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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 - II

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and John C. Evvard

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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 - II

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SUMMARY

The knock-limited performance of nine fuels, comprising isolated members of four classes of hydrocarbons (aromatics, paraffins, cyclo-paraffins, and olefins), is presented in the form of three-dimensional plots of fuel-air ratio, compression temperature, and compression-air density. The plots are based on a correlation that is shown to apply for these fuels over a wide range of compression ratios and inlet-air temperatures. The significance of the term "temperature sensitivity" is sketched, and it is emphasized that no generalized number such as octane number can be applied even to members of a given class of hydro-carbons when broad ranges of engine severity are encountered.

INTRODUCTION

One of the aims of fundamental studies of fuel knock is to define the knocking characteristics of the fuel in such a manner as to be independent of the test engine and the test conditions. Comparison rating scales (such as octane number) partly accomplish this aim but they do not indicate the magnitude nor the trends in engine performance with engine conditions and, furthermore, the reference fuel itself is not rated in terms of absolute units. The use of end-gas densities and temperatures to define the knock-limited performance of a fuel was suggested in reference 1 as a means of mitigating these disadvantages. Any calculation of the end-gas density and temperature in terms of normally measured engine variables, however, is complicated and uncertain enough to suggest that a more easily calculated density and temperature might be used. In reference 2 the compression-air

density when the piston is at top center is plotted against the compression temperature as calculated by adiabatic-compression formulas. This plot was found to be effective in correlating the effects of compression ratio and inlet-air temperature upon the knock-limited performance of a CFR engine. Tests conducted by Pratt & Whitney Aircraft showed the plot to be equally effective for data taken on an R-1830 C-9 single-cylinder engine.

In the present report the correlation presented in reference 2 is applied in evaluating most of the types of fuel currently used or being considered for use in reciprocating aircraft engines.

The data for this report were obtained at the NACA Cleveland laboratory between December 1944 and June 1945.

FUELS AND APPARATUS

The fuels tested were chosen because they represent most of the important classes of fuel used or considered for use in reciprocating aircraft engines. The fuels are:

S-4 reference fuel
28-R fuel
Aviation alkylate
Cyclohexane
Cyclopentane
Triptene
Diisopropyl
Triptane
Toluene

All of the fuels except 28-R were leaded to 4 ml TEL per gallon.

Three CFR engines were used to obtain the data for this report. For the tests on all of the fuels except cyclopentane, toluene, and triptane, a CFR engine was equipped with a four-hole cylinder (part No. 106074), dual ignition, and fuel- and air-metering systems similar to those described in reference 3. The coolant for this engine was a mixture of ethylene glycol and water that gave a boiling temperature of 250° F.

Because of anticipated high power levels in the tests of triptane, cyclopentane, and toluene, some engine alterations were considered advisable. A CFR engine was equipped with a strengthened cylinder

(part No. 109098) and the test setup described in reference 4, except for the following features:

1. An auxiliary intake-valve spring was installed inside the standard spring when it was found that a manifold pressure over 85 pounds per square inch gage would open the intake valve.

2. An aluminum piston was used for the triptane tests, which corresponded to part No. 106360D except that the second ring land was double width and the diameter of this land was relieved 0.005 inch. With piston part No. 106360D, considerable trouble had been experienced with either burning or breaking of the second ring land at high-power operation.

3. A pressure water-cooling system was installed and a jacket-outlet water temperature maintained at 250° F. Because of the better cooling characteristics of water, it was hoped that the lower cylinder-wall temperature at a constant coolant temperature would reduce the preignition encountered at high power.

During the toluene tests the connecting rod broke just below the piston-pin boss and demolished the second engine. (The failure occurred when the engine was operating at a compression ratio of 8.0, an inlet-air temperature of 350° F, and an indicated mean effective pressure of 696 lb/sq in.)

The third engine was set up exactly like the second except for the following two features:

1. The connecting rod was shot-peened before installation

2. Piston part No. 106360D was used with the second ring-land diameter relieved 0.005 inch.

Check tests using 28-R fuel indicated that the knock-limited power outputs were only slightly affected by the various design alterations of the three engines. Similar test data obtained on the three engines are therefore considered comparable. In tests of all the engines, knock and preignition were detected by a cathode-ray oscilloscope in conjunction with a magnetostriction pickup unit.

TEST PROCEDURE

Each fuel was tested at 11 sets of engine conditions covering a wide range of severity. For a given fuel and an inlet-air

temperature of 250° F, the compression ratio was set at 5.0, 6.0, 7.3, 8.7, and 10.0 and a knock curve was run at each of these compression ratios; likewise, for a given fuel and a compression ratio of 8.0, the inlet-air temperature was set at 100°, 150°, 200°, 250°, 300°, and 350° F and a knock curve was run at each of these inlet-air temperatures. The other engine conditions were:

Spark advance, deg B.T.C.	30
Speed, rpm	1800
Coolant temperature, °F	250
Oil temperature, °F	145

Although only knock-limited performance data are presented, the curves are often incomplete (particularly at the high power levels) because of the occurrence of preignition. The data were taken at the knock limits until the engine continued to fire 15 to 30 seconds after the ignition was turned off. Because no fuel- or air-flow measurements were made under conditions of occasional afterfiring, the beginning of afterfiring is not noted on the curves but concurrent afterfiring is noted by tails on the knock-limited points. In obtaining the data for triptane at a compression ratio of 5.0, the power level was so high and afterfiring and preignition were so prevalent that the data had to be taken within 15 seconds after the ignition was turned on. For this reason, the data for the triptane curve at a compression ratio of 5.0 may be in error. (The maximum error is estimated to be about 50 lb/sq in. indicated mean effective pressure.)

Presentation of Data

The knock-limited-performance data for the nine fuels is presented in figures 1 to 9. (Because of the wide range of power it was necessary to use several ordinate scales for these plots.) The correlation of the effects of compression ratio and inlet-air temperature on the knock-limited performance of the nine fuels was made by plotting the knock-limited compression-air density against the compression-air temperature (figs. 10 to 18). These compression densities and temperatures were calculated from the formulas set up in reference 2. The density factor is calculated by dividing the air flow to the cylinder per intake cycle by the clearance volume. In terms of the cylinder-displacement volume and the compression ratio, the knock-limited compression-air density is

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

where

ρ compression-air density, pounds per cubic inch

A intake-air flow, pounds per minute

n intake cycles per minute

r engine compression ratio

v_d engine displacement volume, cubic inches

The temperature factor is calculated by the adiabatic compression formula

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

where

T compression-air temperature, °R

T_o intake-air temperature, °R

γ ratio of specific heats of charge air at constant volume and constant pressure (As in reference 1, a value of 1.41 was used for γ.)

In figures 10 to 18 knock-limited data obtained in tests of variable inlet-air temperature are shown by the plain data points; the tailed data points denote variable compression-ratio data. The check of the correlation method was determined by how well the plain and tailed points fell along a single curve at any given fuel-air ratio. (The test at a compression ratio of 8.0 and an inlet-air temperature of 250° F is common to both sets of data.) Curves are presented for fuel-air ratios of 0.06, 0.07, 0.08, 0.09, 0.10, and 0.11. In the case of toluene, when preignition limited the extent of the knock-limited data, other fuel-air ratios were chosen to check the correlation. On certain other correlation plots some of the points are lacking because of incomplete data due to preignition.

TEST RESULTS AND DISCUSSION

Although this project was set up primarily to check further the correlation presented in reference 2 (figs. 10 to 18), other

interesting features appear in the knock-limited-performance data presented in figures 1 to 9. In some cases (of which the triptane data is a notable example), as the engine conditions become milder, the fuel-air ratio of peak knock-limited power shifted toward the stoichiometric. This trend occurred when the severity of engine conditions was altered by variations in either the compression ratio or the inlet-air temperature. No corresponding shift in the fuel-air ratio of minimum power was observed.

As an indication of the possible trends in future reciprocating-engine designs, broad ranges of knock-limited-power outputs are permissible simply by choosing the various ranges of engine severity. In the case of triptane in these tests, an eightfold range of knock-limited power outputs was obtained. All the fuels tested also showed relatively low knock-limited power outputs at lean fuel-air ratios and extreme engine conditions.

Greater changes in knock-limited indicated mean effective pressures were accomplished by variations of the compression ratio through the practical limits than by changes in the inlet-air temperature (figs. 1 to 9). Whereas a decrease in compression ratio is usually accompanied by an increase in the fuel consumption, the question of which method would be the better for increasing the knock limits of an aircraft engine depends upon the practicability of using intercoolers and aftercoolers.

In connection with fuel-rating experiments, the data show that no generalized scale such as octane number can be applied even to members of a given class of hydrocarbons when broad ranges of engine severity are encountered. For example, under mild conditions the performance of triptane was approximately twice as good as that of S reference fuel; whereas at lean fuel-air ratios and severe conditions, S reference fuel gave better performance than all the other fuels tested, including triptane.

As indicated by the inlet-air-temperature curve of 150° F at fuel-air ratios above about 0.084 (fig. 8), increases of knock-limited power may not always accompany decreases of inlet-air temperature. This effect is also reflected in the positive slopes of the curves of compression density against compression temperature in figure 17. Knock-limited data are lacking, because of preignition, for triptane at a compression ratio of 8.0 and an inlet-air temperature of 100° and 150° F, except for three points at an inlet-air temperature of 150° F. The dotted curve was calculated from the curves of compression density plotted against compression temperature presented in figure 17 by the use of the identity

$$\frac{A}{nv_d} \cong \frac{imep \times isfc}{(F/A) \times 2.376 \times 10^7}$$

where F/A is the fuel-air ratio. This calculation illustrates one application of the correlation.

As the severity of engine conditions was lessened for the toluene tests, the knock-limited performance curves became steeper until, at a compression ratio of 6.0 and an inlet-air temperature of 250° F, the operator could not determine knock anywhere below an indicated mean effective pressure of 460 pounds per square inch, when preignition halted further testing. A check at even milder conditions also gave preignition before knock. Similar results were experienced at a compression ratio of 8.0 and an inlet-air temperature of 150° F. This result was expected on the basis of the curve of compression density plotted against compression temperature common to both sets of data (fig. 18). (Because of the absence of knock within the permissible test range at the milder engine conditions, the compression-density surface of fig. 22 was extrapolated.)

In the jargon of fuel test engineers, the term "temperature sensitivity" is applied to explain a multitude of effects. No universal and clear-cut definition of temperature sensitivity, however, exists. The curves of knock-limited compression density plotted against compression temperature presented herein suggest that the slope of the curve of compression density plotted against compression temperature would give a precise measurement of temperature sensitivity. Whereas this definition is less general than the all-inclusive statement of the jargon, it is more general than temperature sensitivities that are often calculated from knock-limited indicated mean effective pressure data in that it includes the effects of compression ratio as well as inlet-air temperature. On a CFR engine operating at constant speed, fuel-air ratio, and compression ratio, where the correlation has been shown to be valid, this definition would be proportional to the rate of change of knock-limited indicated mean effective pressure with inlet-air temperature. As the effects of other engine variables such as spark advance and coolant temperature are included in the correlation, the definition would become increasingly general.

As judged by the slopes of the curves of knock-limited compression density plotted against compression temperature presented in figures 10 to 18, the temperature sensitivities of S reference fuel, 28-R fuel, an aviation alkylate, and diisopropyl were almost independent of engine conditions; the temperature sensitivity of triptane decreased as the severity of the engine conditions decreased, whereas

the temperature sensitivities of cyclopentane, cyclohexane, triptene, and toluene increased as the severity of the engine conditions decreased.

If the hypothesis is correct that the knock limit of a fuel can be represented in terms of compression density, compression temperature, and fuel-air ratio, then three-dimensional plots containing these variables should give comprehensive indications of the absolute knock-limited performance of fuels. Such plots have been prepared from figures 10 to 18 for the nine fuel components studied and are presented in figures 19 to 22. For comparison purposes, S reference fuel is repeated on each of the plots with two other fuels. On these charts visible boundary lines and visible intersections of the three knock-limited performance surfaces are drawn as solid lines. All invisible lines and intersections are shown as dotted lines. The same color has been used throughout the four figures for S reference fuel but the other two colors have been used to signify various fuels on these figures. The three-dimensional plots give a rapid and adequate summary of the knock-limited performance of the nine fuels tested in this program.

SUMMARY OF RESULTS

The results of knock tests of nine fuels in a CFR engine at 11 sets of engine conditions involving variations of inlet-air temperature and compression ratio are summarized as follows:

1. A good correlation of the effects of compression ratio and inlet-air temperature upon the knock-limited performance exists for the nine fuels, comprising isolated members of four classes of hydrocarbons: aromatics, paraffins, cycloparaffins, and olefins.

2. For some of the fuels tested (of which triptane was a notable example) the fuel-air ratio of peak knock-limited power decreased as the severity of engine conditions decreased; for a given fuel, the fuel-air ratio of minimum knock-limited power remained nearly constant regardless of engine severity.

3. As judged by the slopes of the curves of knock-limited compression density plotted against compression temperature, the temperature sensitivities of S reference fuel, 28-R fuel, an aviation alkylate, and diisopropyl were almost independent of engine conditions. The temperature sensitivity of triptane decreased as the severity of the engine conditions decreased; whereas the temperature sensitivities of cyclohexane, cyclopentane, triptene, and toluene increased as the severity of engine conditions decreased.

4. The data show that no generalized number such as octane number can be applied even to the members of a given class of hydrocarbons when broad ranges of engine severity are encountered. As an example, at mild conditions triptane gave a higher knock limited performance than the other paraffins tested; whereas at severe conditions and lean fuel-air ratios, S reference fuel gave a better performance than all of the fuels tested.

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3. Bellman, Donald R., and Evvard, John C.: Knock-Limited Performance of Several Internal Coolants. NACA ACR No. 4B08, 1944.

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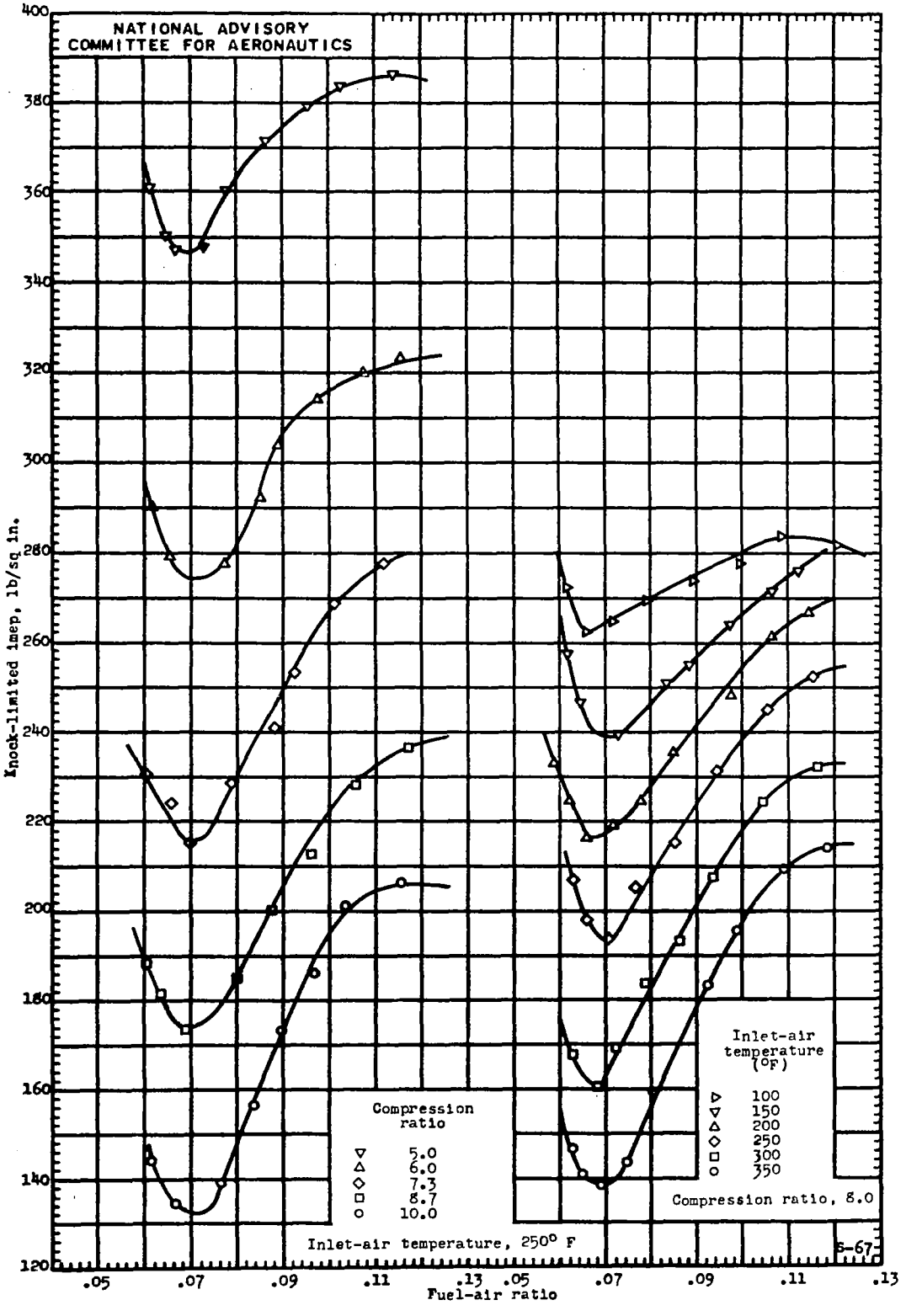
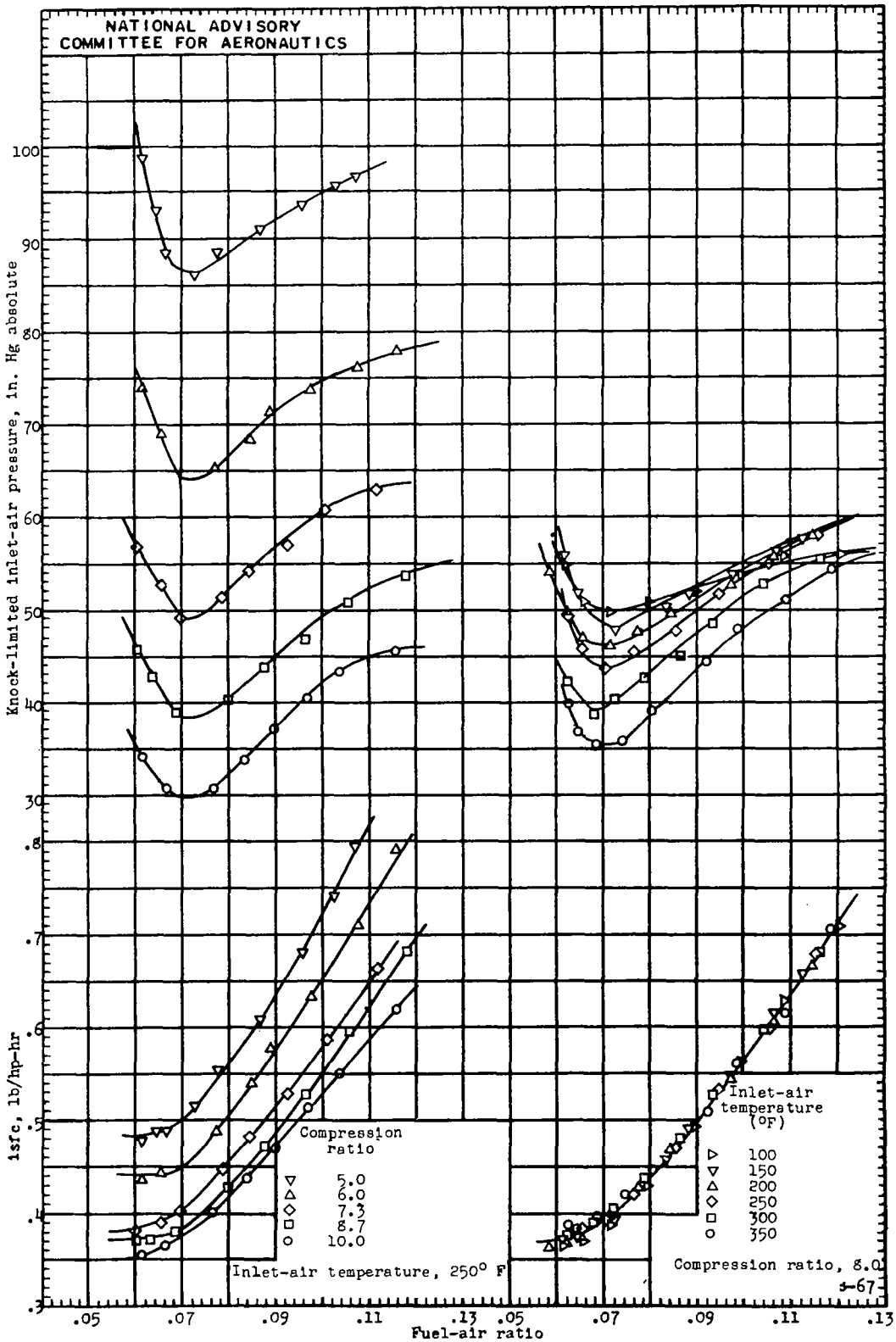


Figure 1. - Effect of compression ratio and inlet-air temperature on knock-limited performance of S reference fuel plus 4 ml TEL per gallon in CFR engine.



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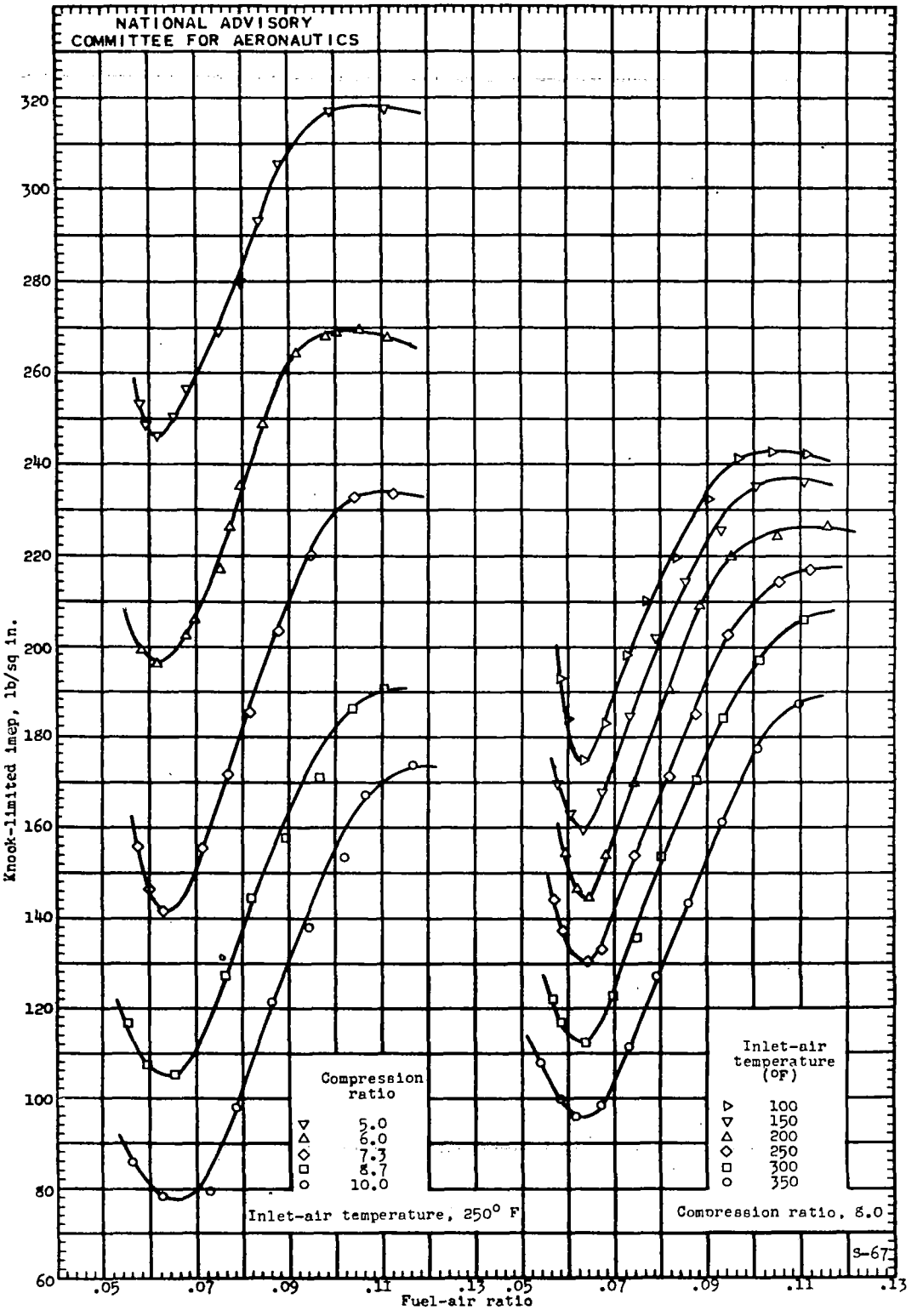
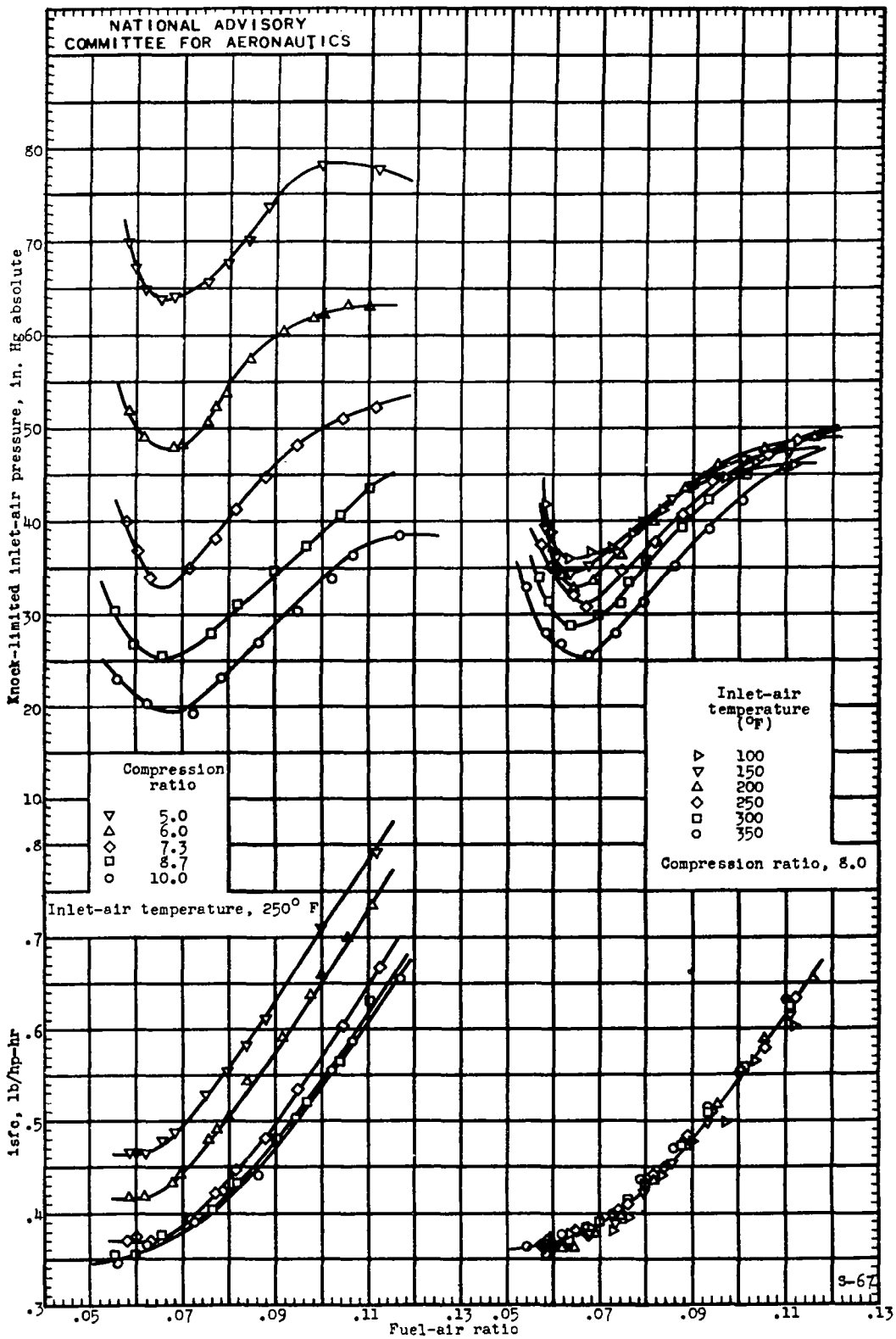


Figure 2. - Effect of compression ratio and inlet-air temperature on knock-limited performance of 28-R fuel in CFR engine.



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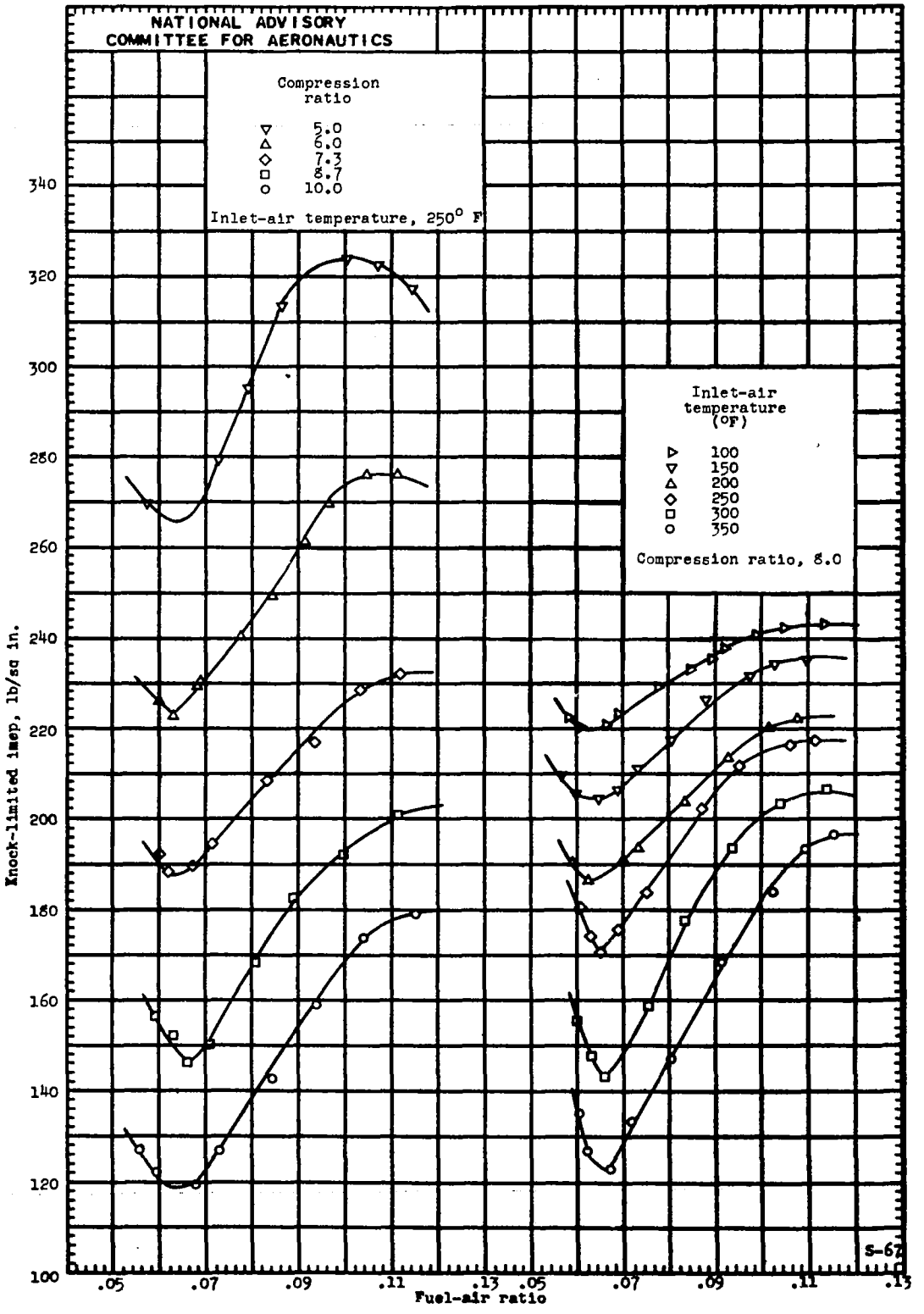
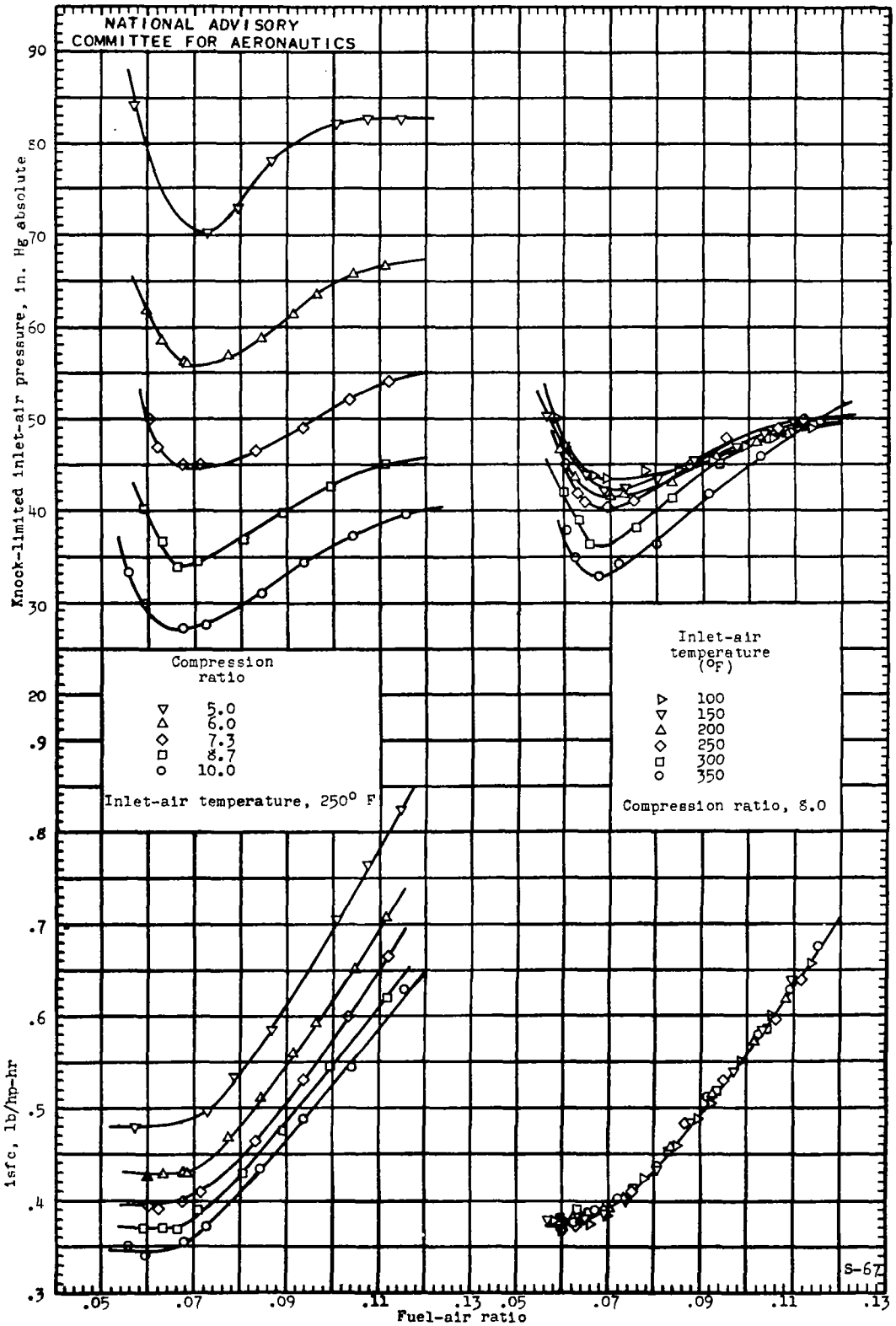


Figure 3. - Effect of compression ratio and inlet-air temperature on knock-limited performance of aviation alkylate plus 4 ml TEL per gallon in CFR engine.



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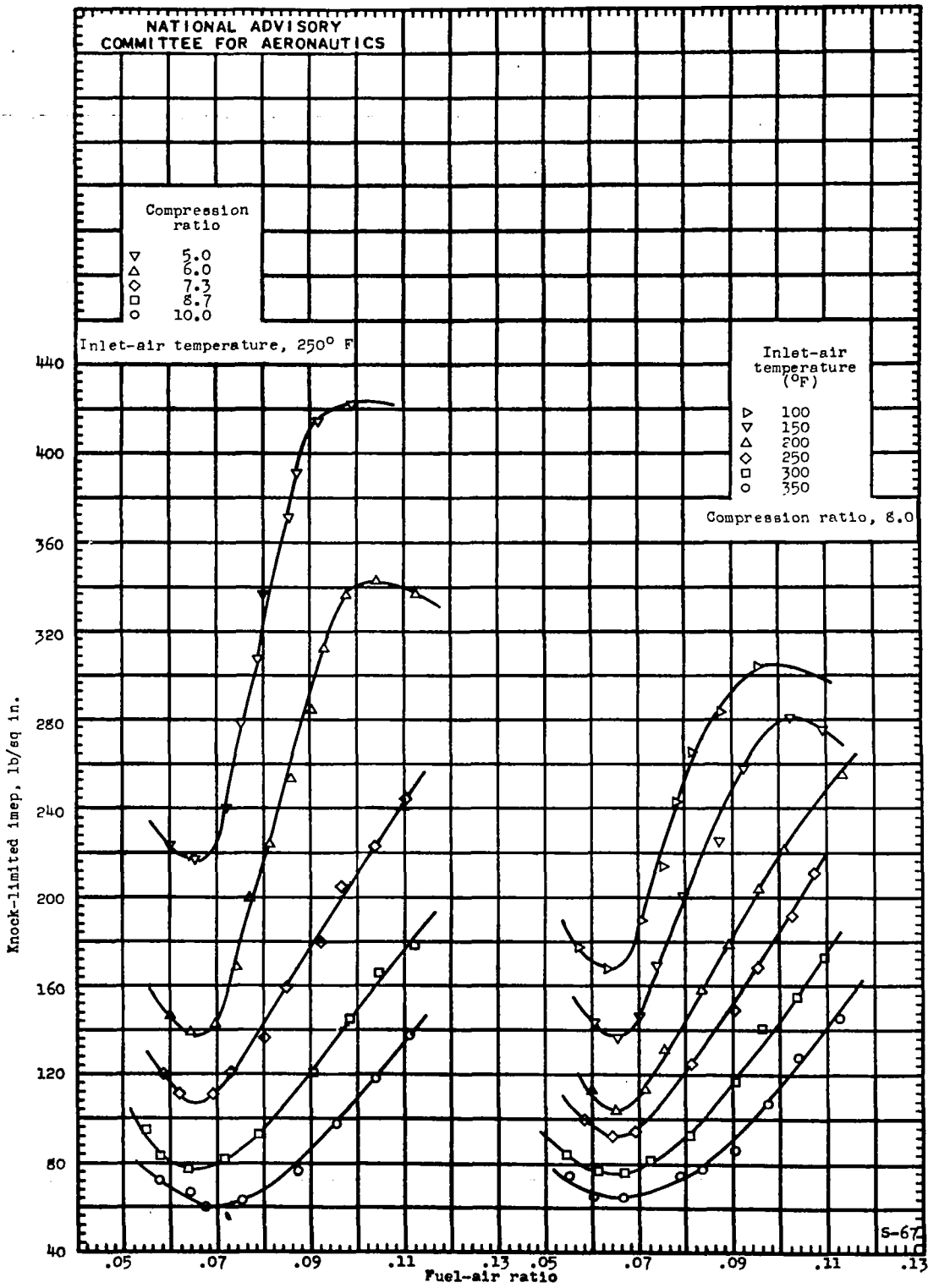
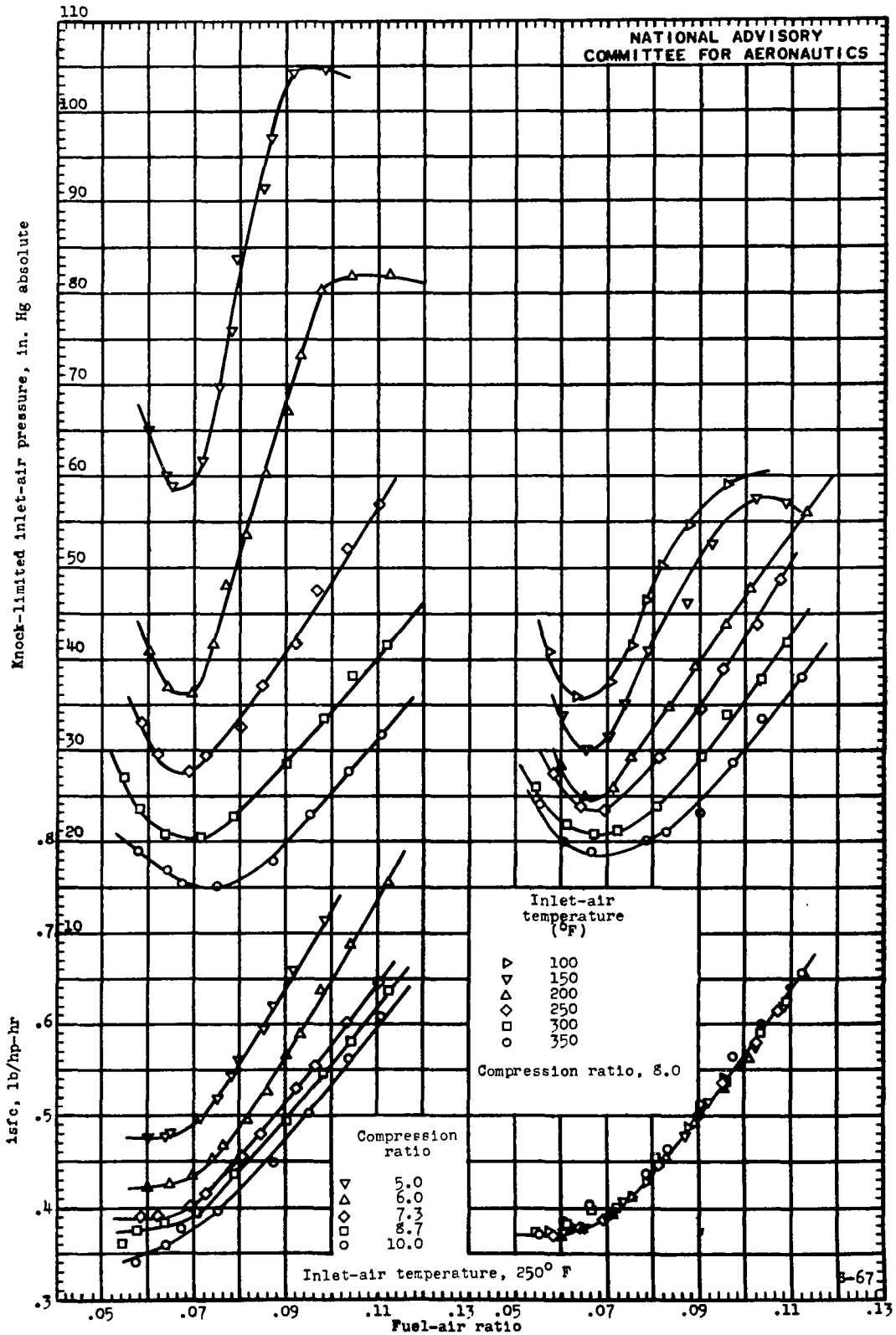


Figure 4. - Effect of compression ratio and inlet-air temperature on knock-limited performance of cyclohexane plus 4 ml TEL per gallon in CFR engine.



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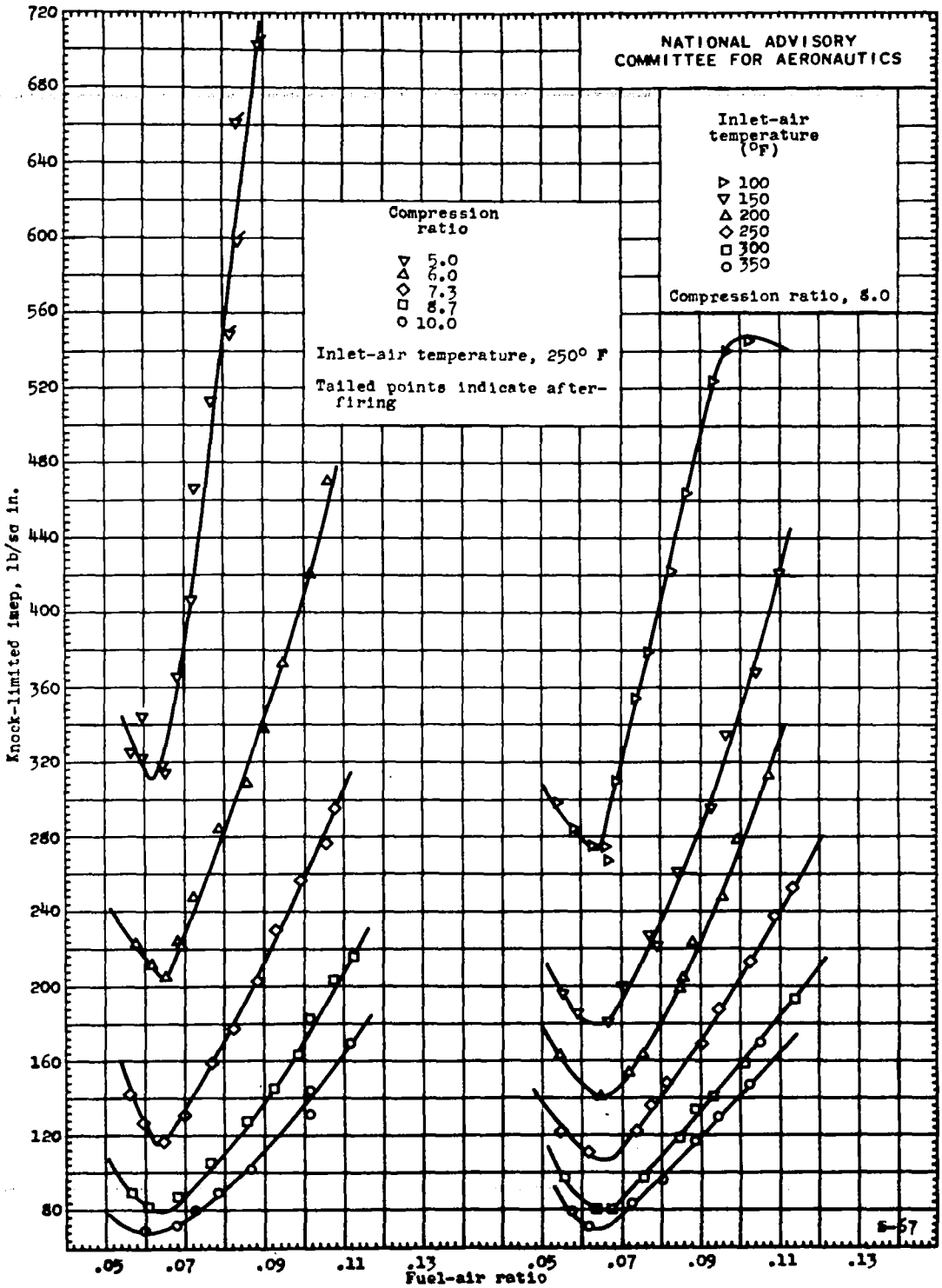
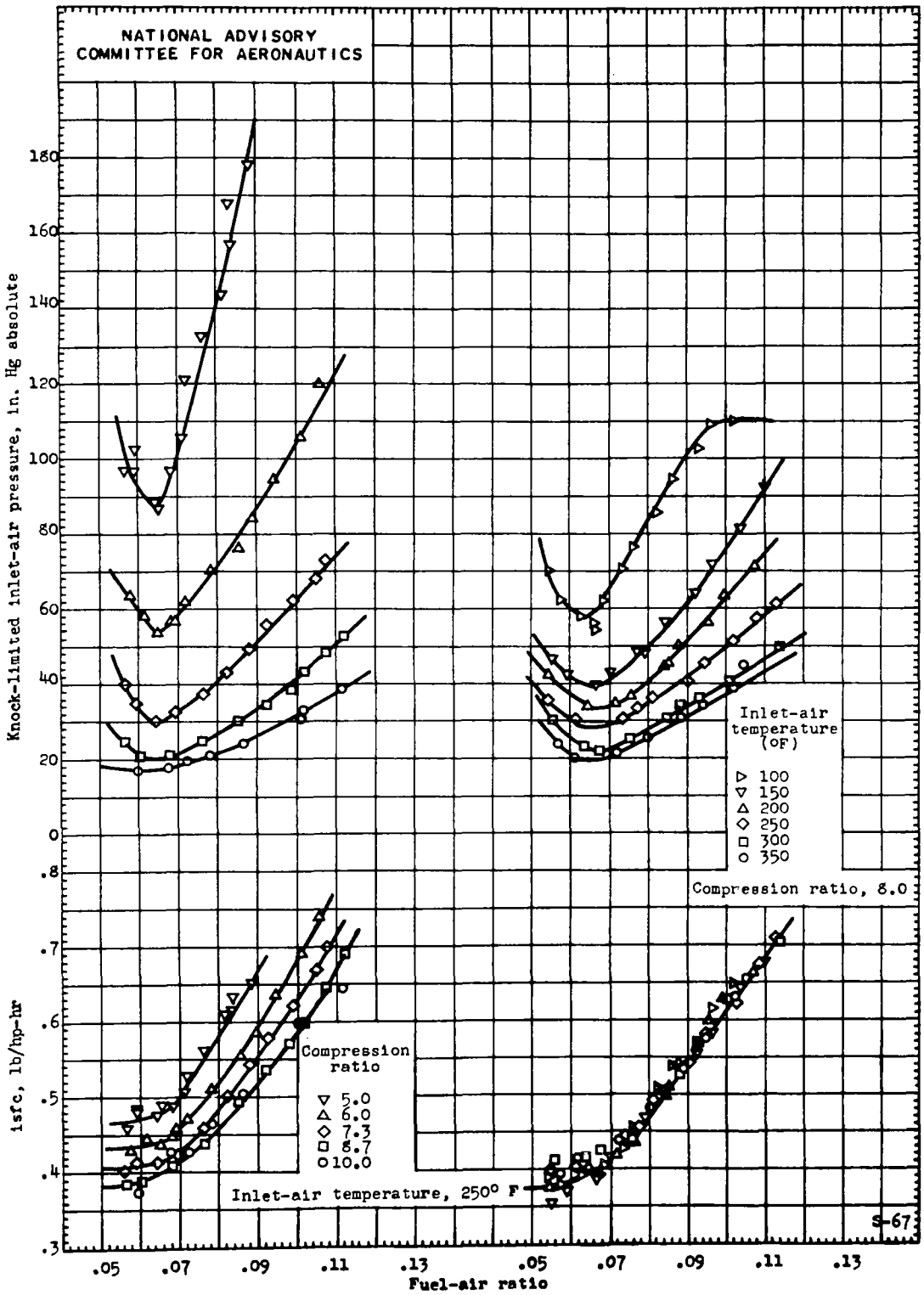


Figure 5. - Effect of compression ratio and inlet-air temperature on knock-limited performance of cyclopentane plus 4 ml TEL per gallon in CFR engine.



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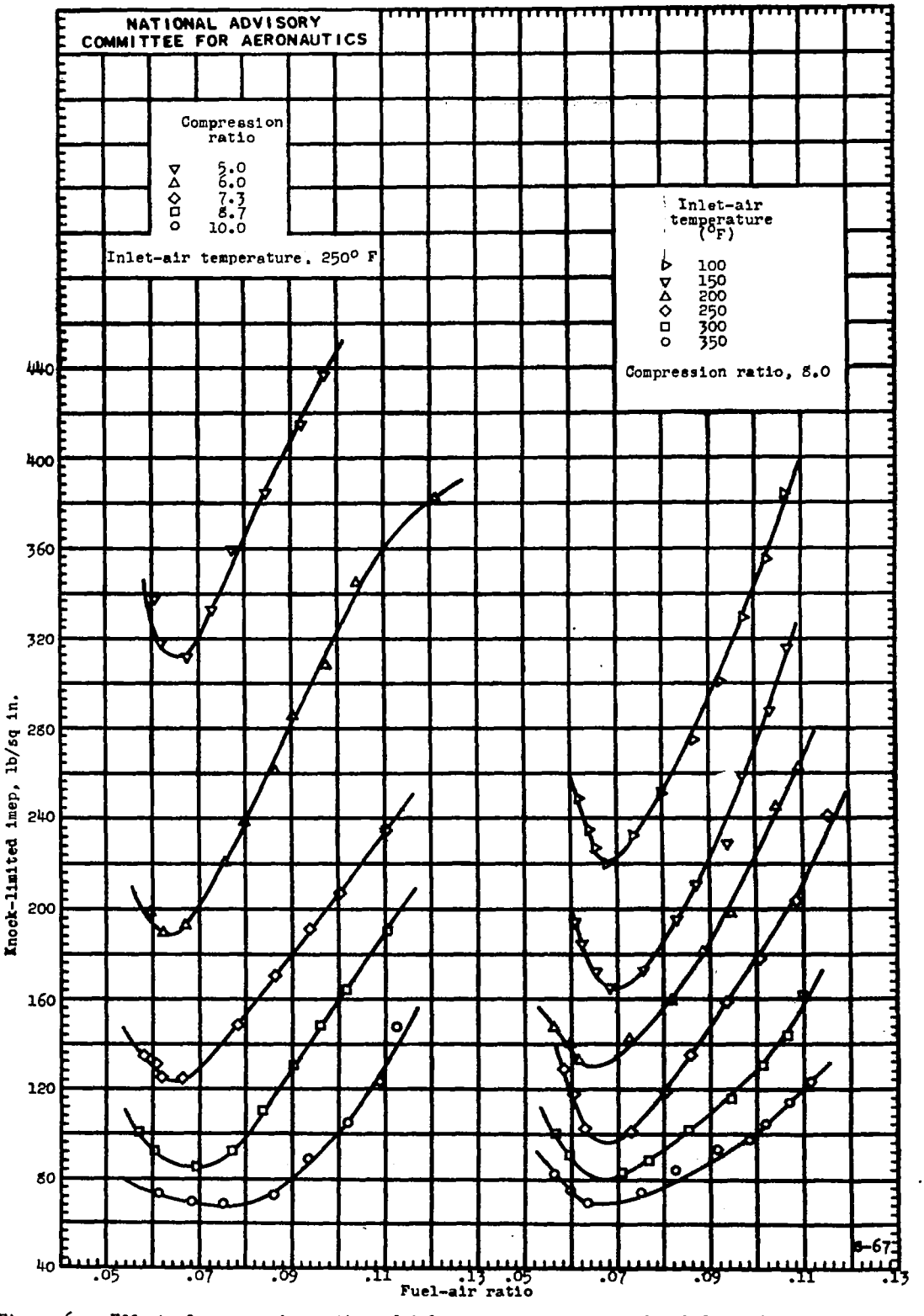
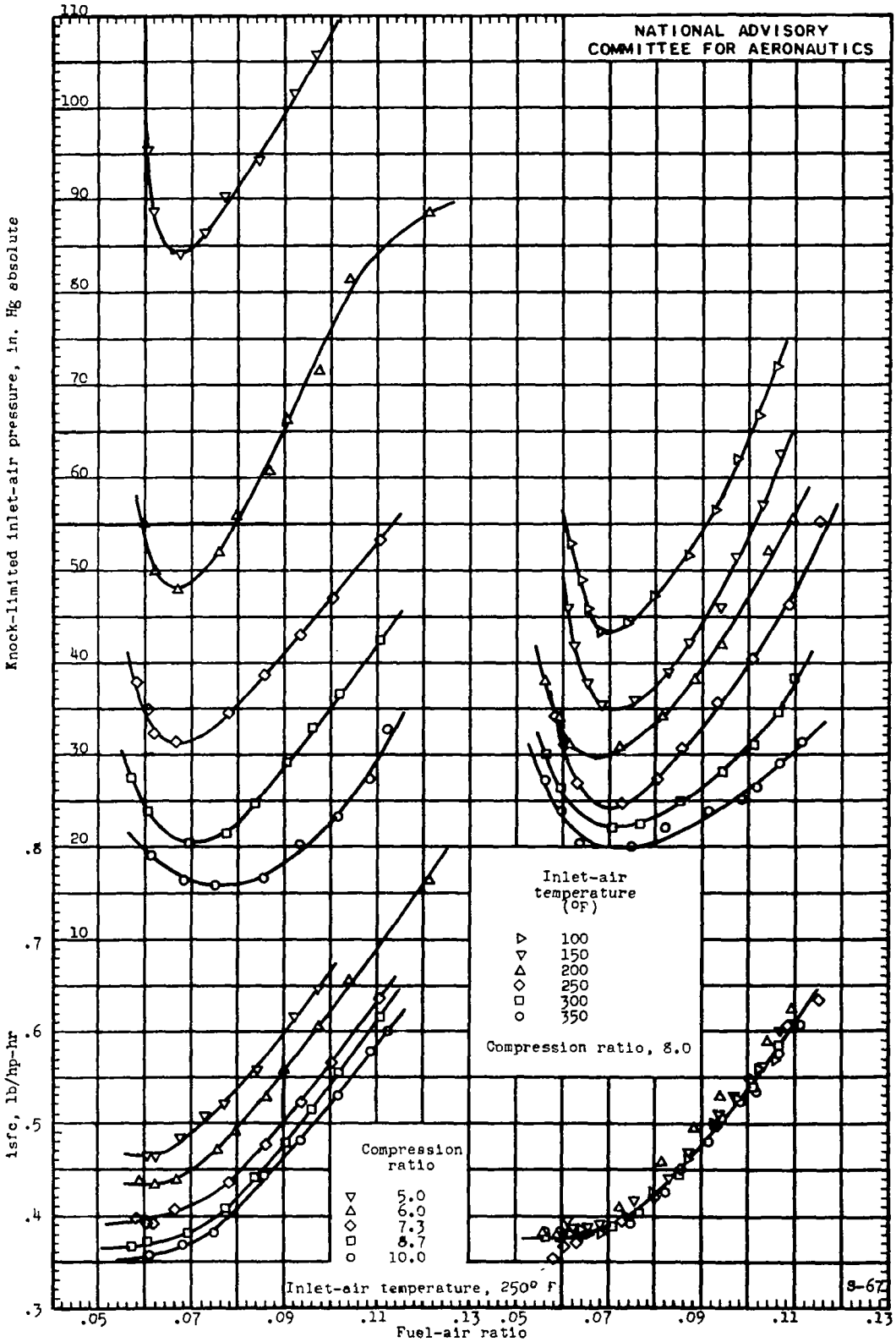


Figure 6. - Effect of compression ratio and inlet-air temperature on knock-limited performance of triptene plus 4 ml TEL per gallon in CFR engine.



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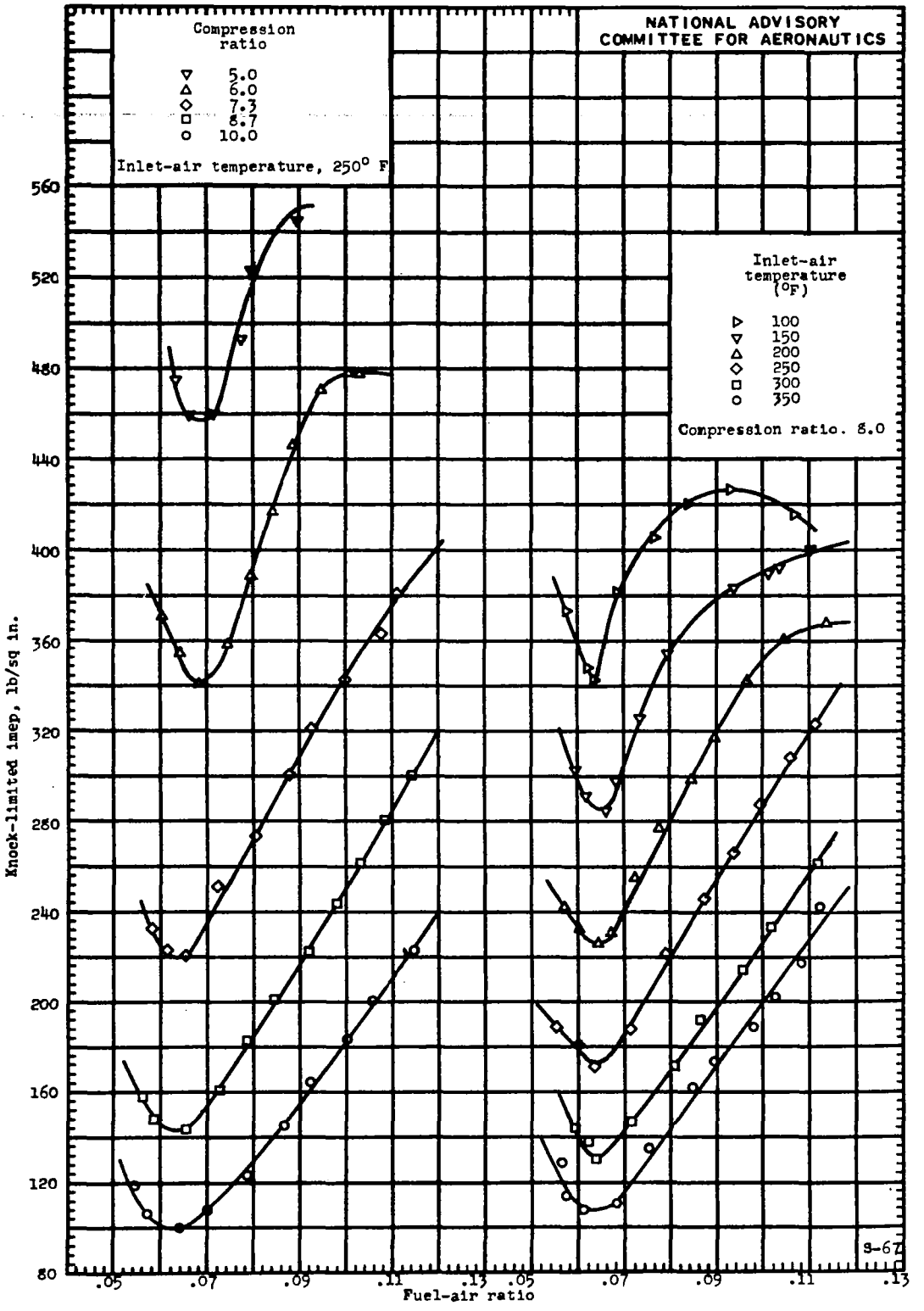
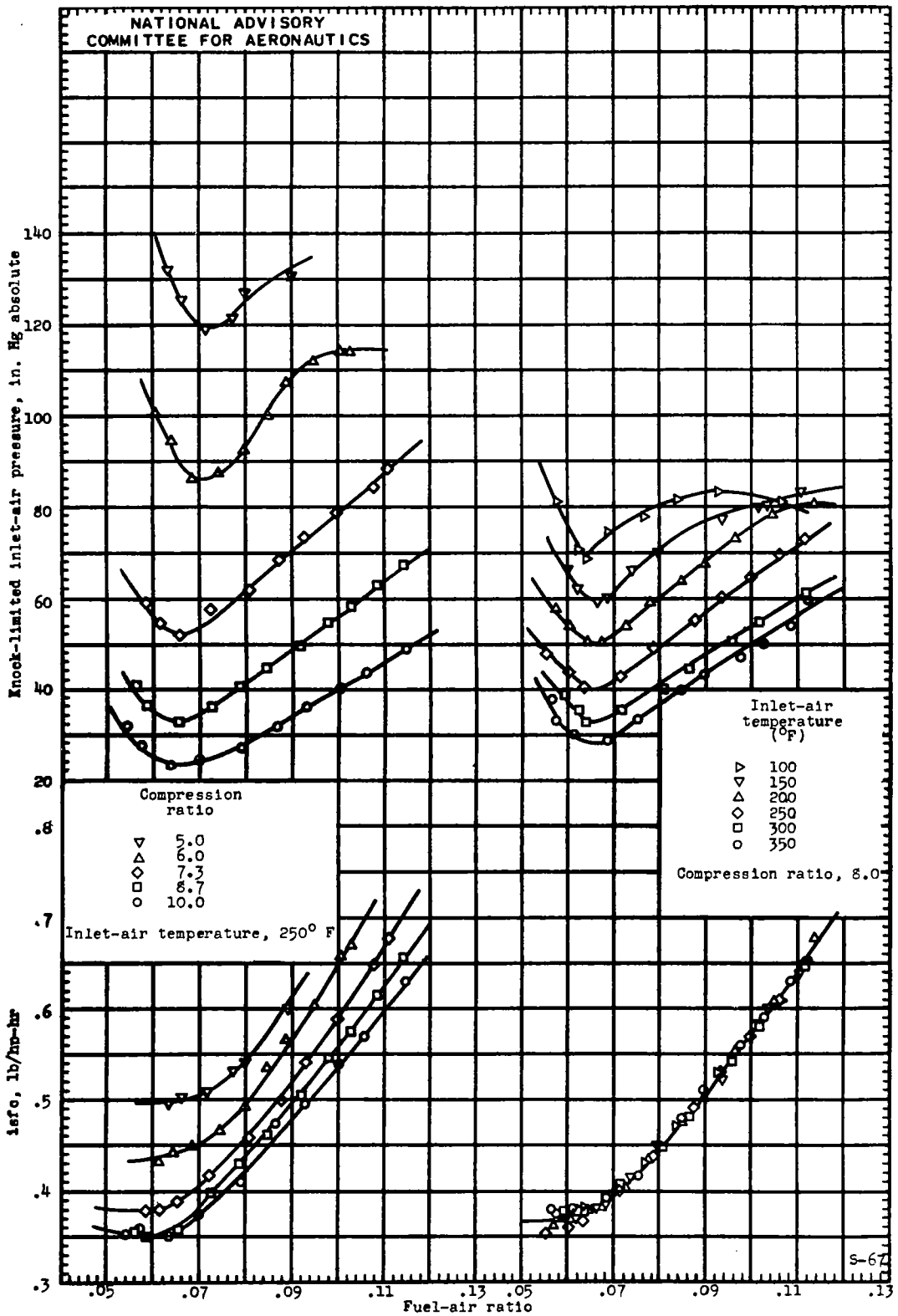


Figure 7. - Effect of compression ratio and inlet-air temperature on knock-limited performance of diisopropyl plus 4 ml TEL per gallon.



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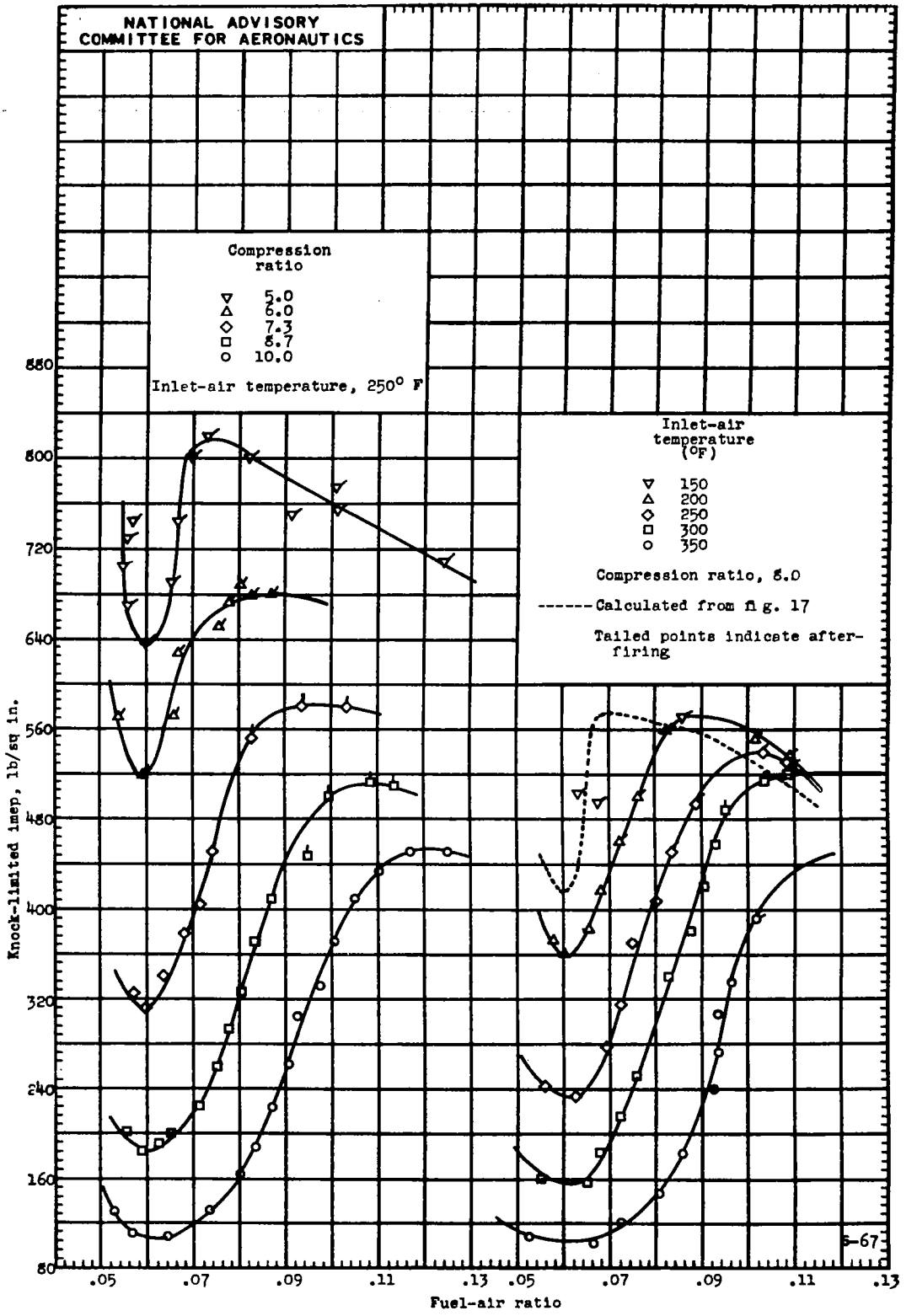
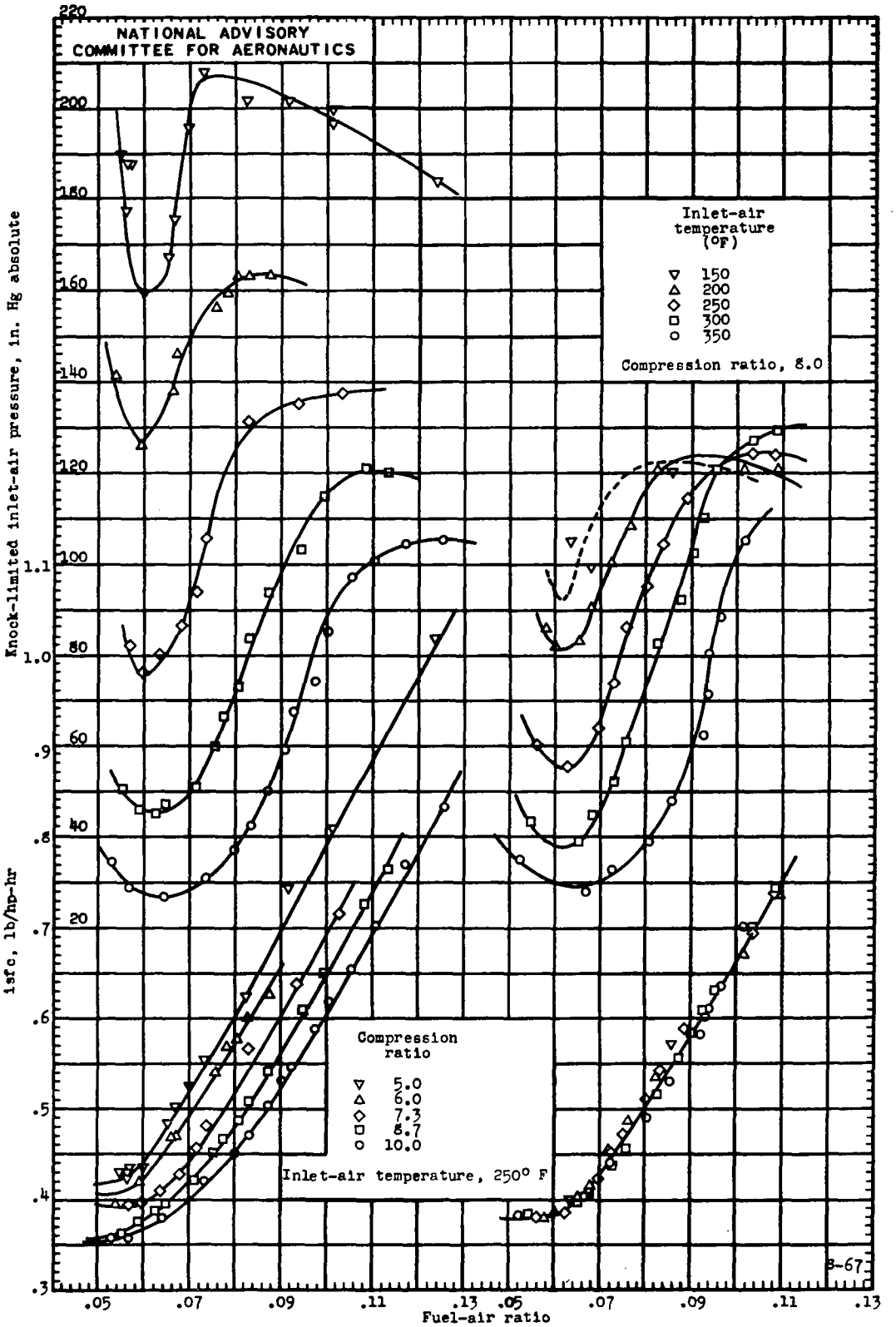


Figure 8. - Effect of compression ratio and inlet-air temperature on knock-limited performance of triptane plus 4 ml TEL per gallon in CFR engine.



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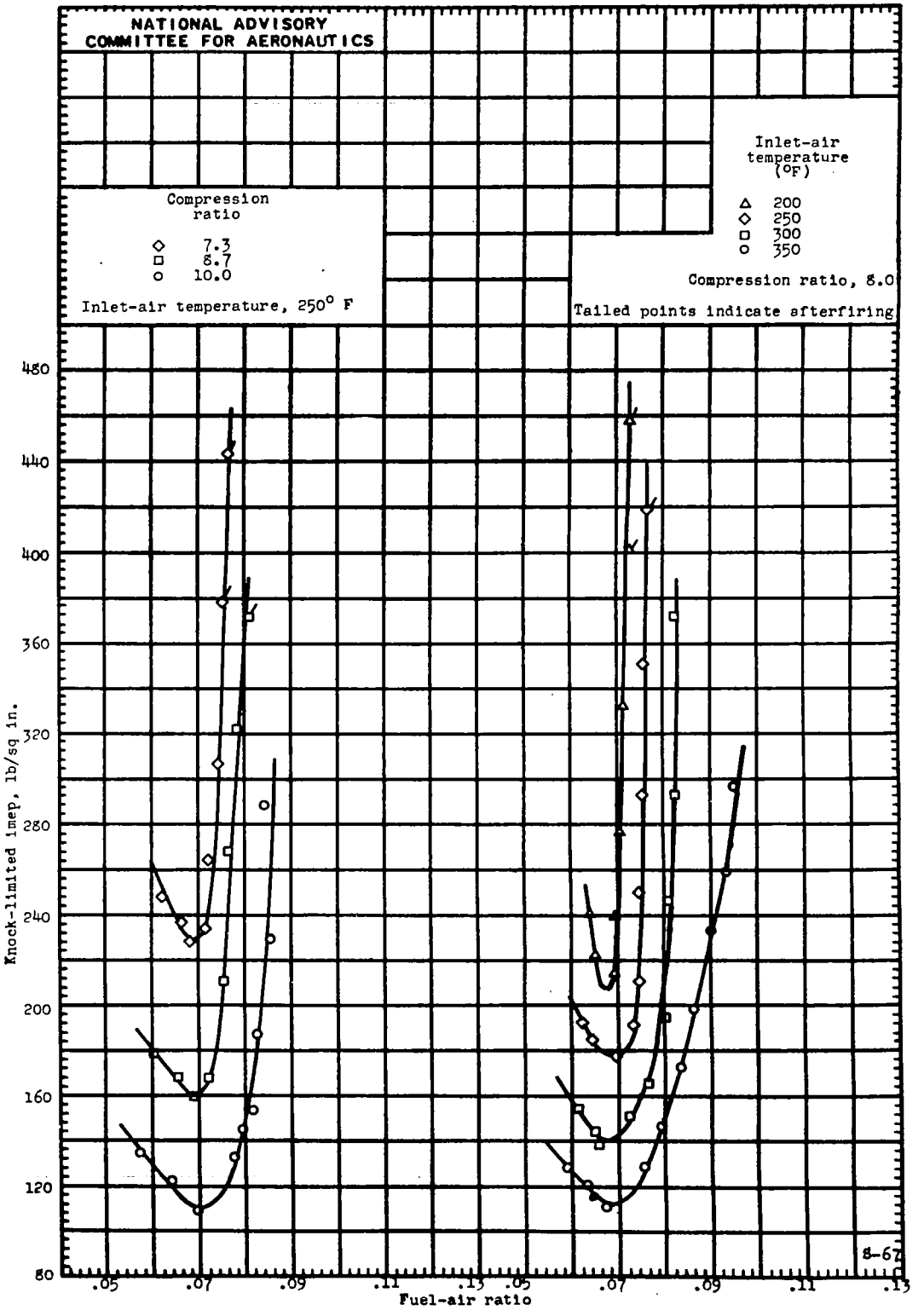
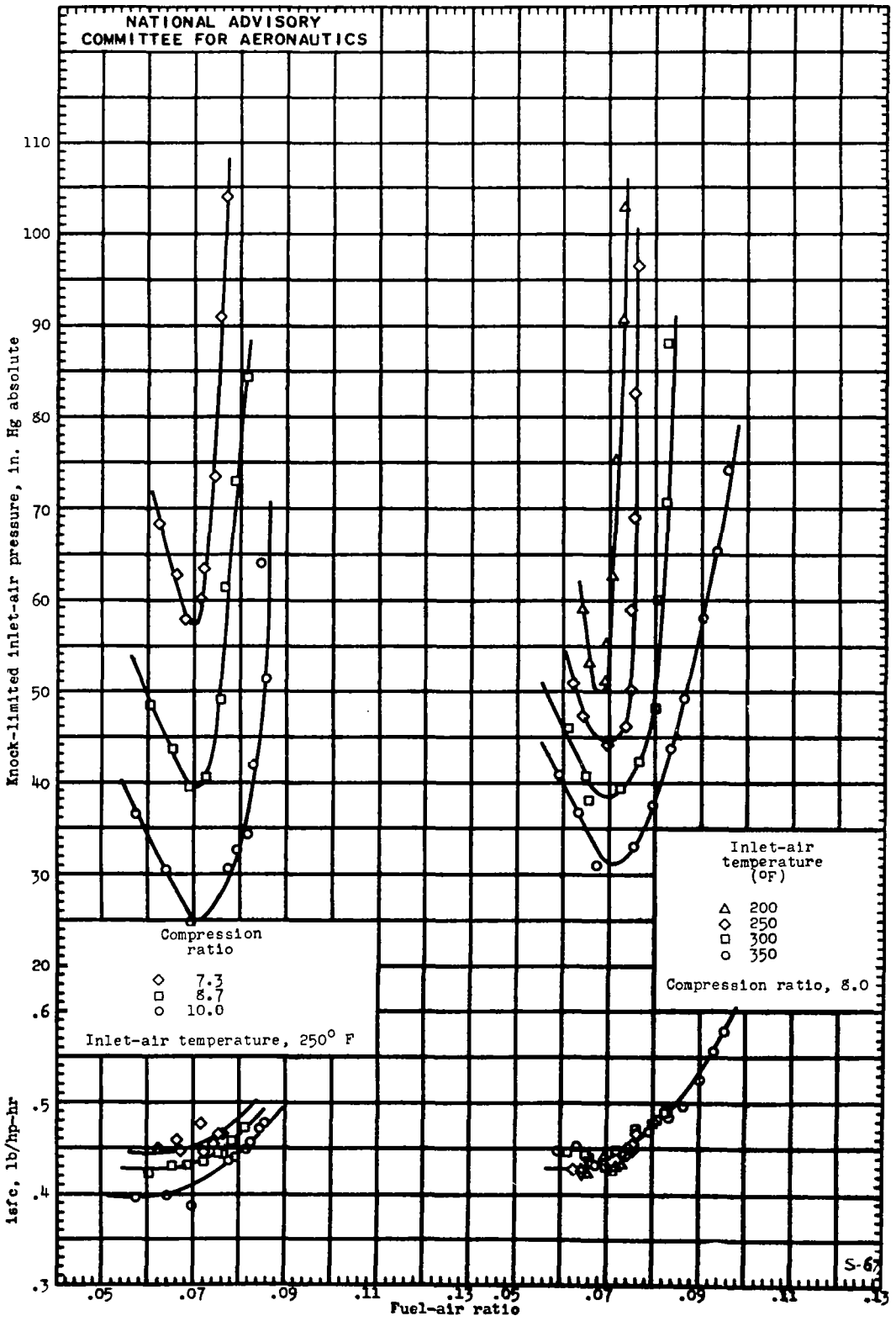


Figure 9. - Effect of compression ratio and inlet-air temperature on knock-limited performance of toluene plus 4 ml TEL per gallon in CFR engine.



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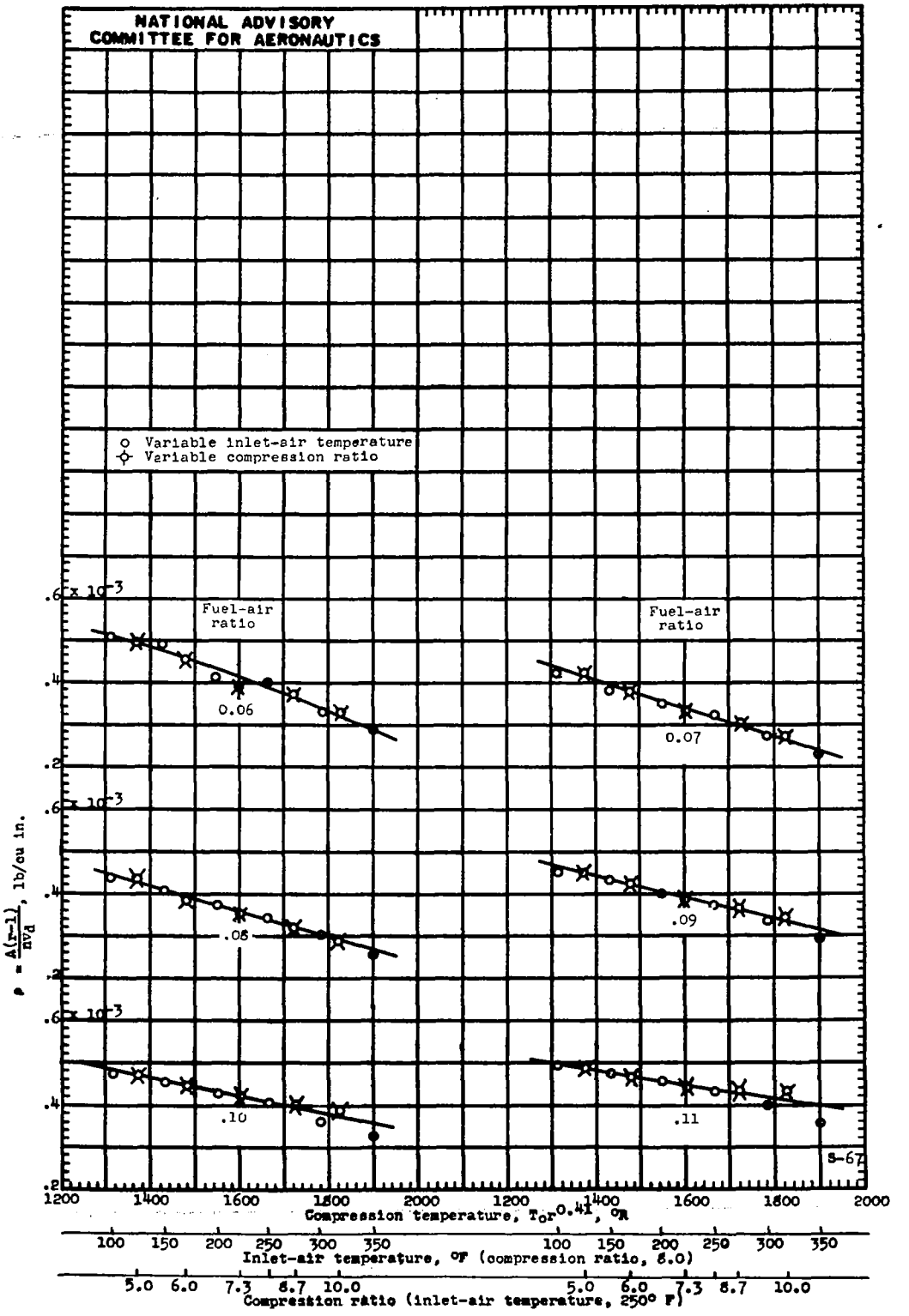

Figure 10. - Effect of compression temperature on knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for S reference fuel plus 4 ml TEL per gallon.

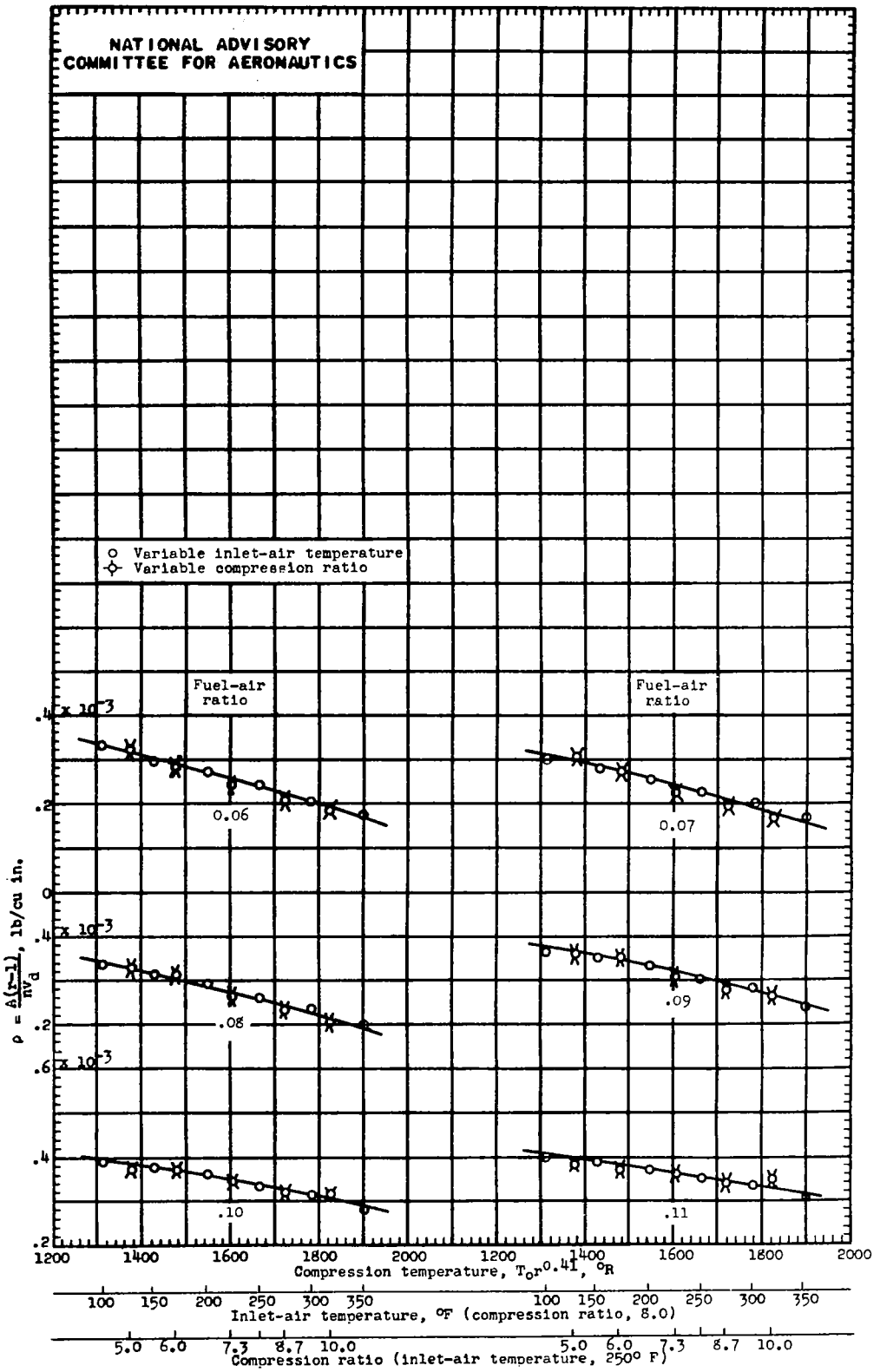

Figure 11. - Effect of compression temperature on knock-limited compression=air density $\frac{A(r-1)}{nv_d}$ for 28-R fuel.

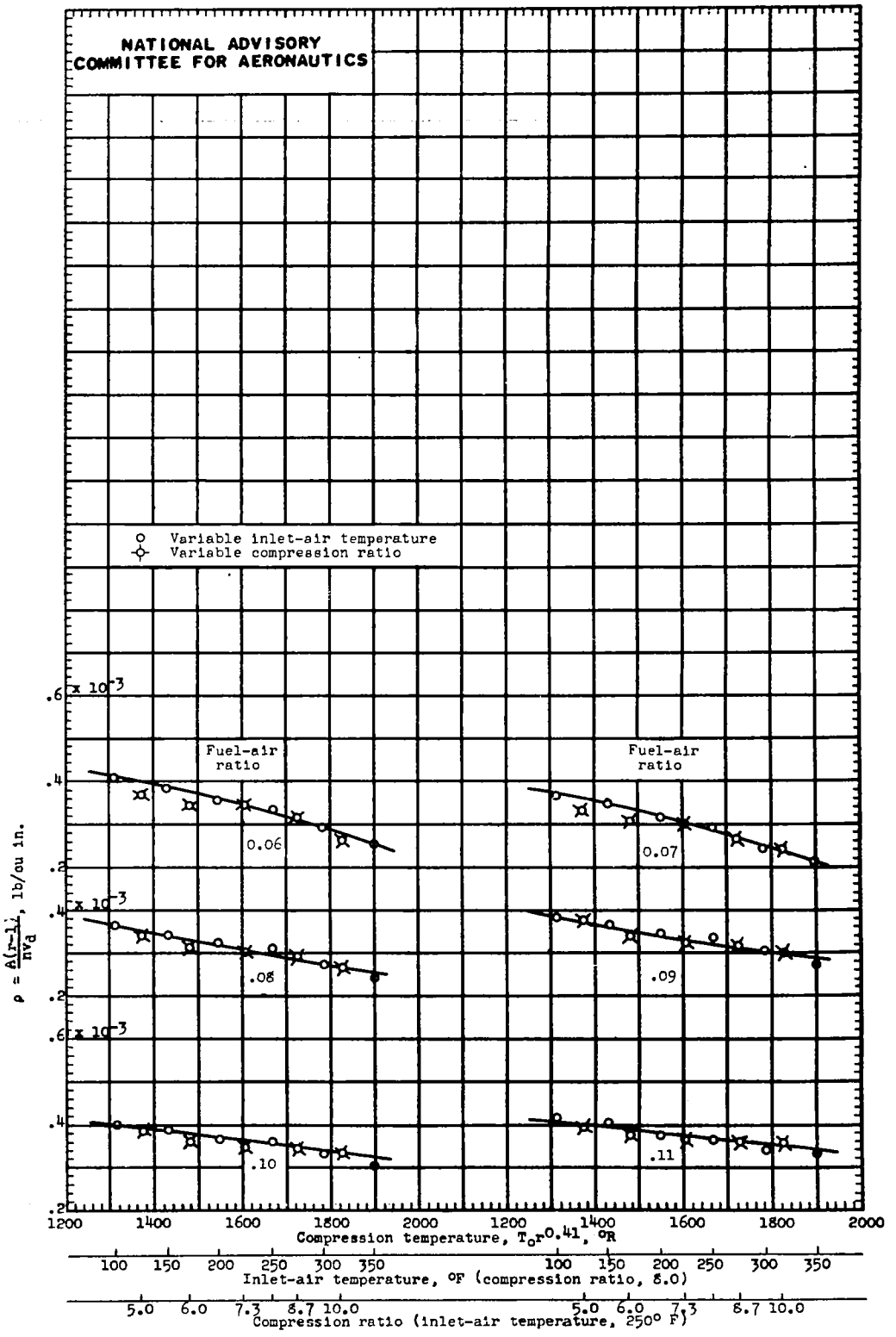

Figure 12. - Effect of compression temperature on knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for aviation alkylate plus 4 ml TEL per gallon.

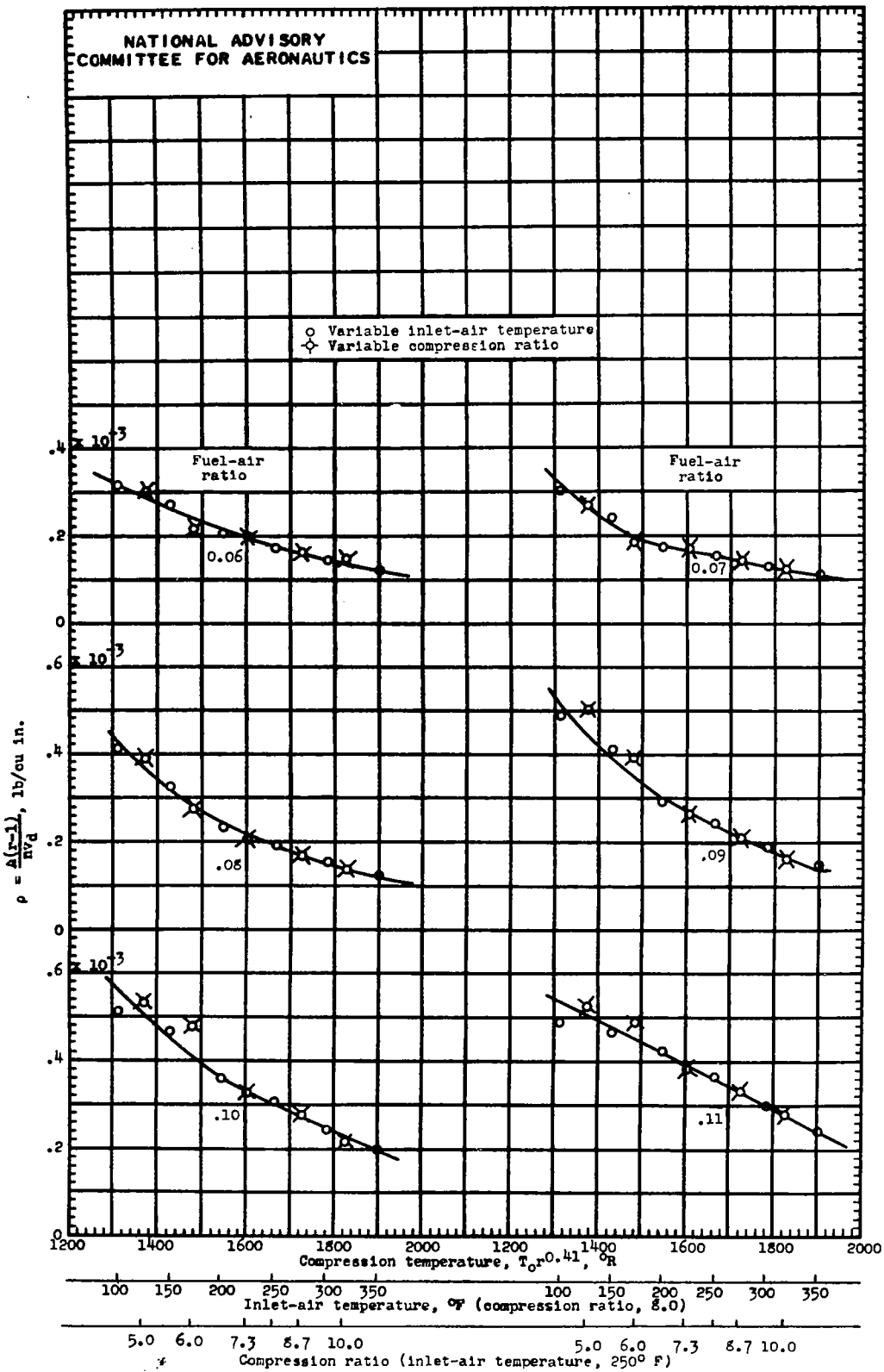

Figure 13. - Effect of compression temperature on knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for cyclohexane plus 4 ml TEL per gallon.

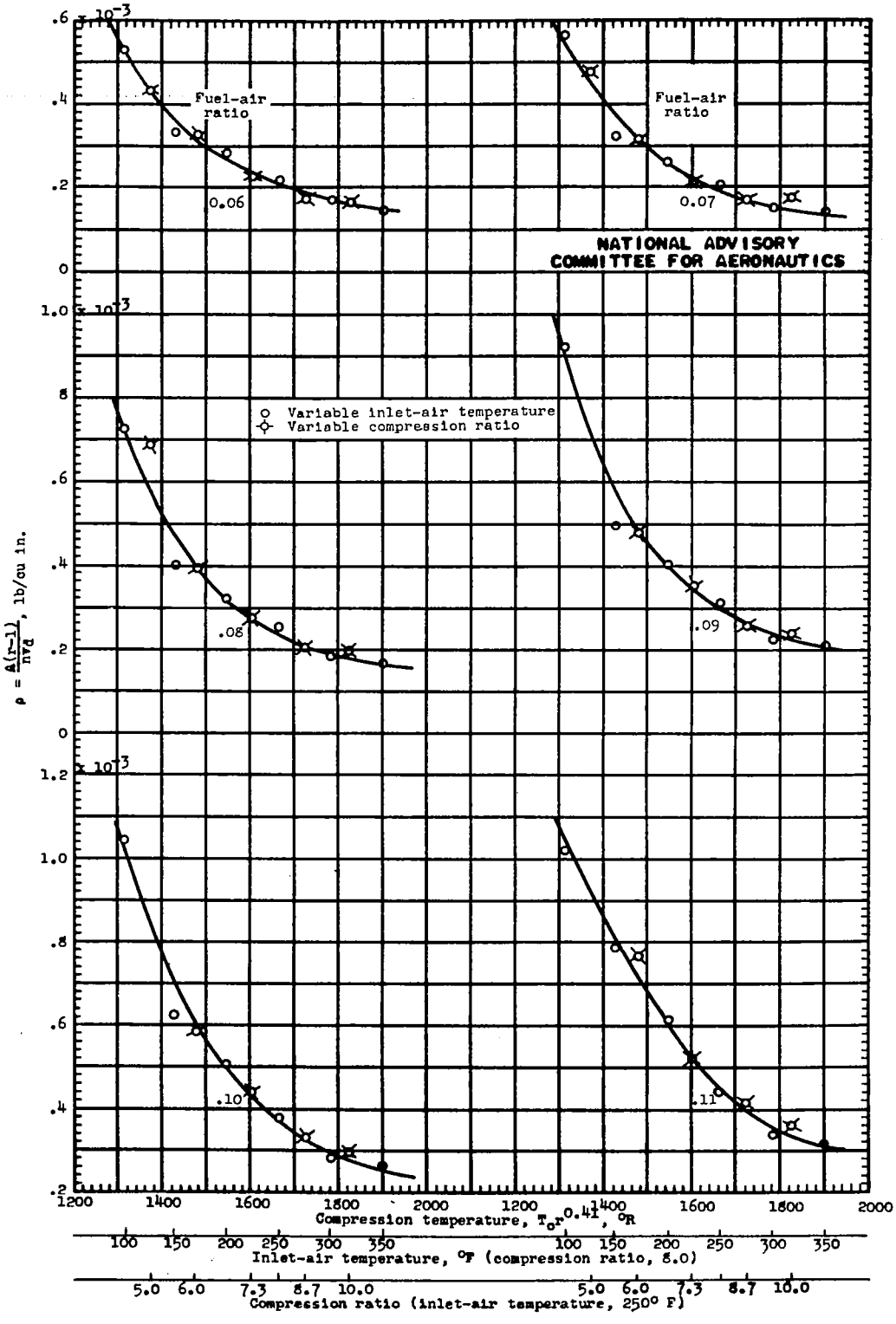

Figure 14. - Effect of compression temperature on the knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for cyclopentane plus 4 ml TEL per gallon.

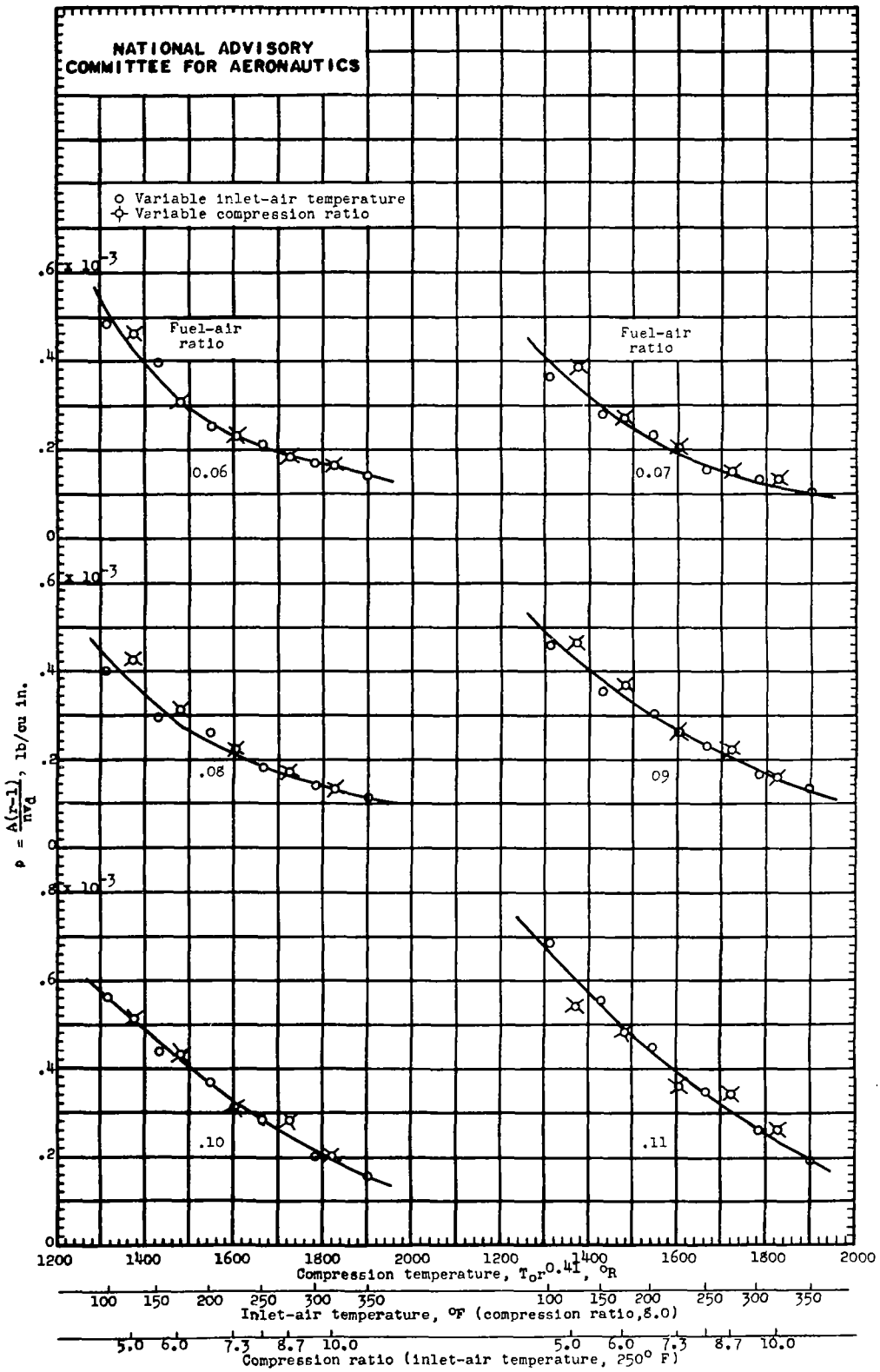

Figure 15. - Effect of compression temperature on knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for triptene plus 4 ml TEL per gallon.

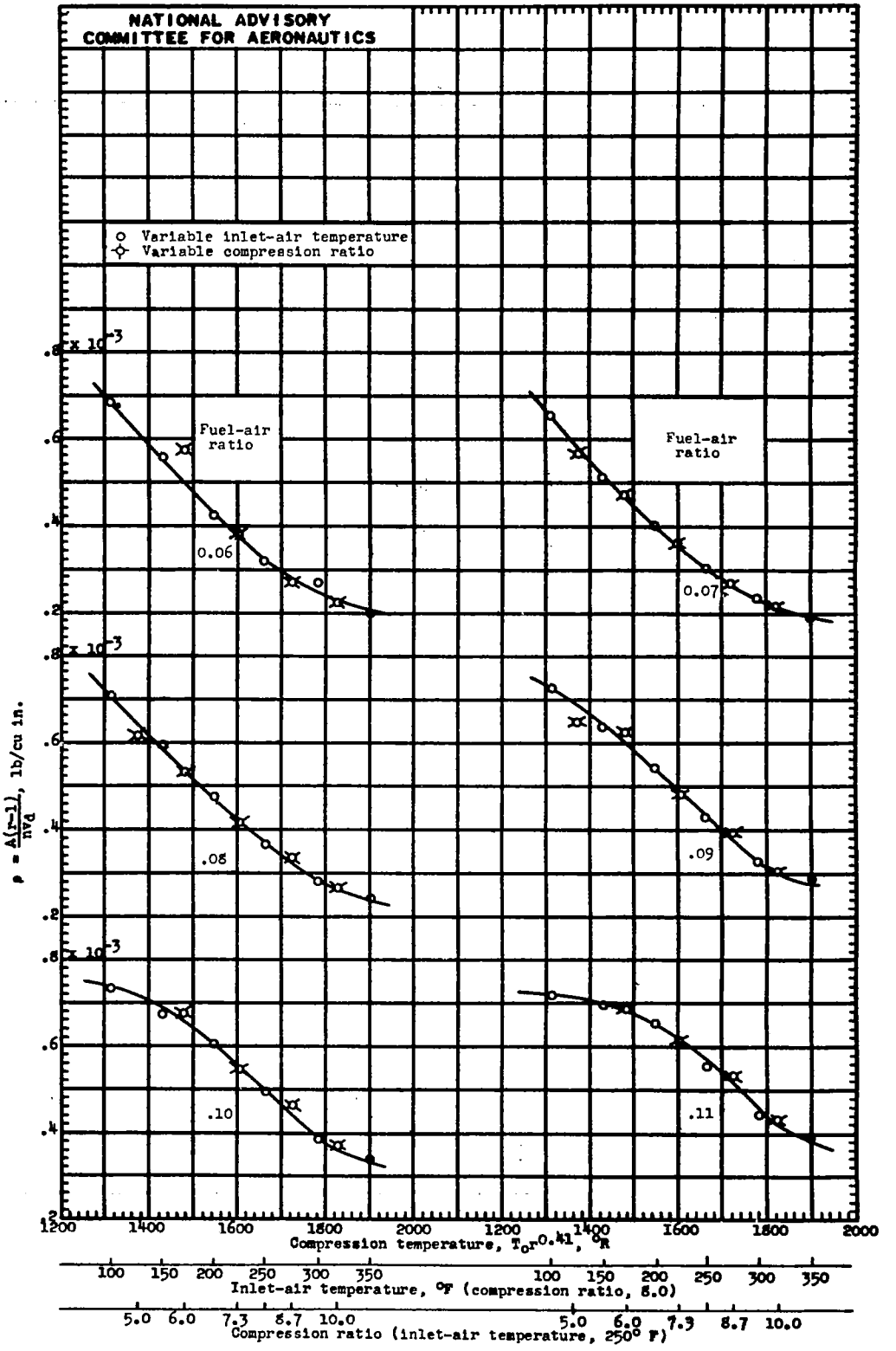

Figure 16. - Effect of compression temperature on knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for diisopropyl plus 4 ml TEL per gallon.

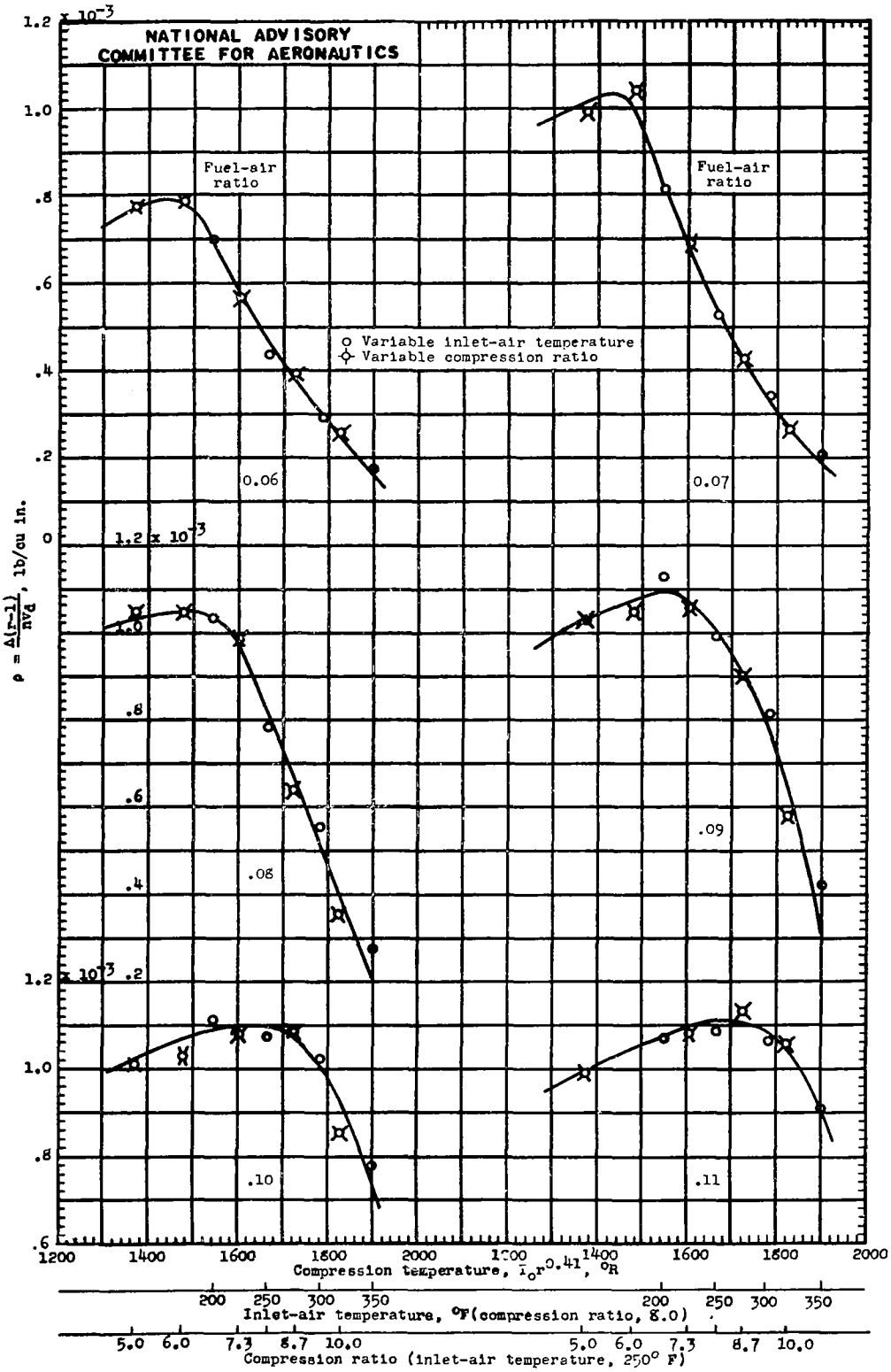

Figure 17. - Effect of compression temperature on knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for triptane plus 4 ml TEL per gallon.

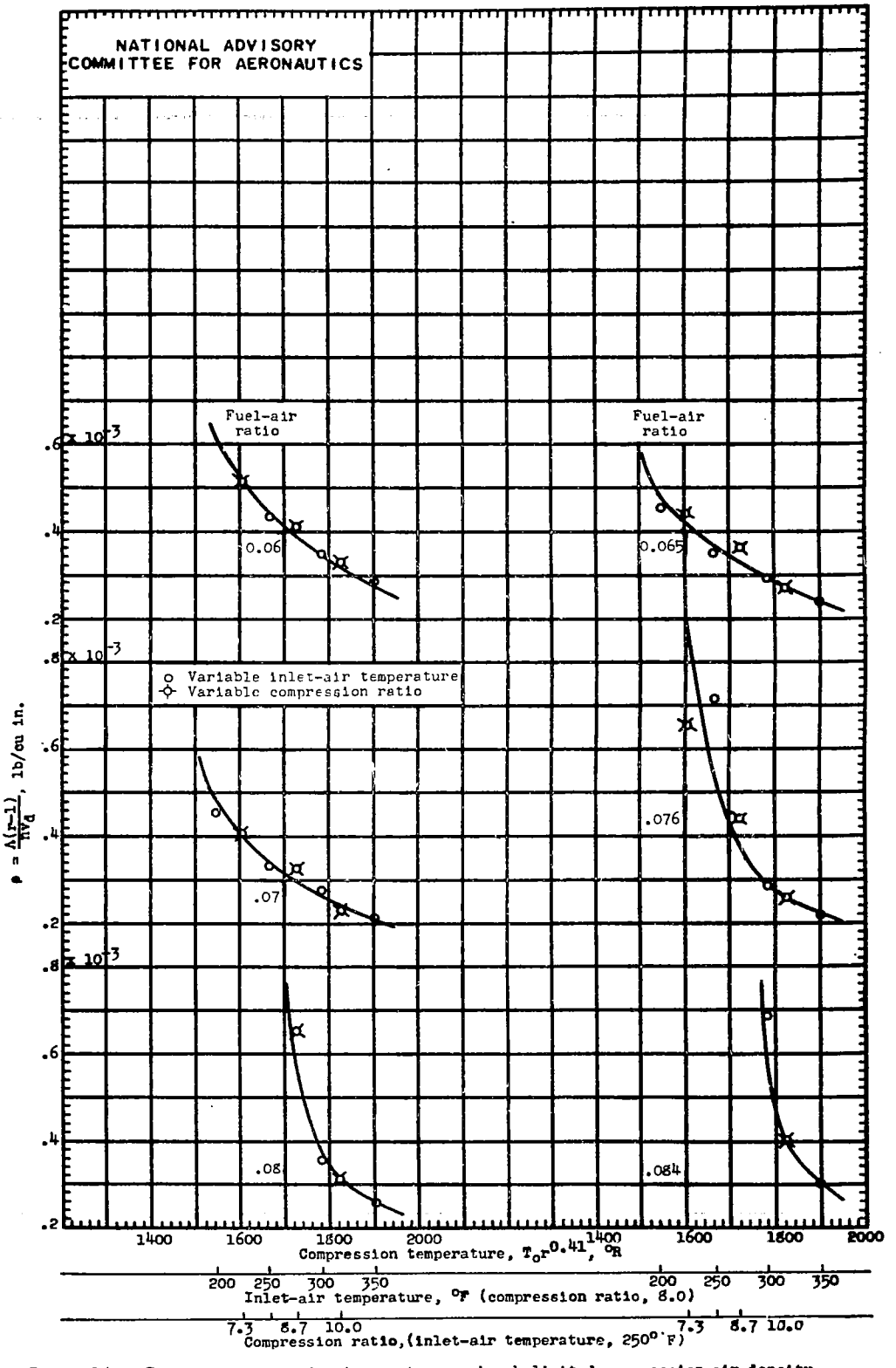

Figure 18. - Effect of compression temperature on knock-limited compression-air density $\frac{A(r-1)}{nv_d}$ for toluene plus 4 ml TEL per gallon.

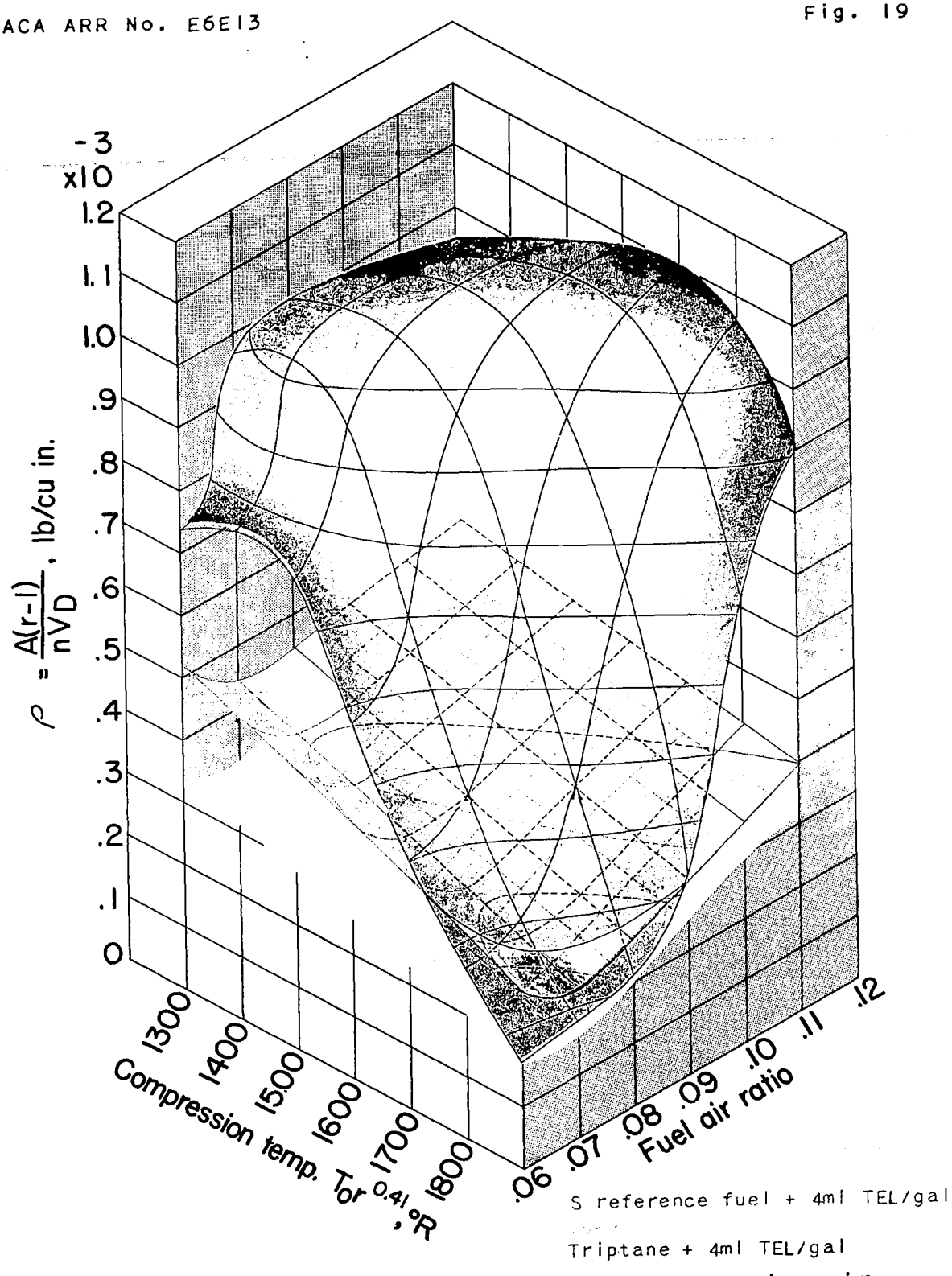

Figure 19. - Correlation of knock-limited compression-air density, compression temperature, and fuel-air ratio using S reference fuel, 28-R fuel, and triptane.

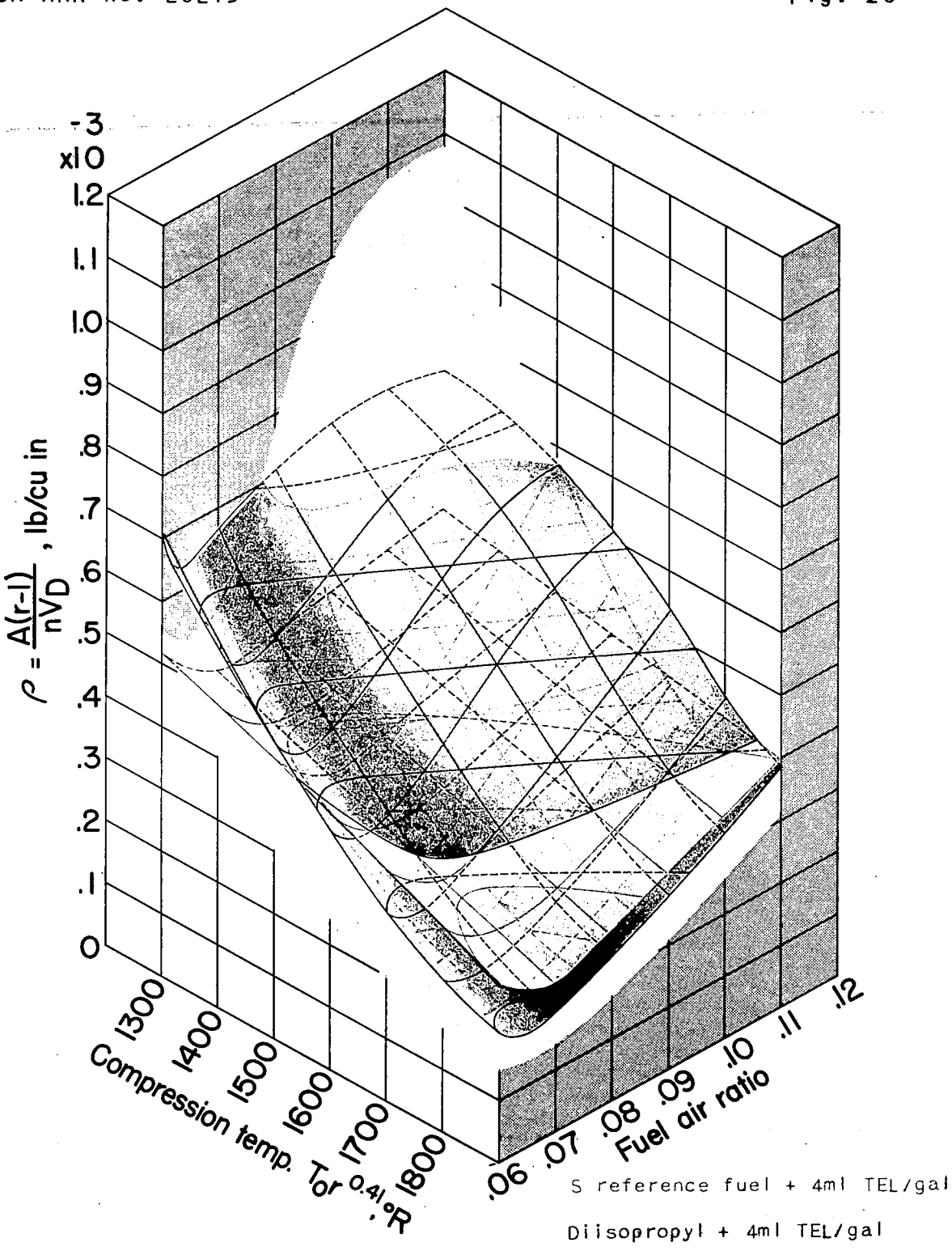

Figure 20. - Correlation of knock-limited compression-air density, compression temperature, and fuel-air ratio using S reference fuel, diisopropyl, and cyclopentane.

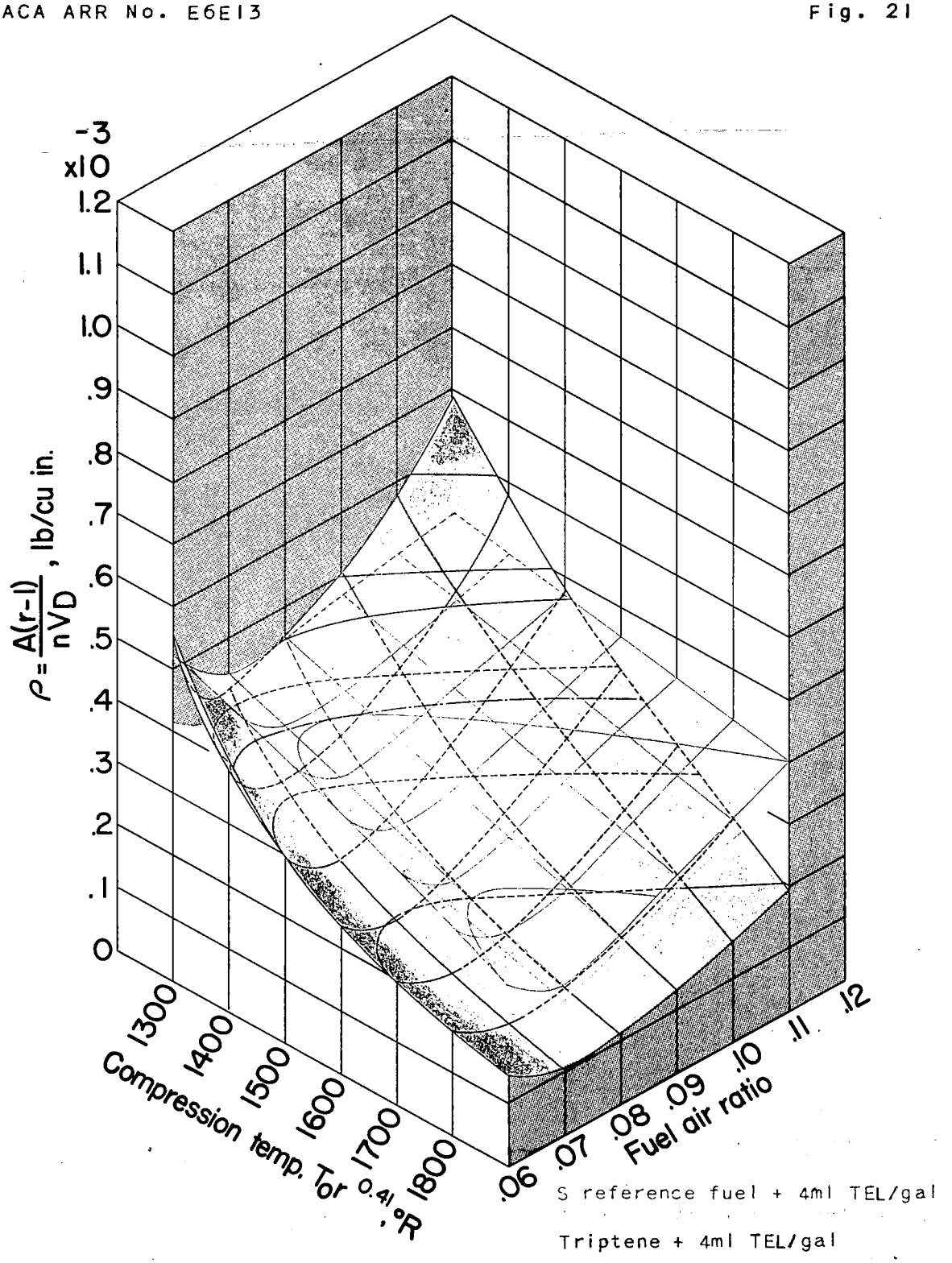

Figure 21. - Correlation of knock-limited compression-air density, compression temperature, and fuel-air ratio using S reference fuel, aviation alkylate, and triptene.

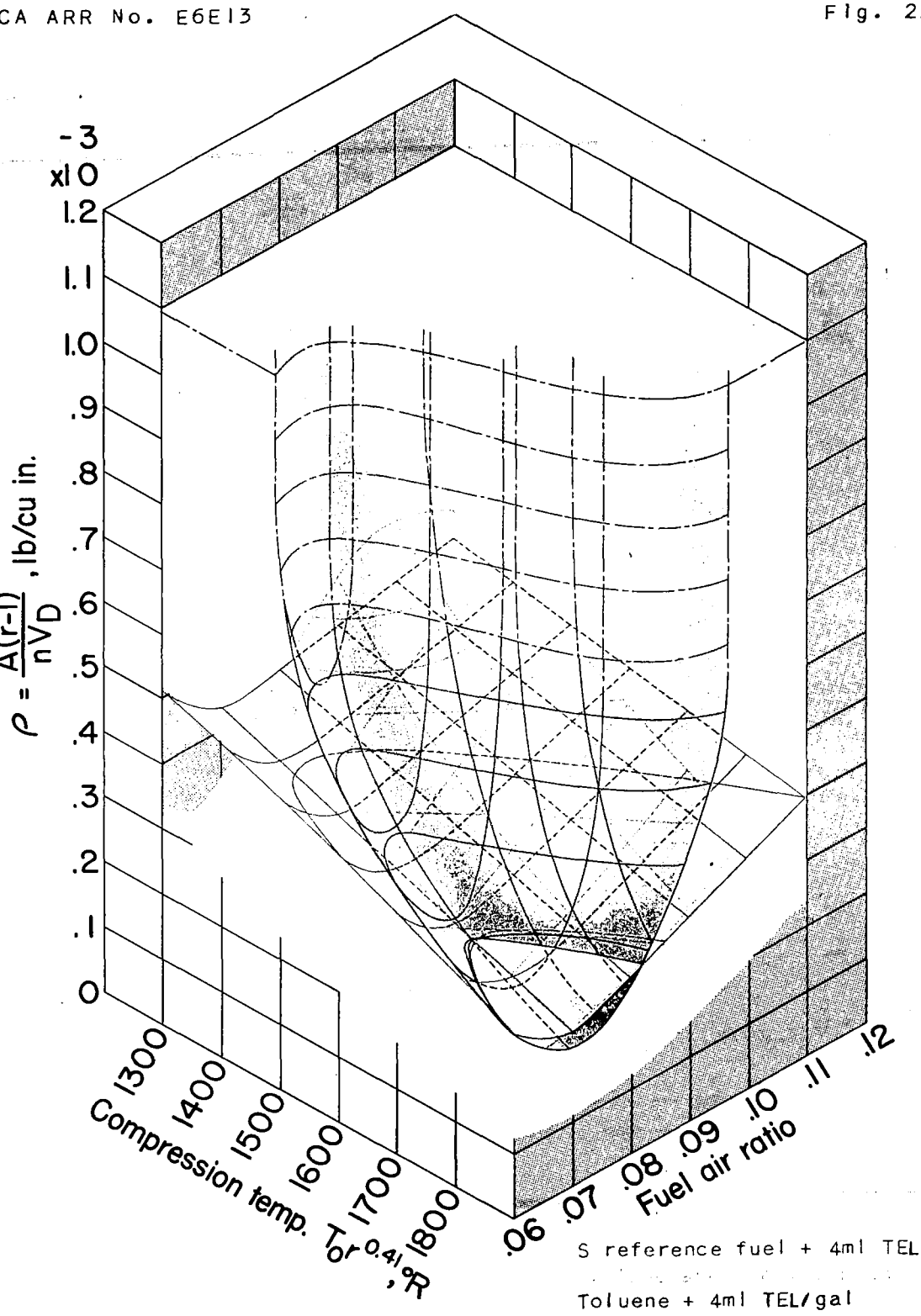

Figure 22. - Correlation of knock-limited compression-air density, compression temperature, and fuel-air ratio using S reference fuel, cyclohexane and toluene.

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