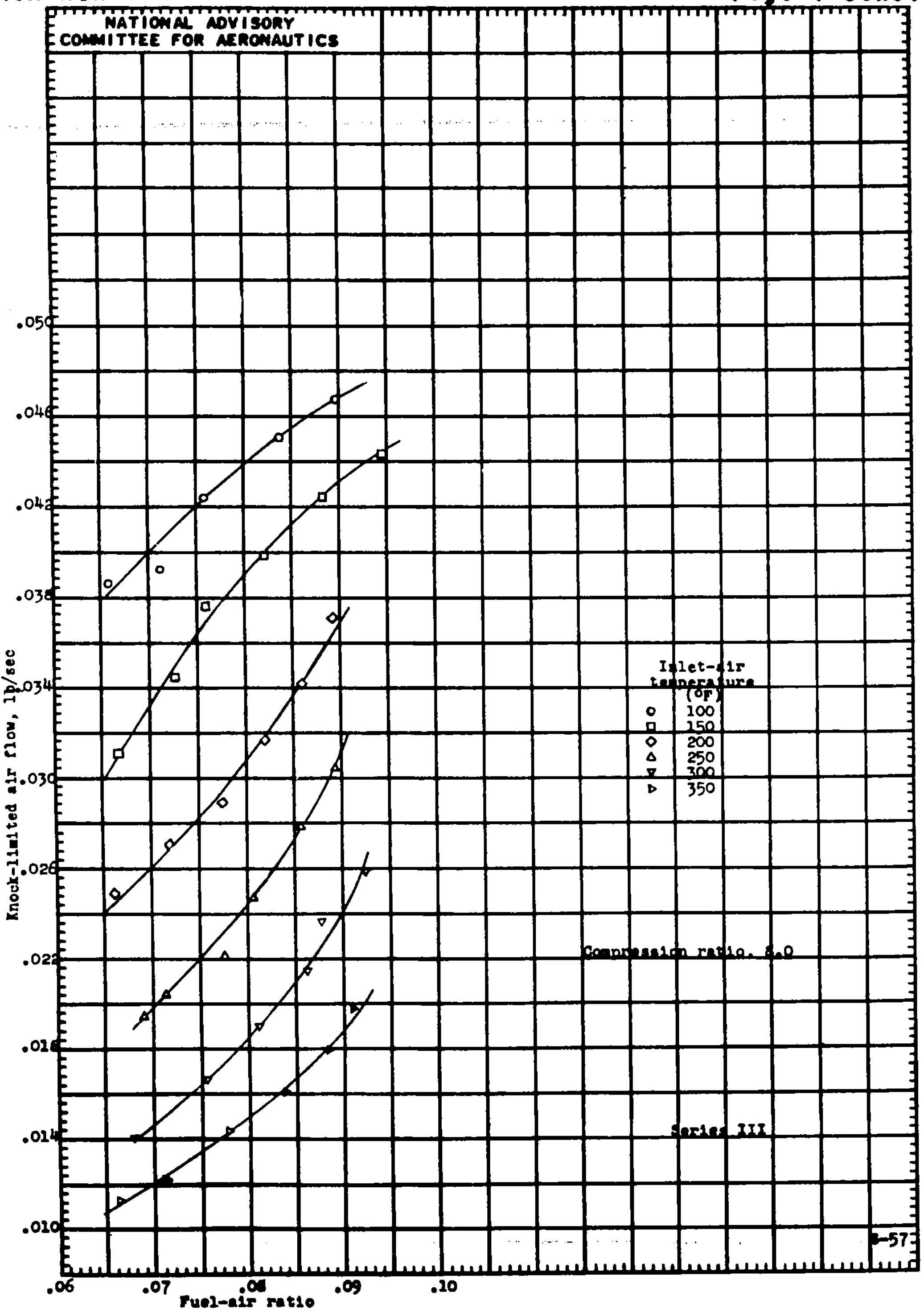

Figure 4. - Concluded. Effect of inlet-air temperature on knock-limited performance of a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. CFR engine; four-hole cylinder, dual ignition; spark advance, 30° B.T.C.; coolant temperature, 250° F; engine speed, 1800 rpm.

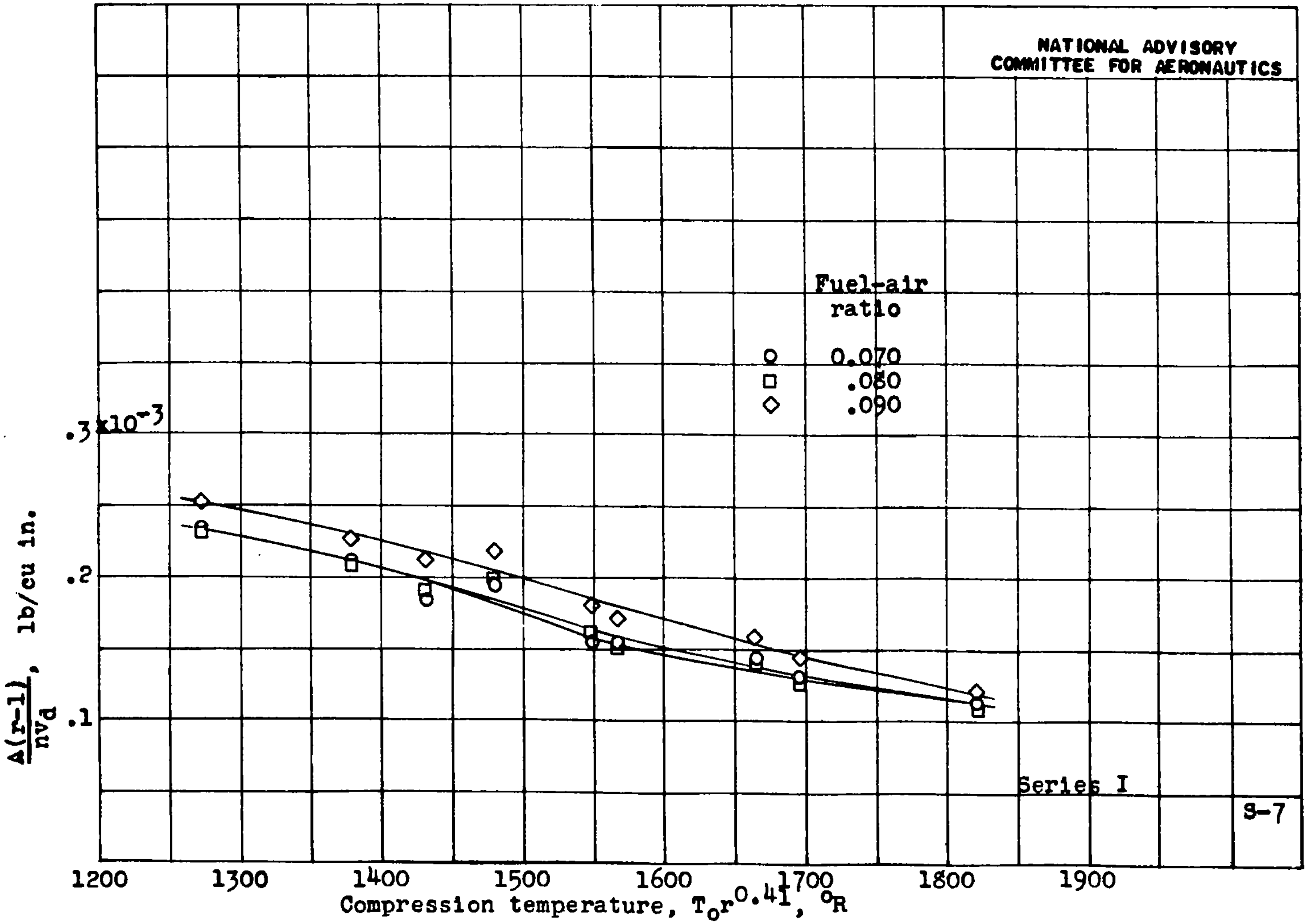

Figure 5. - Effect of compression temperature on the knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for S-2 fuel. Data calculated from figure 1.

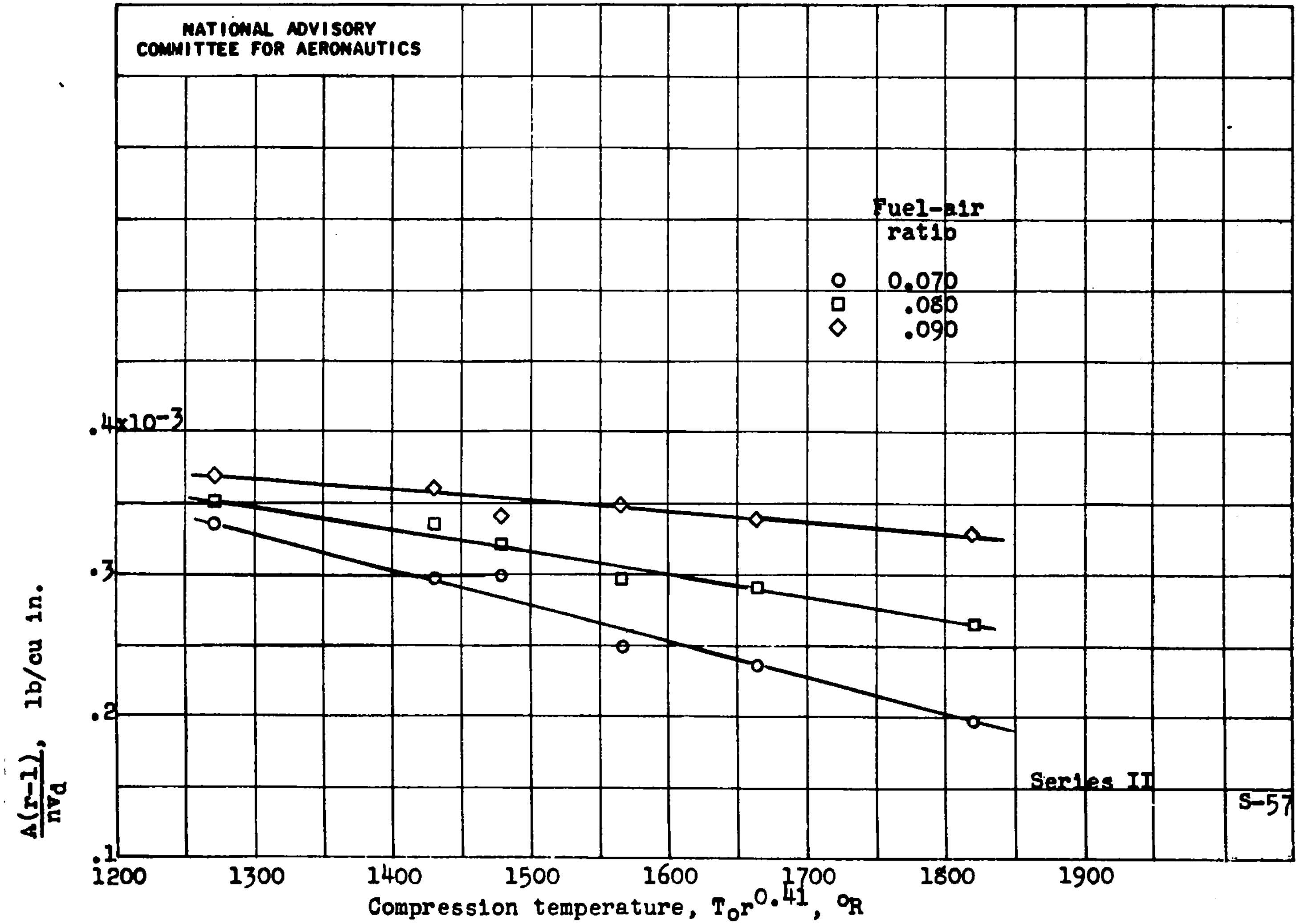

Figure 6. - Effect of compression temperature on the knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for 28-R fuel. Data calculated from figure 2.

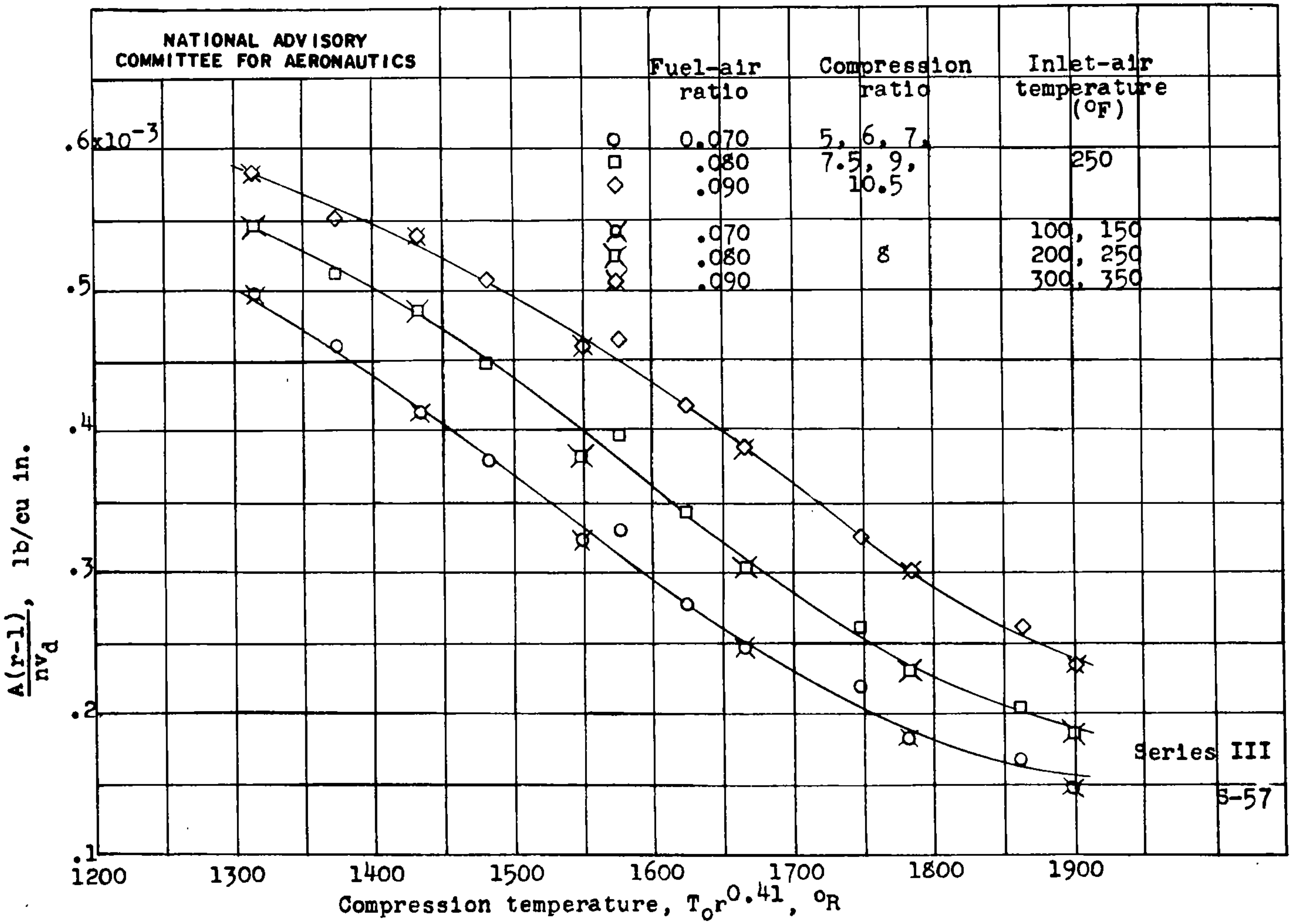

Figure 7. - Effect of compression temperature on the knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. Data calculated from figures 3 and 4.

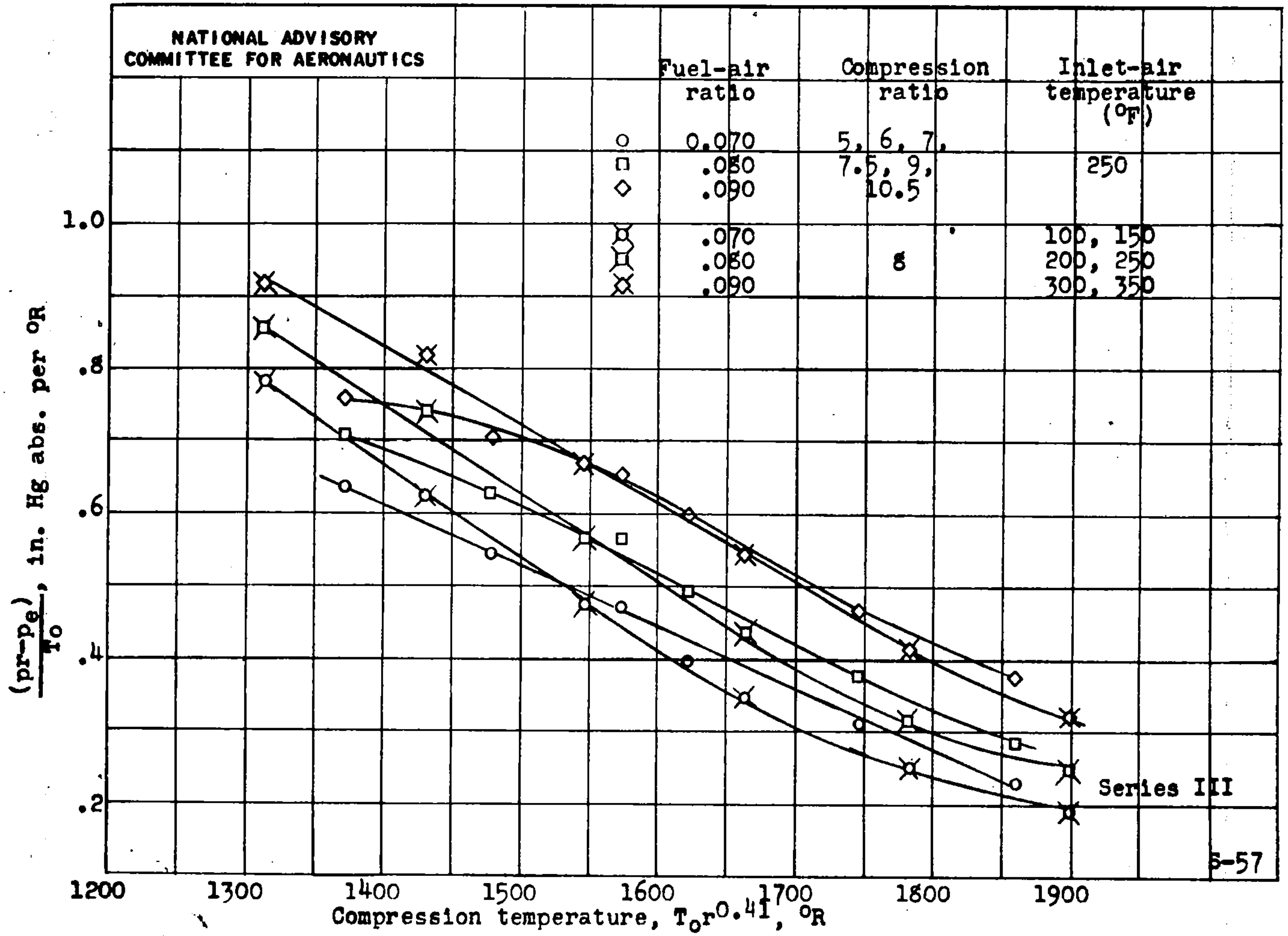

Figure 8. - Effect of compression temperature on the approximate knock-limited air density factor $\frac{(pr-p_e)}{T_o}$ for a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. Data calculated from figures 3 and 4.

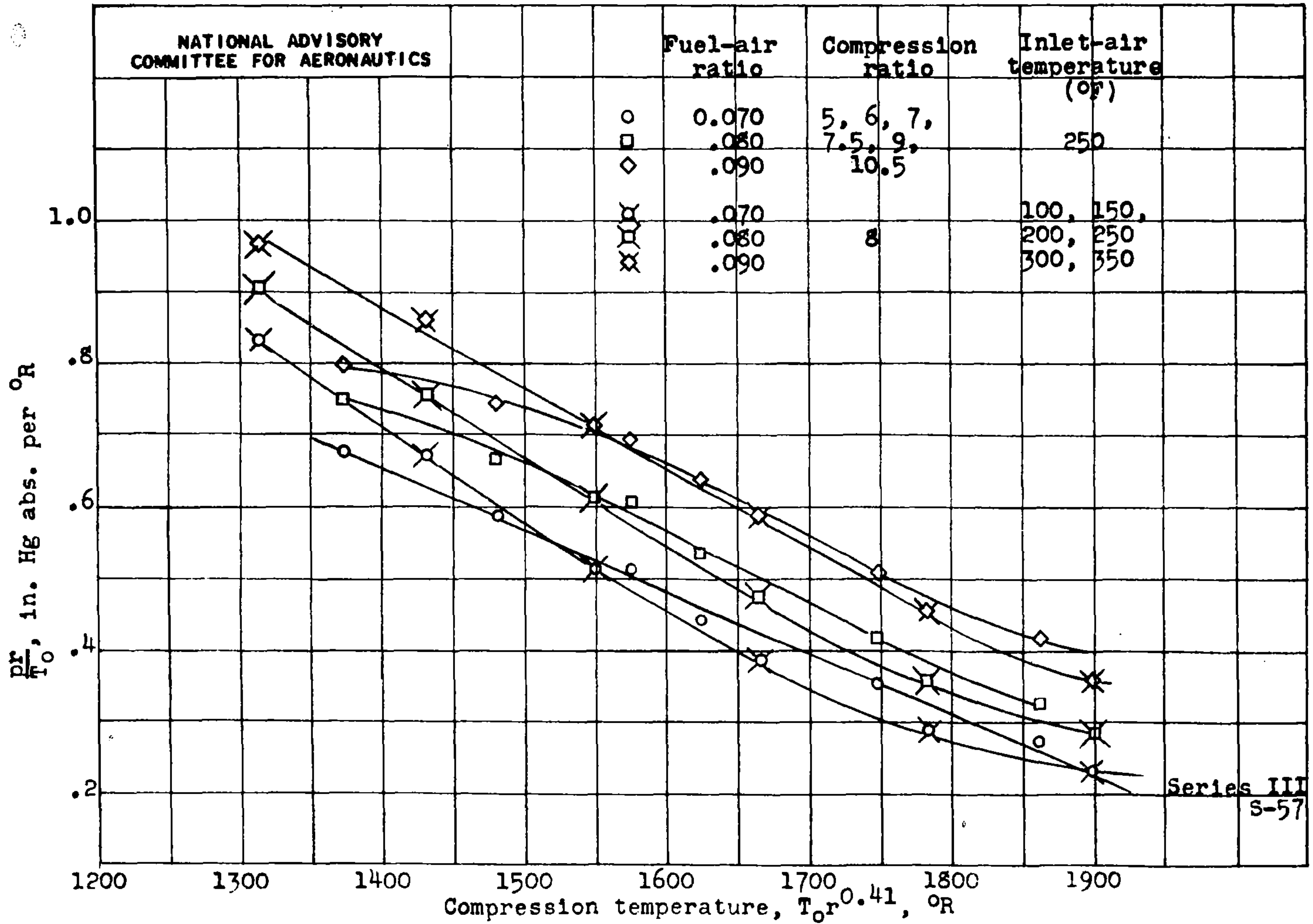

Figure 9. - Effect of compression temperature on the approximate knock-limited air density factor $\frac{pr}{T_o}$ for a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. Data calculated from figures 3 and 4.

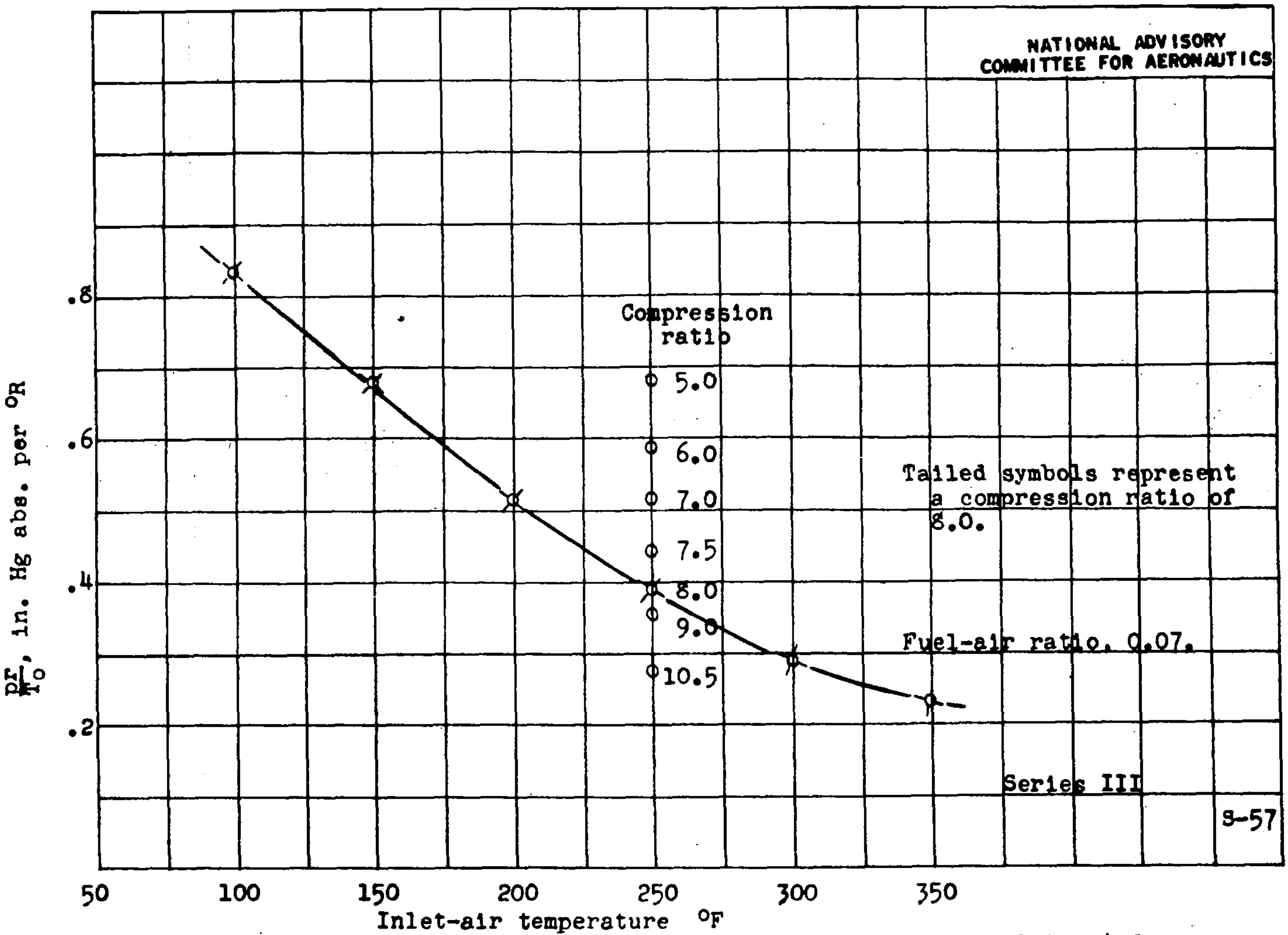

Figure 10. - Effect of inlet-air temperature on the approximate knock-limited air density factor $\frac{pr}{T_o}$ for a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. Data calculated from figures 3 and 4.

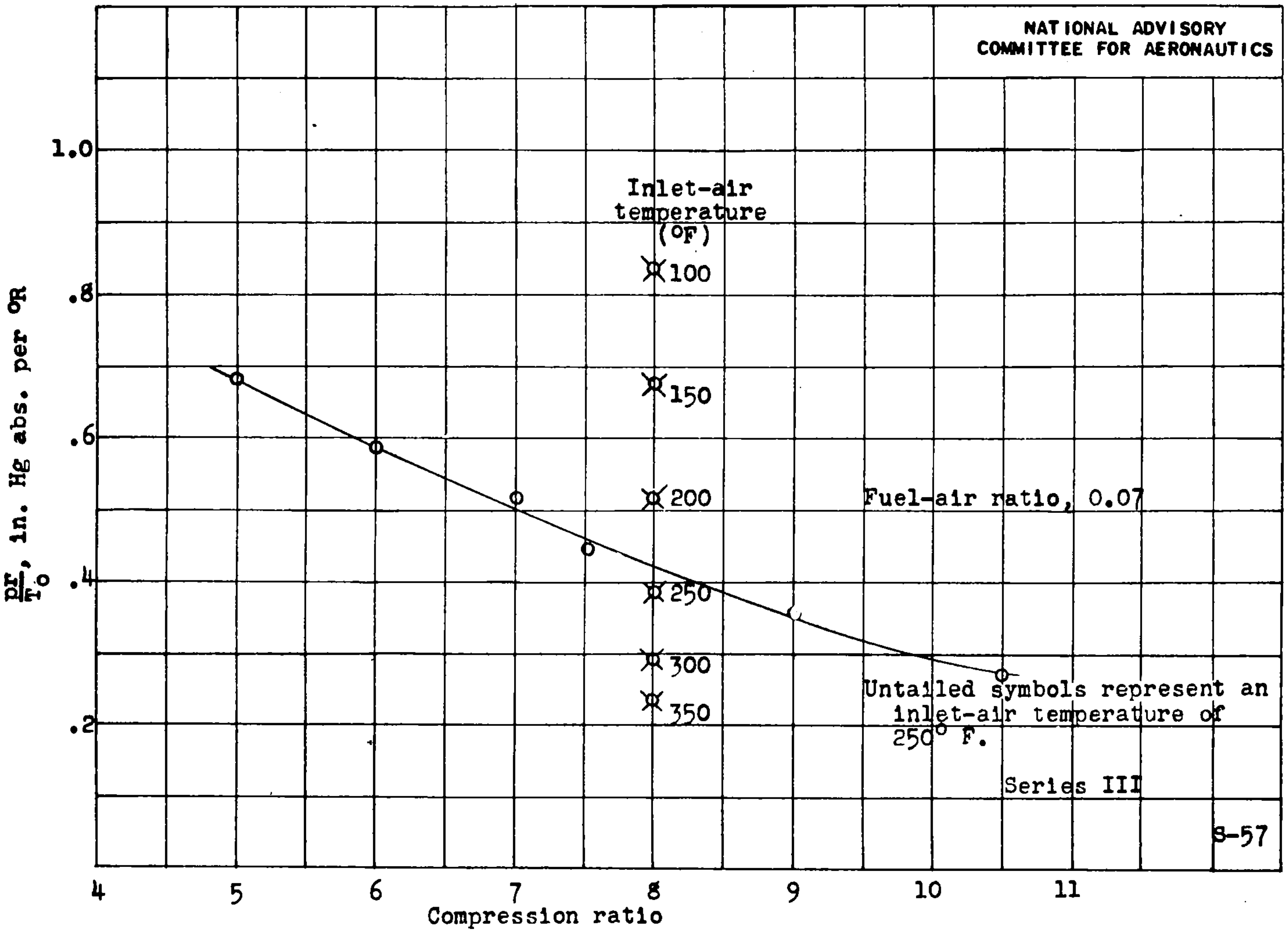

Figure 11. - Effect of compression ratio on the approximate knock-limited air density factor $\frac{pr}{T_o}$ for a blend of 50 percent triptane plus 4.53 ml TEL per gallon and 50 percent 28-R fuel. Data calculated from figures 3 and 4.