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THE EFFECT OF ENGINE CONDITIONS ON THE LEAD SUSCEPTIBILITY OF PARAFFINIC FUELS

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THE EFFECT OF ENGINE CONDITIONS OF THE LEAD SUSCEPTIBILITY OF PARAFFINIC FUELS

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SUMMARY

An investigation was made on a supercharged CFR engine to determine a method for estimating lead susceptibilities of pure or blended paraffinic fuels. Concentrations of tetraethyl lead up to 8 ml per gallon were investigated. In order to further extend the data, the effects of variations of inlet-air temperature, spark advance, and fuel-air ratio on lead susceptibility were examined.

As a result of these studies a chart consisting of a series of straight lines passing through the origin was developed to represent the lead susceptibilities of pure and blended paraffinic fuels in terms of knock-limited indicated mean effective pressures and octane numbers.

INTRODUCTION

The study of clear and leaded hydrocarbon-fuel ratings (reference 1) indicated that the lead susceptibility of paraffins and cycloparaffins could be represented by straight lines passing through the origin by plotting the knock-limited indicated mean effective pressures (supercharged conditions) of the pure hydrocarbons against the knock-limited indicated mean effective pressures of the leaded hydrocarbons at constant fuel-air ratio and concentration of tetraethyl lead. This relation means that, at one set of engine operating conditions, the percentage increase in knock-limited indicated mean effective pressure for a given tetraethyl-lead addition is a constant for all paraffins and all cycloparaffins although the respective constants for the two classifications are different.

At the time of the analysis in reference 1, data were not available to test the validity of this linear relation under supercharged conditions for concentrations of tetraethyl lead other than 1.0 ml per gallon or fuel-air ratios other than 0.07. On the assumption that the linear relation was valid for all concentrations of tetraethyl lead, the suggestion was made in reference 1 that a chart could be prepared from data on one paraffinic fuel which would permit the estimation of lead susceptibilities of any other paraffinic fuel or blends of paraffinic fuels from the knock-limited performance of the unleaded fuel.

The object of the present investigation is to prepare such a lead-susceptibility chart for paraffinic fuels as represented by blends of S and M reference fuels and to show how this chart is affected by variations of inlet-air temperature, spark advance, and fuel-air ratio.

The preparation of the lead-susceptibility chart discussed in this analysis is essentially a method of averaging data. For this reason, occasional differences between the lead-susceptibility chart and the experimental data will be found.

The investigation was made at the Aircraft Engine Research Laboratory of the NACA, Cleveland, Ohio, between July and October 1943 and is part of an investigation of lead susceptibility, the first part of which was reported in reference 1.

APPARATUS AND TEST PROCEDURE

All tests were made in a supercharged CFR engine modified as described in reference 2.

Knock-limited performance data necessary for the lead-susceptibility chart were obtained by testing blends of S-2 and M-3 reference fuels. These blends were tested clear and with 1, 2, 4, 6, and 8 ml tetraethyl lead per gallon at the following engine conditions:

Engine speed, rpm	2000
Compression ratio	7.0
Spark advance, deg B.T.C.	35
Inlet-air temperature, °F	250
Inlet-coolant temperature, °F	250

These tests exhausted the supply of S-2 reference fuel, and the rest of the test program was completed on S-3 reference fuel.

At inlet-air temperatures of 150°, 200°, 250°, and 325° F, S-3 reference fuel was tested clear and with 2, 4, and 8 ml tetraethyl lead per gallon. Tests were also made of S-3 reference fuel clear and with 2 ml tetraethyl lead per gallon at spark advances of 20° and 35° B.T.C. During the test of any one of the conditions all other engine conditions were the same as those used in the preceding tests on blends of S-2 and M-3 reference fuels.

For each test the knock-limited indicated mean effective pressures were obtained over a range of fuel-air ratios from 0.07 to 0.12.

The precision of the engine data is indicated by the curves for S reference fuels in figure 1. The data are from tests made at the beginning and the end of the program as well as from intermediate runs. In the present analysis fuel-air ratios in excess of 0.10 are not treated. The precision with fuels containing high concentrations of tetraethyl lead was not so satisfactory as the precision shown in figure 1.

Afterfiring and spark-plug fouling were encountered in the tests of fuel blends containing 6 and 8 ml tetraethyl lead per gallon. These difficulties were partly eliminated by the use of new spark plugs for each test.

TEST RESULTS

The experimental results recorded at AERL on which this analysis is based are presented in figures 2, 3, and 4. The average reference-fuel curves (fig. 5) supplied by the Coordinating Research Council for the F-4 rating method and data of the same general type (presented later) obtained by and published with the permission of the Ethyl Corporation are included in the analysis.

DISCUSSION

Development of lead-susceptibility chart. - Heron and Beatty (reference 3) have shown that, for supercharged tests, a linear relation exists between the reciprocal of the knock-limited indicated mean effective pressures and the octane numbers. This relation is used in figure 6 to relate the indicated mean effective pressure, the percentage of S-2 reference fuel in M-3 reference fuel, and the concentration of tetraethyl lead for the data presented in figure 2. The points shown are cross-plotted from the faired curves in figure 2.

The lines of constant tetraethyl-lead concentration in figure 6 can be represented by the equation of an equilateral hyperbola:

$$P(A - N) = B \qquad (1)$$

where

P knock-limited indicated mean effective pressure

A constant

N volume percentage of S-2 in M-3

B slope

The asymptotes of the hyperbola represented by equation (1) are zero and A. For the data in figure 6, the constant A is independent of tetraethyl-lead concentration and fuel-air ratio and is equal to 145 (the intersection of the curves with the zero ordinate).

In figure 7 the lead susceptibility of paraffinic fuels as represented by blends of S-2 and M-3 reference fuels is shown as a plot of the knock-limited indicated mean effective pressure of the clear fuel against the knock-limited indicated mean effective pressure of the leaded fuel. This figure is a cross plot of the faired lines in figure 6. This type of plot has an advantage over that in figure 6 because the lead susceptibility can be represented by a linear relation without the use of a reciprocal scale. The fact that figure 7 consists of a series of straight lines which pass through the origin shows that, for a given addition of tetraethyl lead, the percentage increase in power is constant for blends of S-2 and M-3 reference fuels regardless of the rating of the clear blends.

The octane scale shown in figure 7 was determined by assuming a linear relation between the percentage S-2 in M-3 and the octane number. This scale corresponds to the ordinate values of knock-limited indicated mean effective pressure; that is, a 90-octane fuel whether clear or leaded (fig. 7(a)) has a knock-limited indicated mean effective pressure of 85 pounds per square inch under the conditions presented.

The results presented in figures 6 and 7 show that a lead-susceptibility chart consisting of a series of straight lines passing through the origin can be prepared for paraffinic fuels. From the data presented in reference 1, it is probable that a single chart will represent all paraffinic fuels at one set of engine conditions and can be constructed from data of knock-limited indicated mean effective pressure for one paraffinic fuel tested with and without tetraethyl lead. If such is the case, only the unleaded fuel need be tested in order to estimate the lead response of any paraffin.

The chart may be used to obtain either the knock-limited indicated mean effective pressure or the octane number of the paraffinic fuel with various quantities of tetraethyl lead.

The estimation of lead susceptibility according to the foregoing procedure is of value in the study of paraffinic fuels in which the quantity of fuel available for testing is limited. In such cases the rating of the clear fuel could be obtained by a standard rating method such as the F-4 rating method, and the rating of the test fuel plus various amounts of tetraethyl lead could be estimated from the lead-susceptibility chart for the rating method used.

The average reference-fuel curves used by the Coordinating Research Council for the F-4 rating method can be used to construct a lead-susceptibility chart representative of the F-4 conditions. Such a chart is shown in figure 8, which was obtained by cross-plotting the data from figure 5. The values below 90 octane number on the rating scale in figure 8 were estimated. Inasmuch as data for the lead susceptibility of S reference fuel (fig. 5(a)) were the only data available for the F-4 rating method, figure 8 represents a rather wide extrapolation of data and should be considered only as an illustrative chart.

The specific values shown in figures 7 and 8 agree reasonably well for concentrations of 2 ml tetraethyl lead per gallon but are not the same for 4 and 6 ml tetraethyl lead per gallon. The differences result from either lack of precision at the higher concentrations of tetraethyl lead or differences in engines and engine conditions.

Effect of fuel-air ratio on lead susceptibility. - Figures 6, 7, and 8 show that the lead susceptibilities of paraffinic fuels are affected by fuel-air ratio. This effect can readily be seen in figures 9 and 10, which present curves calculated from the data in figures 7 and 8, respectively.

In figure 9 the percentage increase in power (lead susceptibility) caused by a given addition of tetraethyl lead is approximately the same at fuel-air ratios of 0.07 and 0.085. The data in figure 10 for the F-4 rating method show considerably greater speed.

Effect of inlet-air temperature on lead susceptibility. - The lead susceptibility from tests at different inlet-air temperatures (fig. 3) are represented in figure 11 by a plot of knock-limited indicated mean effective pressure of the clear fuel against the knock-limited indicated mean effective pressure of the leaded fuel.

Figure 11 does not agree with figure 7 for tetraethyl-lead concentrations of 4 and 8 ml per gallon. This difference can possibly be attributed to the previously mentioned difficulties encountered in tests of blends containing high concentrations of tetraethyl lead or to changes caused by the engine overhaul, which did not show up in the check runs on unleaded S-3 reference fuel. These data (fig. 11) show that, for the range of inlet-air temperatures examined, the lead susceptibility of S-3 reference fuel was constant; that is, the percentage increase of knock-limited indicated mean effective pressure caused by the addition of a given amount of tetraethyl lead was the samr regardless of the inlet-air temperature.

Effect of spark advance and engine speed on lead susceptibility. - The tests made on S-3 reference fuel clear and with 2 ml tetraethyl lead per gallon at spark advances of 20° and 35° B.T.C. are presented in figure 12 (cross-plotted from fig. 4). These data indicate that the lead susceptibility of S-3 reference fuel is independent of variations of spark advance.

Data obtained by the Ethyl Corporation on an engine of 17.6-cubic-inch displacement (fig. 13) also indicate that lead susceptibility is not affected by spark advance or engine speed.

CONCLUSIONS

The following conclusions are drawn from tests on small-scale engines to investigate the lead susceptibility of paraffinic fuels and are believed to be indicative of the results that might be obtained on other engines:

1. A chart consisting of a series of straight lines passing through the origin can be prepared to represent the lead susceptibilities of pure or blended paraffinic fuels in terms of knock-limited indicated mean effective pressures and octane numbers.

2. From such a chart prepared from one paraffinic fuel the lead susceptibility of any pure or blended paraffinic fuel can be estimated provided that the knock-limited indicated mean effective pressure or octane number of the clear fuel is known.

3. The relations shown in the chart are not affected by variations of inlet-air temperature or spark advance but are changed by variations of fuel-air ratio and changes in engine design.

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Cleveland, Ohio.

REFERENCES

1. Barnett, Henry C.: Lead Susceptibility of Paraffins, Cycloparaffins, and Olefins. NACA ARR No. 3E26, 1943.

2. Imming, Harry S.: Effect of Piston-Head Temperature on Knock-Limited Power. NACA ARR No. E4G13, 1944.

3. Heron, S. D., and Beatty, Harold A.: Aircraft Fuels. Jour. Aero. Sci., vol. 5, no. 12, Oct. 1938, pp. 463-479.

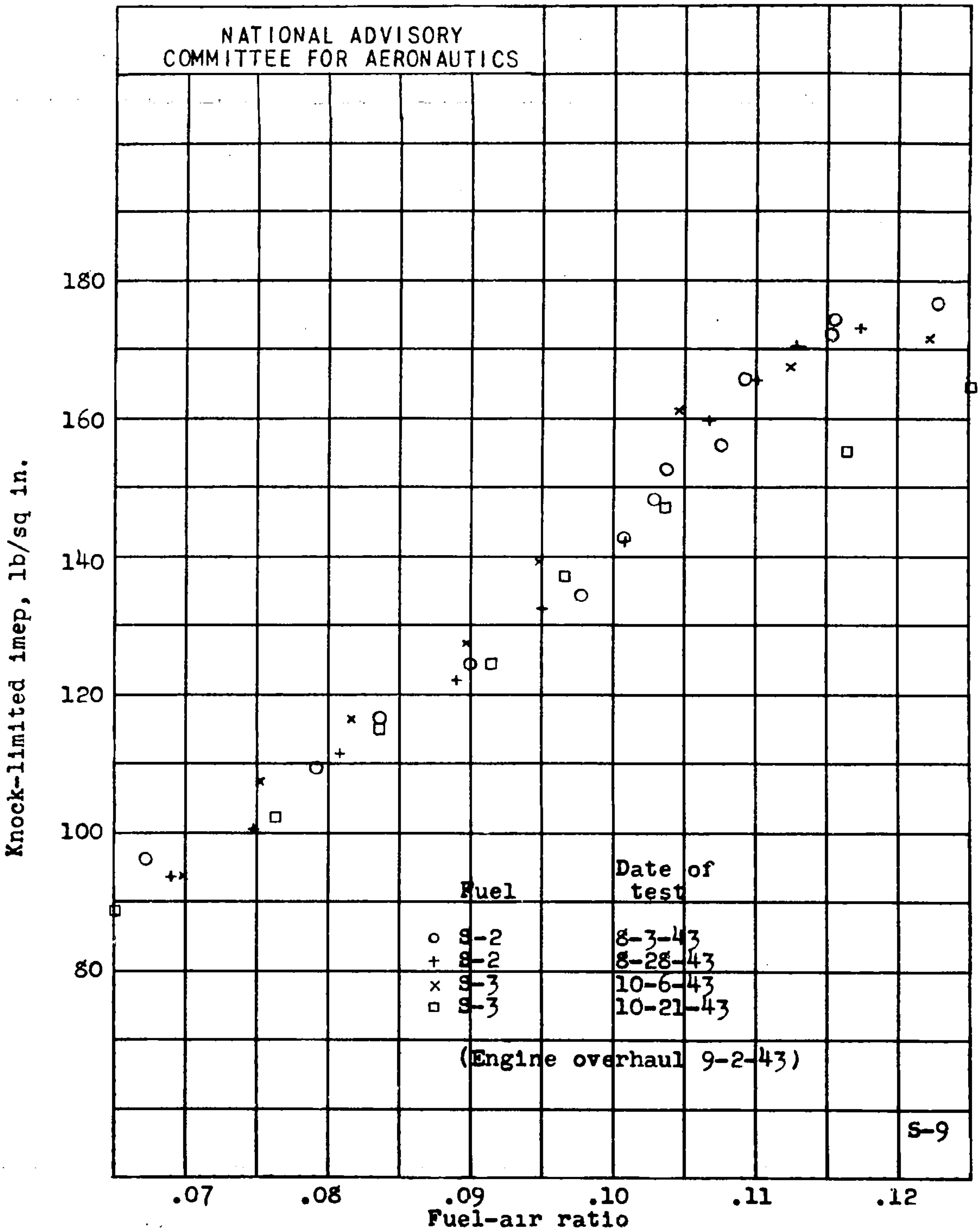
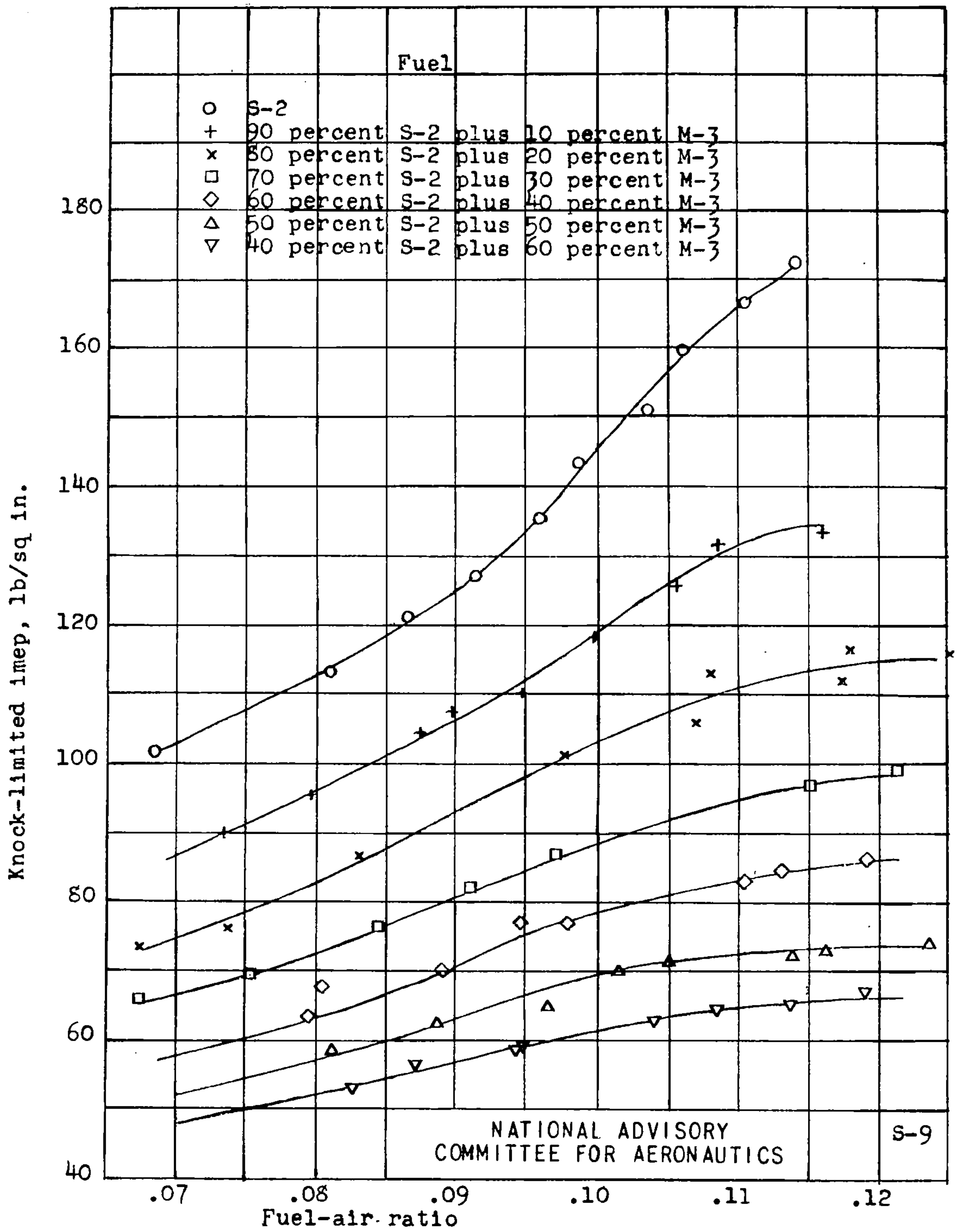
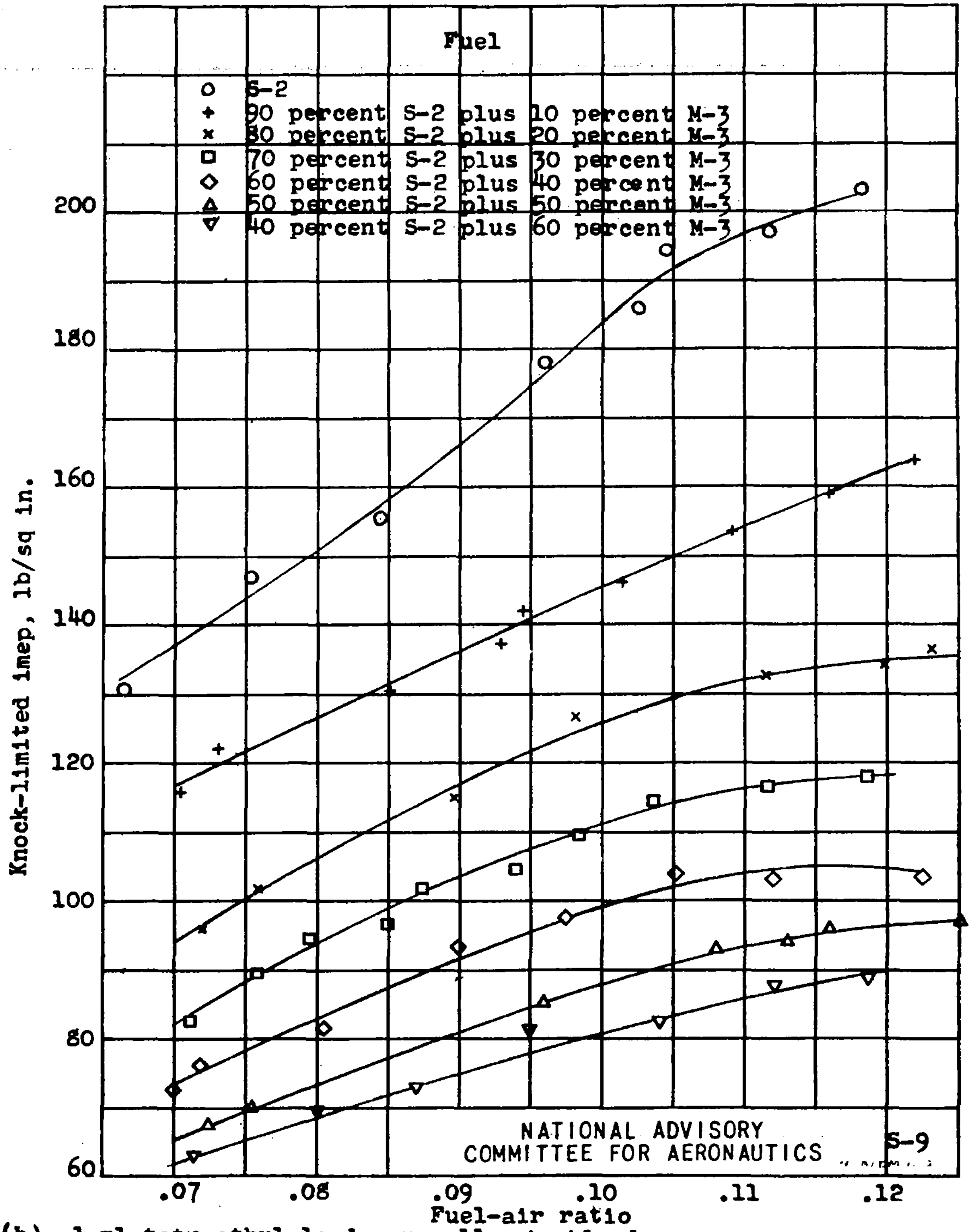


Figure 1. - Check tests on S reference fuels, CFR engine; inlet-air temperature, 250° F; spark advance, 35° B.T.C.; compression ratio, 7.0; engine speed, 2000 rpm; inlet-coolant temperature, 250° F.

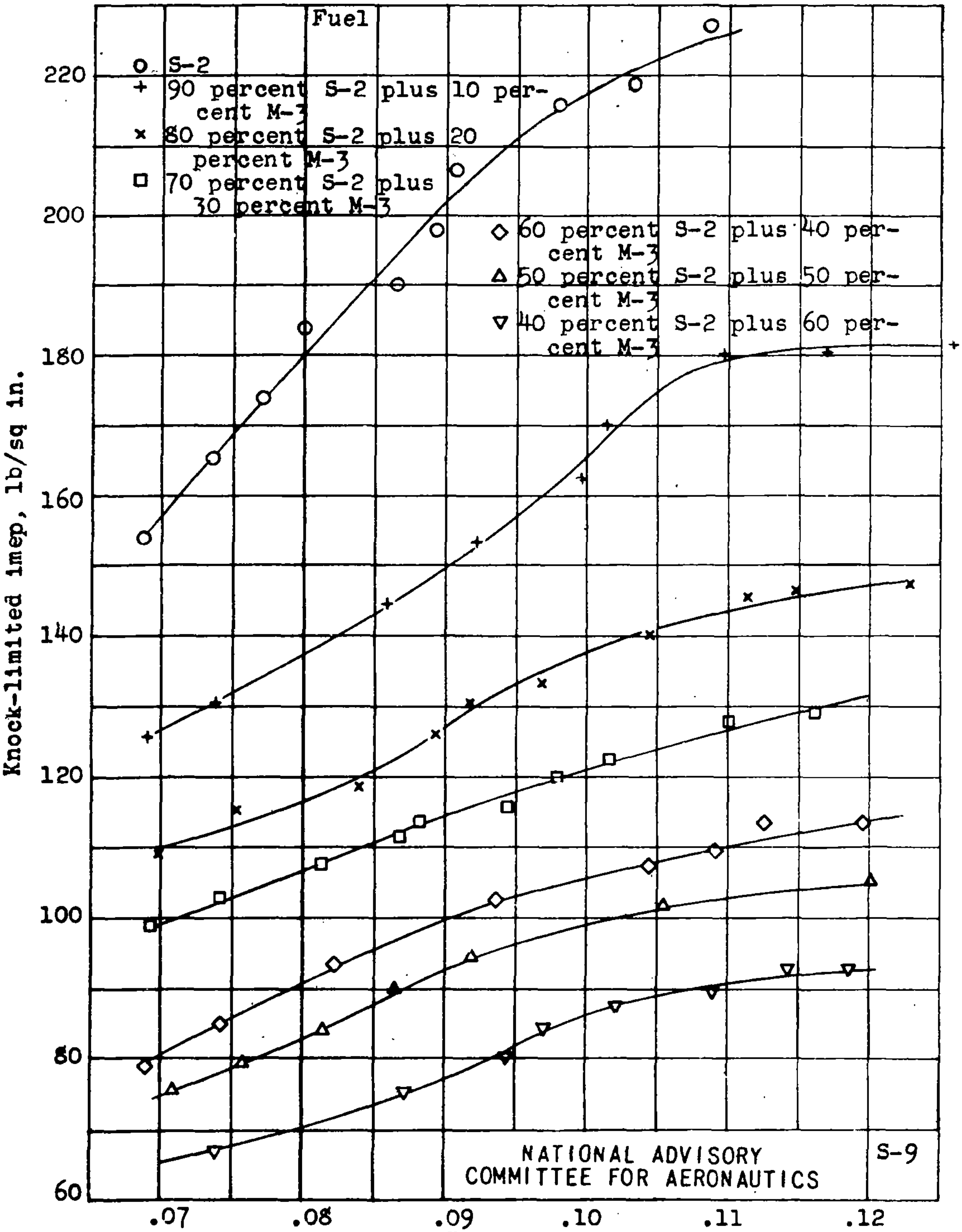


(a) Unleaded blends.

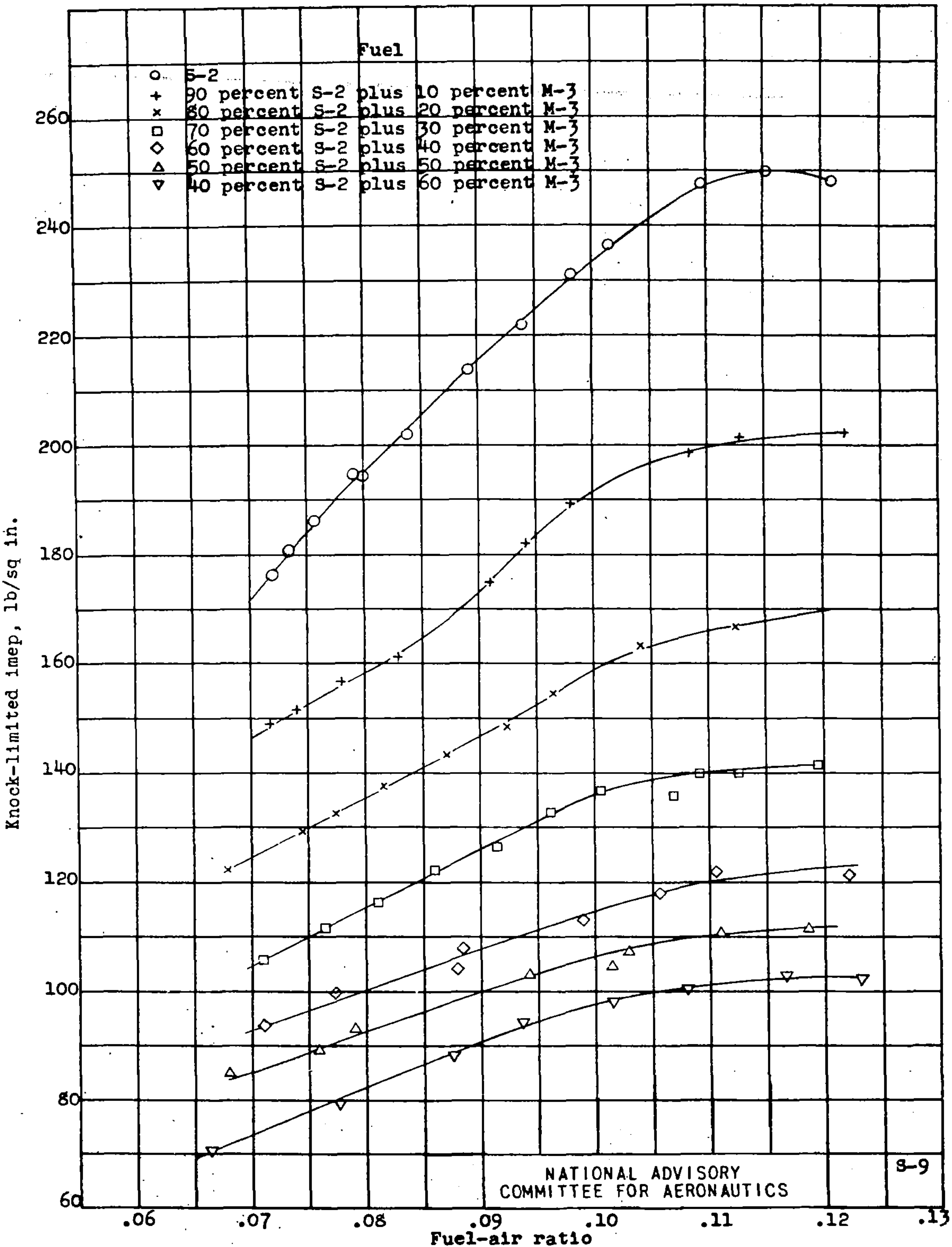
Figure 2. - Knock-limited performance of blends of S-2 and M-3 reference fuels with different tetraethyl-lead concentrations. CFR engine; inlet-air temperature, 250° F; spark advance, 35° B.T.C.; compression ratio, 7.0; engine speed, 2000 rpm; inlet-coolant temperature, 250° F.



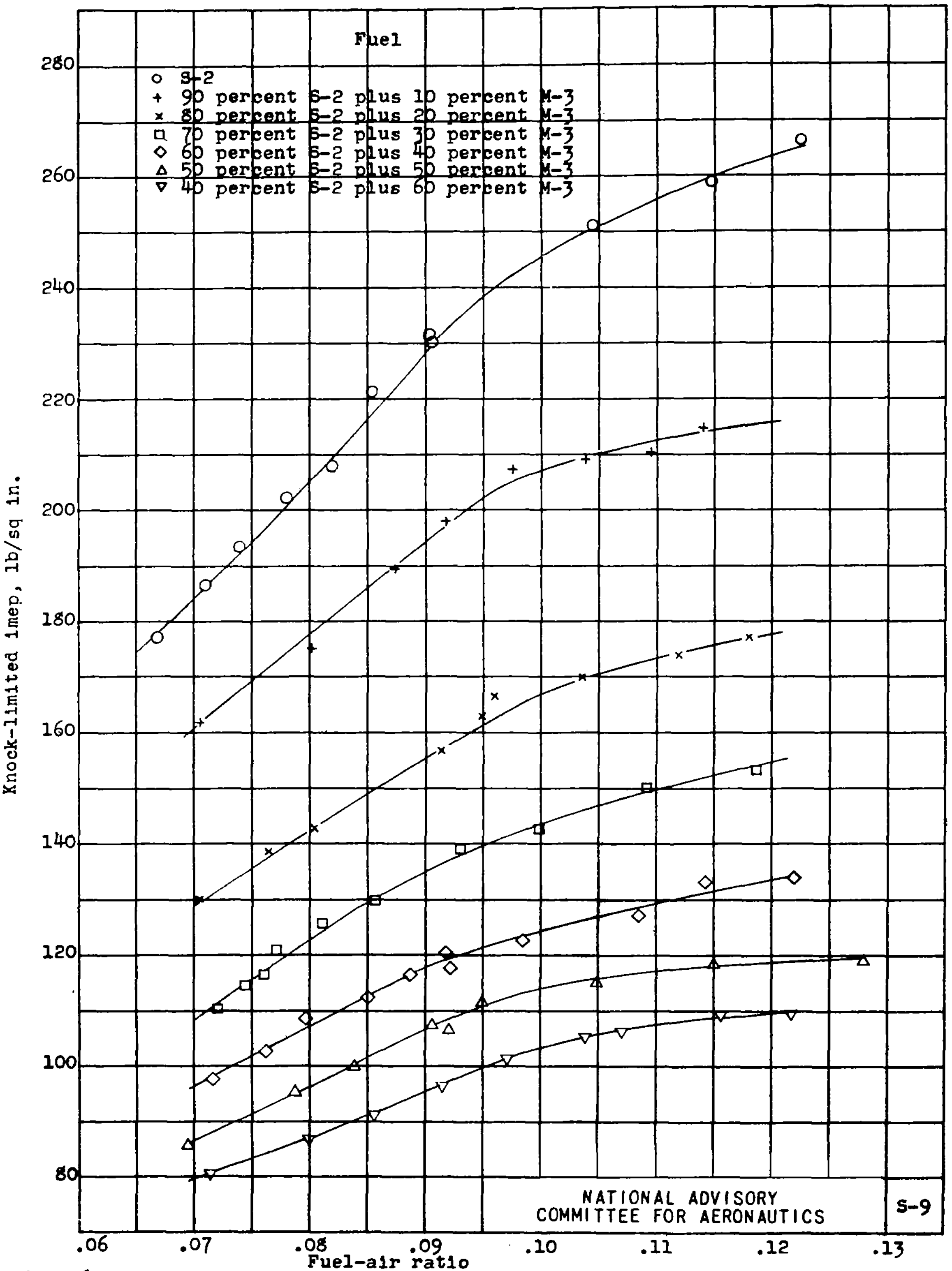
(b) 1 ml tetraethyl lead per gallon in blends.
Figure 2. - Continued.



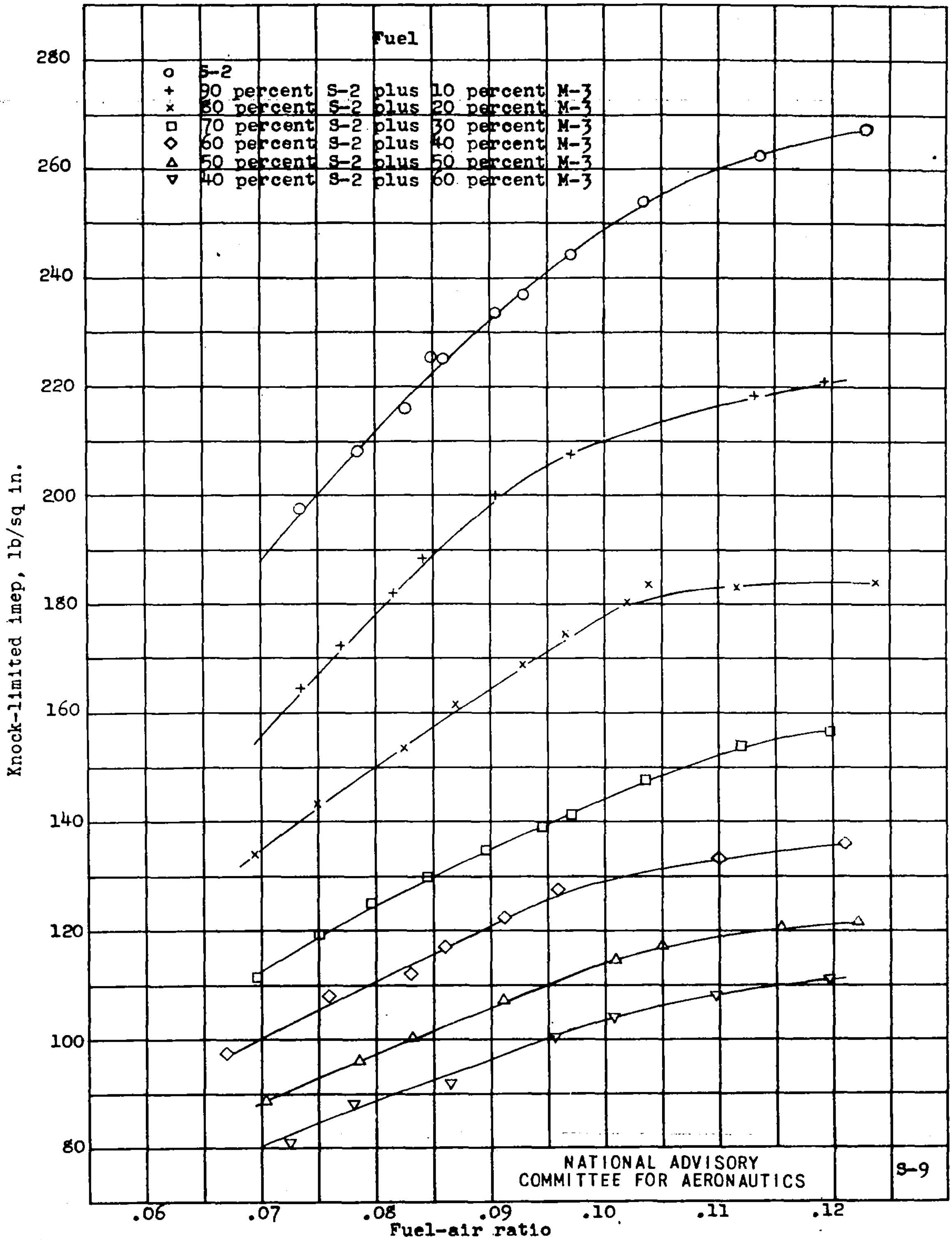
(c) 2 ml tetraethyl lead per gallon in blends.
Figure 2. - Continued.



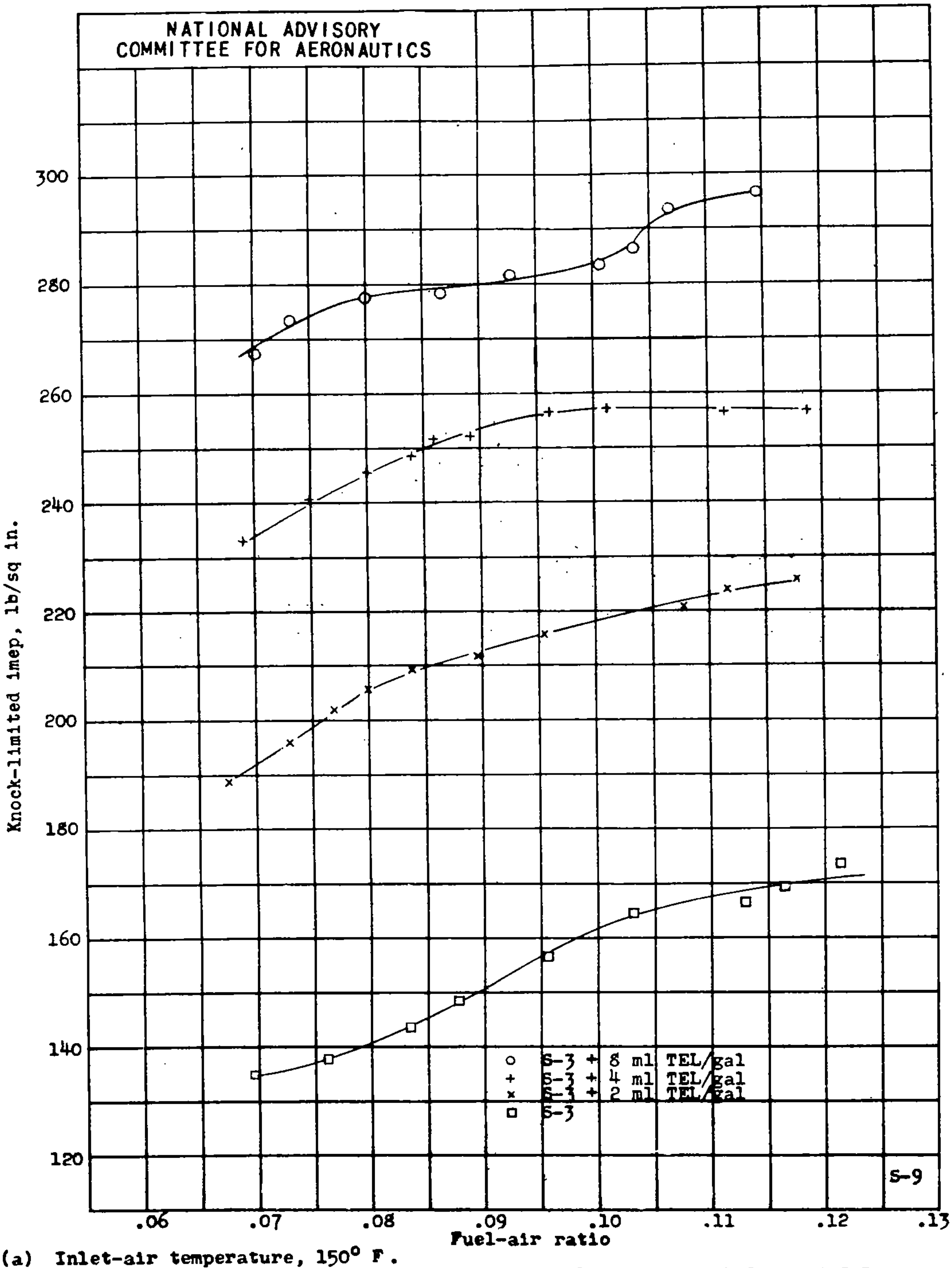
(d) 4 ml tetraethyl lead per gallon in blends.
Figure 2. - Continued.



(e) 6 ml tetraethyl lead per gallon in blends.
Figure 2. - Continued.

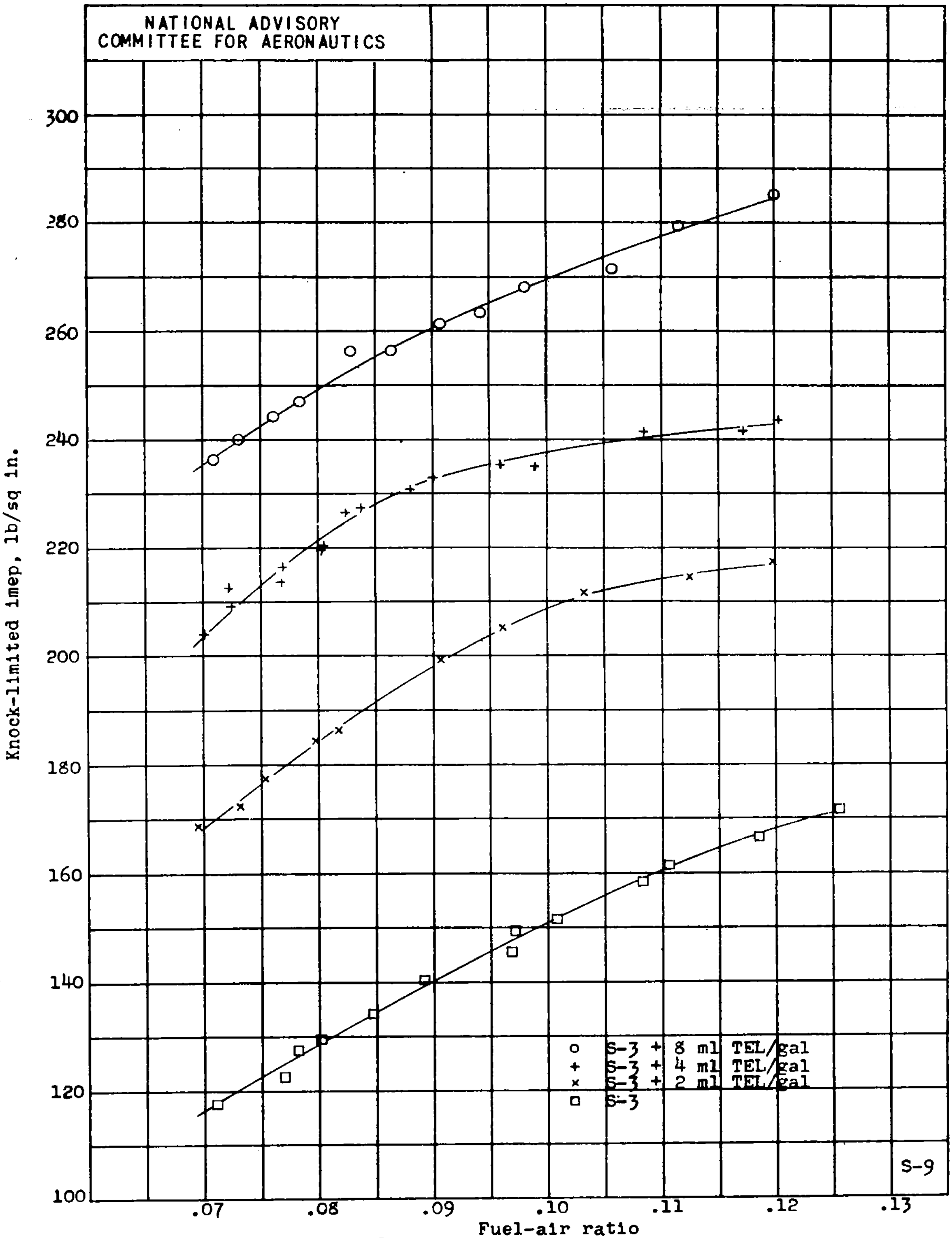


(f) 8 ml tetraethyl lead per gallon in blends.
Figure 2. - Concluded.

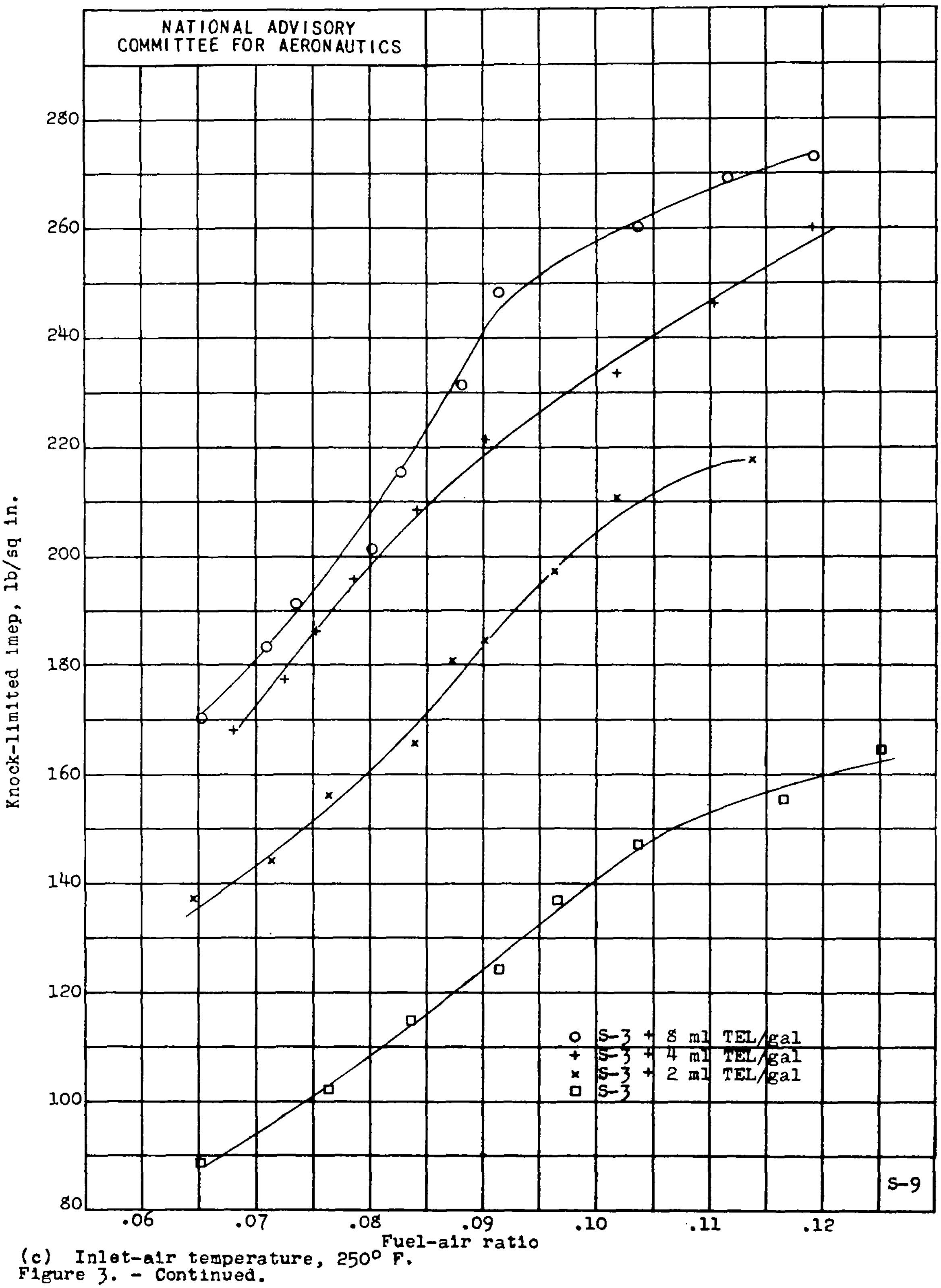


(a) Inlet-air temperature, 150° F.

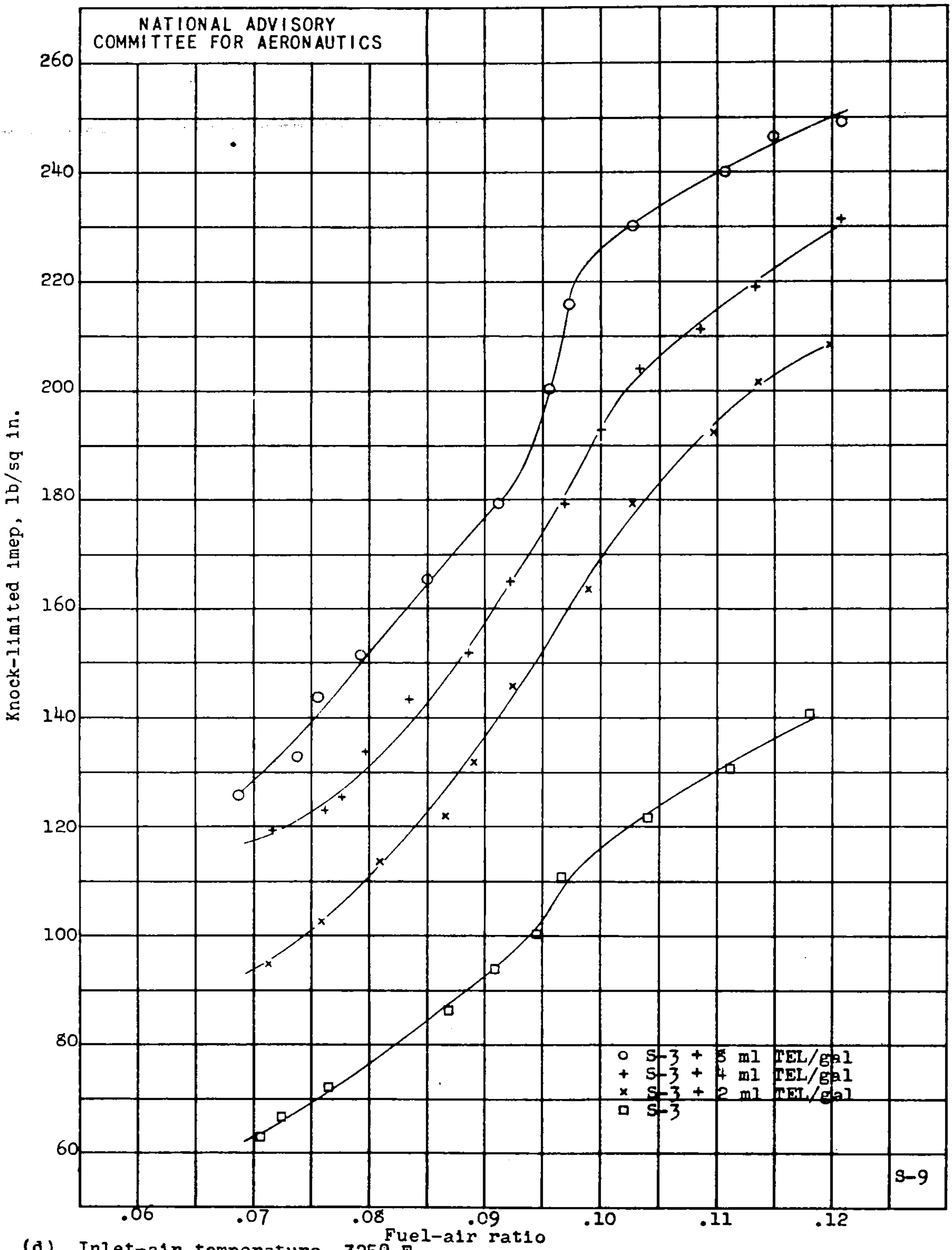
Figure 3. - Effect of inlet-air temperature on the lead susceptibility of S-3 reference fuel. CFR engine; spark advance, 35° B.T.C.; compression ratio, 7.0; engine speed, 2000 rpm; inlet-coolant temperature, 250° F.



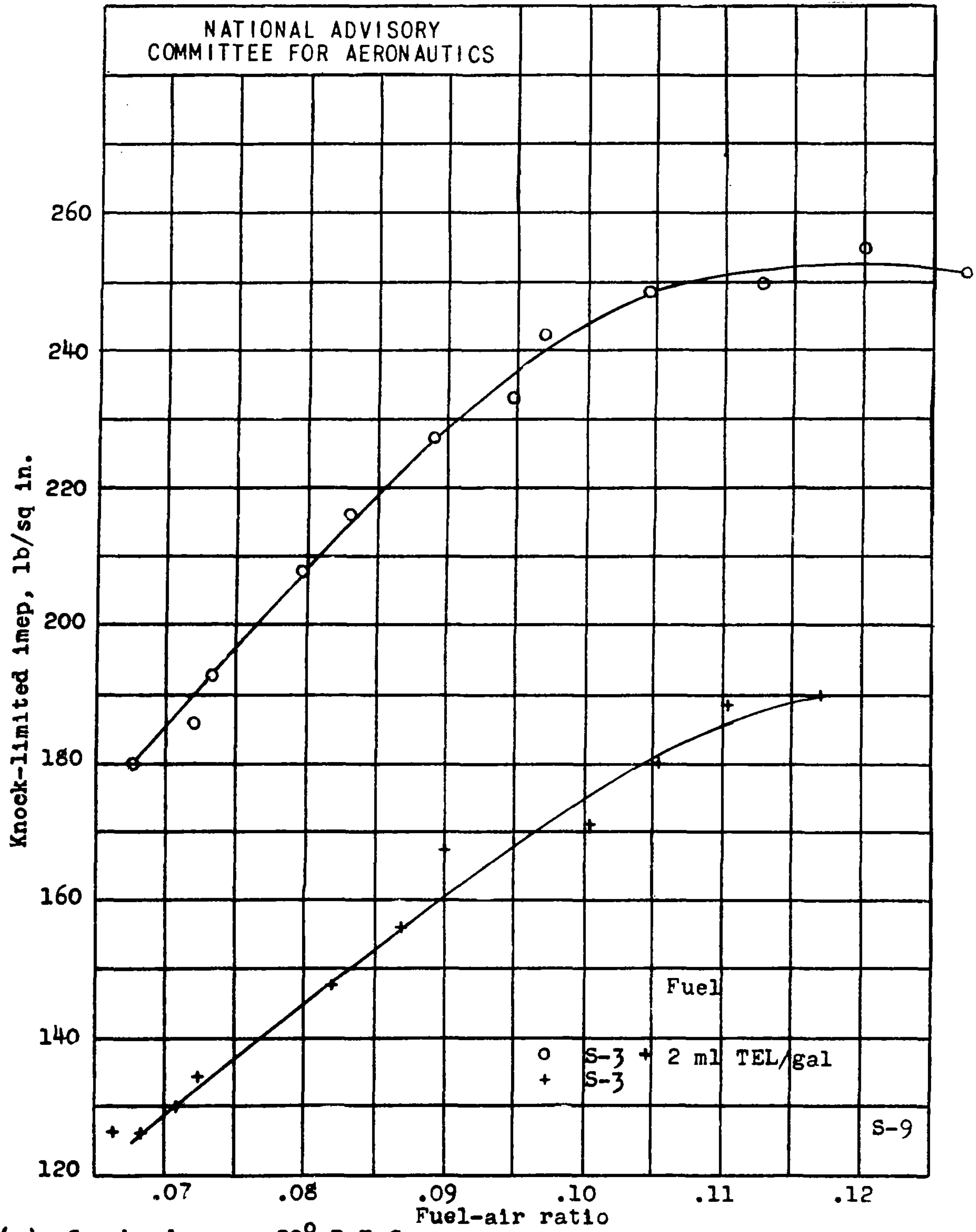
(b) Inlet-air temperature, 200° F.
Figure 3. - Continued.



(c) Inlet-air temperature, 250° F.
Figure 3. - Continued.

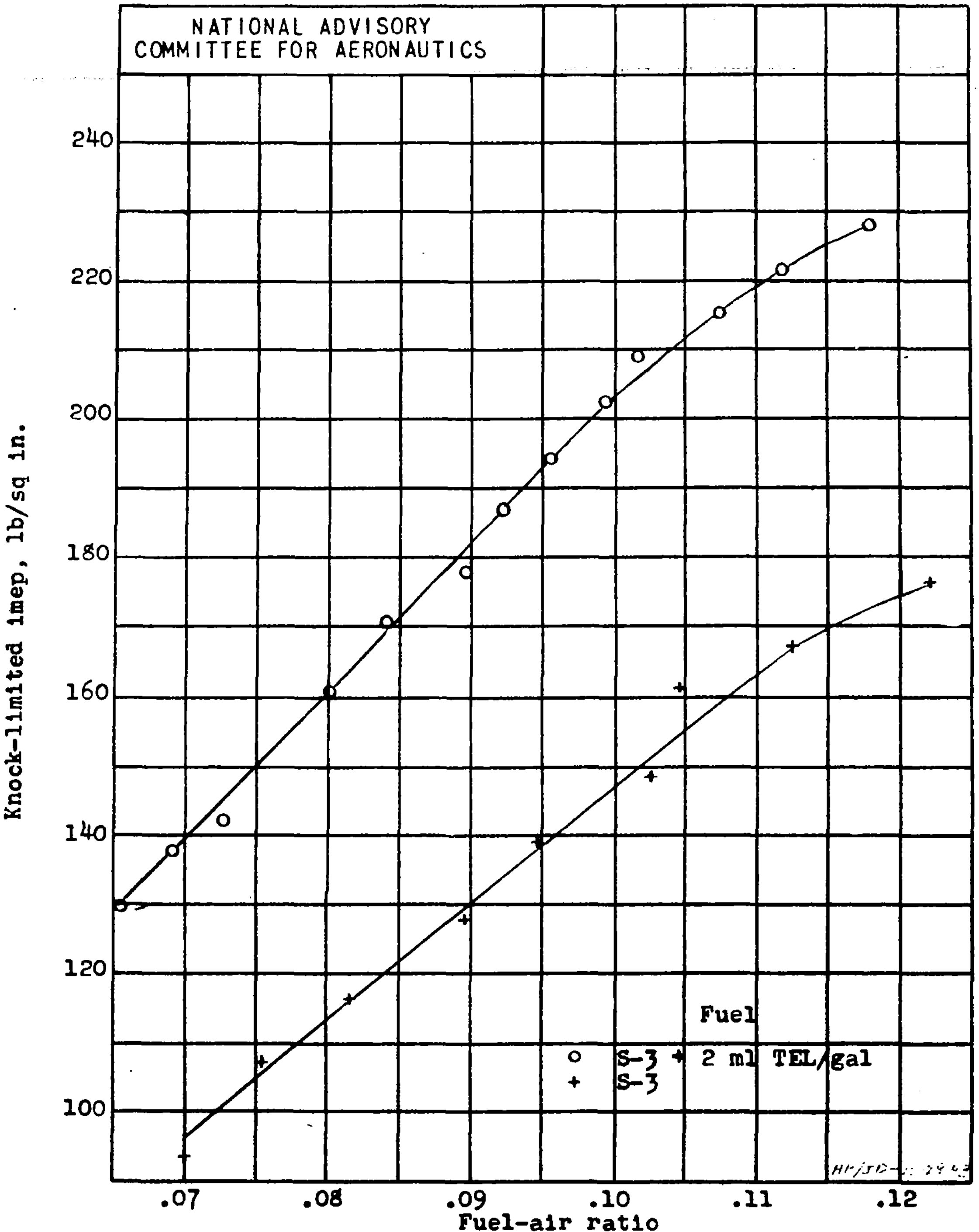


(d) Inlet-air temperature, 325° F.
Figure 3. - Concluded.



(a) Spark advance, 20° B.T.C.

Figure 4. - Effect of spark advance on the lead susceptibility of S-3 reference fuel. CFR engine; inlet-air temperature, 250° F; compression ratio, 7.0; engine speed, 2000 rpm; inlet-coolant temperature, 250° F.



(b) Spark advance, 35° B.T.C.
Figure 4. - Concluded.

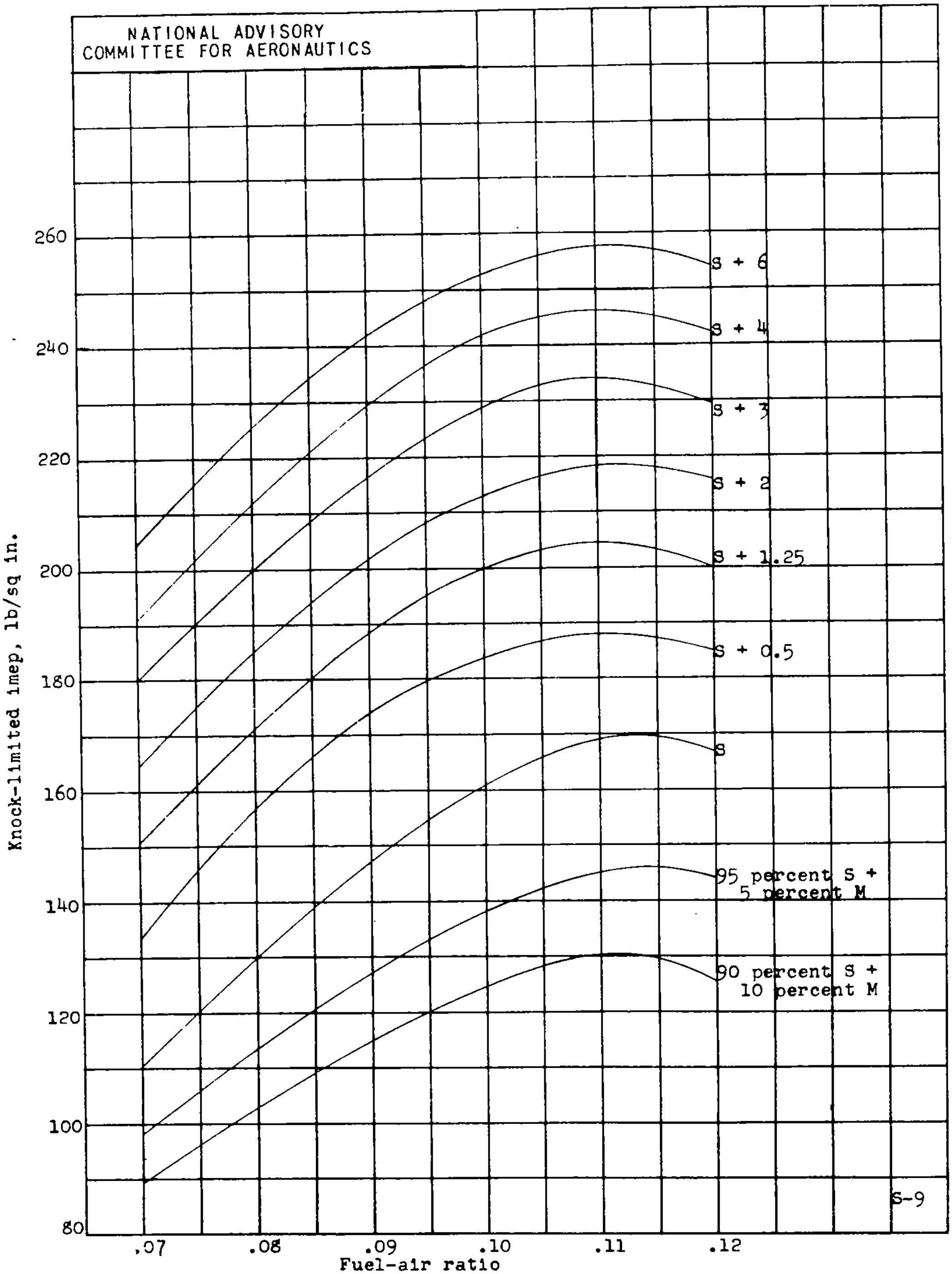
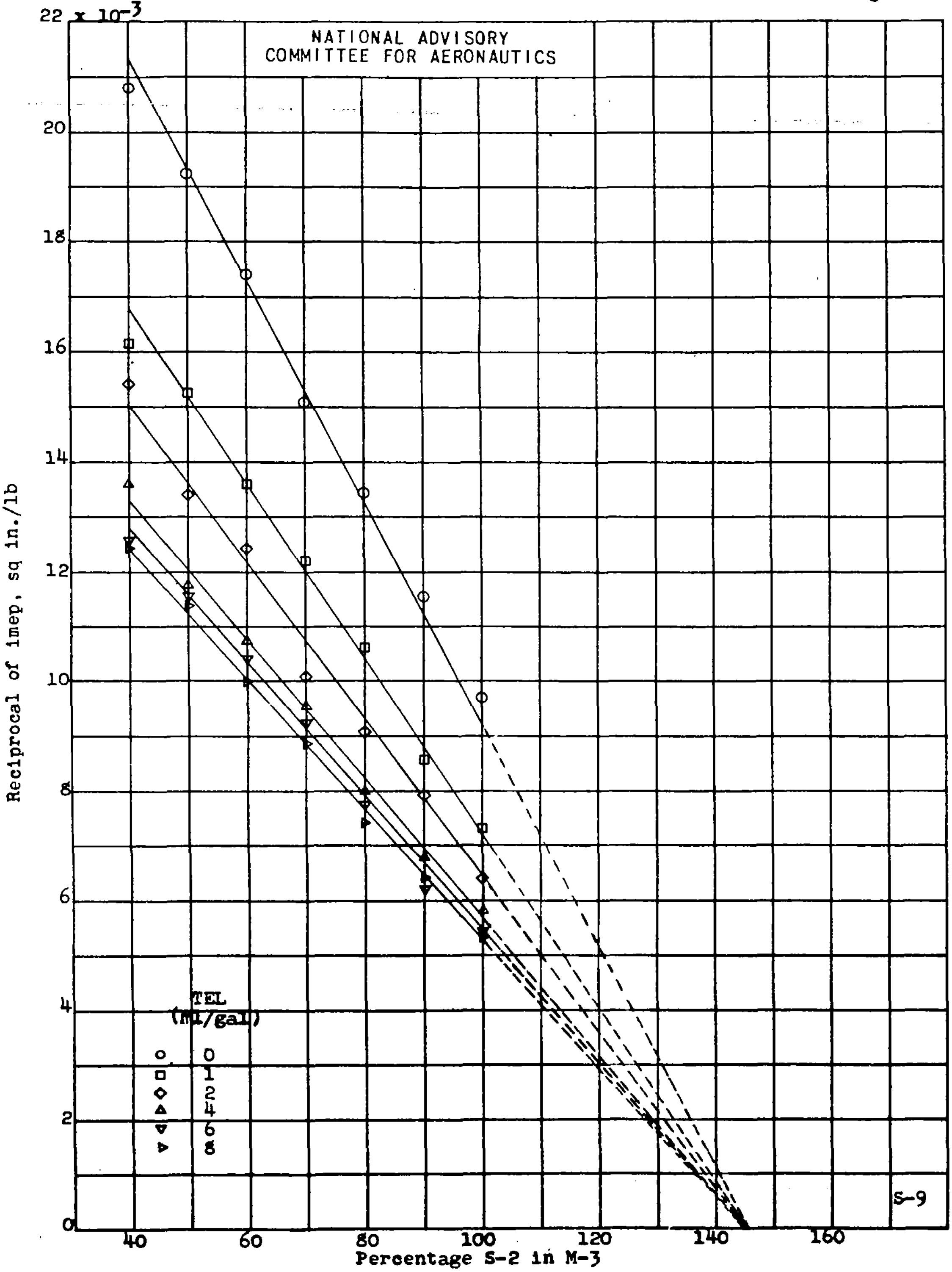
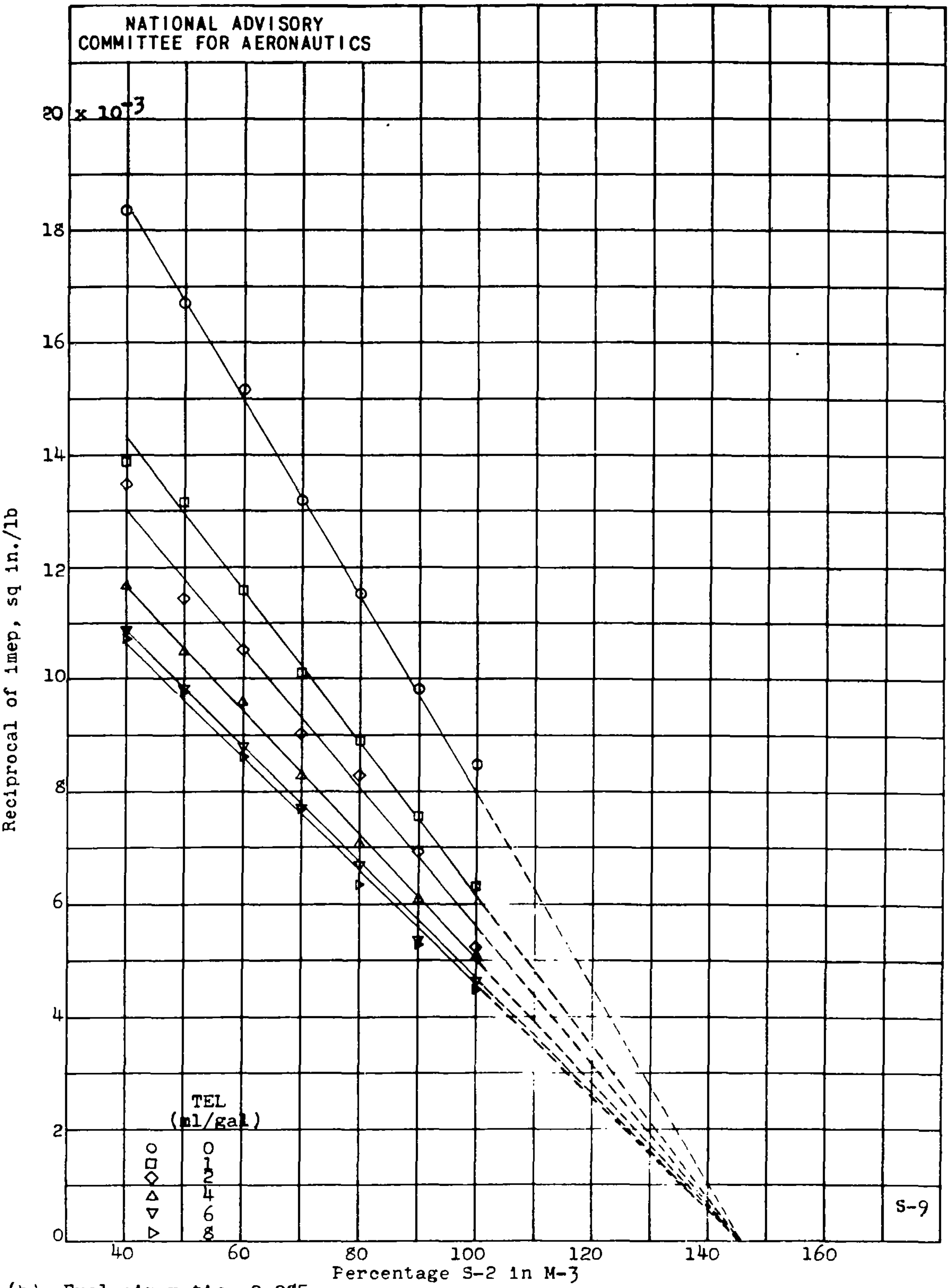


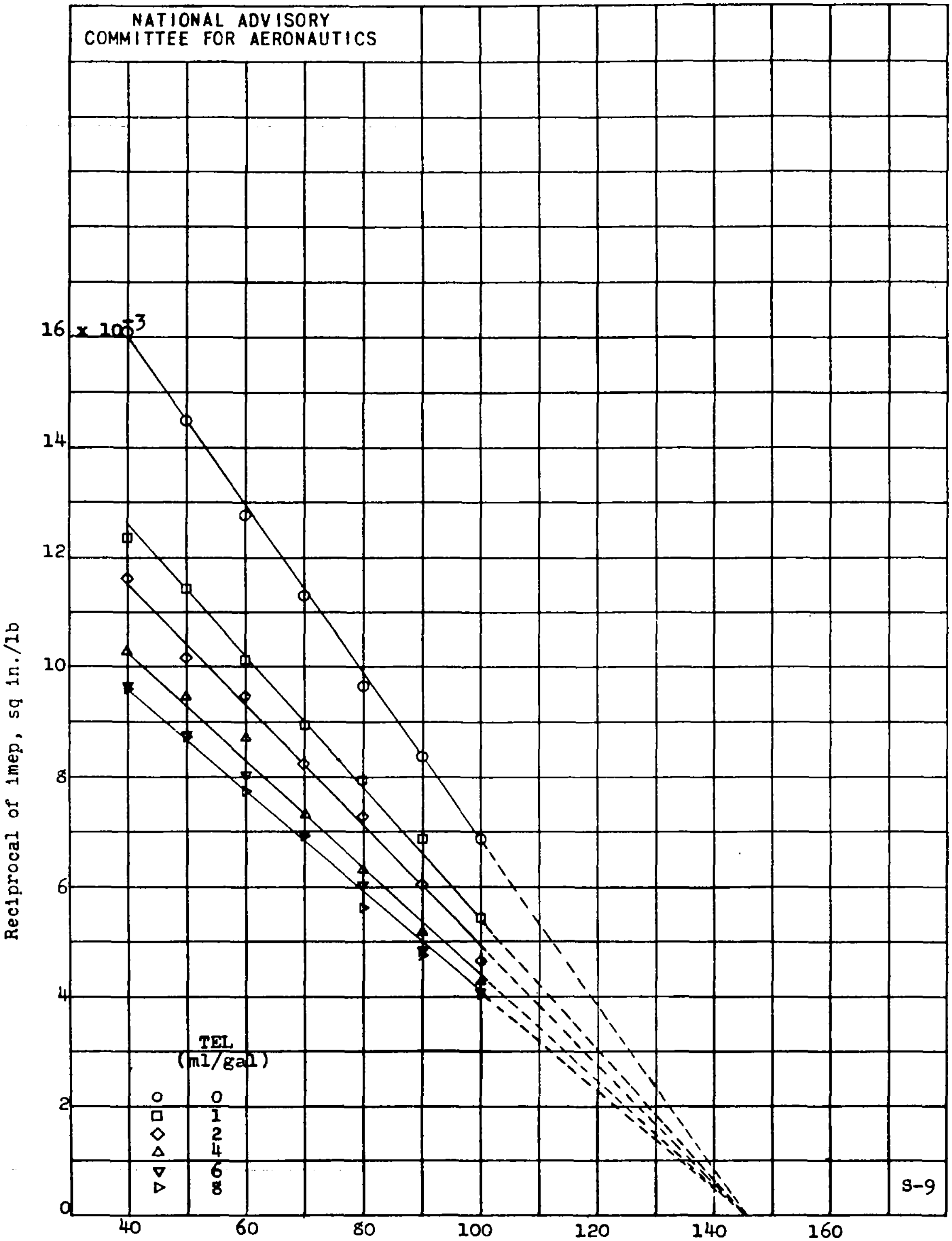
Figure 5. - Standard reference curves for F-4 rating method. (Courtesy of the Coordinating Research Council.)



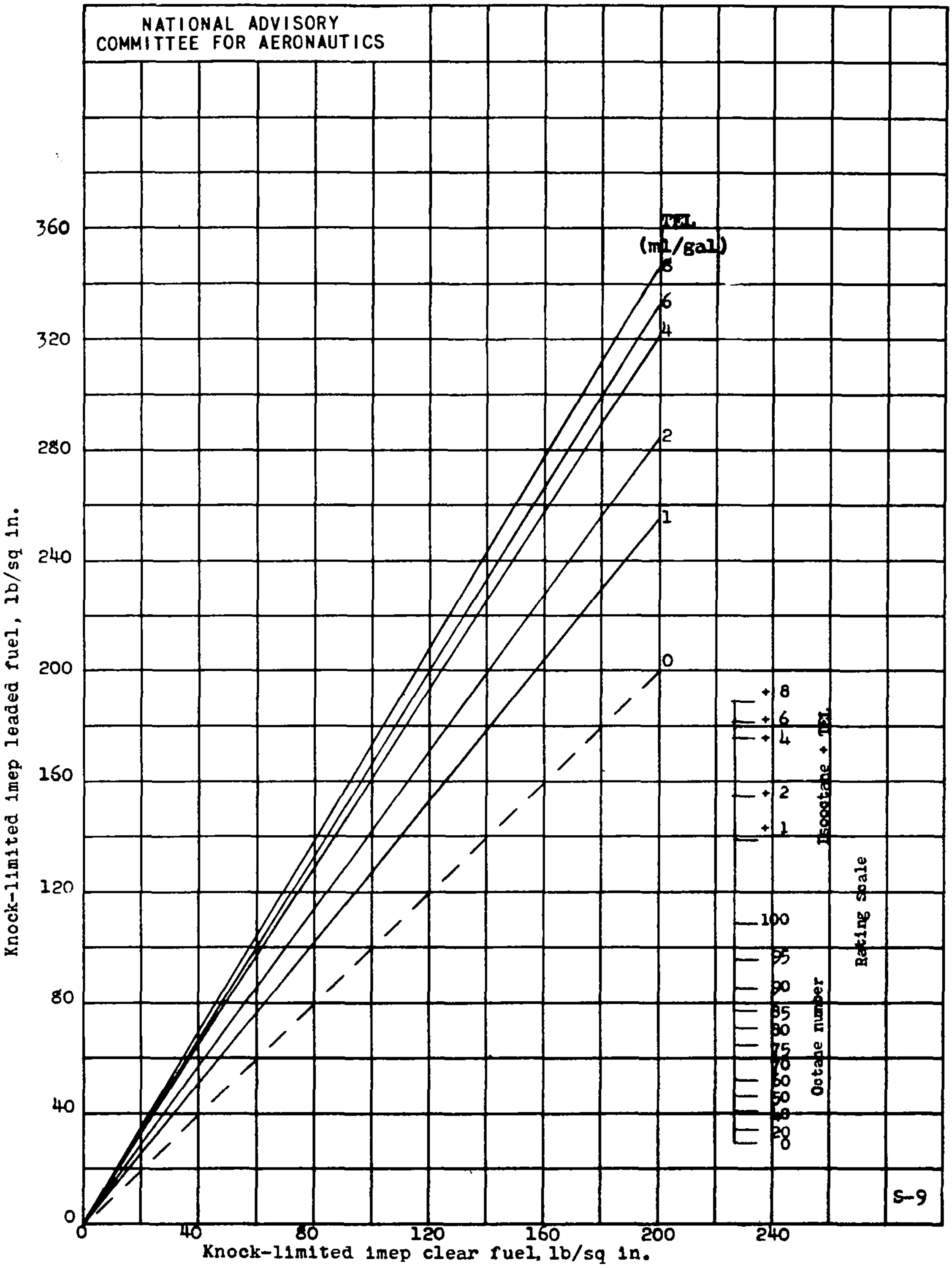
(a) Fuel-air ratio, 0.07.
Figure 6. - Lead susceptibility of blends of S-2 and M-3 reference fuels at different fuel-air ratios. CFR engine; inlet-air temperature, 250° F; spark advance, 35° B.T.C.; compression ratio, 7.0; engine speed, 2000 rpm; inlet-coolant temperature, 250° F.



(b) Fuel-air ratio, 0.085.
Figure 6. - Continued.

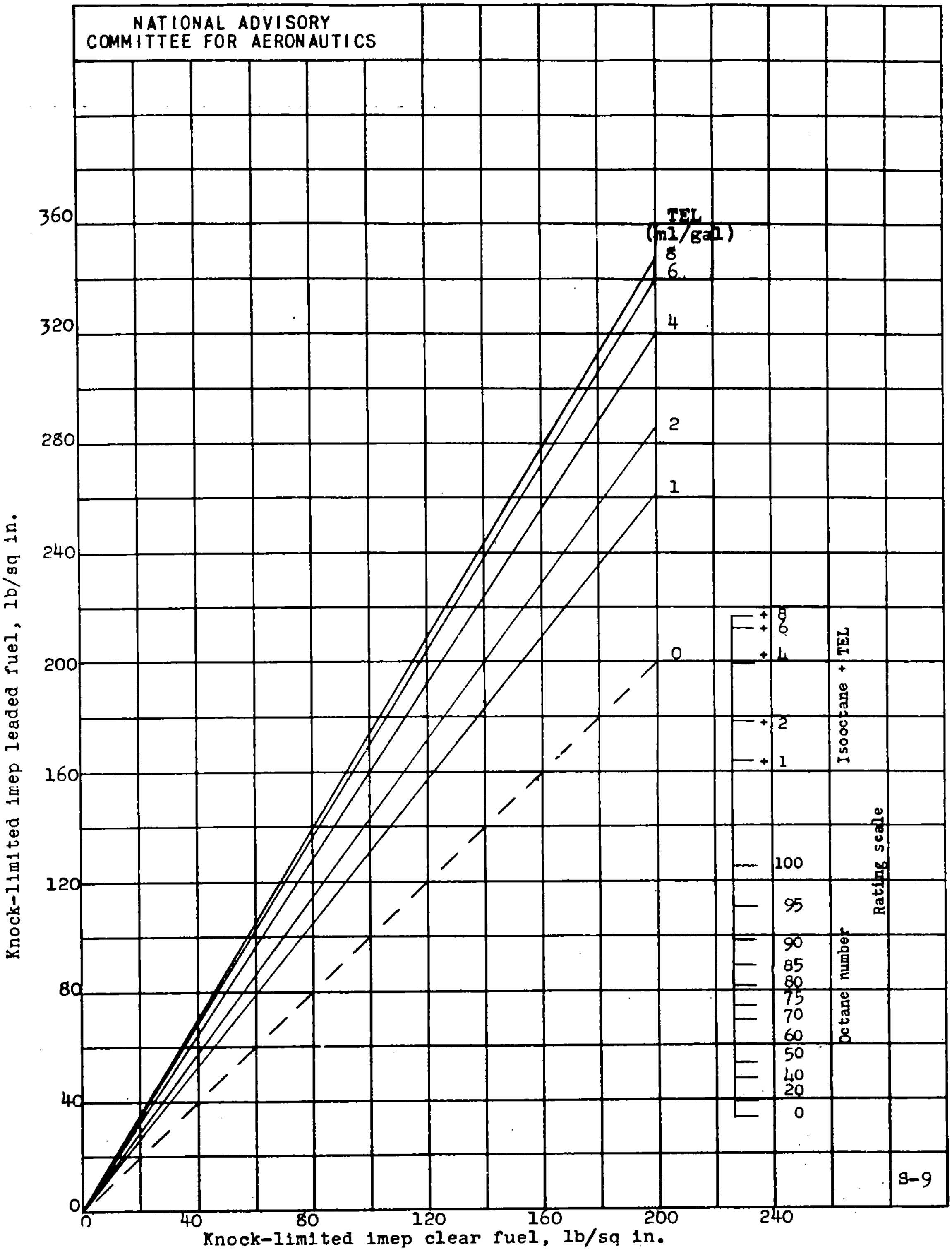


(c) Fuel-air ratio, 0.10.
Figure 6. - Concluded.

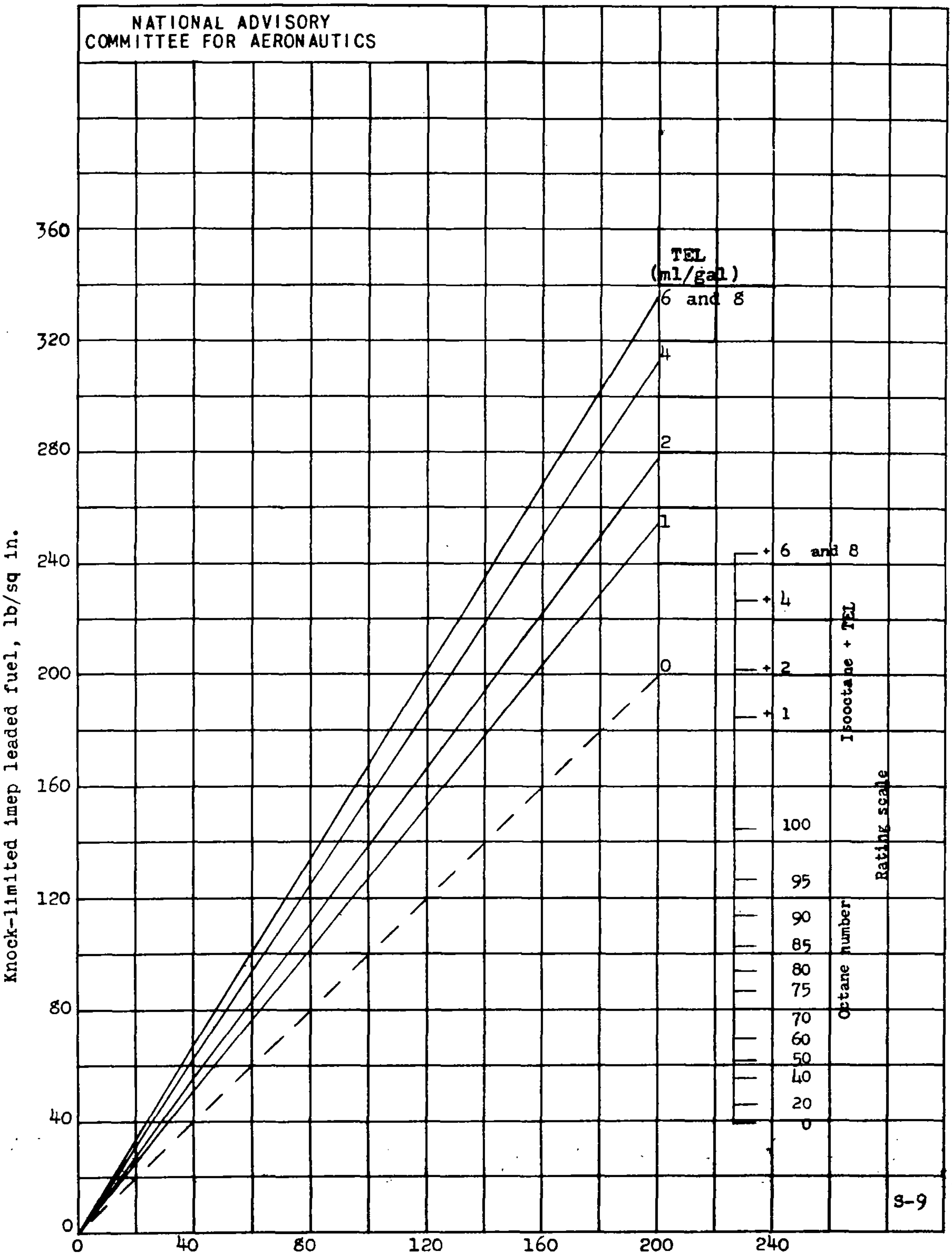


(a) Fuel-air ratio, 0.07.

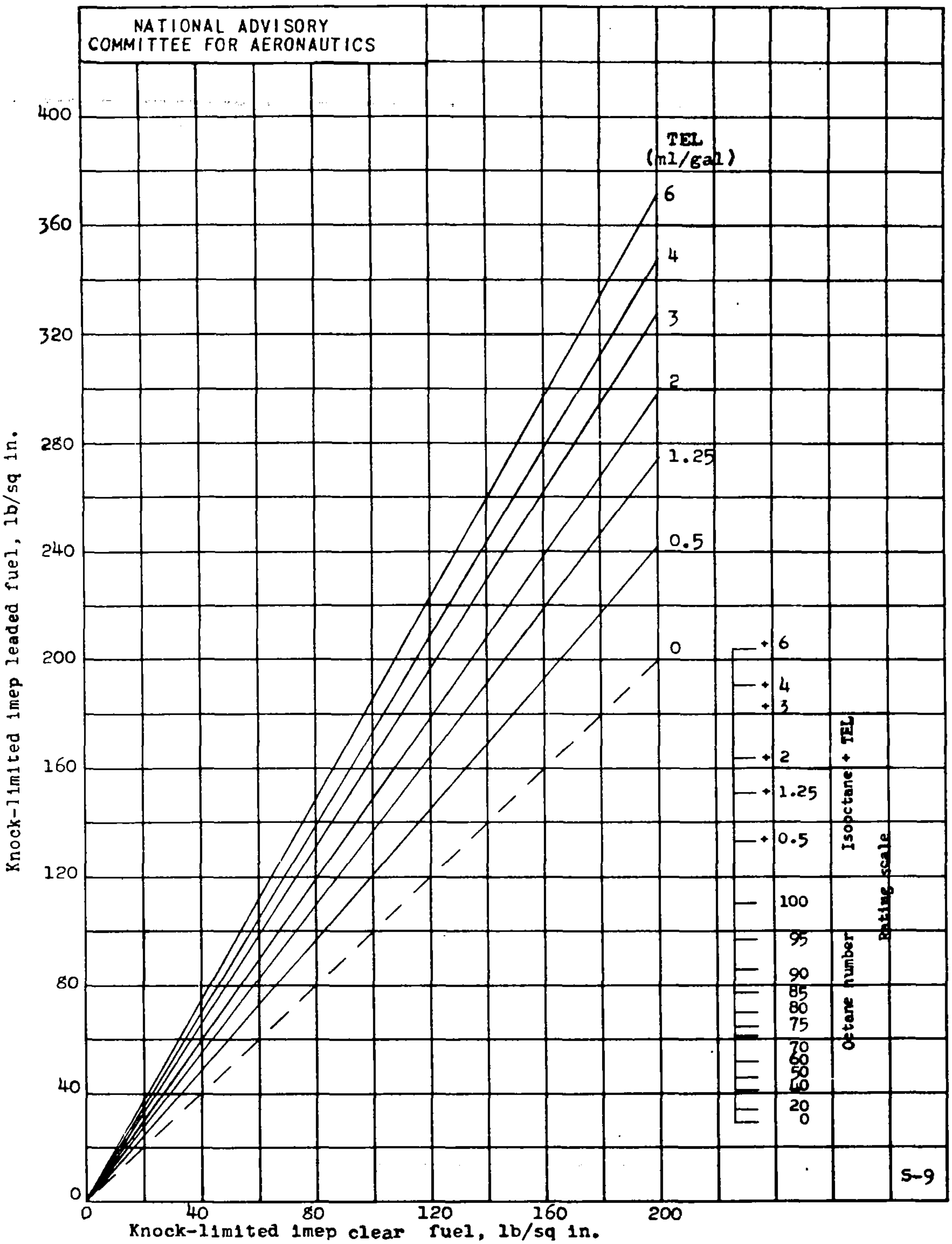
Figure 7. - Lead-susceptibility charts for paraffinic fuels at different fuel-air ratios. CFR engine; inlet-air temperature, 250° F; spark advance, 35° B.T.C.; compression ratio, 7.0; engine speed, 2000 rpm; inlet-coolant temperature, 250° F.



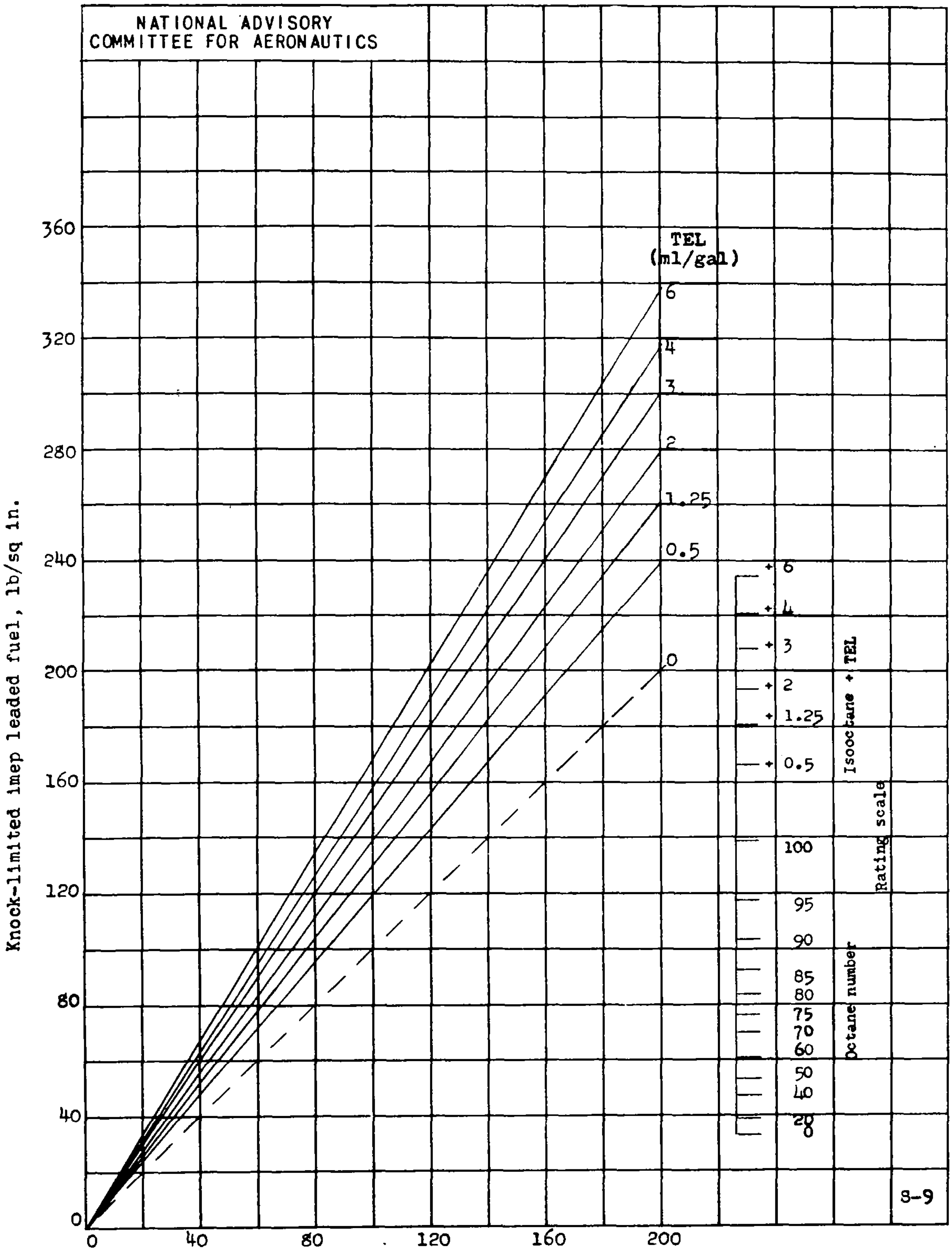
(b) Fuel-air ratio, 0.085.
Figure 7. - Continued.



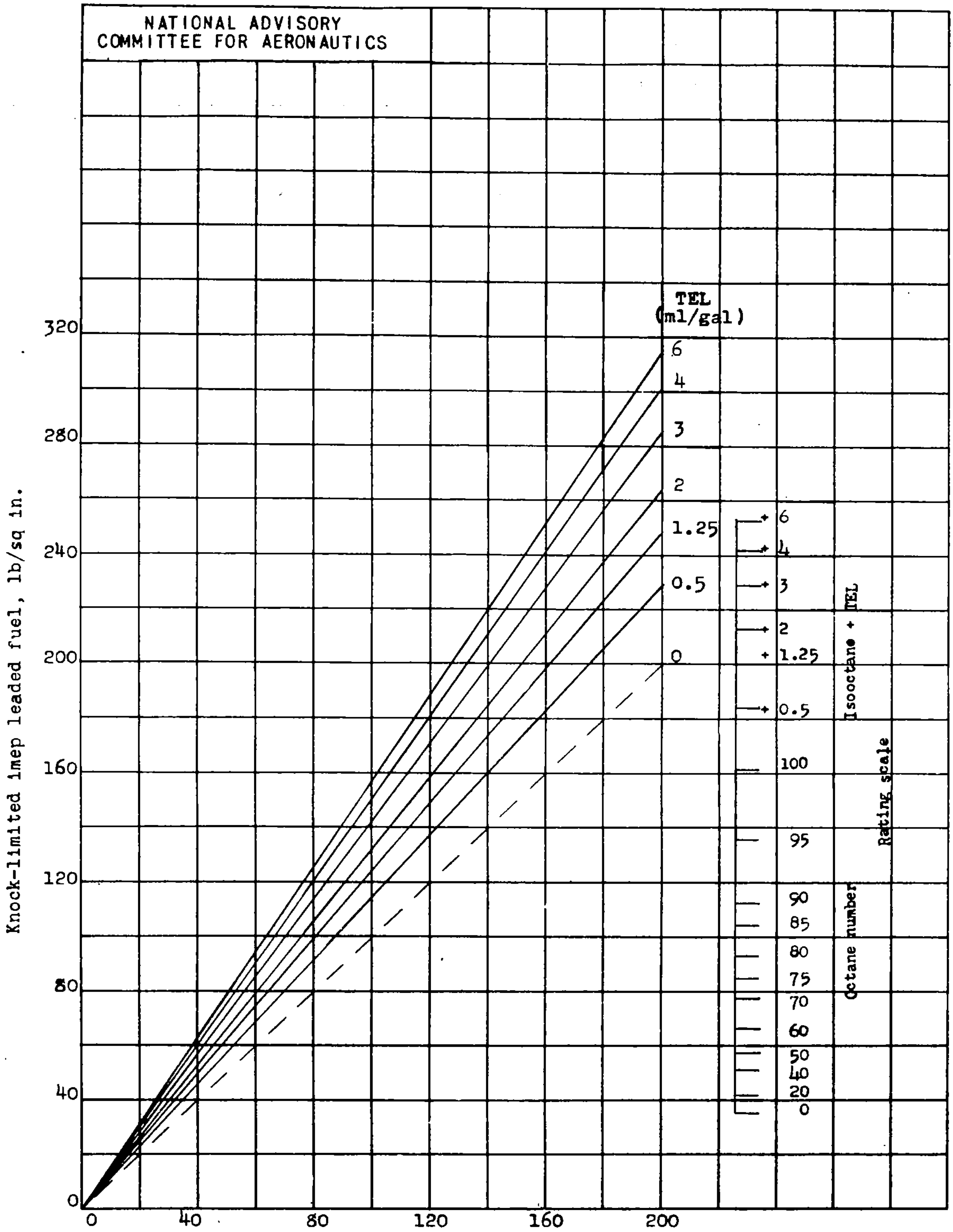
(c) Fuel-air ratio, 0.10.
Figure 7. - Concluded.



(a) Fuel-air ratio, 0.07.
Figure 8. - Lead-susceptibility charts for F-4 rating method at different fuel-air ratios.



(b) Fuel-air ratio, 0.085.
Figure 8. - Continued.



(c) Fuel-air ratio, 0.10.
Figure 8. - Concluded.

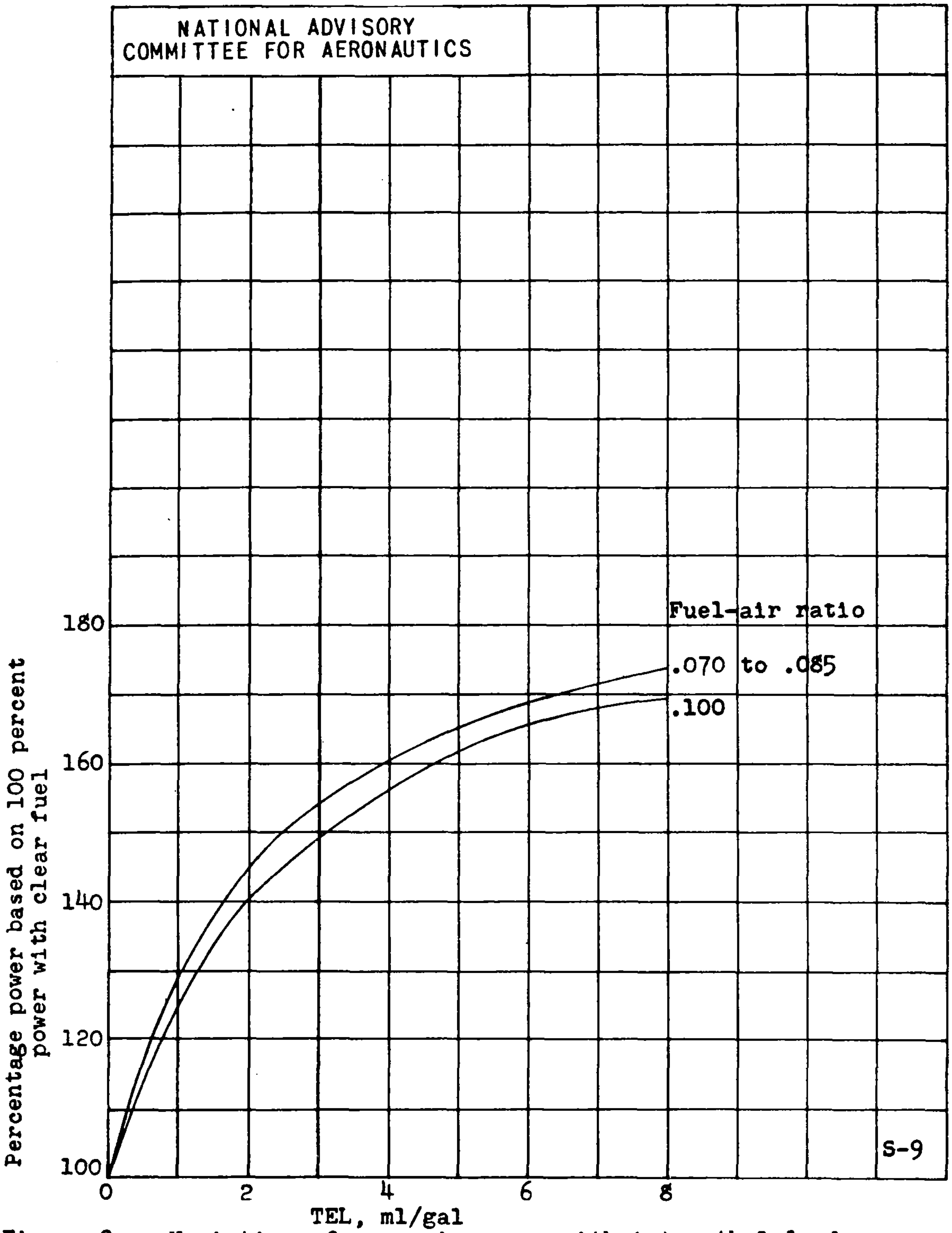


Figure 9. - Variation of power increase with tetraethyl-lead concentration for paraffinic fuels. CFR engine; inlet-air temperature, 250° F; spark advance, 35° B.T.C.; compression ratio, 7.0; engine speed, 2000 rpm; inlet-coolant temperature, 250° F.

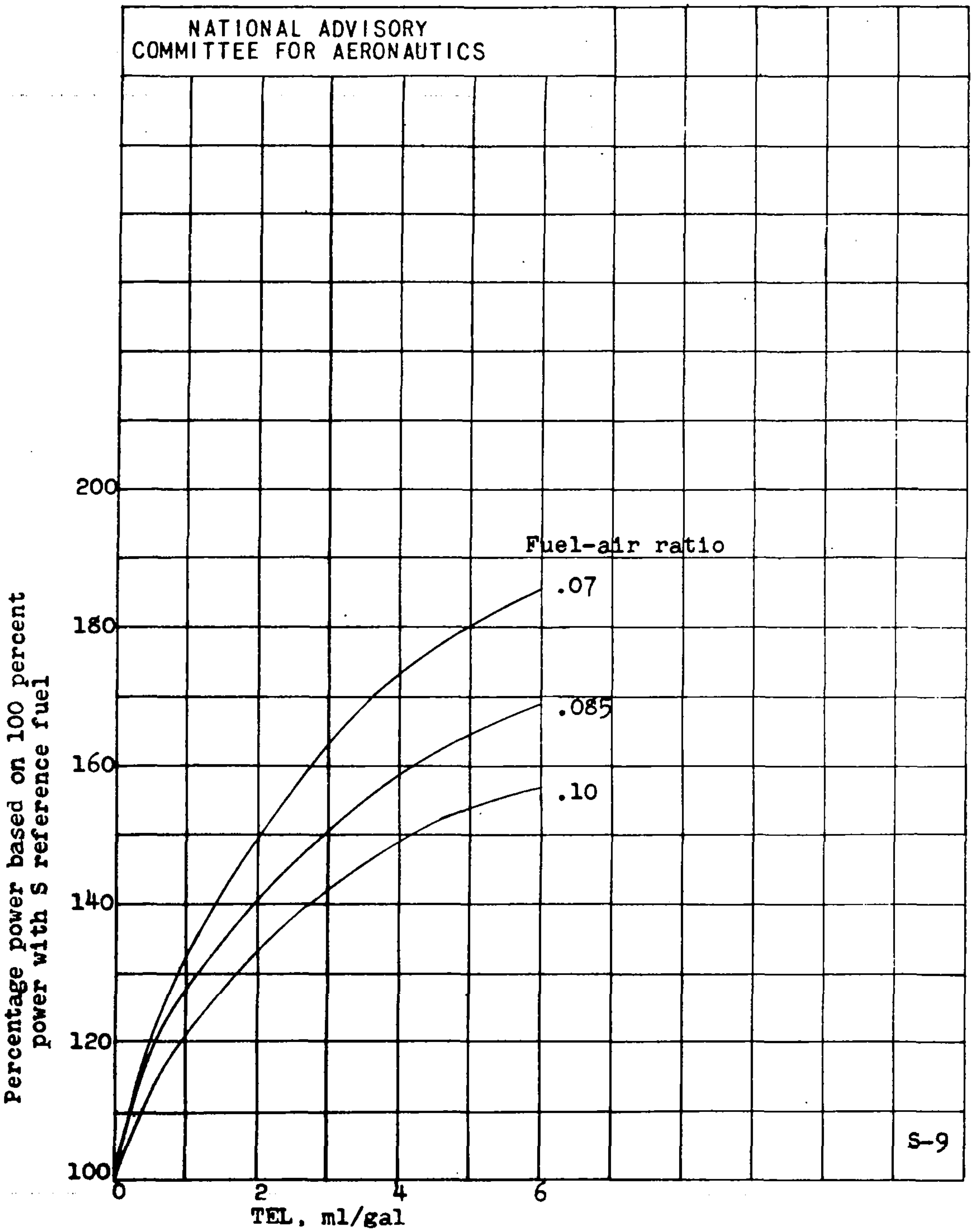
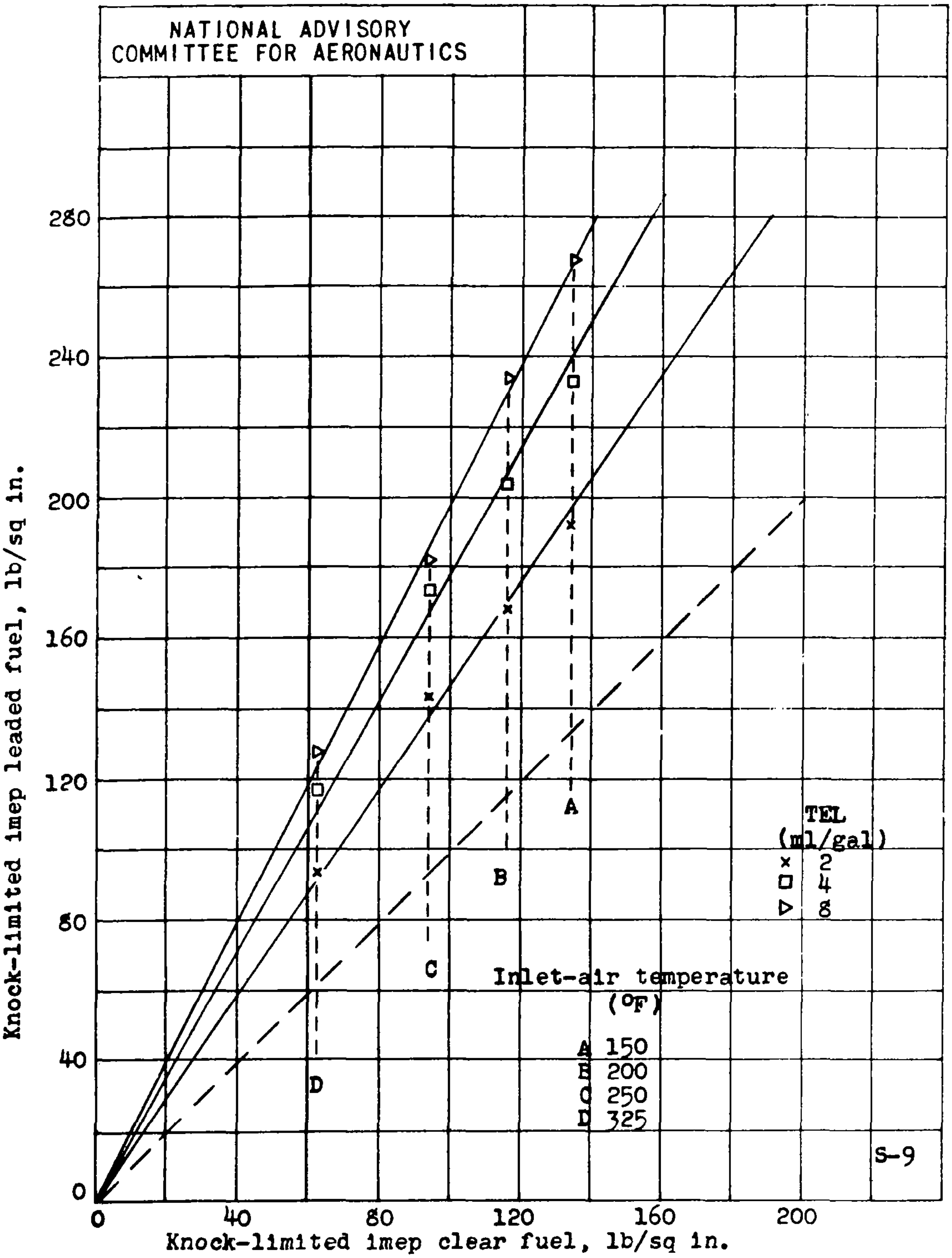
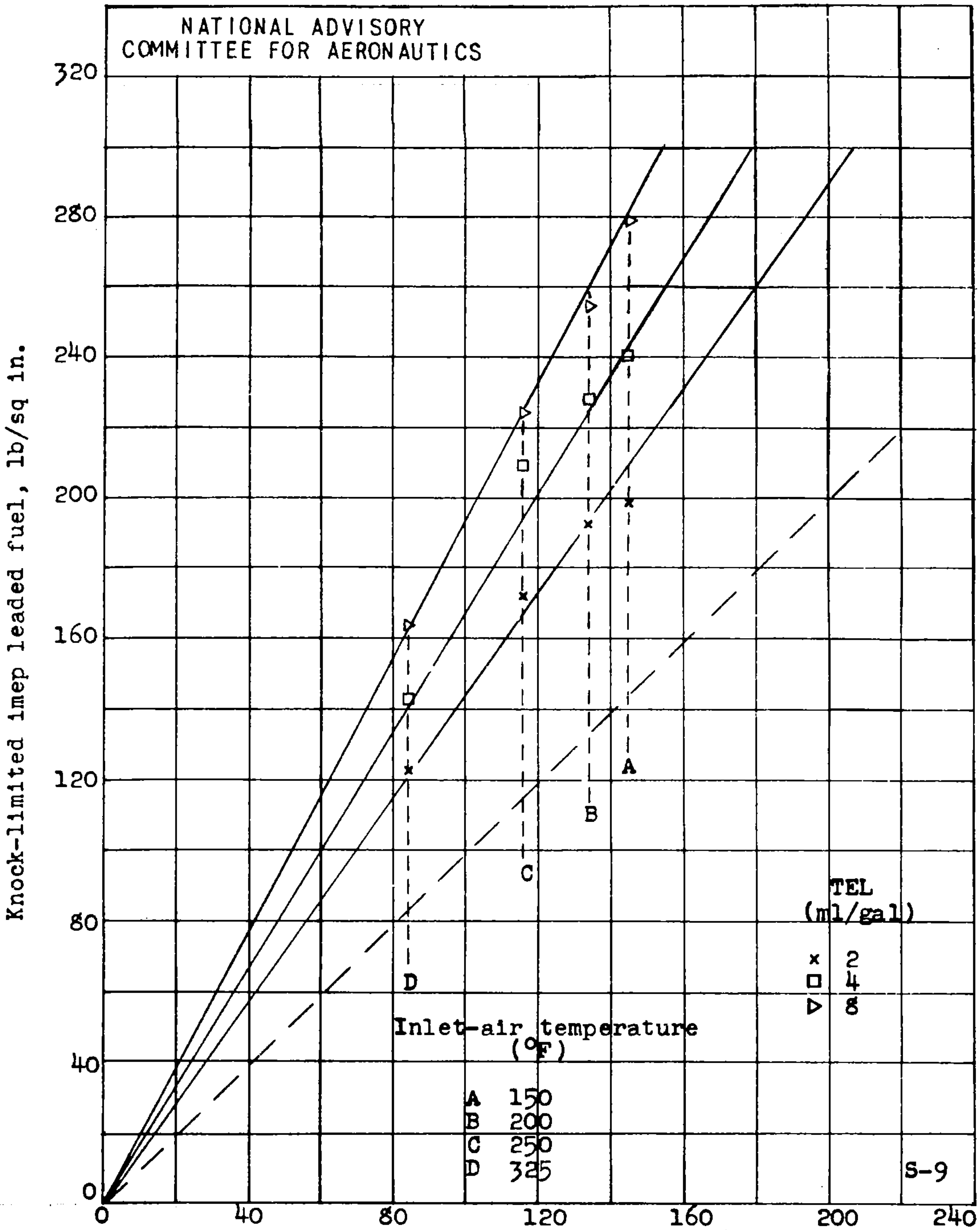


Figure 10. - Variation of power increase with tetraethyl-lead concentration for S reference fuel as determined by the F-4 rating method.

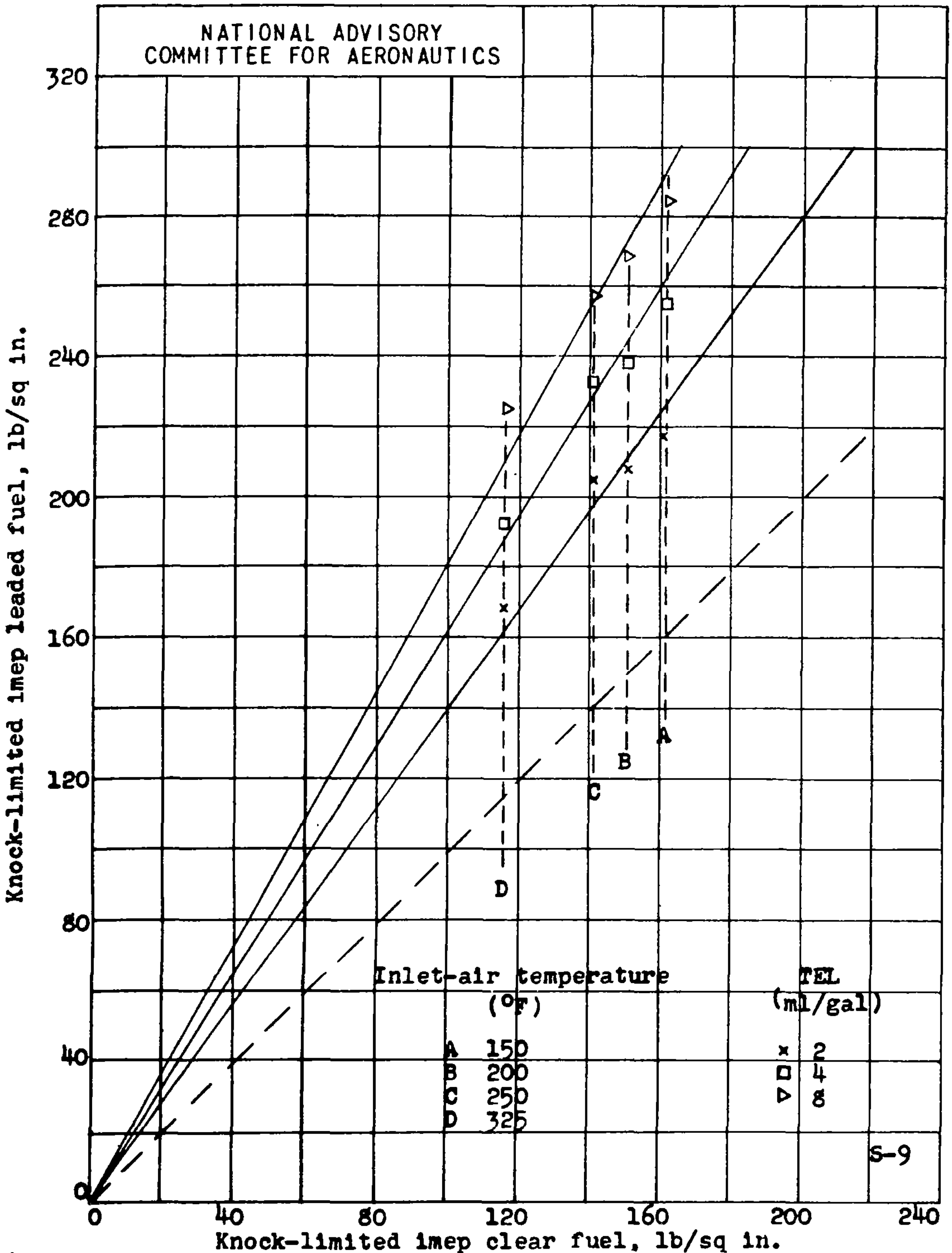


(a) Fuel-air ratio, 0.07.

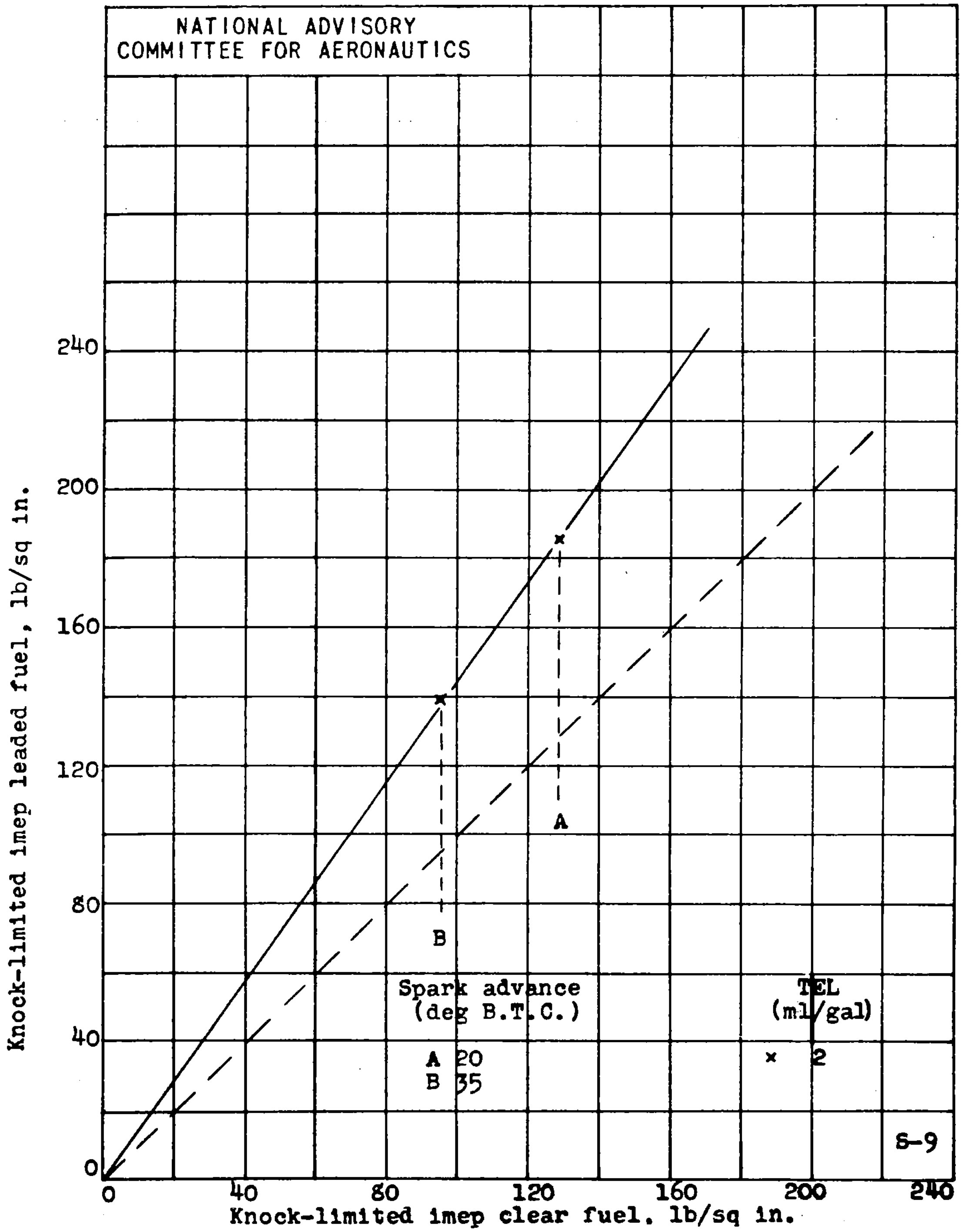
Figure 11. - Effect of inlet-air temperature on the lead susceptibility of S-3 reference fuel at different fuel-air ratios. CFR engine; spark advance, 35° B.T.C.; compression ratio, 7.0; engine speed, 2000 rpm; inlet-coolant temperature, 250° F.



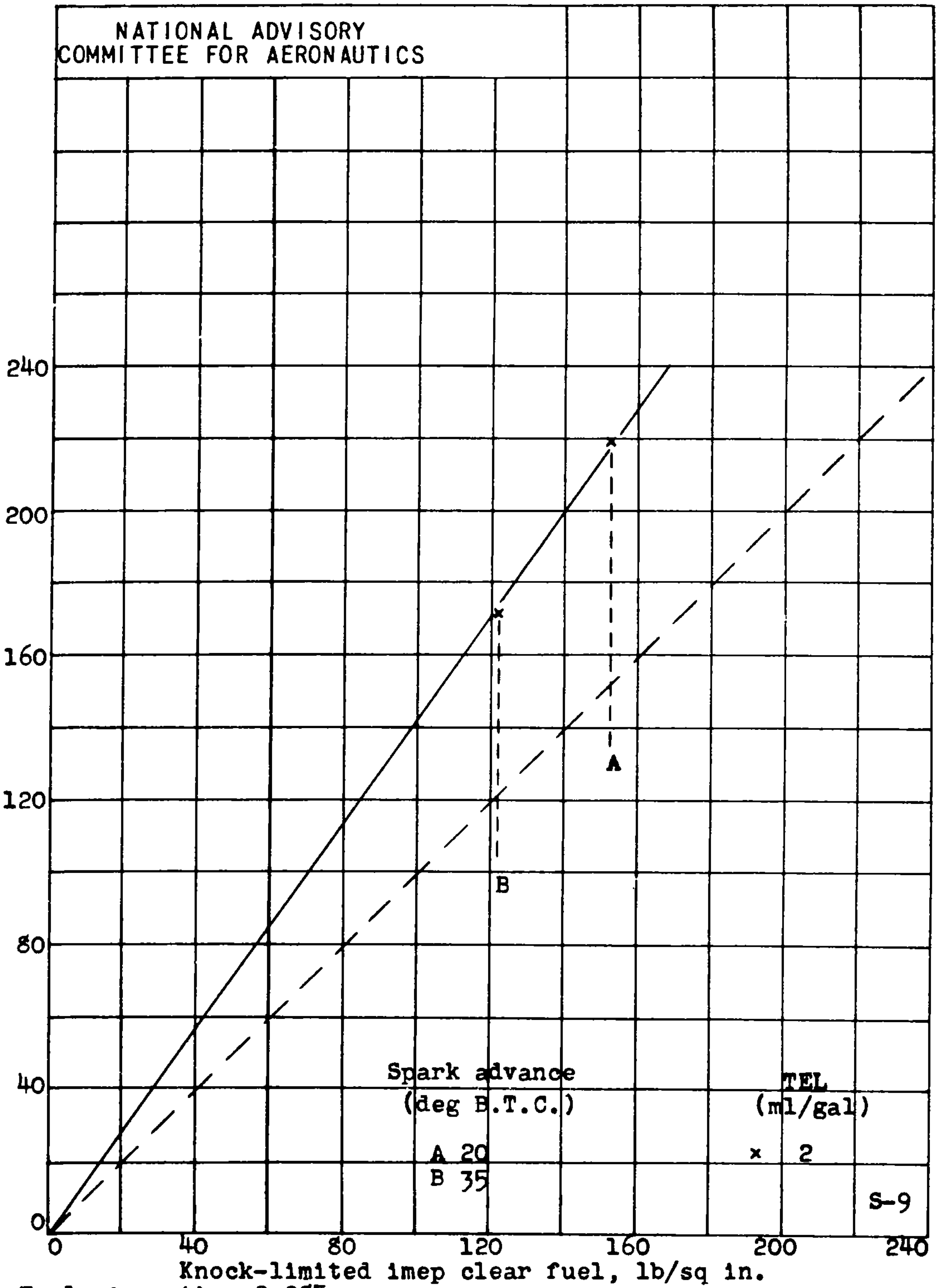
(b) Fuel-air ratio, 0.085.
Figure 11. - Continued.



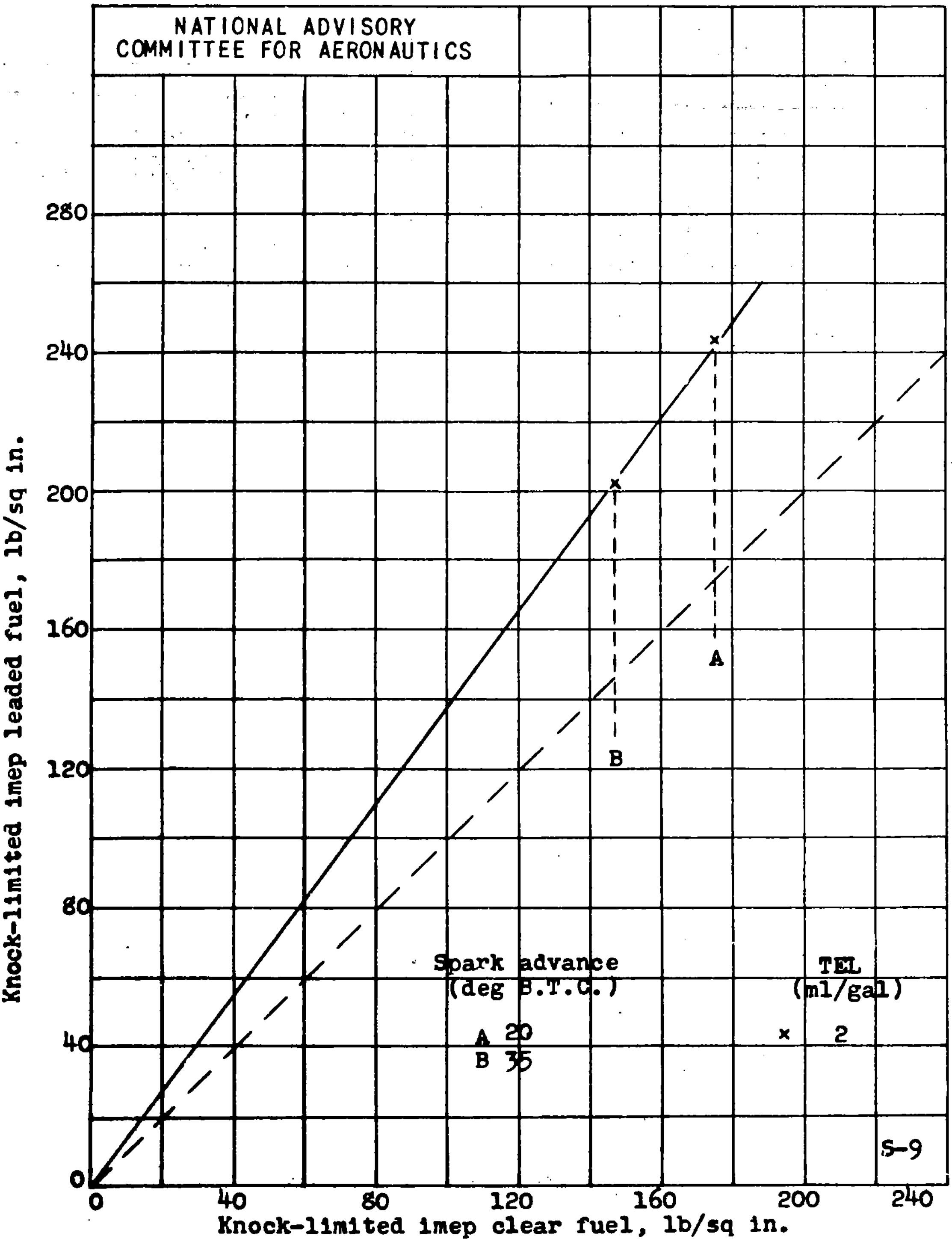
(c) Fuel-air ratio, 0.10.
Figure 11. - Concluded.



(a) Fuel-air ratio, 0.07.
Figure 12. - Effect of spark advance on the lead susceptibility of S-3 reference fuel at different fuel-air ratios. CFR engine; inlet-air temperature, 250° F; compression ratio, 7.0; engine speed, 2000 rpm; inlet-coolant temperature, 250° F.



(b) Fuel-air ratio, 0.085.
Figure 12. - Continued.



(c) Fuel-air ratio, 0.10.
Figure 12. - Concluded.

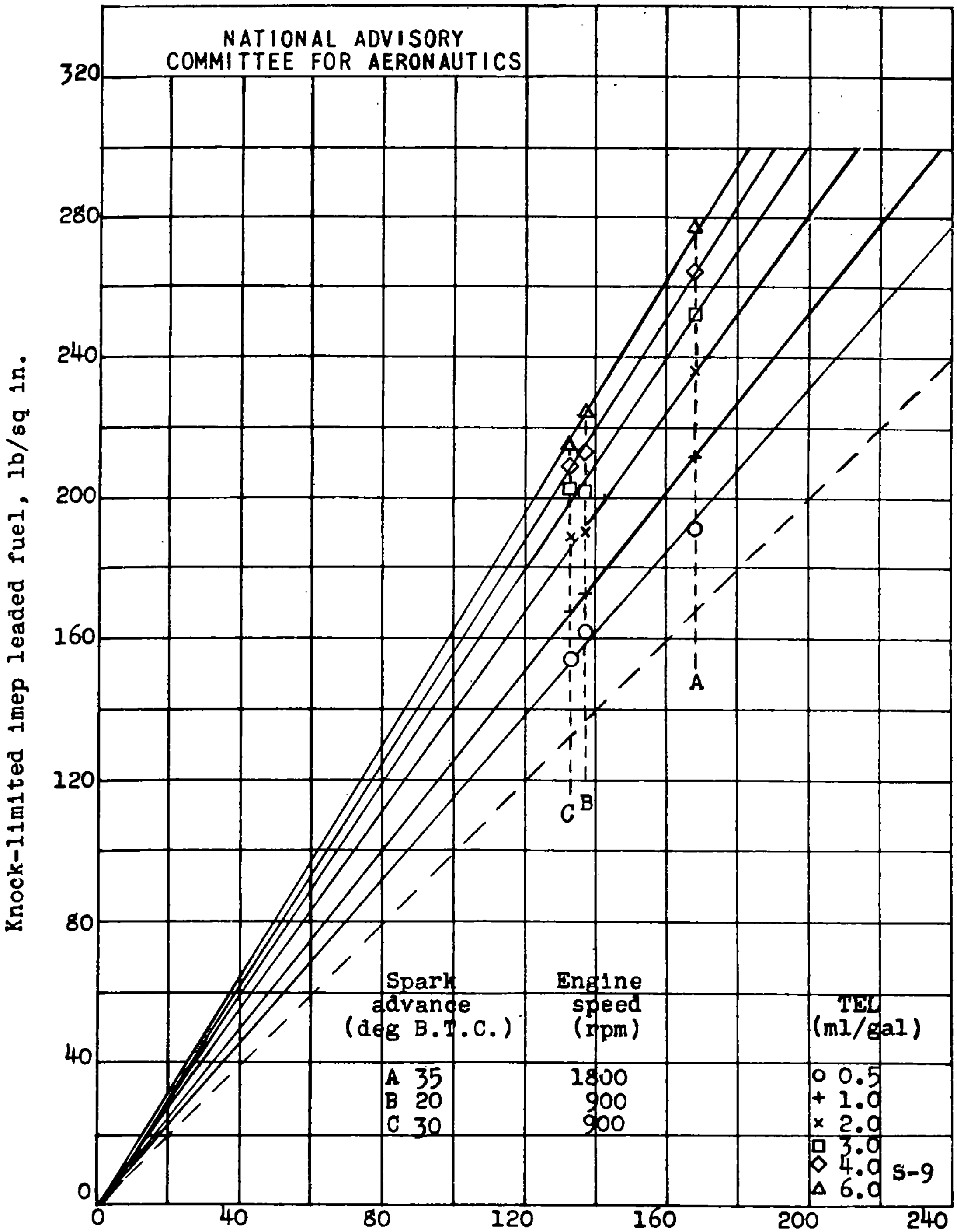


Figure 13. - Effect of engine speed and spark advance on the lead susceptibility of S-1 reference fuel. 17.6 engine; inlet-air temperature, 225° F; compression ratio, 5.6; inlet-coolant temperature, 300° F; fuel-air ratio, approximately 0.07. (Courtesy of the Ethyl Corporation.)