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ENGINE AND INSPECTION TESTS OF METHYL tert-BUTYL ETHER AS A COMPONENT OF AVIATION FUEL

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WASHINGTON

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SUMMARY

The suitability of methyl tert-butyl ether as a component of aviation fuel from considerations of knock-limited performance tests and laboratory inspection tests was investigated. Knock-limited performance data were obtained from tests on the 17.6 engine under supercharged conditions with fuel blends containing 10 and 20 percent methyl tert-butyl ether. Blends were tested at engine speeds of 1800 and 2700 rpm and inlet-air temperatures of 150° and 250° F. Knock-limited performance data for the blends were compared with similar data for AN-F-28 (130 grade) and AN-F-29 (140-P) aviation fuels.

Knock-limited performance data were also obtained on a full-scale aircraft-engine cylinder with a blend containing 10 percent methyl tert-butyl ether. Tests were made at an engine speed of 2000 rpm and an inlet-air temperature of 210° F and also at an engine speed of 2500 rpm and an inlet-air temperature of 250° F. Inspection data for two blends containing methyl tert-butyl ether were compared with data for AN-F-28 and AN-F-29 fuels.

The following results were obtained in this investigation: At all conditions examined, data from both small-scale and full-scale engines indicated that methyl tert-butyl ether is a satisfactory blending agent for improving lean- and rich-mixture knock-limited performance. Inspection data indicated that the amount of methyl tert-butyl ether that can be added to aviation fuels will be limited by the effects of the ether on the specified heat of combustion. It was estimated that a 10-percent addition of this ether will decrease the heat of combustion of an aviation fuel 1 to 2 percent. The addition of methyl tert-butyl ether to the base blends did not seriously lower the A.S.T.M. distillation temperatures.

INTRODUCTION

Supercharged tests made by the Shell Development Company, the Ethyl Gasoline Corporation, the Army Air Forces, Materiel Command, and the NACA have indicated that methyl tert-butyl ether has better antiknock characteristics than current aviation fuels in the complete range of fuel-air ratios. For this reason additional tests were conducted at the Aircraft Engine Research Laboratory of the NACA between April 1943 and January 1944 to provide information on the effect of engine speed and inlet-air temperature on blends of methyl tert-butyl ether with aviation blending stocks. Particular consideration was given to the possibilities of using this material to increase the lean-mixture as well as the rich-mixture knock-limited performance of aviation fuel.

Small-scale-engine tests were made with fuels prepared by blending various concentrations of methyl tert-butyl ether with aviation alkylate blending agent, straight-run motor gasoline, or reference fuel. The engine data for these fuels were compared with data obtained for two current aviation fuels. Knock-limited performance data were also obtained in a full-scale aircraft-engine cylinder on a reference-fuel blend containing methyl tert-butyl ether.

Results of all tests are presented in standard knock-limited performance curves and in tabular form. Inspection data were obtained on several blends for comparison with standard military aviation fuels.

APPARATUS AND TEST CONDITIONS

Fuel blends and inspection data. - Small-scale-engine tests of the following blends were made:

Blend	Composition
A	60 percent 72-octane straight-run motor fuel plus 40 percent 91-octane aviation alkylate blending agent plus 4 ml TEL per gallon
B	90 percent blend A plus 10 percent (methyl tert-butyl ether plus 4 ml TEL per gal)
C	80 percent S-2 reference fuel plus 20 percent M-3 reference fuel plus 4 ml TEL per gallon

Blend	Composition
D	80 percent blend C plus 20 percent (methyl *tert*-butyl ether plus 4 ml TEL per gal)
E	AN-F-28 (130 grade) aviation fuel
F	AN-F-29 (140-P) aviation fuel
G	80 percent blend F plus 20 percent methyl *tert*-butyl ether

Full-scale-engine tests were made on the following blends:

Blend	Composition
H	85 percent S-3 reference fuel plus 15 percent M-3 reference fuel plus 4 ml TEL per gallon
I	90 percent blend H plus 10 percent (methyl *tert*-butyl ether plus 4 ml TEL per gal)

Inspection data consisting of tetraethyl-lead concentrations, specific gravities, Reid vapor pressures, heats of combustion, and A.S.T.M. distillations were determined for blends B, E, F, and G.

Small-scale-engine tests. - Small-scale-engine tests were made on the 17.6 engine described in reference 1. All tests with this engine were knock-limited and were made at the following conditions:

Engine speed, rpm	1800, 2700
Compression ratio	7.0
Inlet-coolant temperature, °F	250
Inlet-air temperature, °F	150, 250
Spark advance, deg B.T.C.	40

Full-scale-engine tests. - Knock-limited performance data were obtained on an R-1820 G200 cylinder. A detailed description of the engine installation is included in reference 2. All full-scale-engine tests were made at the following conditions, as recommended by the Coordinating Research Council:

Engine speed, rpm	2000, 2500
Compression ratio	7.3
Inlet-air temperature, °F	210, 250
Spark advance, deg B.T.C.	20/20

The cooling-air flow was set to give a rear spark-plug-bushing temperature of 365° F at a fuel-air ratio of 0.10 and a brake mean effective pressure of 140 pounds per square inch.

RESULTS AND DISCUSSION

Small-Scale-Engine Data

Accuracy of results. - At intervals throughout the test program the 17.6 engine operation was checked with S-2 reference fuel at an engine speed of 2700 rpm and an inlet-air temperature of 250° F. Data for three representative tests covering an operating period of 17 days are presented in figure 1.

Reference fuels. - Knock-limited performance curves for S-2 reference fuel plus various concentrations of tetraethyl lead are shown at three sets of engine conditions in figure 2. The performance numbers corresponding to the concentrations of tetraethyl lead are given on the figure. These curves were used for rating other blends in terms of performance numbers. The data for indicated specific fuel consumptions indicate that the fuel consumption at any fuel-air ratio is not dependent on the knock-limited inlet-air pressure.

Service-type fuels. - The results of tests on AN-F-28 and AN-F-29 aviation fuels are presented in figure 3. These fuels were tested for comparison with prepared blends containing methyl tert-butyl ether.

Engine performance of blends. - The effect of inlet-air temperature and engine speed on the knock-limited performance of blends A and B is shown in figure 4. Comparison of the knock-limited performance curves of blend A and AN-F-28 fuel shows that blend A is approximately representative of current aviation gasoline. The methyl tert-butyl ether increased the knock limit of the base fuel over the complete range of fuel-air ratios, as shown by comparing blends A and B in figure 4. This fact is of particular interest because of the need of fuel blending agents that will increase the knock-limited performance at lean mixtures as well as at rich mixtures under all engine operating conditions. The addition of the ether did not increase the indicated specific fuel consumption except in the lean region for the conditions shown in figure 4(c); the lowering of the heat of combustion by a 10-percent addition of ether, however, was estimated to be approximately 1 to 2 percent and consequently lies within the experimental accuracy of the data.

Results that were obtained with blends C and D are shown in figure 5. In this case the gains in knock-limited performance caused by the addition of 20 percent ether were quite appreciable and again appeared over the whole range of fuel-air ratios investigated. These data indicate that the use of methyl tert-butyl ether as an aviation blending agent will result in an increase in the knock limit over a wide range of engine conditions. Changes in the indicated specific fuel consumption attributable to the addition of ether are noticeable in both the rich and lean regions.

The effect of adding 20 percent of methyl tert-butyl ether to AN-F-29 fuel is shown by blends F and G in figure 6. This addition of ether reduced the tetraethyl-lead content from 4 ml per gallon to 3.4 ml per gallon. The gains here were not so great as were obtained when 20 percent of the methyl tert-butyl ether was added to blend C (fig. 5) but again the increase existed over the complete range of fuel-air ratios. The indicated specific fuel consumption showed (within the accuracy of the data) an increase by the addition of ether for fuel-air ratios lower than 0.065; for a constant knock-limited mean effective pressure, however, the ether blend had a lower indicated specific fuel consumption than pure AN-F-29 fuel.

Table I gives the estimated performance numbers at various fuel-air ratios from 0.065 to 0.10. These performance numbers were determined from a comparison of the knock-limited performance curves for fuel blends with the knock-limited performance curves for S-2 reference fuel presented in figure 2. Tables II and III summarize temperature and speed sensitivities of the blends tested in the 17.6 engine; sensitivities are expressed as percentage increases in indicated mean effective pressure for a given change in engine conditions.

Full-Scale-Engine Data

Knock-limited performance tests made in the full-scale-engine cylinder are presented in figure 7. Data for the base fuel (blend H) are compared with the performance of blend I containing 10 percent methyl tert-butyl ether.

The increase in knock-limited power caused by the addition of 10 percent ether was very similar to the gain determined in the small-scale-engine tests, as shown in table I. Data for the indicated specific fuel consumption (fig. 7) show a slight increase in fuel consumption at lean fuel-air ratios.

Inspection Data

Inspection data for blends B, E, F, and G are presented in table IV. Fuel prepared by adding 20 percent methyl tert-butyl ether to AN-F-29 (blend G) met all the specification requirements presented with the exception of heat of combustion. Blend B containing 10 percent ether met the specification limits. In this case, however, the heat of combustion was not determined.

The data presented in table IV indicate that the amount of ether which can be added to aviation fuels will be limited by the effects of the ether on the specified heat of combustion. Although the addition of methyl tert-butyl ether to the base blends lowered the distillation temperatures, this effect should offer no serious limitation to the use of the ether in aviation fuels.

SUMMARY OF RESULTS

Results obtained from inspection tests and small- and full-scale-engine knock-limited performance tests on blends containing methyl tert-butyl ether were as follows:

1. At all conditions examined, both small-scale- and full-scale-engine data indicated that methyl tert-butyl ether is a satisfactory blending agent for improving lean- and rich-mixture knock-limited performance.

2. Inspection data indicated that the amount of methyl tert-butyl ether that can be added to aviation fuels will be limited by the effects of the ether on the specified heat of combustion. It was estimated that a 10-percent addition of this ether will decrease the heat of combustion of an aviation gasoline 1 to 2 percent.

3. The addition of methyl tert-butyl ether to the base blends did not seriously lower the A.S.T.M. distillation temperatures.

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REFERENCES

1. Barnett, Henry C., and Slough, James W., Jr.: Supercharged-Engine Knock Tests of Methyl tert-Butyl Ether. NACA ACR No. E4H10, 1944.

2. Jones, Anthony W., and Bull, Arthur W.: Knock-Limited Performance of Pure Hydrocarbons Blended with a Base Fuel in a Full-Scale Aircraft-Engine Cylinder. I - Eight Paraffins, Two Olefins. NACA ARR No. E4E25, 1944.

TABLE I - ESTIMATED PERFORMANCE NUMBERS FROM TESTS ON TWO ENGINES AND AT VARIOUS ENGINE CONDITIONS

[Performance numbers from 17.6 engine estimated from fig. 2; performance numbers from full-scale engine estimated from fig. 7; all numbers below 100 represent the percentage power based on 100 percent power with S-2 reference fuel.]

Fuel blend[a] ↓ / Fuel-air ratio →	0.065	0.075	0.08	0.09	0.10
17.6 engine; engine speed, 2700 rpm; inlet-air temperature, 150° F					
A	85	94	101	117	120
B	95	100	112	130	145
C	100	107	109	115	115
D	148	152	156	>160	>160
E	86	92	98	110	124
F	89	97	105	121	133
G	104	107	120	146	-----
17.6 engine; engine speed, 2700 rpm; inlet-air temperature, 250° F					
A	100	100	103	106	111
B	105	108	112	115	120
C	118	122	123	121	117
D	155	154	153	154	160
E	103	106	107	110	113
F	105	111	112	114	118
17.6 engine; engine speed, 1800 rpm; inlet-air temperature, 150° F					
A	101	110	113	118	121
B	106	121	131	137	137
C	112	113	113	114	114
D	156	>160	>160	>160	>160
E	104	113	123	132	133
F	110	121	137	142	142
Full-scale engine; engine speed, 2000 rpm; inlet-air temperature, 210° F					
H	111	112	111	110	111
I	125	128	131	135	137
Full-scale engine; engine speed, 2500 rpm; inlet-air temperature, 250° F					
H	109	109	109	109	109
I	123	124	125	127	131

[a]For composition of fuel blends, see pp. 2-3.

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TABLE II - PERCENTAGE INCREASE IN INDICATED MEAN EFFECTIVE PRESSURES FOR AN INCREASE OF ENGINE SPEED FROM 1800 RPM TO 2700 RPM AT AN INLET-AIR TEMPERATURE OF 150° F FOR THE 17.6 ENGINE

Fuel-air ratio → / Fuel blend[a] ↓	0.065	0.075	0.08	0.09	0.10
A	7.6	3.5	6.3	16	16
B	4.5	1.0	3.5	11	16
C	5.7	10.7	12.7	16	15
D	0	4.0	6.5	11	17
E	4.0	-3.2	-1.2	1.5	10
F	-2	-8.8	-7.1	0	7

[a]For composition of fuel blends, see pp. 2-3.

TABLE III - PERCENTAGE INCREASE IN INDICATED MEAN EFFECTIVE PRESSURES FOR A DECREASE OF INLET-AIR TEMPERATURE FROM 250° F TO 150° F AT AN ENGINE SPEED OF 2700 RPM FOR THE 17.6 ENGINE

Fuel-air ratio → / Fuel blend[a] ↓	0.065	0.075	0.08	0.09	0.10
A	34	40	40	35	20
B	44	39	34	30	23
C	32	24	18	14	9
D	42	34	33	29	22
E	32	30	29	22	20
F	35	29	29	27	21

[a]For composition of fuel blends, see pp. 2-3.

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TABLE IV - INSPECTION DATA FOR FUEL BLENDS

	AN-F-28 specifi- cations	Fuel blend[a]			
		B	E	F	G
Tetraethyl lead, ml/gal	4.0	4.1	4.1	4.2	[b]3.4
Specific gravity at 60° F	-------	0.710	0.718	0.736	0.739
Reid vapor pressure, lb/sq in.	7.0	6.7	6.3	6.3	6.6
Heat of combustion, Btu/lb	18,700	-----	18,380	18,260	17,850
A.S.T.M. distillation data					
Percentage evaporated	Temperature, °F				
0	------	110	110	110	110
10	167	145	134	154	134
20	------	154	150	169	146
30	------	163	166	184	161
40	167	169	183	196	175
50	221	178	203	212	185
60	------	191	220	229	200
70	------	206	232	244	217
80	------	219	252	262	240
90	293	236	276	284	275
End point	356	294	315	334	319
Residue, percent	1.5	0.8	1.5	1.0	1.0
Loss, percent	1.5	.2	1.5	1.0	.2

[a]For composition of fuel blends, see pp. 2-3.

[b]Estimated value.

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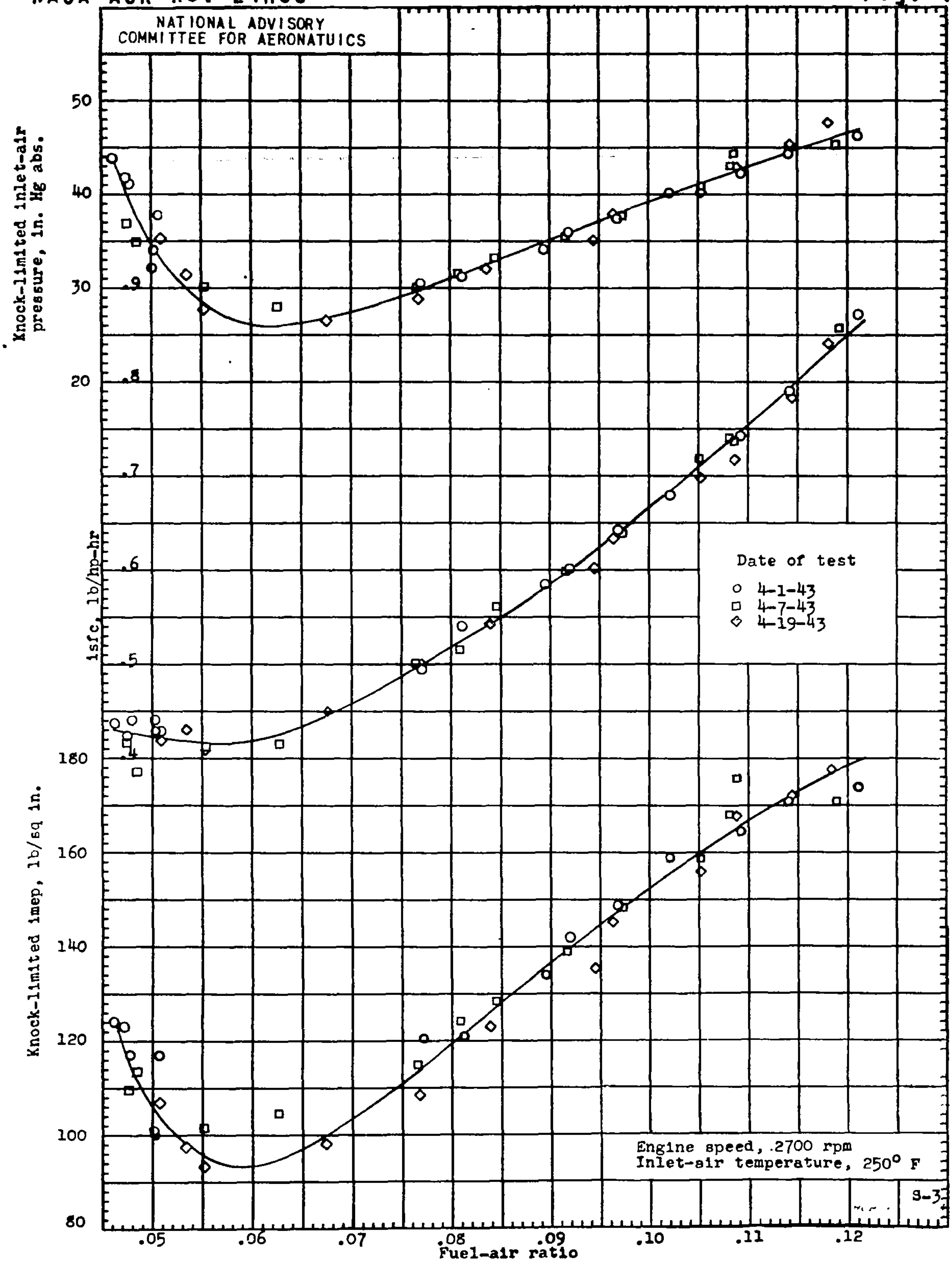
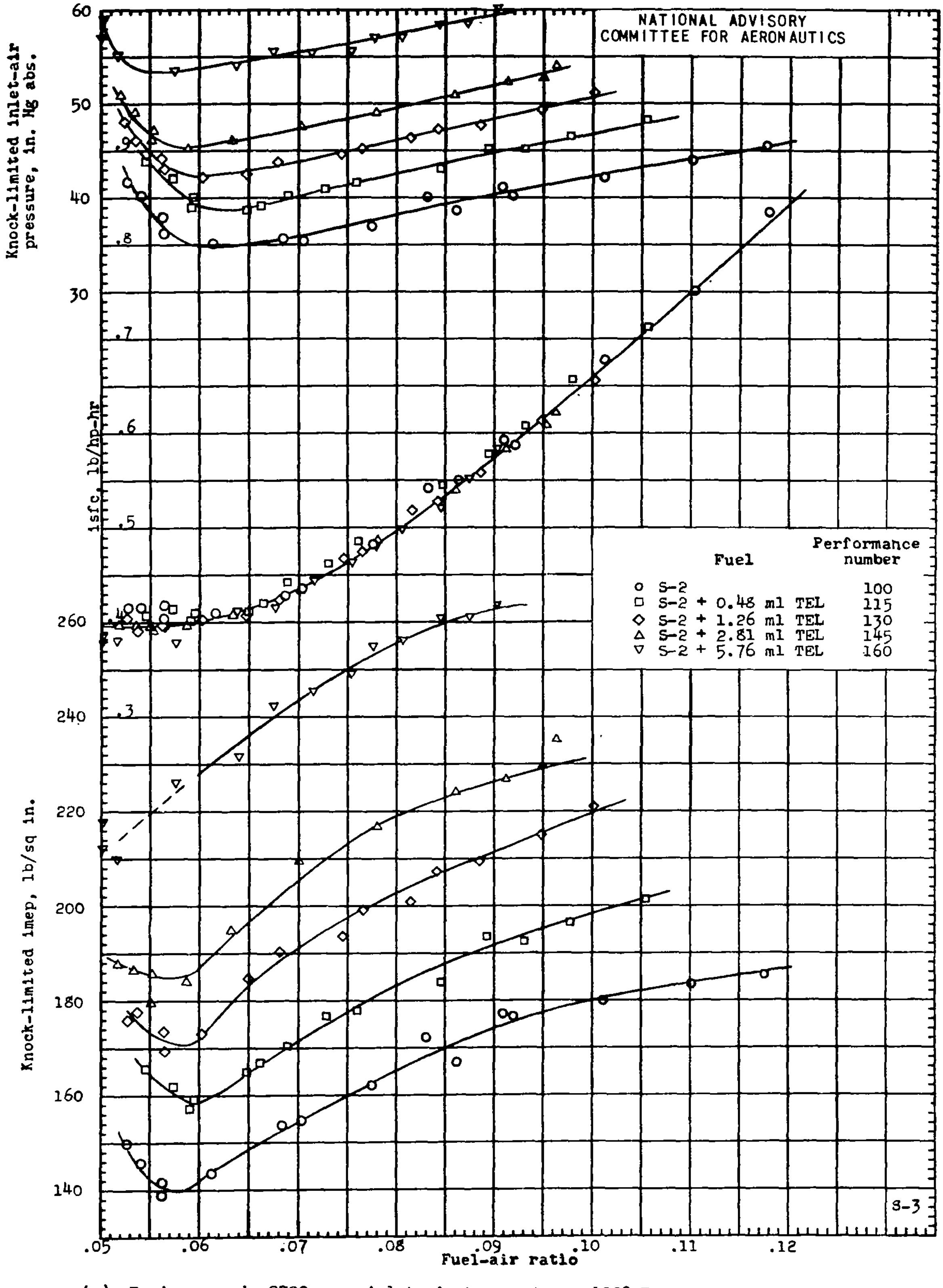
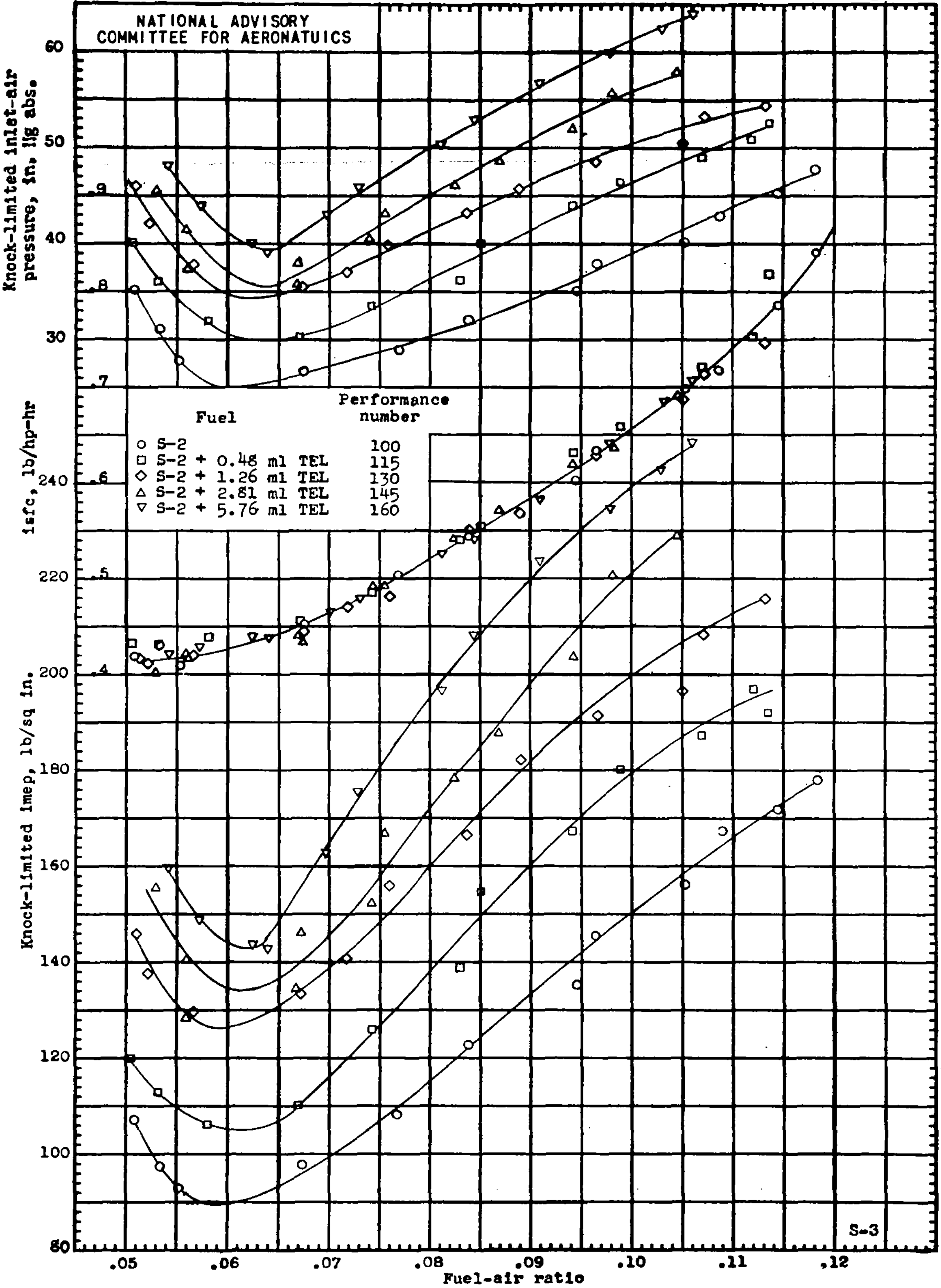


Figure 1. - Check tests on S-2 reference fuel. 17.6 engine; engine speed, 2700 rpm; inlet-air tamperature, 250° F; inlet-coolant temperature, 250° F; spark advance, 40° B.T.C.; compression ratio, 7.0.

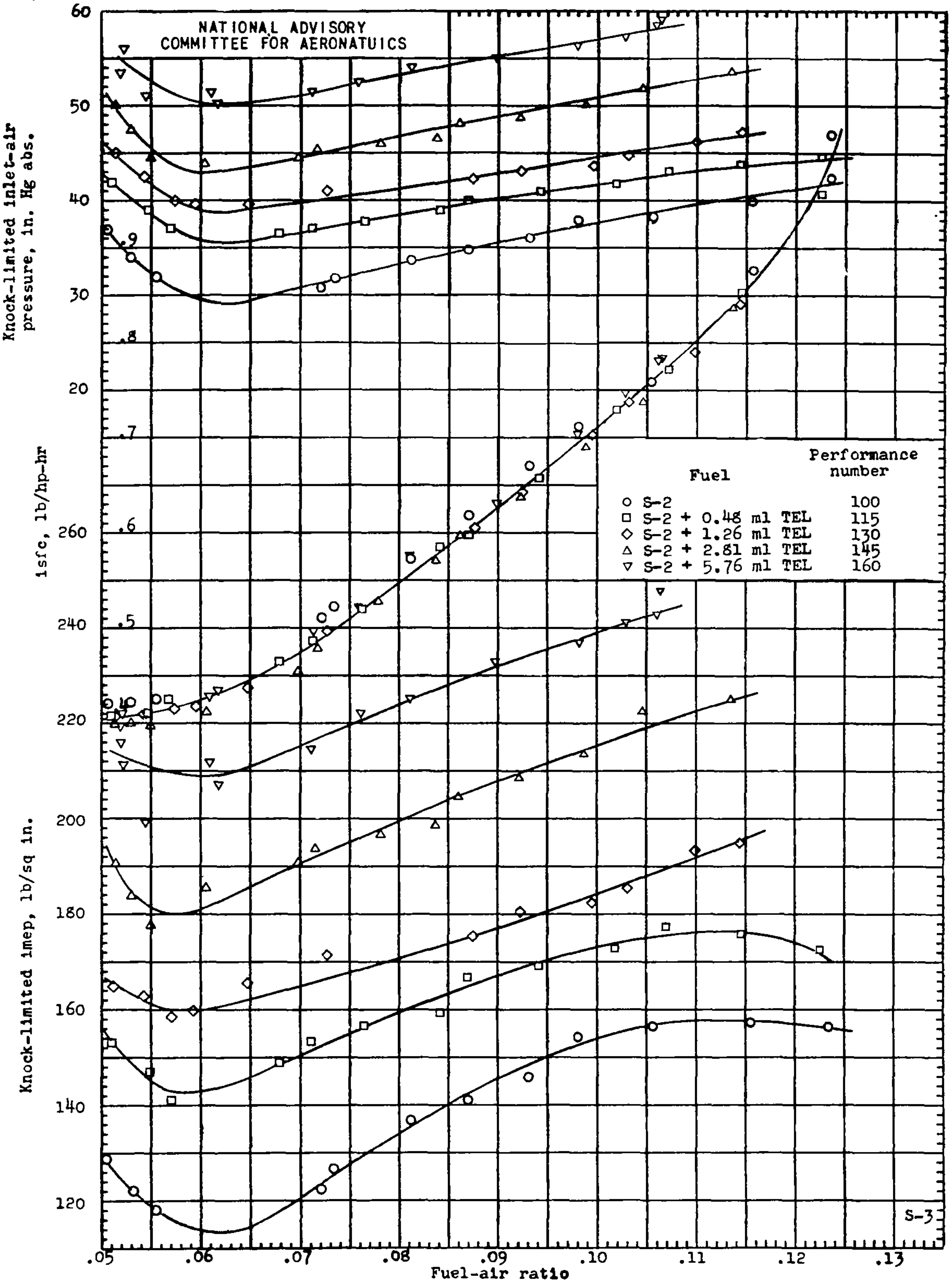


(a) Engine speed, 2700 rpm; inlet-air temperature, 150° F.

Figure 2. - Knock-limited performance of reference fuels. 17.6 engine; spark advance, 40° B.T.C.; compression ratio, 7.0; inlet-coolant temperature, 250° F.

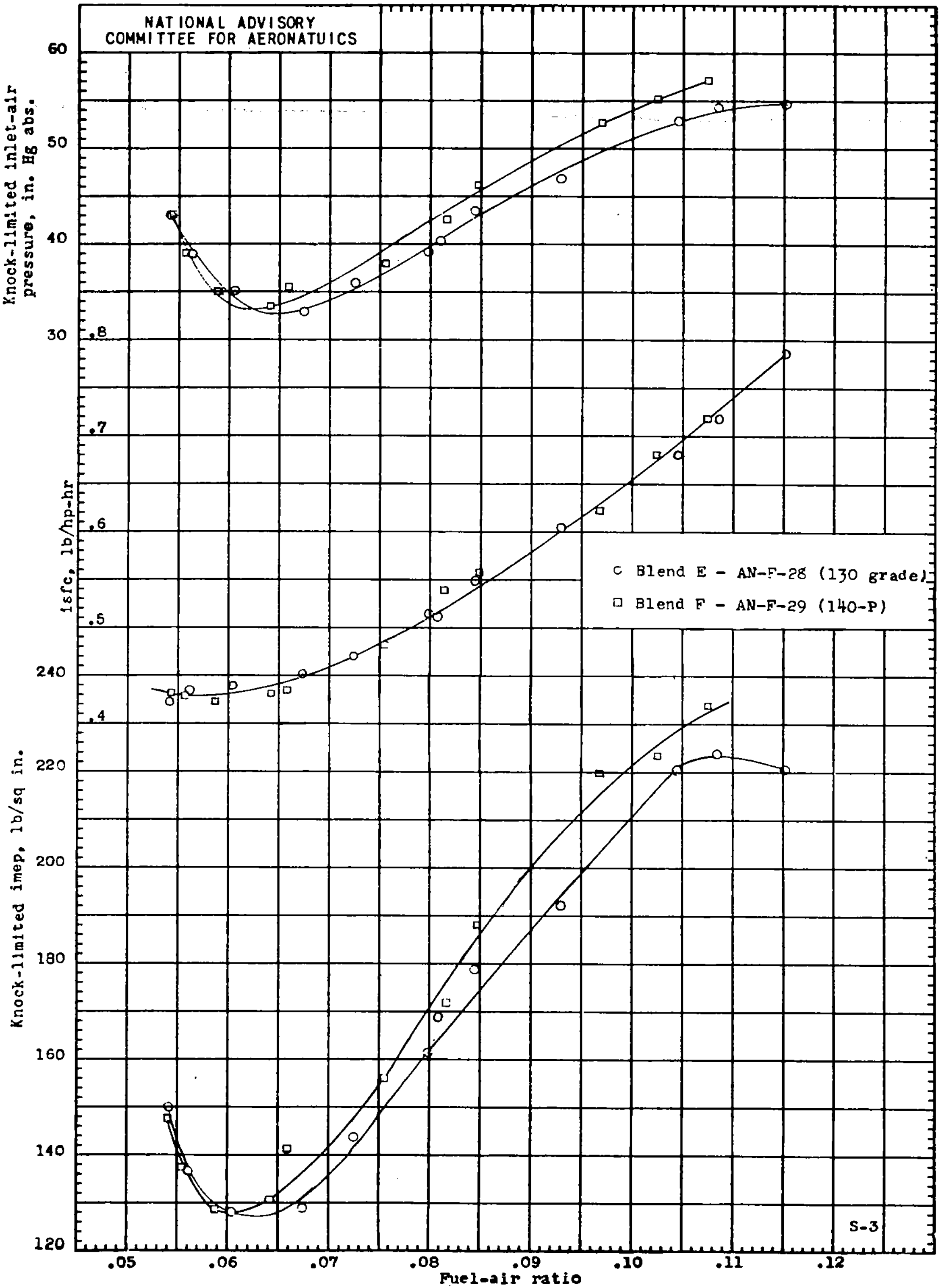


(b) Engine speed, 2700 rpm; inlet-air temperature, 250° F.
Figure 2. - Continued.



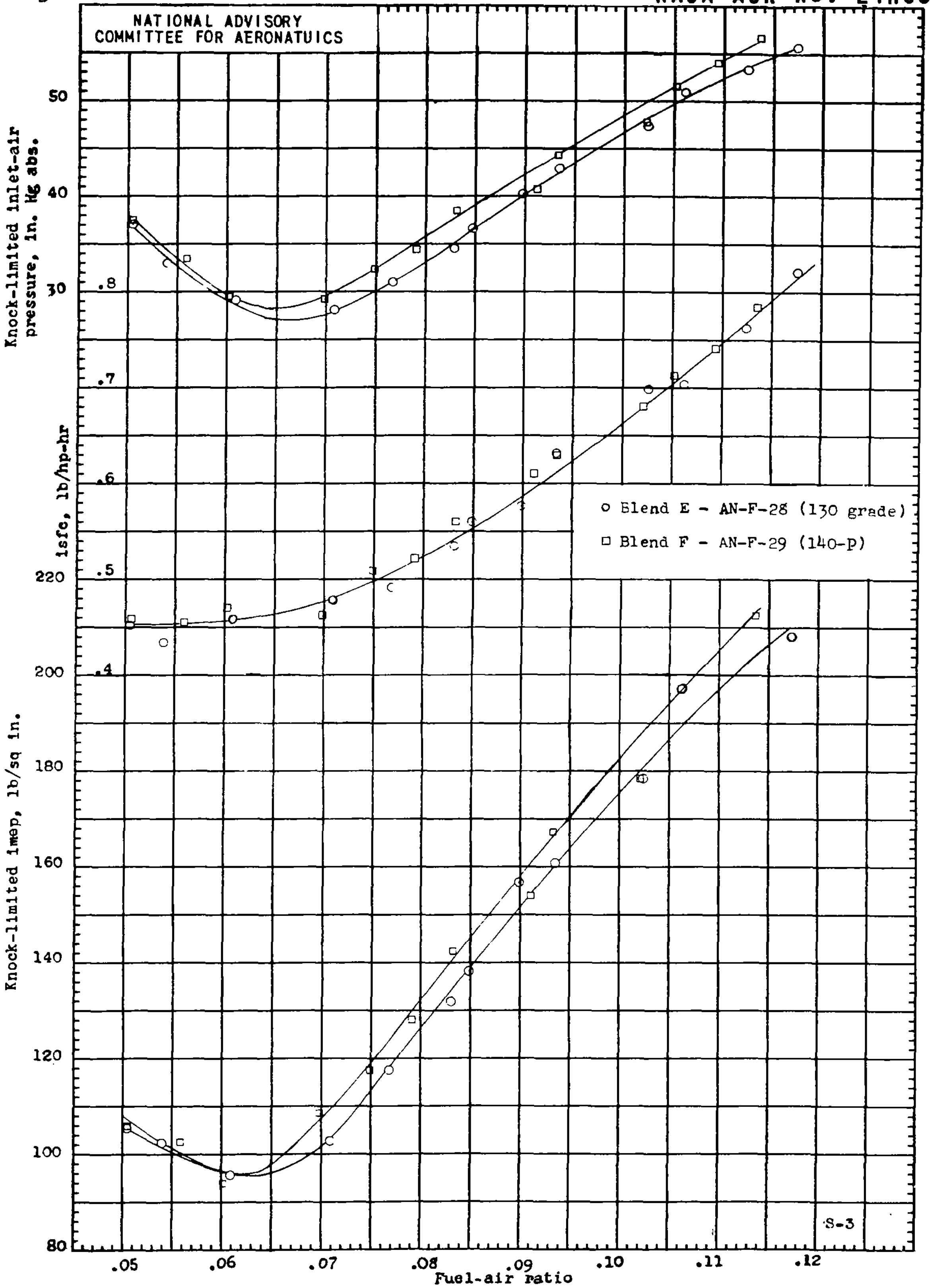
(c) Engine speed, 1800 rpm; inlet-air temperature, 150° F.

Figure 2. - Concluded.

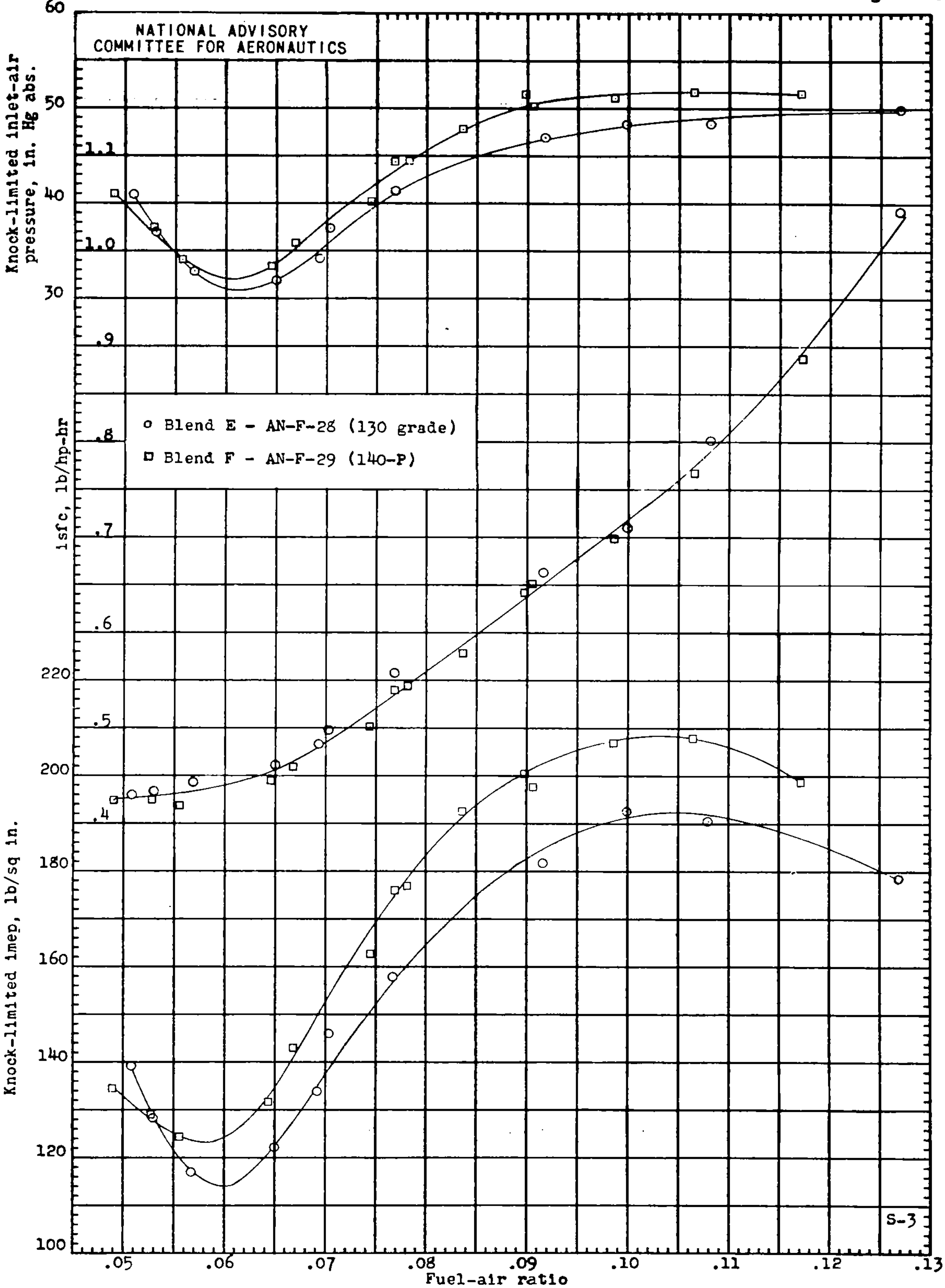


(a) Engine speed, 2700 rpm; inlet-air temperature, 150° F.

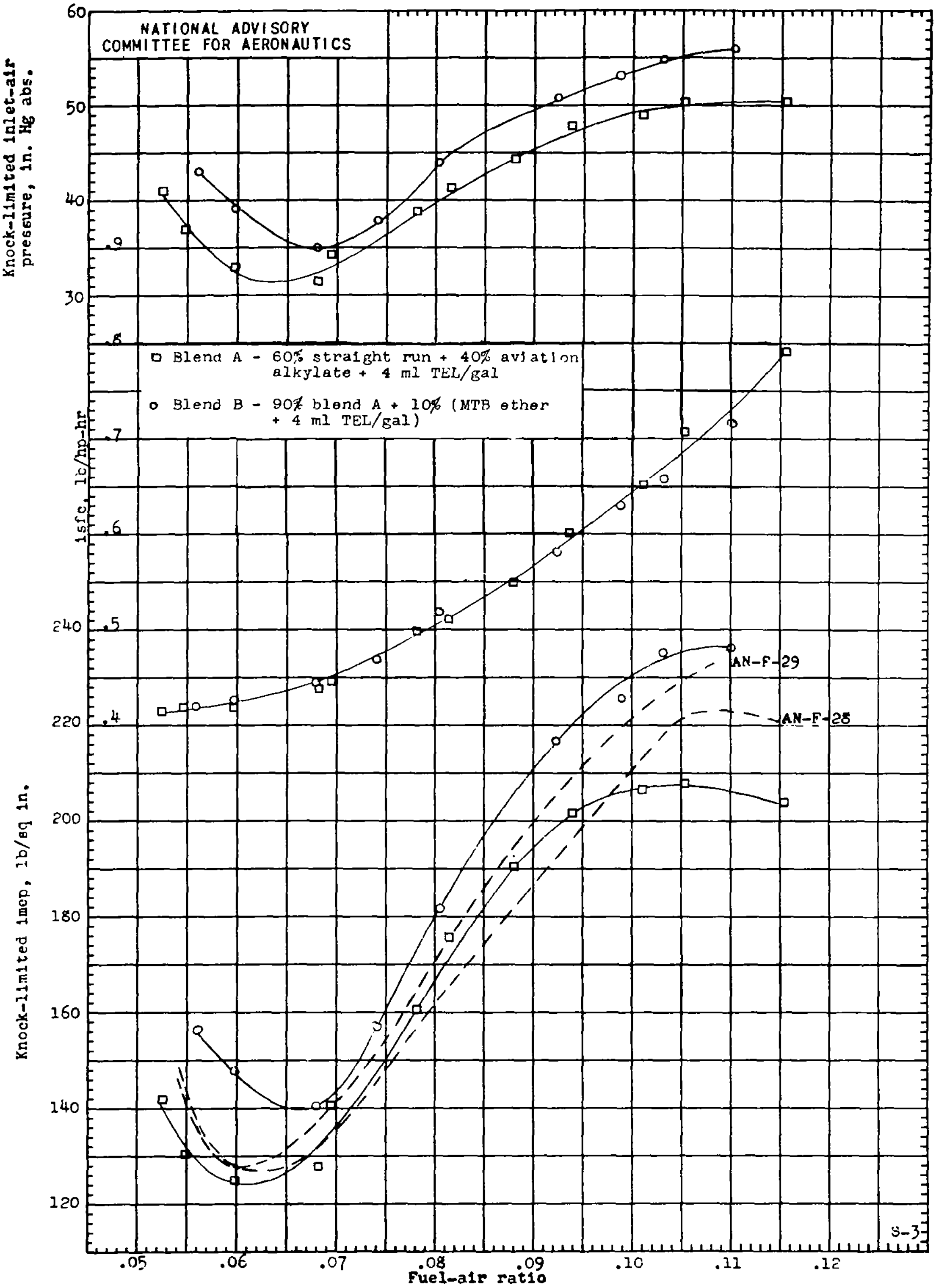
Figure 3. - Knock-limited performance of AN-F-28 and AN-F-29 fuels. 17.6 engine; spark advance, 40° B.T.C.; compression ratio, 7.0; inlet-coolant temperature, 250° F.



(b) Engine speed, 2700 rpm; inlet-air temperature, 250° F.
Figure 3. - Continued.

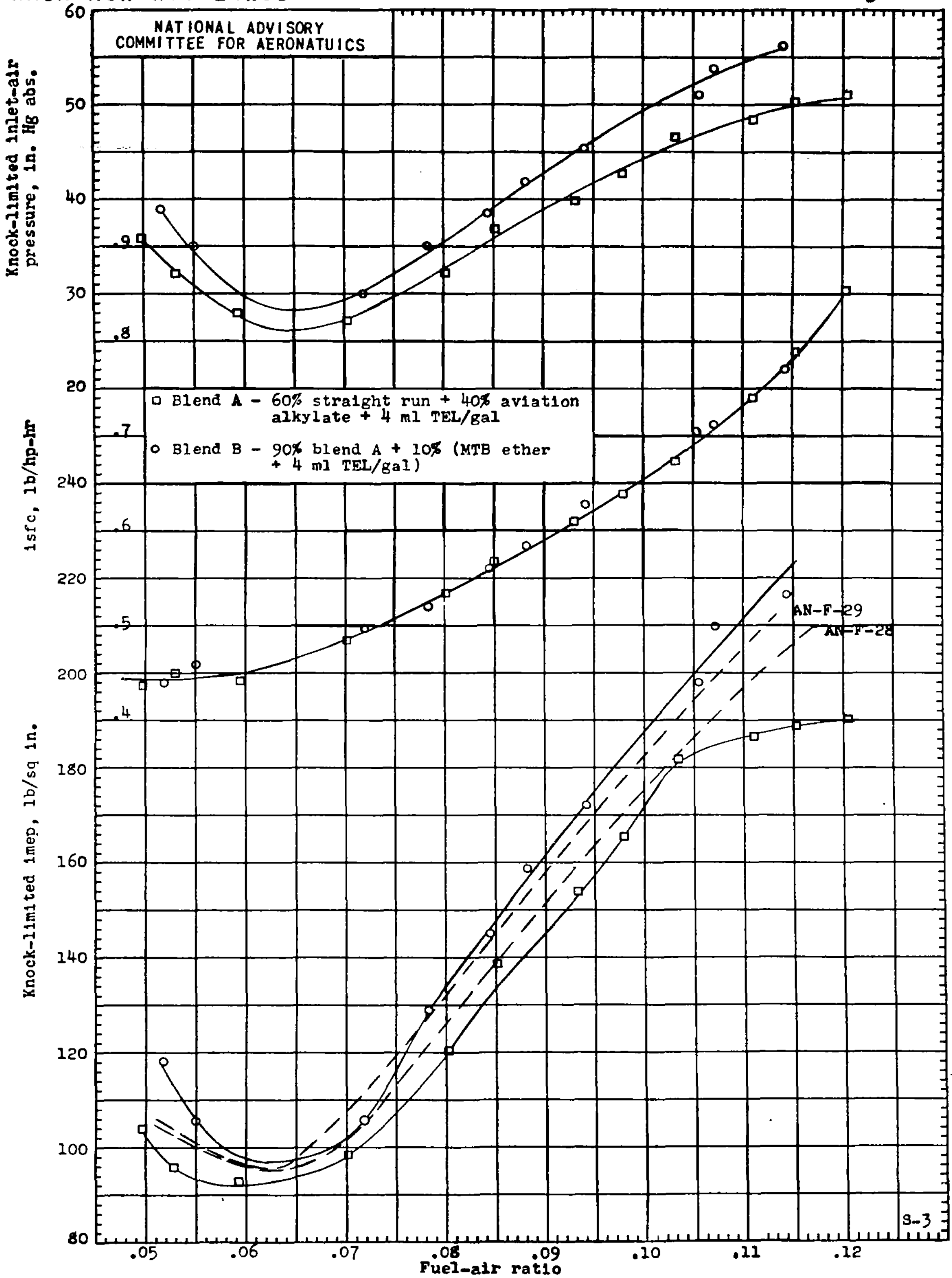


(c) Engine speed, 1800 rpm; inlet-air temperature, 150° F.
Figure 3. - Concluded.

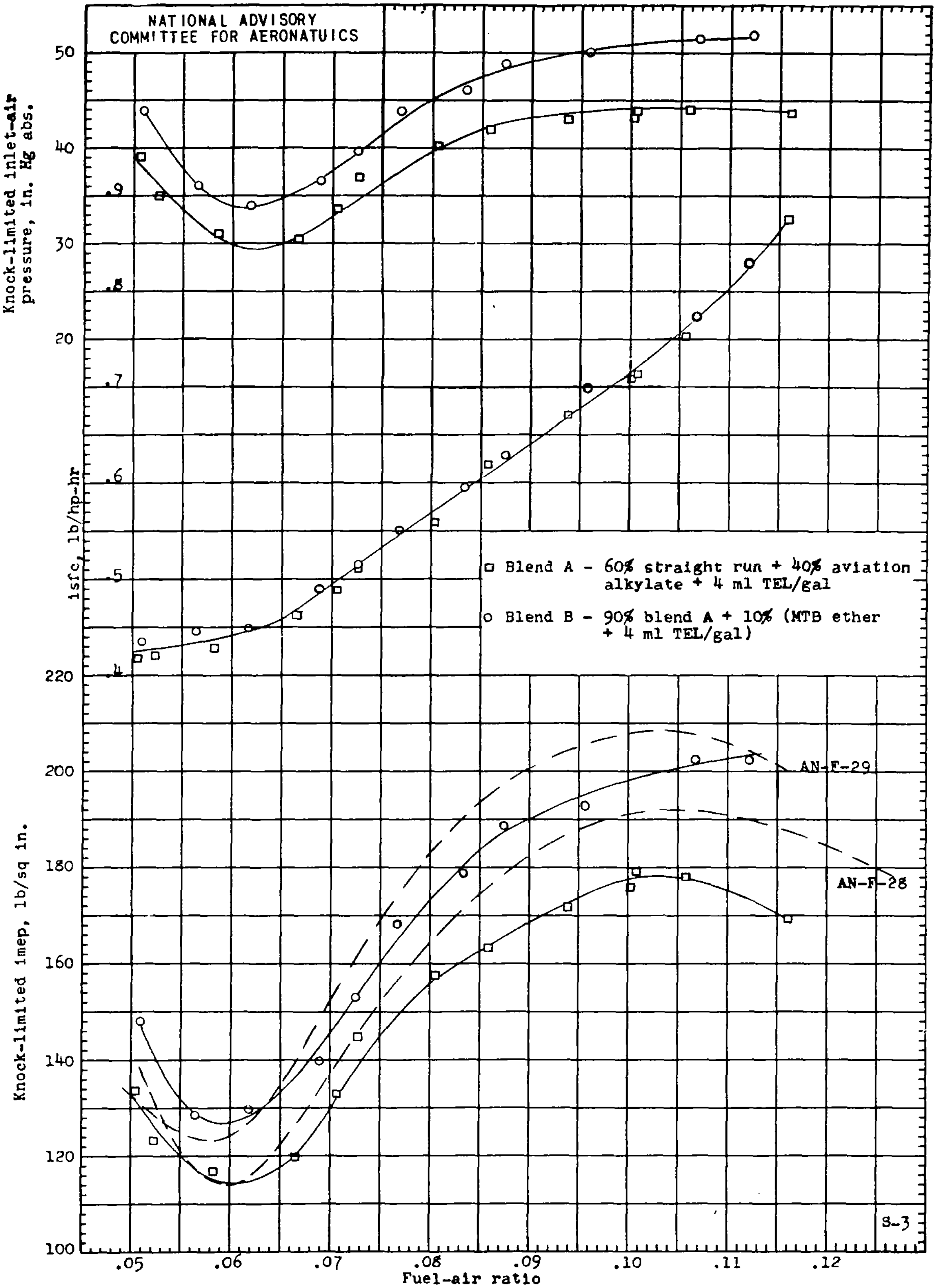


(a) Engine speed, 2700 rpm; inlet-air temperature, 150° F.

Figure 4. - Effect of methyl tert-butyl ether on knock-limited performance of aviation-fuel blending stock. 17.6 engine; spark advance, 40° B.T.C.; compression ratio, 7.0; inlet-coolant temperature, 250° F.

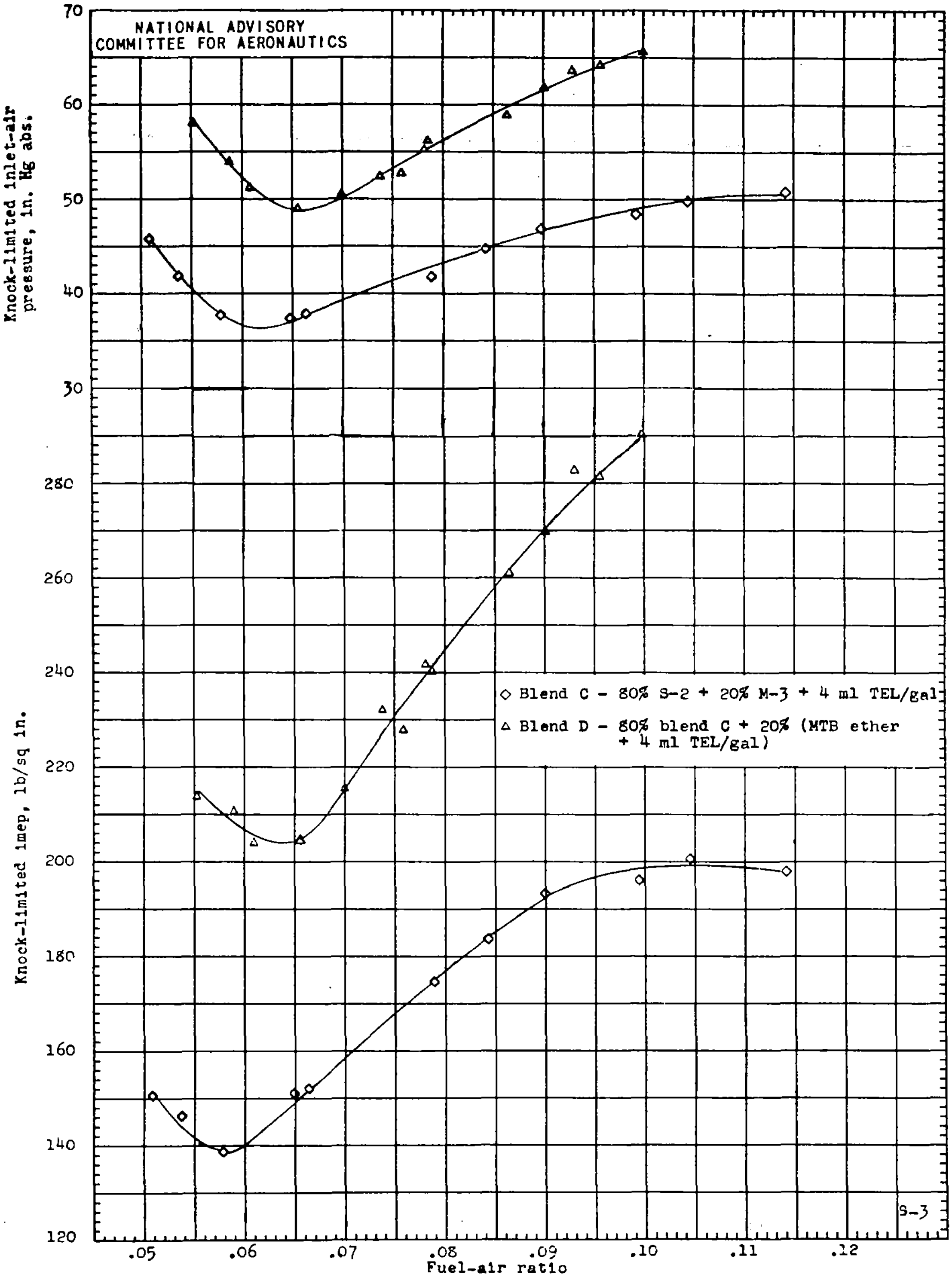


(b) Engine speed, 2700 rpm; inlet-air temperature, 250° F.
Figure 4. - Continued.



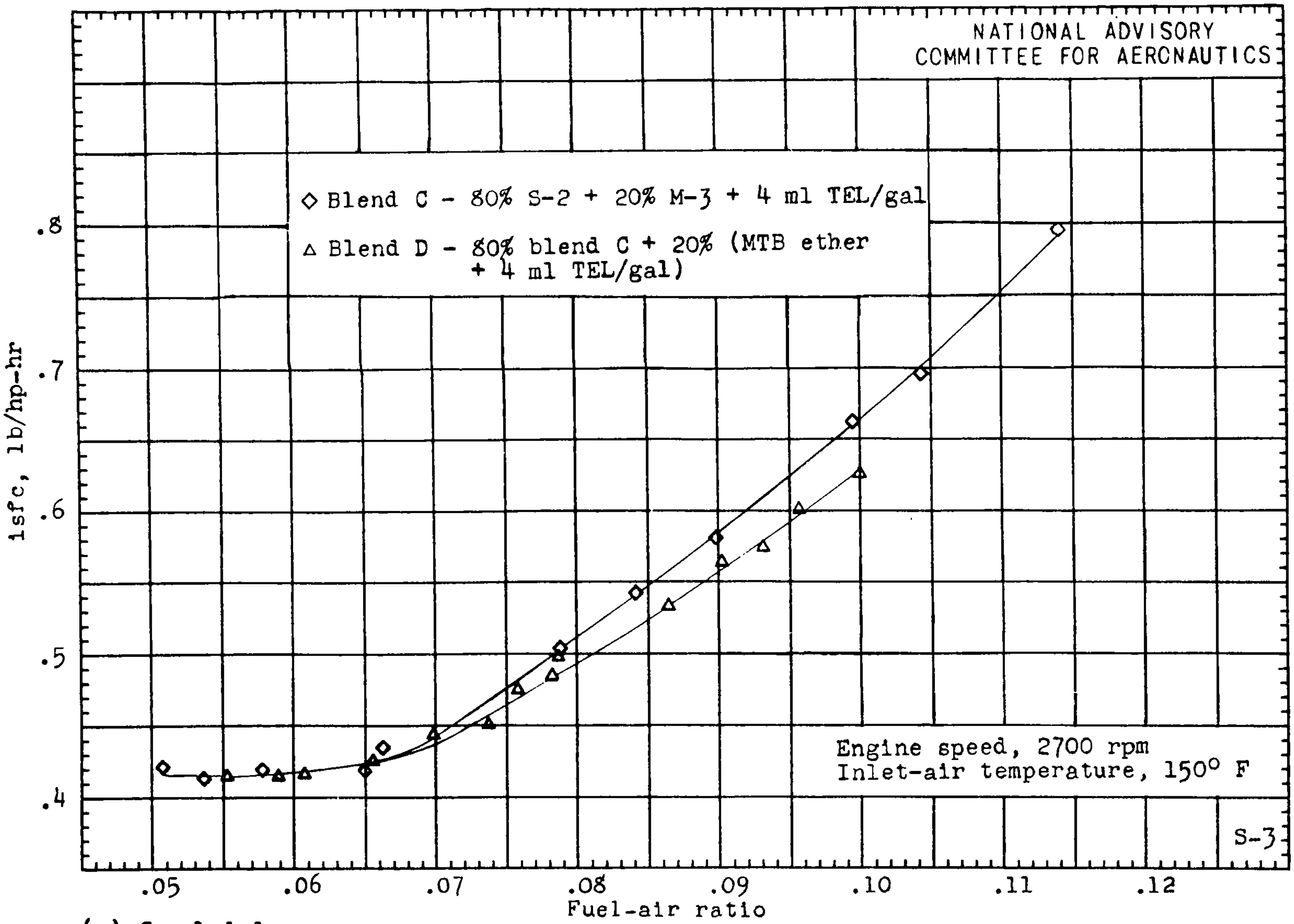
(c) Engine speed, 1800 rpm; inlet-air temperature, 150° F.

Figure 4. - Concluded.

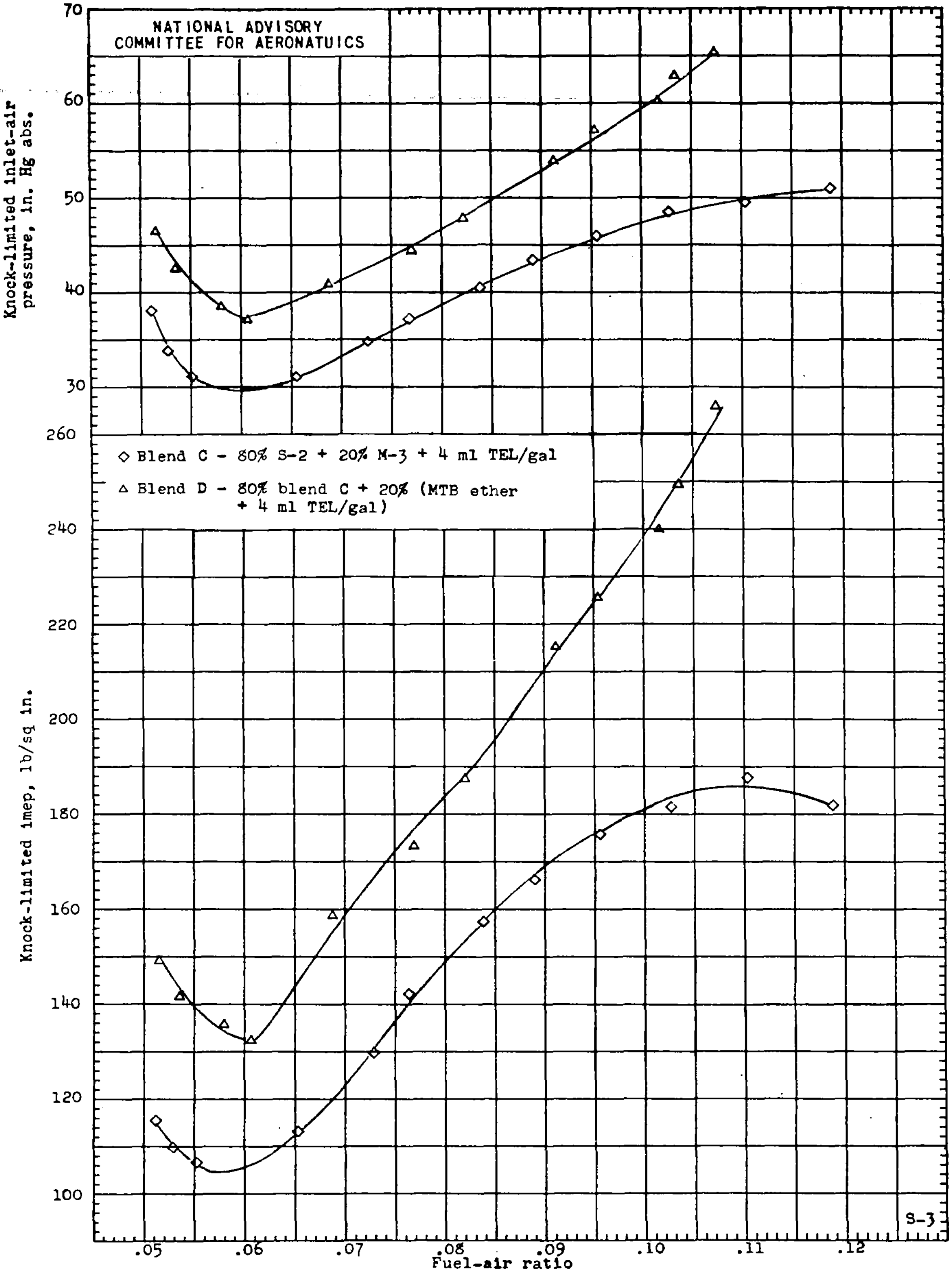


(a) Engine speed, 2700 rpm; inlet-air temperature, 150° F.

Figure 5. - Effect of methyl tert-butyl ether on knock-limited performance of reference fuel base blend. 17.6 engine; spark advance, 40° B.T.C.; compression ratio, 7.0; inlet-coolant temperature, 250° F.

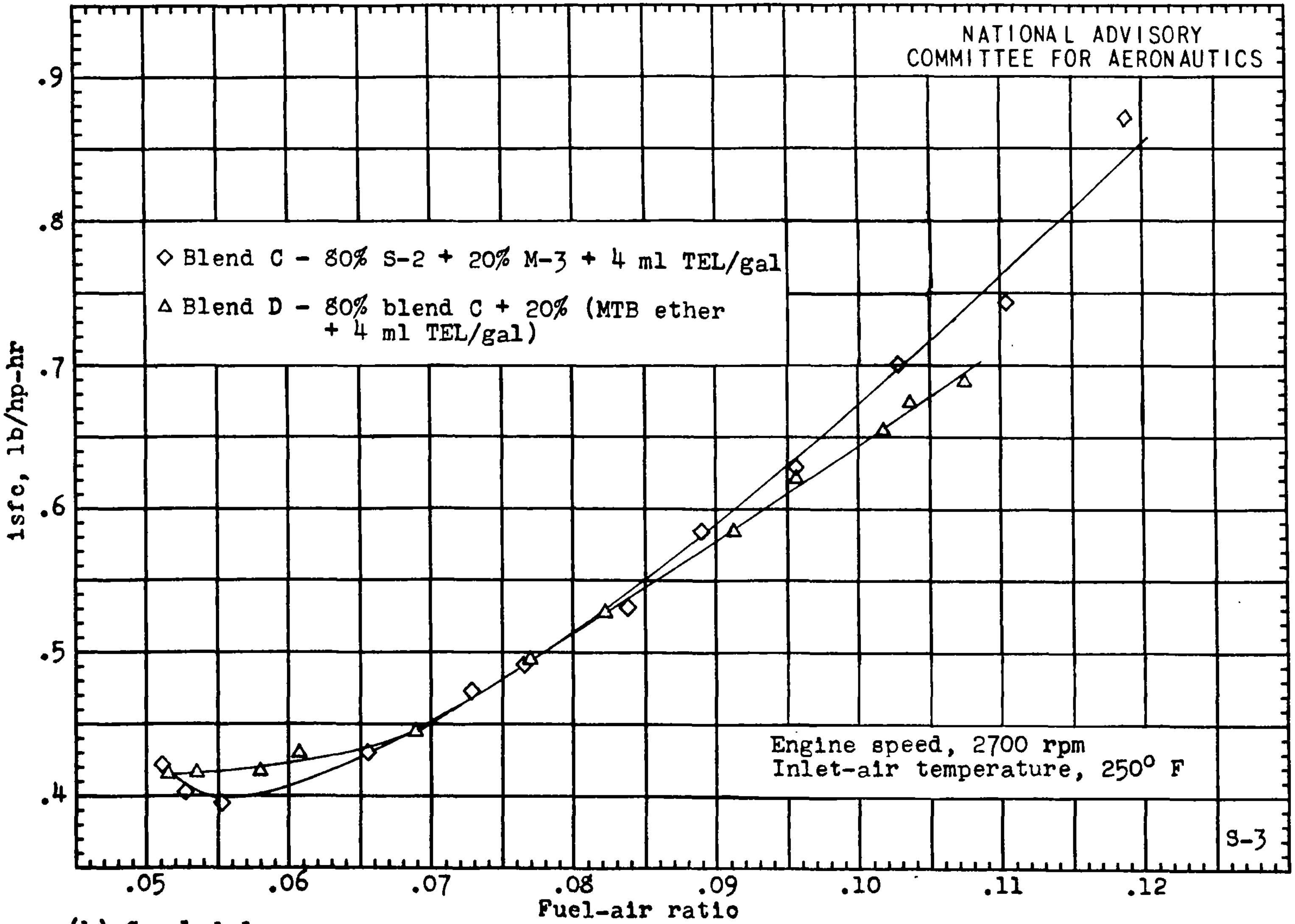


(a) Concluded.
Figure 5. - Continued.

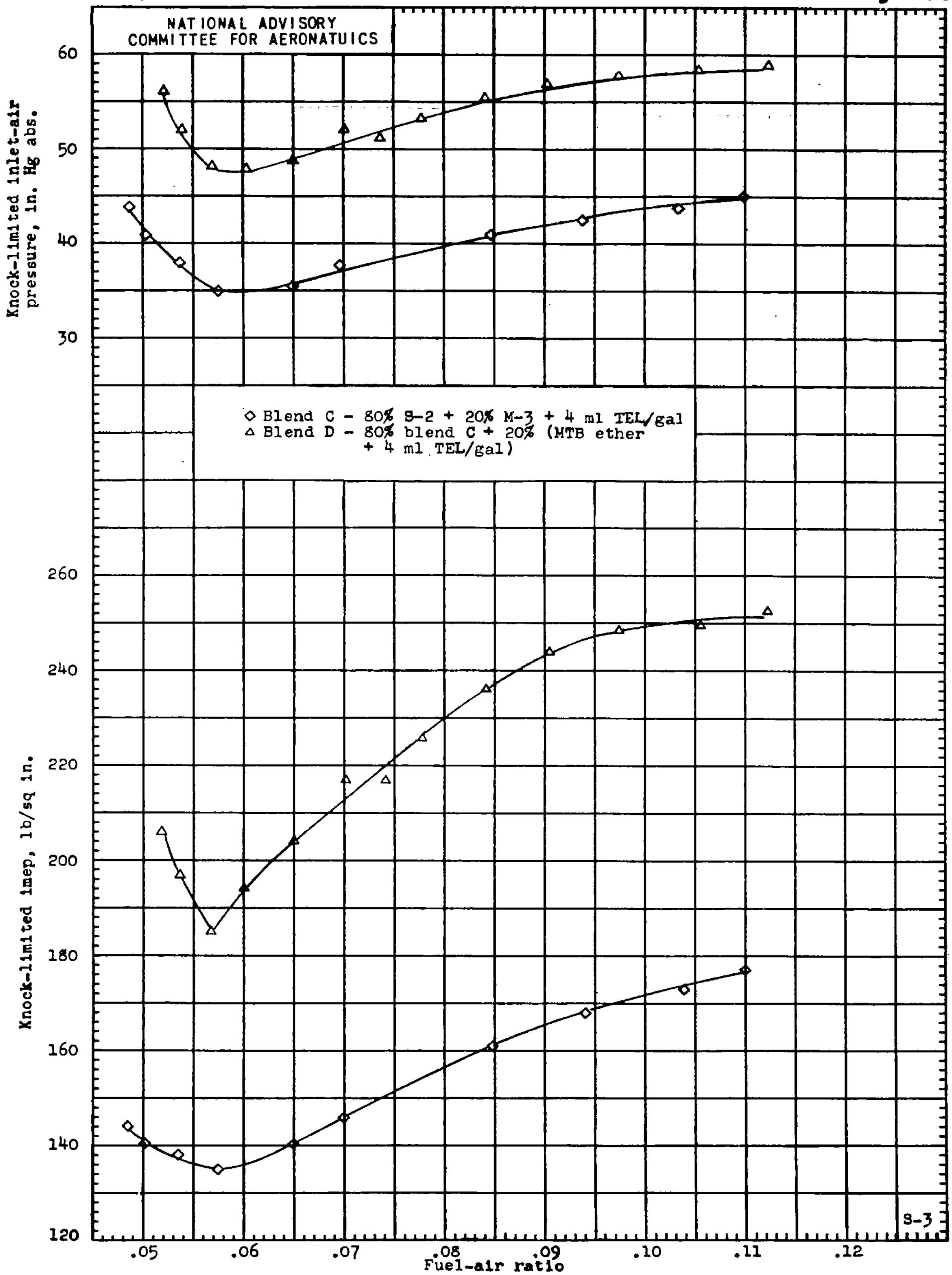


(b) Engine speed, 2700 rpm; inlet-air temperature, 250° F.

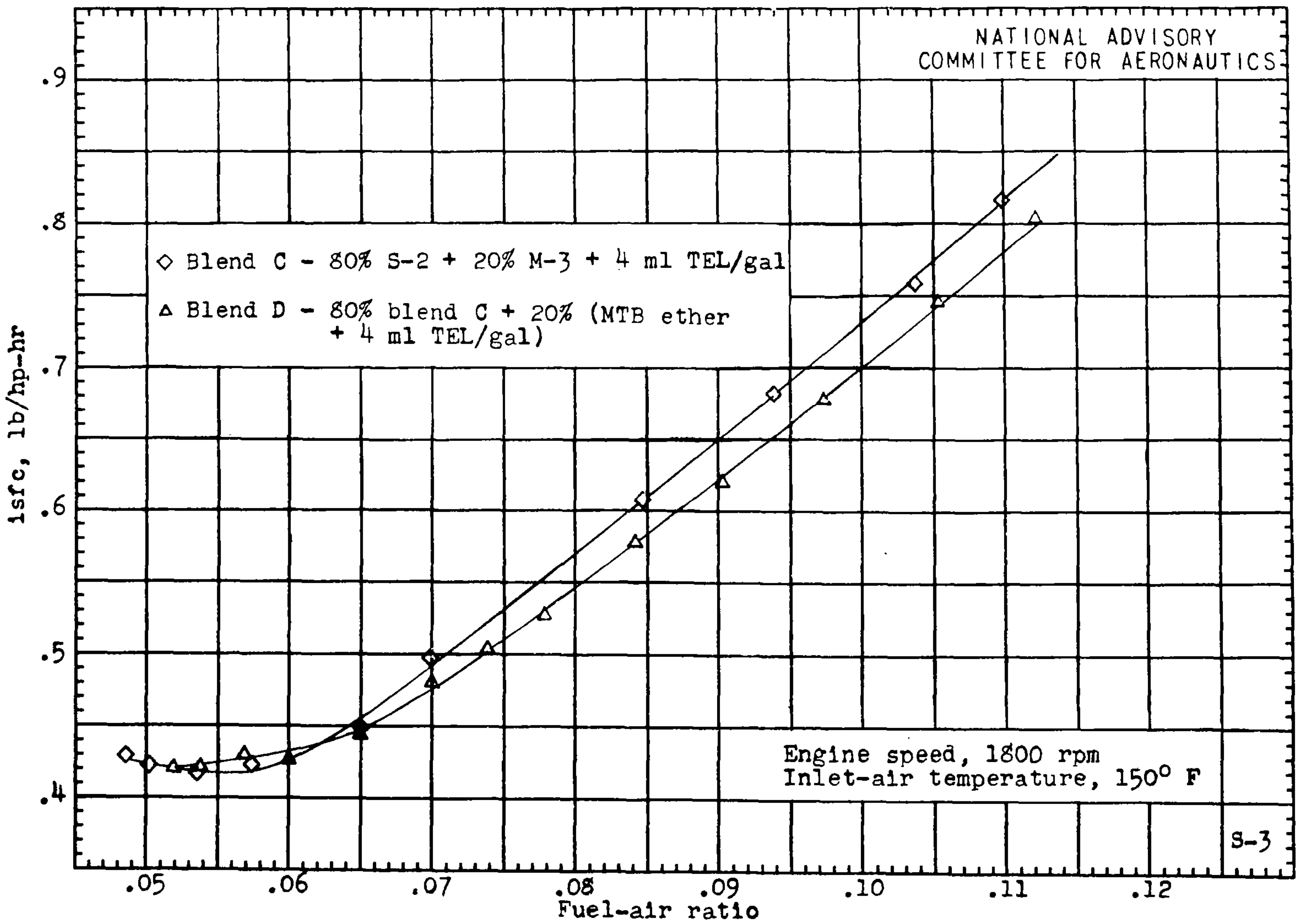
Figure 5. - Continued.



(b) Concluded.
Figure 5. - Continued.



(c) Engine speed, 1800 rpm; inlet-air temperature, 150° F.
Figure 5. - Continued.



(c) Concluded.
Figure 5. - Concluded.

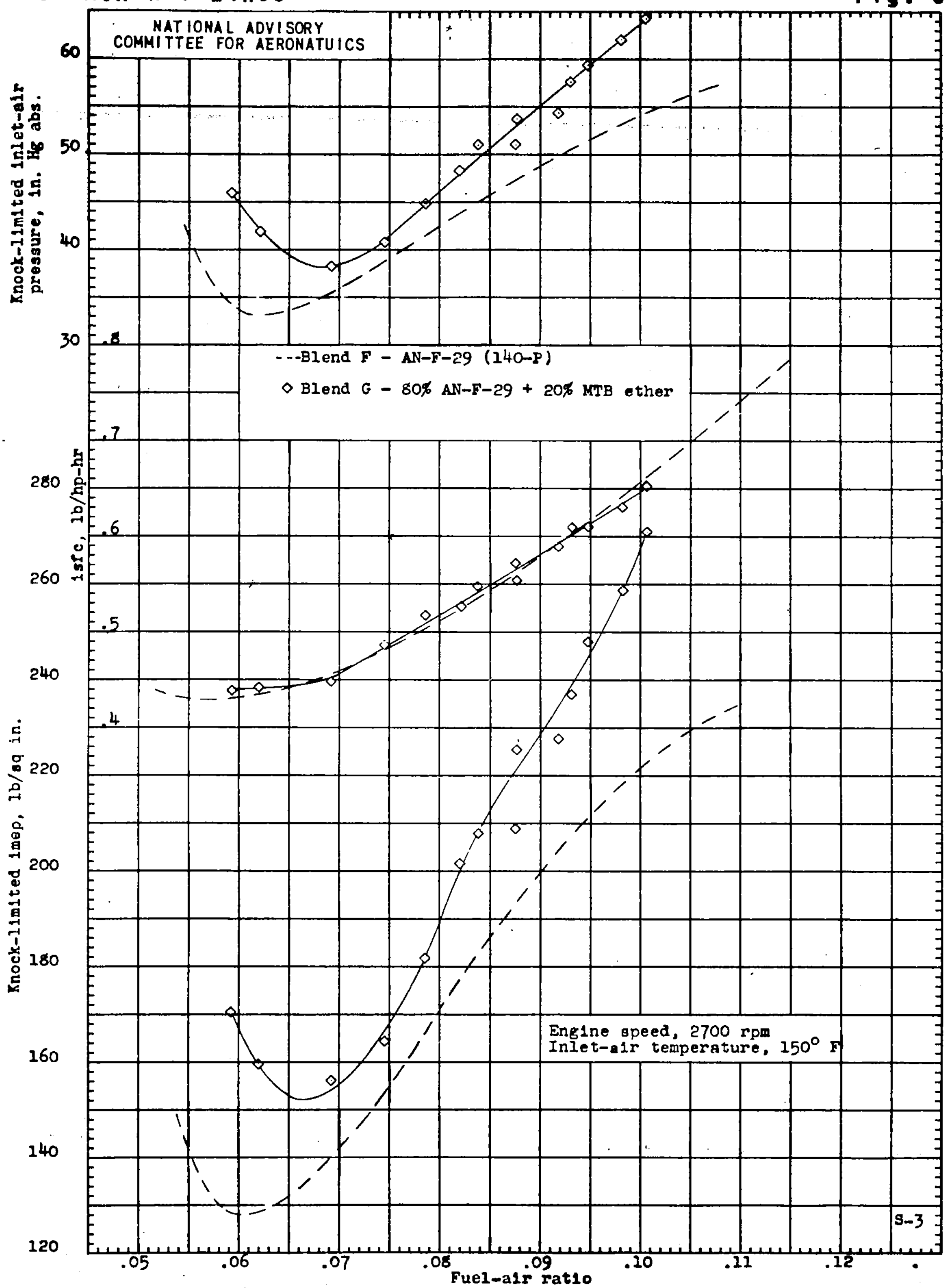
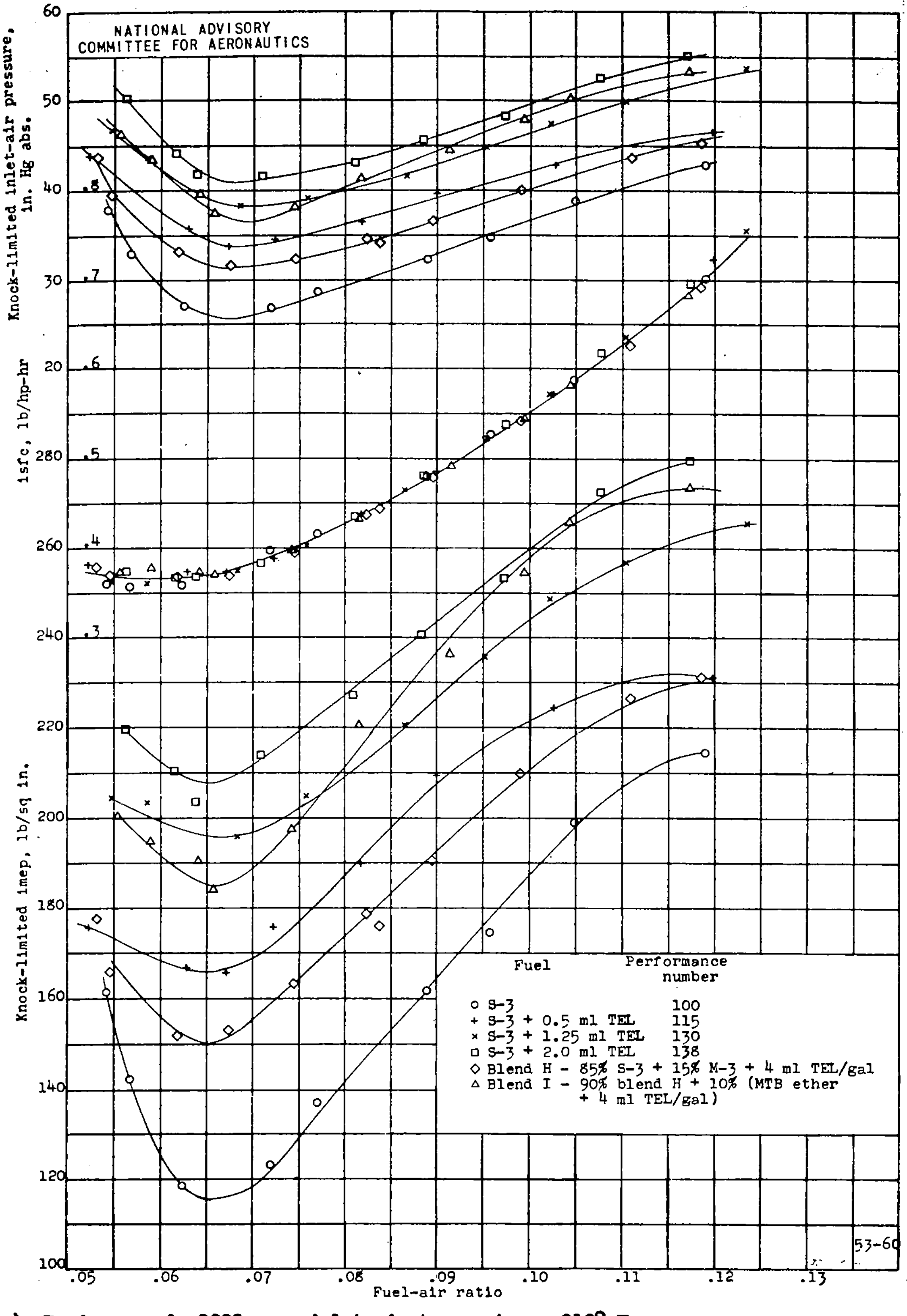
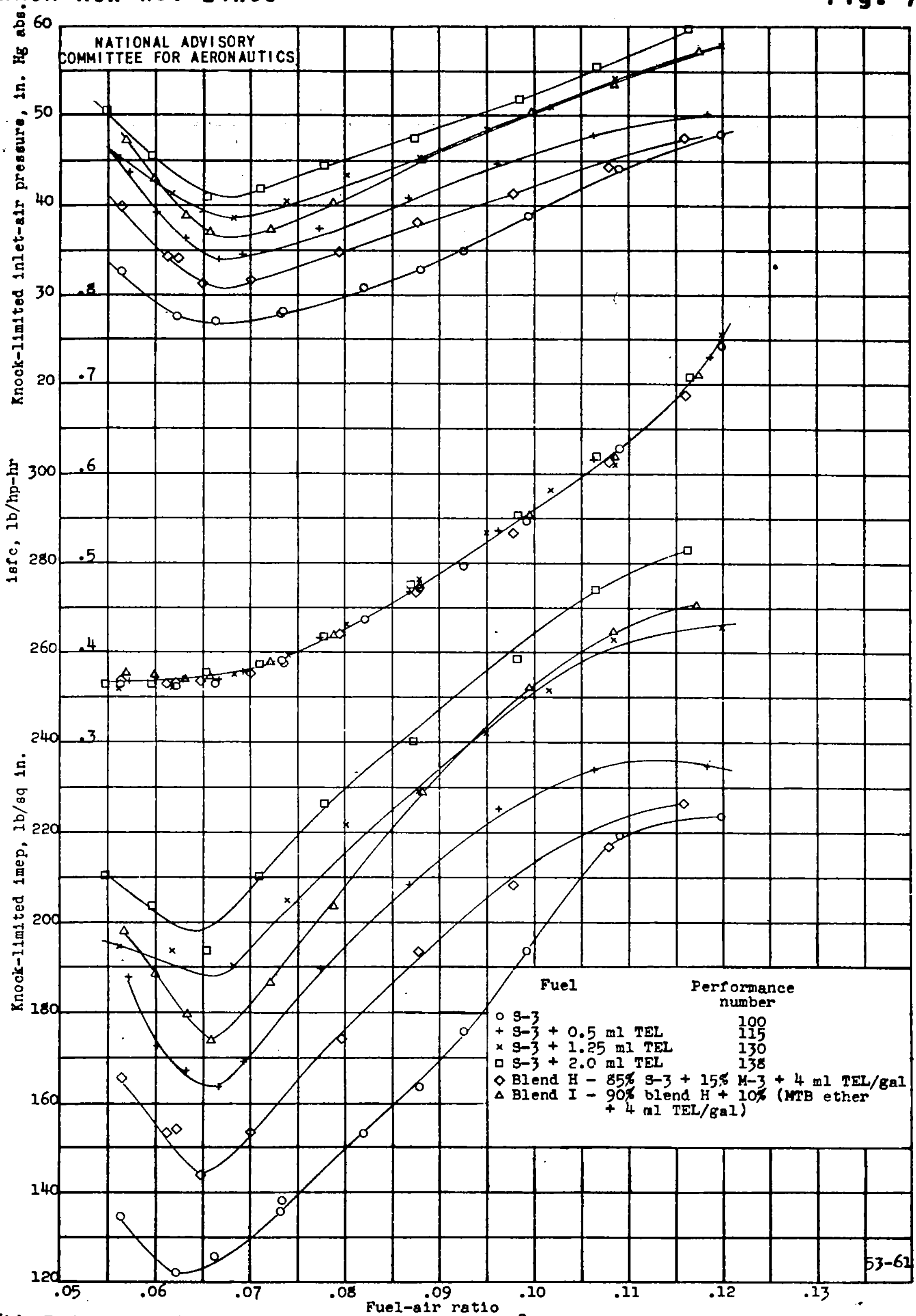


Figure 6. - Effect of methyl tert-butyl ether on knock-limited performance of fuel AN-F-29. 17.6 engine; engine speed, 2700 rpm; spark advance, 40° B.T.C.; compression ratio, 7.0; inlet-air temperature, 150° F; inlet-coolant temperature, 250° F.



(a) Engine speed, 2000 rpm; inlet-air temperature, 210° F.

Figure 7. - Effect of methyl tert-butyl ether on knock-limited performance of reference fuel base blend. Full-scale-engine cylinder; spark advance, 20° B.T.C.; compression ratio, 7.3; cooling air set to give rear spark-plug-boss temperature of 365° F at 140 bmep and 0.10 fuel-air ratio.



(b) Engine speed, 2500 rpm; inlet-air temperature, 250° F.
Figure 7. - Concluded.