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THE KNOCK-LIMITED PERFORMANCE OF FUEL BLENDS CONTAINING AROMATICS

V - n-PROPYLBENZENE, n-BUTYLBENZENE, ISOBUTYLBENZENE m-XYLENE, AND 1-ISOPROPYL-4-METHYLBENZENE

By Carl L. Meyer and J. Robert Branstetter

Aircraft Engine Research Laboratory
Cleveland, Ohio

NACA

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ADVANCE RESTRICTED REPORT

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SUMMARY

Knock-limited tests were made of n-propylbenzene, n-butylbenzene, isobutylbenzene, m-xylene, and 1-isopropyl-4-methylbenzene blended individually in various concentrations with selected base fuels. Data were obtained for the five aromatics to determine: (a) the blending sensitivity, (b) the sensitivity of the blends to inlet-air temperatures, (c) the lead susceptibility of the blends, and (d) the correlation of small-scale and full-scale engine results. The data presented herein were obtained with small-scale engines; published full-scale single-cylinder engine data are presented for comparison.

The five aromatics in most instances rated in the following order of decreasing antiknock effectiveness in leaded blends at a fuel-air ratio of 0.10: m-xylene, 1-isopropyl-4-methylbenzene, n-propylbenzene, isobutylbenzene, and n-butylbenzene. At lean mixtures these aromatics, with the exception of n-butylbenzene, which had the lowest response at most conditions, were comparable as antiknock blending agents.

INTRODUCTION

An investigation to determine the effectiveness of aromatic hydrocarbons as antiknock blending agents for aviation fuels is being conducted at the NACA Cleveland laboratory. The program and its over-all objectives are described in detail in reference 1. In brief, the program consists in determining: (a) the blending sensitivity of the aromatic in the base reference fuels, (b) the sensitivity of the aromatic blends to inlet-air temperature, (c) the lead susceptibility of the aromatic blends, and (d) the correlation of small-scale and full-scale engine results.

Knock-limited performance data obtained with F-4, F-3, and 17.6 small-scale engines for the 12 purified aromatic hydrocarbons tested in the first phase of the program are presented in references 1 to 4. A summarization of these data, together with comparative full-scale single-cylinder engine data from reference 5, is presented in reference 4.

Data for n-propylbenzene, n-butylbenzene, isobutylbenzene, m-xylene, and 1-isopropyl-4-methylbenzene (p-cymene) are presented in this report, which is the last of a series of five reports. Each aromatic, after purification, was individually blended with selected base fuels and the resulting blends were tested in F-4, F-3, and 17.6 engines. R-1820 G200 single-cylinder engine data from reference 6 are included to facilitate comparison of small-scale and full-scale engine results.

APPARATUS, FUELS, AND TEST PROCEDURE

A description of the engines and the engine conditions used for the tests may be found in reference 1 for the 17.6 engine, for the F-3 engine, and the "research" F-4 engine. The 17.6 engine conditions are also given hereinafter in the figures and tables. The F-4 engine is not a package unit but is operated under F-4 test conditions and is, for convenience, called the F-4 engine in this series of reports.

The five aromatic hydrocarbons were synthesized, or purchased, and purified in the Organic Synthesis Section of the Fuels and Lubricants Division. The physical constants of the aromatics tested are presented in the following table:

Aromatic	Freezing point (°C)	Boiling point (°C)	Index of refraction n_D^{20}	Density at 20° C (gram/ml)
n-Propylbenzene	-99.61	159.3	1.4919	0.8618
n-Butylbenzene	-88.19	183.2	1.4898	.8601
Isobutylbenzene	-51.87	172.2	1.4860	.8525
m-Xylene	-48.31	139.1	1.4971	.8641
1-Isopropyl-4-methylbenzene	-68.39	177.2	1.4906	.8566

Each aromatic, after purification, was individually blended by volume with three base fuels: S-4 reference fuel, S-4 plus 4 ml TEL per gallon, and 87.5 percent S-4 plus 12.5 percent n-heptane plus 4 ml TEL per gallon. In order to obtain a base fuel which could be reproduced as needed and which would contain no aromatics, the base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane plus 4 ml TEL per gallon was chosen to replace the base fuel (85 percent S-3 plus 15 percent M-4 plus 4 ml TEL/gal) used in references 1 to 5. It is stated in reference 1 that the use of M-4 as a component of the base fuel does not meet the requirement of reproducibility of the fuel. M-4 reference fuel contains approximately 8 percent aromatics. Tests on an F-4 engine show the base fuel used in the present tests and the tests of references 6 and 7 to be approximately equivalent in knock-limited power to the original base fuel.

The composition of the test-fuel blends and an outline of the tests with the 17.6 and F-4 engines are given in the following table:

Engine	Inlet-air temperature (°F)	Percentage aromatic in blend (by volume)	Base fuel	Tetraethyl lead (ml/gal)
17.6	250	0,10,20	S-4	0
	100	0,20	S-4	0
	250	0,10,20	S-4	4
	100	0,20	S-4	4
	250	0,25	87.5% S-4 + 12.5% n-heptane	4
	100	0,25	87.5% S-4 + 12.5% n-heptane	4
F-4	225	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4

Whenever fuel quantity permitted, the blends were also tested in the F-3 engine.

When F-4 ratings of the various blends are determined on separate days, as was done in references 1 to 4, the knock-limited imep ratios (ratio of the imep of the test fuel blend to the imep of the base fuel) vary possibly because of daily variations in the power level of the engine. Possible day-to-day errors must be minimized if the antiknock blending performance of the aromatics is to be accurately determined. The procedure previously followed for the F-4 engine tests has therefore been altered to permit testing leaded blends of 0, 10, 25, and 50 percent aromatic with the base fuel consisting of S-4 plus n-heptane during a single operating day. An additional test of S-4 plus 4 ml TEL per gallon was made during the same day. The revised procedure allows a direct comparison of blends containing various concentrations of a given aromatic on the basis of data obtained on the same day. It also permits a match rating in terms of S-4 plus 4 ml TEL per gallon and n-heptane plus 4 ml TEL per gallon by the sue of the reciprocal indicated-mean-effective-pressure relation developed in reference 8. The corresponding rich and lean performance numbers were obtained from figure 1. This figure is based on the F-4 standard guide curves and on knock tests conducted at this laboratory.

PRESENTATION AND DISCUSSION OF RESULTS

Table I is an index of figures showing in detail the order of discussing the results obtained for the five aromatics when individually blended with the three base fuels. The table presents the blend compositions, the engines, the inlet-air temperature, and the figure numbers.

F-4 engine data. - The knock-limited performance in the F-4 engine of leaded blends containing 0, 10, 25, and 50 percent aromatic with the base fuel consisting of S-4 plus n-heptane are presented in figures 2, 3, 4, 5, and 6 for n-propylbenzene, n-butylbenzene, isobutylbenzene, m-xylene, and 1-isopropyl-4-methylbenzene, respectively. In each of the aforementioned figures, the results from tests of S-4 plus 4 ml TEL per gallon are also included. Each figure presents data obtained during a single operating day.

Graphs of knock-limited imep ratio (where imep ratio is the ratio of the imep of the aromatic blend to the imep of the base fuel) against aromatic concentration are presented in figure 7. These data show the comparative effect of the addition of each of the five aromatics at fuel-air ratios of 0.07, 0.085, 0.10, and 0.11.

At lean fuel-air mixtures, the aromatics were not effective antiknock agents under F-4 test conditions; the differences between the antiknock qualities of the five aromatics were insufficient to determine which had the better characteristics as an antiknock agent. At rich fuel-air mixtures, additions of each of the five aromatics permitted substantial gains in knock-limited power relative to the base fuel. In nearly all cases at rich mixtures, m-xylene and 1-isopropyl-4-methylbenzene were rated as the most effective antiknock agents and n-butylbenzene as the least effective antiknock agent of the five aromatics.

17.6 engine data. - The knock-limited performance in the 17.6 engine of blends containing the five aromatics is presented in figures 8 to 10 for n-propylbenzene, 11 to 13 for n-butylbenzene, 14 to 16 for isobutylbenzene, 17 to 19 for m-xylene, and 20 to 22 for 1-isopropyl-4-methylbenzene. For each aromatic, unleaded and leaded blends with S-4 and leaded blends with a base fuel consisting of S-4 plus n-heptane are presented for inlet-air temperatures of 250° and 100° F. The data given in each figure for a given inlet-air temperature were obtained during a single operating day.

In unleaded blends with S-4 (figs. 8, 11, 14, 17, and 20) additions of the five aromatics decreased the knock-limited power of S-4 at fuel-air ratios in the neighborhood of 0.065 and 0.07 at the higher inlet-air temperature. Additions of n-propylbenzene, m-xylene, and 1-isopropyl-4-methylbenzene permitted gains at fuel-air ratios greater than 0.085; additions of n-butylbenzene and isobutylbenzene permitted gains only at fuel-air ratios greater than approximately 0.10. At the lower inlet-air temperature, additions of each of the five aromatics increased the knock-limited power of S-4 at all fuel-air ratios tested. This influence of temperature agrees, in general, with that observed for the aromatic fuels reported in references 1 to 4. The greatest gains at the lower inlet-air temperature were obtained from n-propylbenzene, m-xylene, and 1-isopropyl-4-methylbenzene, and the smallest gain was obtained from n-butylbenzene.

In leaded blends with S-4 (figs. 9, 12, 15, 18, and 21) the data show that even at the lean mixtures and at the higher inlet-air temperature the aromatics increased the knock-limited indicated mean effective pressure of the base fuel (in the case of n-butylbenzene, the gain was almost negligible), indicating that these aromatic blends are more responsive to the lead addition than is S-4. A similar response of the aromatic blends to the addition of tetraethyl lead was also noted at the lower inlet-air temperature.

In leaded blends with the base fuel consisting of S-4 plus n-heptane (figs. 10, 13, 16, 19, and 22), each of the five aromatics increased the knock-limited power of the base fuel at all fuel-air ratios and at both inlet-air temperatures.

In leaded blends, m-xylene and 1-isopropyl-4-methylbenzene were the most effective of the five aromatics in increasing the knock-limited power of the base fuels at rich fuel-air mixtures. At lean mixtures all of the aromatics with the exception of n-butylbenzene were comparable as antiknock blending agents. At both inlet-air temperatures over the range of fuel-air ratios tested, n-butylbenzene was the least effective antiknock agent.

In figures 23 to 27 the 17.6 engine data are presented in the form of graphs of the variation of knock-limited imep ratio with aromatic concentration for unleaded and leaded blends of the aromatics with S-4 reference fuel. These data indicate the comparative effect of additions of each of the five aromatics at fuel-air ratios of 0.07, 0.085, 0.10, and 0.11, as well as the effect of inlet-air temperature and tetraethyl lead.

Summary of engine data. - Table II presents the F-4 ratings of leaded blends of the five aromatics with the base fuel consisting of S-4 plus n-heptane. This table also includes the F-3 ratings of the blends for which sufficient fuel was available. These ratings are recorded in terms of percentage S-4 plus 4 ml TEL per gallon in n-heptane plus 4 ml TEL per gallon, in terms of S-4 plus ml TEL per gallon, or octane number, and also in terms of Army-Navy performance numbers.

Knock-limited performance data, together with imep-ratio data, for each of the five aromatics individually blended with the three base fuels are presented in table III. Data are included from tests with the 17.6 engine, the full-scale cylinder (reference 6), and the F-4 engine. Full-scale-cylinder data were not available for m-xylene. It should be noted that, of the two sets of engine conditions used for the full-scale-cylinder tests, only one (spark advance, 20° B.T.C.; exhaust pressure, 29 in. Hg absolute; inlet-air temperature, 210° F) corresponds to the conditions used for tests with that cylinder in reference 5 (from which data are included in references 1 to 4). The simulated take-off conditions recommended by the Coordinating Research Council have been replaced by modified cruise conditions involving a more advanced spark, a lower exhaust pressure, and a higher inlet-air temperature than the recommended CRC cruise conditions. This change was made to give more emphasis to the temperature sensitivity of the aromatic blends than did the original simulated take-off conditions (reference 5). The present test conditions of the full-scale cylinder are outlined in detail in reference 6; the pertinent conditions are given in table III of the present report. The test conditions of the small-scale engines were unchanged.

The data in table III show that, with few exceptions, the full-scale cylinder and the small-scale engines rated the aromatics (leaded blends for which complete data are available) in the same order at fuel-air ratios of 0.10 and 0.11. Although full-scale-cylinder data are not available for the m-xylene blend, it appears valid to list the five aromatics in the following order of decreasing antiknock effectiveness at fuel-air ratios of 0.10 and 0.11: m-xylene, 1-isopropyl-4-methylbenzene, n-propylbenzene, isobutylbenzene, and n-butylbenzene. In the 20- and 25-percent leaded blends at a fuel-air ratio of 0.10, m-xylene and 1-isopropyl-4-methylbenzene appear comparable with the five aromatics (1,3,5-trimethylbenzene, m-diethylbenzene, tert-butylbenzene, p-xylene, and 1-ethyl-4-methylbenzene) which were found in reference 4 to rate as the best antiknock agents of the 12 aromatics summarized therein.

Table IV presents a summary of the temperature sensitivities of blends containing each of the five aromatics. With few exceptions, the aromatic blends were more sensitive to changes of inlet-air temperature than the base fuels.

The lead susceptibilities of blends containing the five aromatics are summarized in table V. The aromatic blends were more susceptible to the addition of tetraethyl lead than was S-4 reference fuel.

The correlation of small-scale and full-scale engine results. - In reference 6, the F-4 engine performance is compared with the full-scale-cylinder performance on an imep-ratio basis at fuel-air ratios of 0.07 and 0.10 for blends containing 25 percent aromatic (for the aromatics reported herein) with the base fuel consisting of S-4 plus n-heptane. The correlation was better at the richer fuel-air mixtures at the two engine conditions used in the full-scale-cylinder tests. In each case, the full-scale cylinder rated the blends higher than did the F-4 engine.

Also in reference 6, the F-3 engine performance is compared with the full-scale-cylinder performance (at a fuel-air ratio of 0.07) on the basis of performance number for the 25-percent aromatic blends reported herein. The F-3 engine appeared to be relatively insensitive for comparing the merits of fuel blends containing aromatics.

In figure 28 of the present report the 17.6 engine performance is compared with the full-scale-cylinder performance and in figure 29 the F-4 engine performance is compared with the 17.6 engine performance. Those two comparisons are made on an imep-ratio basis, at fuel-air ratios of 0.07 and 0.10, for blends containing 25 percent aromatic with the base fuel consisting of S-4 plus n-heptane. In the two figures, the dashed lines indicate the match lines and the solid lines indicate the lines of correlation that were drawn on corresponding engine correlation plots in reference 4 for the 12 aromatics summarized therein. No correlation lines are shown for the more severe test conditions of the full-scale cylinder because these conditions differ from the conditions formerly used for tests conducted with that cylinder.

At the more severe test conditions of the 17.6 engine and the full-scale cylinder (fig. 28) the correlation is better at the richer mixture. At the milder test conditions of the two engines, the correlation appears to be good at both fuel-air ratios but, at a fuel-air ratio of 0.10, the correlation line more nearly approaches the match line. In figure 29, the 17.6 engine performance compares more closely with the F-4 engine performance at the richer fuel-air mixture and at the more severe test conditions of the 17.6 engine. In figures 28 and 29, the solid correlation lines from reference 4 agree reasonably well with the data presented for the five aromatics; this statement is also true for the comparison of the F-4 engine performance with the full-scale-cylinder performance presented in reference 6, again indicating the possibility of predicting the performance of aromatic fuel blends in a full-scale cylinder from performance data obtained in small-scale engines.

SUMMARY OF RESULTS

Knock-limited tests of five aromatics, each individually blended with selected base fuels and tested with and without tetraethyl lead, were conducted with 17.6, F-4, and F-3 small-scale engines. From these tests and from comparative published tests with a full-scale cylinder, the following results were obtained:

1. The five aromatics, in most instances, rated in the following order of decreasing antiknock effectiveness in leaded blends at a fuel-air ratio of 0.10: m-xylene, 1-isopropyl-4-methylbenzene, n-propylbenzene, isobutylbenzene, and n-butylbenzene. At lean mixtures the aromatics, with the exception of n-butylbenzene which had the lowest response at most conditions, were comparable as antiknock blending agents.

2. The performance data indicate that the aromatic blends were generally more sensitive to changes of inlet-air temperature than the base fuels and were more susceptible to the addition of tetraethyl lead than was S-4 reference fuel.

3. The present results further substantiate the validity of the correlations previously reported between full-scale and small-scale engine data for a specific aromatic concentration in the base fuel.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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TABLE I.- INDEX OF FIGURES

Figure	Aromatic	Percentage aromatic in blend (by volume)	Base fuel	Tetra-ethyl lead (ml/gal)	Inlet-air temper-ature (°F)
F-4 engine (knock-limited imep against fuel-air ratio)					
2	n-Propylbenzene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
3	n-Butylbenzene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
4	Isobutylbenzene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
5	m-Xylene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
6	1-Isopropyl-4-methylbenzene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
F-4 engine (knock-limited imep ratio against aromatic concentration)					
7(a)	n-Propylbenzene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
(b)	n-Butylbenzene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
(c)	Isobutylbenzene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
(d)	m-Xylene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
(e)	1-Isopropyl-4-methylbenzene	0,10,25,50	87.5% S-4 + 12.5% n-heptane	4	225
17.6 engine (knock-limited imep against fuel-air ratio)					
8(a)	n-Propylbenzene	0,10,20	S-4	0	250
(b)		0,20			100
9(a)	n-Propylbenzene	0,10,20	S-4	4	250
(b)		0,20			100
10(a)	n-Propylbenzene	0,25	87.5% S-4 + 12.5% n-heptane	4	250
(b)		0,25			100
11(a)	n-Butylbenzene	0,10,20	S-4	0	250
(b)		0,20			100
12(a)	n-Butylbenzene	0,10,20	S-4	4	250
(b)		0,20			100
13(a)	n-Butylbenzene	0,25	87.5% S-4 + 12.5% n-heptane	4	250
(b)		0,25			100
14(a)	Isobutylbenzene	0,10,20	S-4	0	250
(b)		0,20			100
15(a)	Isobutylbenzene	0,10,20	S-4	4	250
(b)		0,20			100
16(a)	Isobutylbenzene	0,25	87.5% S-4 + 12.5% n-heptane	4	250
(b)		0,25			100
17(a)	m-Xylene	0,10,20	S-4	0	250
(b)		0,20			100
18(a)	m-Xylene	0,10,20	S-4	4	250
(b)		0,20			100
19(a)	m-Xylene	0,25	87.5% S-4 + 12.5% n-heptane	4	250
(b)		0,25			100
20(a)	1-Isopropyl-4-methylbenzene	0,10,20	S-4	0	250
(b)		0,20			100
21(a)	1-Isopropyl-4-methylbenzene	0,10,20	S-4	4	250
(b)		0,20			100
22(a)	1-Isopropyl-4-methylbenzene	0,25	87.5% S-4 + 12.5% n-heptane	4	250
(b)		0,25			100
17.6 engine (knock-limited imep ratio against aromatic concentration)					
23	n-Propylbenzene	0,10,20	S-4	0,4	250,100
24	n-Butylbenzene	0,10,20	S-4	0,4	250,100
25	Isobutylbenzene	0,10,20	S-4	0,4	250,100
26	m-Xylene	0,10,20	S-4	0,4	250,100
27	1-Isopropyl-4-methylbenzene	0,10,20	S-4	0,4	250,100
Engine correlation plots					
28	Comparison of the 17.6 engine performance with the full-scale-cylinder performance.				
29	Comparison of the F-4 engine performance with the 17.6 engine performance.				

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TABLE II. - F-4 and F-3 RATINGS OF AROMATIC BLENDS

Compound	Blend composition (percent by volume)			Tetraethyl lead (ml/gal)	F-4 ratings				F-3 ratings	
					Lean		Rich (F/A=0.11)			
	Aromatic	S-4 reference fuel	87.5 percent S-4 plus 12.5 percent n-heptane		Percentage S-4 + 4 ml TEL/gal in n-heptane + 4 ml TEL/gal	Performance number	Percentage S-4 + 4 ml TEL/gal in n-heptane + 4 ml TEL/gal	Performance number	S-4 + ml TEL	Performance number
87.5 percent S-4 + 12.5 percent n-heptane	0	0	100	4	87.5	116	87.5	111	0.63	119
n-Propylbenzene	10	0	90	4	85.5	112	92.0	127	1.00	126
n-Butylbenzene					85.0	112	91.0	123	.60	118
Isobutylbenzene					85.5	112	91.5	125	.70	120
m-Xylene					83.5	109	94.0	134	.95	125
1-Isopropyl-4-methylbenzene					89.0	120	93.0	131	1.00	126
n-Propylbenzene	25	0	75	4	86.0	113	100.0	153	0.80	122
n-Butylbenzene					83.5	109	94.5	135	.60	118
Isobutylbenzene					80.0	103	97.5	145	.64	119
m-Xylene					79.0	101	>100.0	[a]166	.85	123
1-Isopropyl-4-methylbenzene					83.5	109	>100.0	[a]157	.82	123
n-Propylbenzene	50	0	50	4	74.0	92	>100.0	[a]205	0.58	118
n-Butylbenzene					77.5	98	>100.0	[a]156	.33	111
Isobutylbenzene					84.5	111	>100.0	[a]173	.50	116
m-Xylene					78.5	100	>100.0	[a]297	.80	122
1-Isopropyl-4-methylbenzene					77.0	97	>100.0	[a]223	.40	113
n-Propylbenzene	10	90	0	4	-------	-------	-------	-------	2.9	146
m-Xylene					-------	-------	-------	-------	3.6	150
n-Propylbenzene	10	90	0	0	-------	-------	-------	-------	[b]98.8	96
n-Butylbenzene					-------	-------	-------	-------	[b]98.8	96
Isobutylbenzene					-------	-------	-------	-------	[b]99.1	97
m-Xylene					-------	-------	-------	-------	[b]100.0	100
1-Isopropyl-4-methylbenzene					-------	-------	-------	-------	[b]99.5	98
n-Propylbenzene	20	80	0	0	-------	-------	-------	-------	[b]97.8	93
n-Butylbenzene					-------	-------	-------	-------	[b]96.6	89
Isobutylbenzene					-------	-------	-------	-------	[b]97.8	93
m-Xylene					-------	-------	-------	-------	[b]99.5	98
1-Isopropyl-4-methylbenzene					-------	-------	-------	-------	[b]98.6	95

[a]Estimated performance number = $\frac{\text{imep of aromatic blend}}{\text{imep of S-4 + 4 ml TEL/gal}}$ × performance number of S-4 + 4 ml TEL/gal.

[b]Octane number.

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TABLE III.- SUPERCHARGED-ENGINE TESTS OF BLENDS CONTAINING AROMATICS

Fuel composition					Engine conditions			Test results									
Compound	Blend composition (percent by volume)			Tetraethyl lead (ml/gal)	Spark advance (deg B.T.C.)	Exhaust pressure (in. Hg absolute)	Inlet-air temperature (°F)	Fuel-air ratio									
	Aromatic	S-4 reference fuel	87.5 percent S-4 plus 12.5 percent n-heptane					0.065		0.07		0.085		0.10		0.11	
								imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]
17.6 engine																	
n-Propylbenzene	10	90	0	0	30	Atmospheric	250	134	0.99	133	0.99	155	1.00	191	1.10	203	1.16
n-Butylbenzene								136	.95	136	.98	155	.97	179	.99	185	1.02
Isobutylbenzene								121	.98	124	.98	146	.99	172	1.02	180	1.07
m-Xylene								120	.97	123	.98	150	1.03	178	1.07	185	1.08
1-Isopropyl-4-methylbenzene								126	.98	128	.99	155	1.04	180	1.07	190	1.12
n-Propylbenzene	20	80	0	0	30	Atmospheric	250	134	0.99	134	0.99	158	1.02	199	1.15	216	1.23
n-Butylbenzene								133	.93	133	.96	153	.96	179	.99	189	1.04
Isobutylbenzene								119	.97	119	.94	142	.96	173	1.03	186	1.11
m-Xylene								115	.93	118	.94	156	1.08	190	1.14	202	1.18
1-Isopropyl-4-methylbenzene								121	.94	122	.95	152	1.02	185	1.10	204	1.20
n-Propylbenzene	20	80	0	0	30	Atmospheric	100	200	1.14	198	1.14	215	1.19	240	1.30	241	1.32
n-Butylbenzene								187	1.04	185	1.05	195	1.08	205	1.10	203	1.09
Isobutylbenzene								169	1.10	170	1.11	189	1.15	206	1.19	208	1.20
m-Xylene								176	1.14	176	1.15	201	1.22	236	1.35	243	1.40
1-Isopropyl-4-methylbenzene								176	1.14	176	1.14	201	1.21	234	1.33	241	1.37
n-Propylbenzene	10	90	0	4	30	Atmospheric	250	226	1.05	235	1.05	270	1.09	302	1.14	311	1.16
n-Butylbenzeno								221	1.01	231	1.03	259	1.04	278	1.03	285	1.06
Isobutylbenzene								223	1.09	226	1.08	264	1.09	297	1.14	298	1.15
m-Xylene								219	1.07	228	1.09	273	1.13	310	1.19	321	1.23
1-Isopropyl-4-methylbenzene								219	1.09	227	1.08	277	1.13	305	1.17	312	1.19
n-Propylbenzene	20	80	0	4	30	Atmospheric	250	239	1.11	251	1.13	299	1.21	340	1.29	356	1.33
n-Butylbenzene								224	1.02	233	1.04	267	1.07	296	1.10	300	1.11
Isobutylbenzene								234	1.14	242	1.15	287	1.18	326	1.25	333	1.29
m-Xylene								228	1.12	243	1.16	311	1.29	367	1.41	381	1.46
1-Isopropyl-4-methylbenzene								228	1.12	237	1.13	300	1.22	363	1.39	379	1.45
n-Propylbenzene	20	80	0	4	30	Atmospheric	100	388	1.34	396	1.38	412	1.42	398	1.36	377	1.31
n-Butylbenzene								307	1.10	309	1.11	318	1.12	326	1.14	321	1.14
Isobutylbenzene								342	1.20	344	1.22	355	1.23	359	1.25	351	1.24
m-Xylene								366	1.28	365	1.29	416	1.44	430	1.48	428	1.51
1-Isopropyl-4-methylbenzene								372	1.30	376	1.32	408	1.42	414	1.42	409	1.43

[a]imep ratio = $\frac{\text{imep of aromatic blend}}{\text{imep of base fuel}}$. For the blends tested with the 17.6 engine, the base fuel was S-4, S-4 plus 4 ml TEL/gal, or 87.5 percent S-4 plus 12.5 percent n-heptane plus 4 ml TEL/gal; in all other instances, 87.5 percent S-4 plus 12.5 percent n-heptane plus 4 ml TEL/gal was used.

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TABLE III.- SUPERCHARGED-ENGINE TESTS OF BLENDS CONTAINING AROMATICS - Concluded

Fuel composition					Engine conditions			Test results									
Compound	Blend composition (percent by volume)			Tetra-ethyl lead (ml/gal)	Spark advance (deg B.T.C.)	Exhaust pressure (in. Hg absolute)	Inlet-air temperature (°F)	Fuel-air ratio									
	Aromatic	S-4 reference fuel	87.5 percent S-4 plus 12.5 percent n-heptane					0.065		0.07		0.085		0.10		0.11	
								imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]	imep	imep ratio[a]
17.6 engine - Concluded																	
n-Propylbenzene	25	0	75	4	30	Atmospheric	250	213	1.22	219	1.24	249	1.31	267	1.31	271	1.34
n-Butylbenzene								159	1.03	165	1.04	195	1.12	217	1.16	219	1.18
Isobutylbenzene								168	1.09	177	1.13	210	1.18	233	1.23	236	1.26
m-Xylene								193	1.21	199	1.22	260	1.46	290	1.53	290	1.54
1-Isopropyl-4-methylbenzene								196	1.23	203	1.23	246	1.36	273	1.44	280	1.49
n-Propylbenzene	25	0	75	4	30	Atmospheric	100	290	1.34	290	1.36	301	1.39	298	1.38	292	1.40
n-Butylbenzene								221	1.13	223	1.14	235	1.17	241	1.18	237	1.19
Isobutylbenzene								252	1.27	252	1.27	262	1.29	258	1.27	249	1.25
m-Xylene								272	1.34	280	1.38	318	1.51	325	1.56	318	1.57
1-Isopropyl-4-methylbenzene								286	1.41	293	1.44	315	1.51	315	1.53	309	1.53
Full-scale cylinder (data from reference 6)																	
n-Propylbenzene	25	0	75	4	30	15	250	165	1.20	166	1.15	206	1.24	259	1.39	275	1.43
n-Butylbenzene								147	1.07	146	1.01	189	1.14	222	1.19	231	1.20
Isobutylbenzene								175	1.27	176	1.22	210	1.27	245	1.31	260	1.35
1-Isopropyl-4-methylbenzene								173	1.25	175	1.22	215	1.30	276	1.48	312	1.63
n-Propylbenzene	25	0	75	4	20	Atmospheric	210	232	1.47	232	1.45	270	1.48	299	1.40	312	1.38
n-Butylbenzene								176	1.11	176	1.10	218	1.20	260	1.22	270	1.19
Isobutylbenzene								214	1.35	209	1.31	245	1.35	286	1.34	297	1.31
1-Isopropyl-4-methylbenzene								238	1.51	241	1.51	292	1.60	323	1.52	343	1.52
F-4 engine																	
n-Propylbenzene	10	0	90	4	45	Atmospheric	225	108	0.94	125	0.99	171	1.08	191	1.10	194	1.11
n-Butylbenzene								106	.95	125	1.00	164	1.04	184	1.07	186	1.08
Isobutylbenzene								99	.95	122	1.04	165	1.09	185	1.09	189	1.11
m-Xylene								102	.93	126	1.02	174	1.12	196	1.15	201	1.16
1-Isopropyl-4-methylbenzene								116	1.01	136	1.06	178	1.12	197	1.15	199	1.15
n-Propylbenzene	25	0	75	4	45	Atmospheric	225	108	0.94	136	1.08	196	1.24	227	1.30	240	1.38
n-Butylbenzene								97	.87	120	.96	176	1.12	200	1.16	204	1.18
Isobutylbenzene								84	.81	114	.97	182	1.20	213	1.25	222	1.30
m-Xylene								90	.82	122	.98	207	1.33	248	1.45	262	1.51
1-Isopropyl-4-methylbenzene								105	.91	132	1.03	196	1.23	231	1.34	248	1.43
n-Propylbenzene	50	0	50	4	45	Atmospheric	225	84	0.73	98	0.78	186	1.18	239	1.37	323	1.86
n-Butylbenzene								86	.77	114	.91	193	1.23	230	1.34	245	1.42
Isobutylbenzene								94	.90	119	1.02	195	1.28	244	1.44	272	1.59
m-Xylene								88	.80	114	.92	268	1.72	403	2.36	467	2.70
1-Isopropyl-4-methylbenzene								89	.77	111	.87	215	1.35	316	1.84	351	2.03

[a]imep ratio = $\frac{\text{imep of aromatic blend}}{\text{imep of base fuel}}$. For the blends tested with the 17.6 engine, the base fuel was S-4, S-4 plus 4 ml TEL/gal, or 87.5 percent S-4 plus 12.5 percent n-heptane plus 4 ml TEL/gal; in all other instances, 87.5 percent S-4 plus 12.5 percent n-heptane plus 4 ml TEL/gal was used.

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TABLE IV. - TEMPERATURE SENSITIVITY OF THE AROMATIC BLENDS RELATIVE TO THAT OF THE BASE FUELS

[17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F]

Compound	Composition (percent by volume)			Tetraethyl lead (ml/gal)	Relative temperature sensitivity[a]				
					Fuel-air ratio				
	Aromatic	S-4 reference fuel	87.5 percent S-4 plus 12.5 percent n-heptane		0.065	0.07	0.085	0.10	0.11
S-4 reference fuel	0	100	0	0	1.00	1.00	1.00	1.00	1.00
n-Propylbenzene	20	80	0	0	1.15	1.15	1.17	1.13	1.07
n-Butylbenzene					1.12	1.09	1.12	1.11	1.05
Isobutylbenzene					1.13	1.18	1.20	1.16	1.08
m-Xylene					1.23	1.22	1.13	1.18	1.19
1-Isopropyl-4-methylbenzene					1.21	1.20	1.19	1.21	1.14
S-4 reference fuel	0	100	0	4	1.00	1.00	1.00	1.00	1.00
n-Propylbenzene	20	80	0	4	1.21	1.22	1.17	1.05	0.98
n-Butylbenzene					1.08	1.07	1.05	1.04	1.03
Isobutylbenzene					1.05	1.06	1.04	1.00	.96
m-Xylene					1.14	1.11	1.12	1.05	1.03
1-Isopropyl-4-methylbenzene					1.16	1.17	1.16	1.02	.99
87.5 percent S-4 plus 12.5 percent n-heptane	0	0	100	4	1.00	1.00	1.00	1.00	1.00
n-Propylbenzene	25	0	75	4	1.10	1.10	1.06	1.05	1.04
n-Butylbenzene					1.10	1.10	1.04	1.02	1.01
Isobutylbenzene					1.17	1.12	1.09	1.03	.99
m-Xylene					1.11	1.13	1.03	1.02	1.02
1-Isopropyl-4-methylbenzene					1.15	1.17	1.11	1.06	1.03

[a]Relative temperature sensitivity

$$= \frac{\dfrac{\text{imep of aromatic blend (inlet-air temperature, } 100^\circ \text{ F)}}{\text{imep of aromatic blend (inlet-air temperature, } 250^\circ \text{ F)}}}{\dfrac{\text{imep of base fuel (inlet-air temperature, } 100^\circ \text{ F)}}{\text{imep of base fuel (inlet-air temperature, } 250^\circ \text{ F)}}}$$

$$= \frac{\text{imep ratio (inlet-air temperature, } 100^\circ \text{ F)}}{\text{imep ratio (inlet-air temperature, } 250^\circ \text{ F)}} .$$

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TABLE V. - LEAD SUSCEPTIBILITY OF THE AROMATIC BLENDS RELATIVE TO THAT OF S-4 REFERENCE FUEL

[17.6 engine; compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F]

Compound	Inlet-air temperature (°F)	Composition (percent by volume)		Relative lead susceptibility[a]				
		Aromatic	S-4 reference fuel	Fuel-air ratio				
				0.065	0.07	0.085	0.10	0.11
S-4 reference fuel	250	0	100	1.00	1.00	1.00	1.00	1.00
n-Propylbenzene	250	10	90	1.06	1.06	1.09	1.04	1.00
n-Butylbenzene				1.06	1.05	1.07	1.04	1.04
Isobutylbenzene				1.11	1.10	1.10	1.12	1.07
m-Xylene				1.10	1.11	1.10	1.11	1.14
1-Isopropyl-4-methylbenzene				1.10	1.09	1.09	1.09	1.06
n-Propylbenzene	250	20	80	1.12	1.14	1.19	1.12	1.08
n-Butylbenzene				1.10	1.08	1.11	1.11	1.07
Isobutylbenzene				1.18	1.22	1.23	1.21	1.16
m-Xylene				1.20	1.23	1.19	1.24	1.24
1-Isopropyl-4-methylbenzene				1.19	1.19	1.20	1.26	1.21
S-4 reference fuel	100	0	100	1.00	1.00	1.00	1.00	1.00
n-Propylbenzene	100	20	80	1.18	1.21	1.19	1.05	0.99
n-Butylbenzene				1.06	1.06	1.04	1.04	1.05
Isobutylbenzene				1.09	1.10	1.07	1.05	1.03
m-Xylene				1.12	1.12	1.18	1.10	1.08
1-Isopropyl-4-methylbenzene				1.14	1.16	1.17	1.07	1.04

[a]Relative lead susceptibility

$$= \frac{\dfrac{\text{imep of aromatic blend (with 4 ml TEL/gal)}}{\text{imep of aromatic blend (with 0 ml TEL/gal)}}}{\dfrac{\text{imep of S-4 (with 4 ml TEL/gal)}}{\text{imep of S-4 (with 0 ml TEL/gal)}}}$$

$$= \frac{\text{imep ratio of aromatic blend (with 4 ml TEL/gal)}}{\text{imep ratio of aromatic blend (with 0 ml TEL/gal)}} .$$

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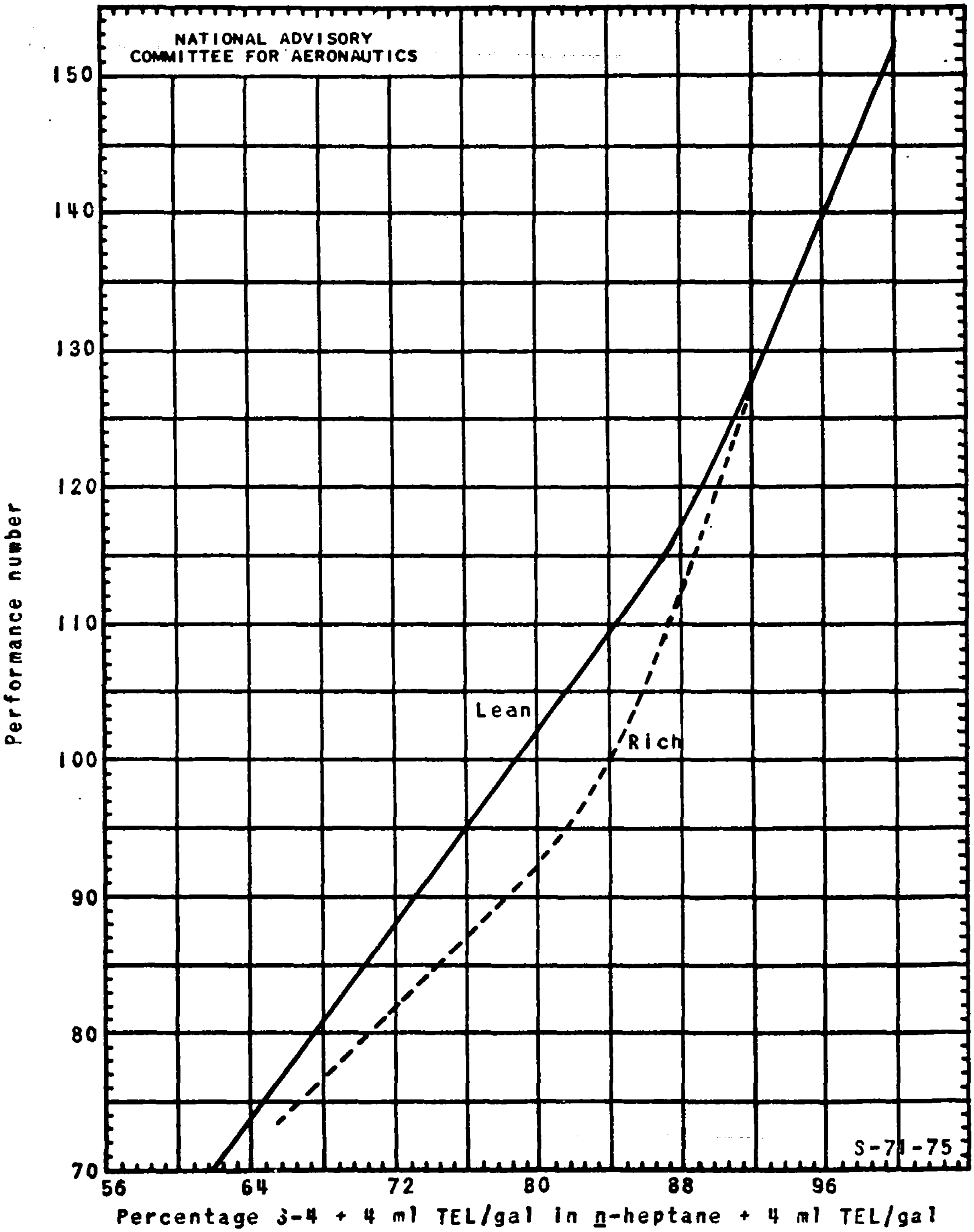


Figure 1. - Performance-number conversion chart for F-4 engine data.

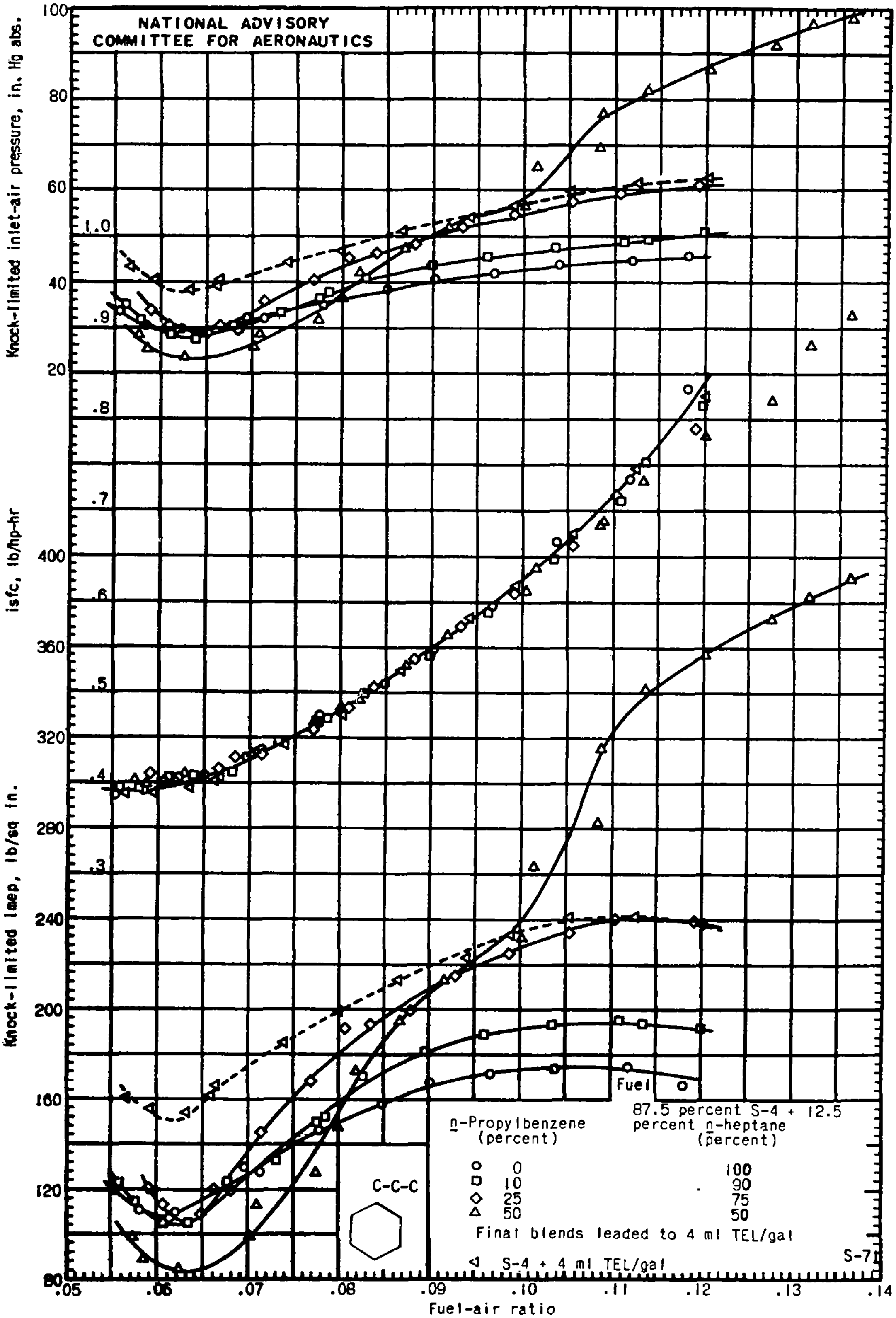


Figure 2. - The knock-limited performance of leaded blends of n-propylbenzene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in an F-4 engine.

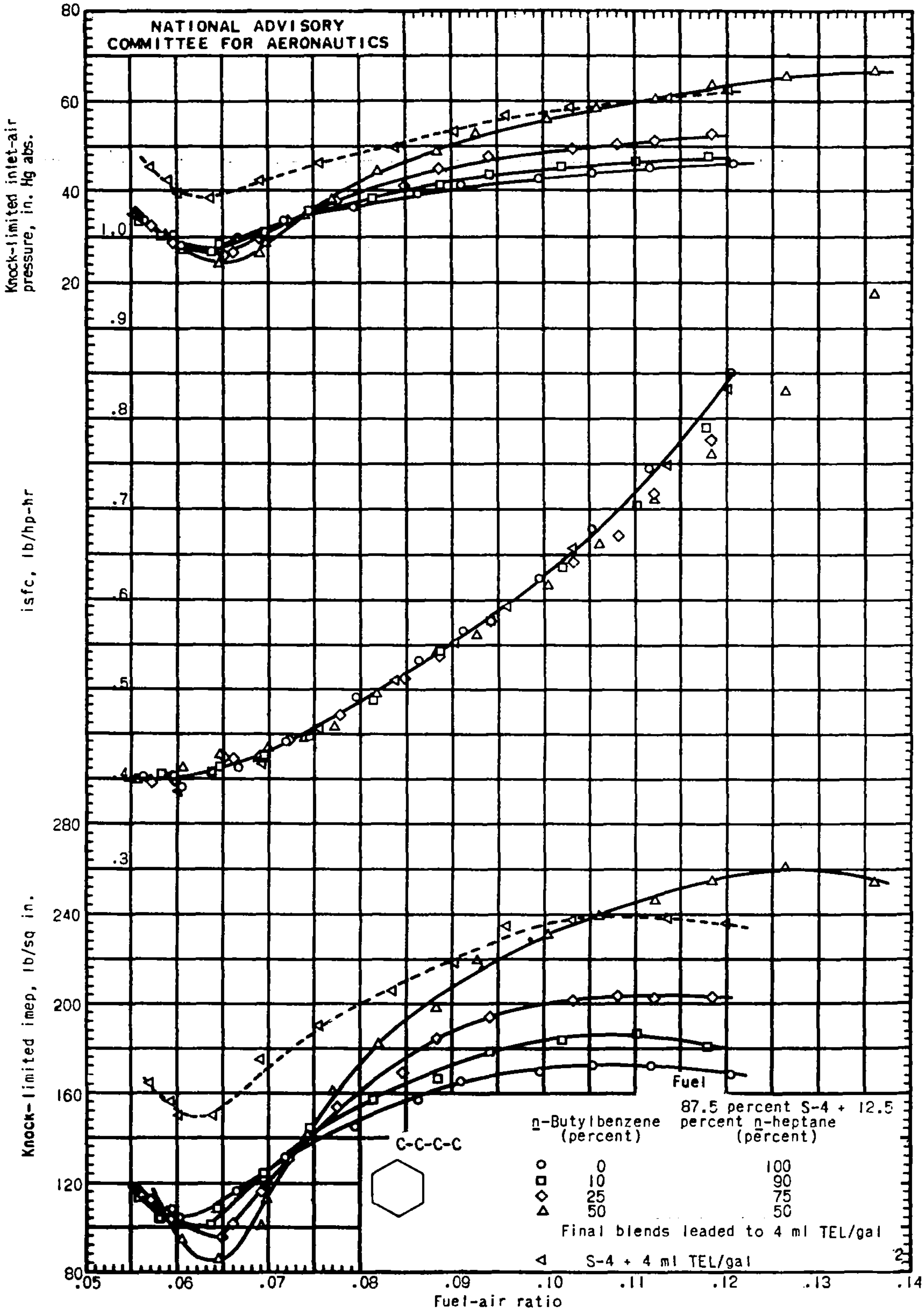


Figure 3. - The knock-limited performance of leaded blends of n-butylbenzene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in an F-4 engine.

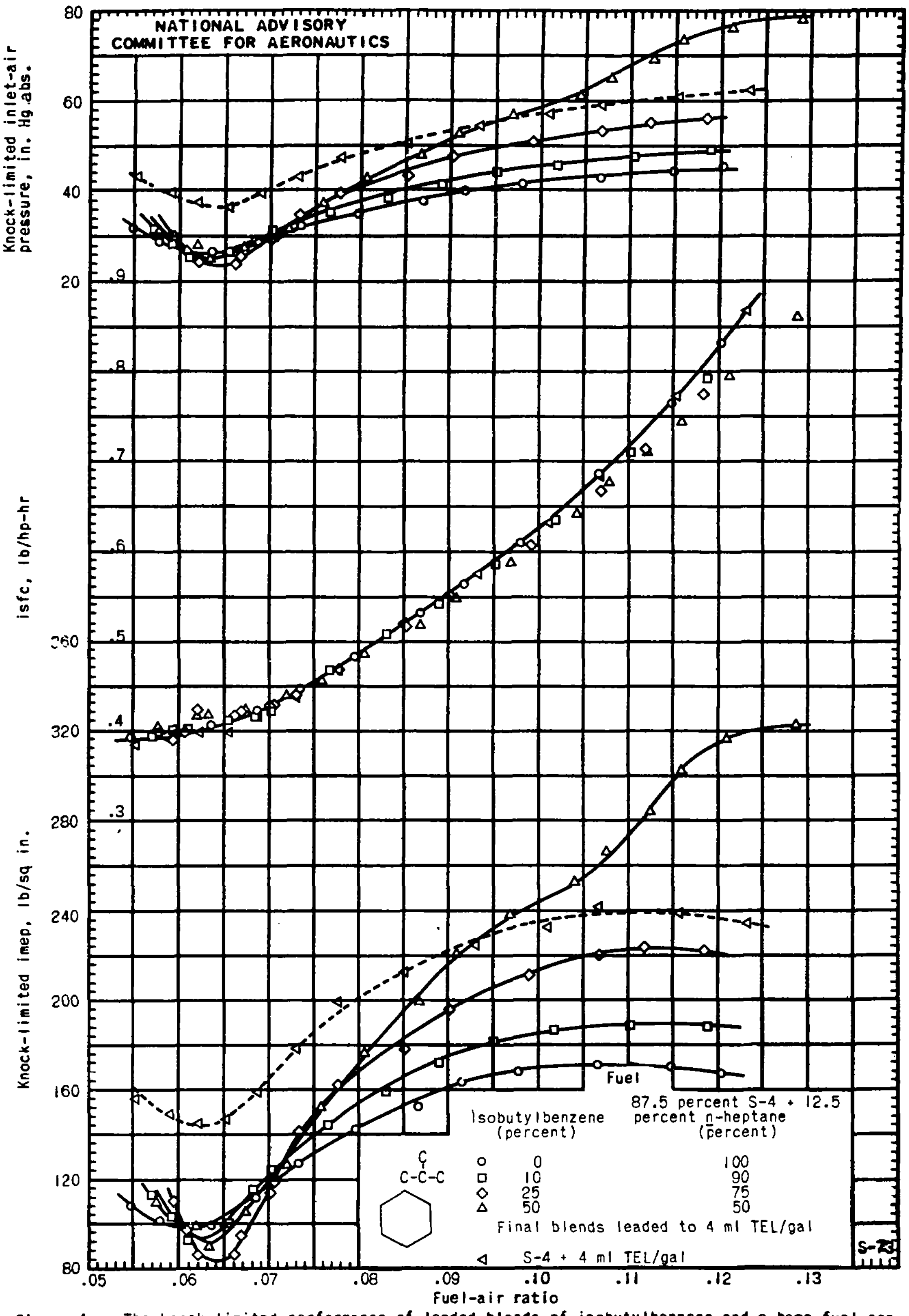


Figure 4. - The knock-limited performance of leaded blends of isobutylbenzene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in an F-4 engine.

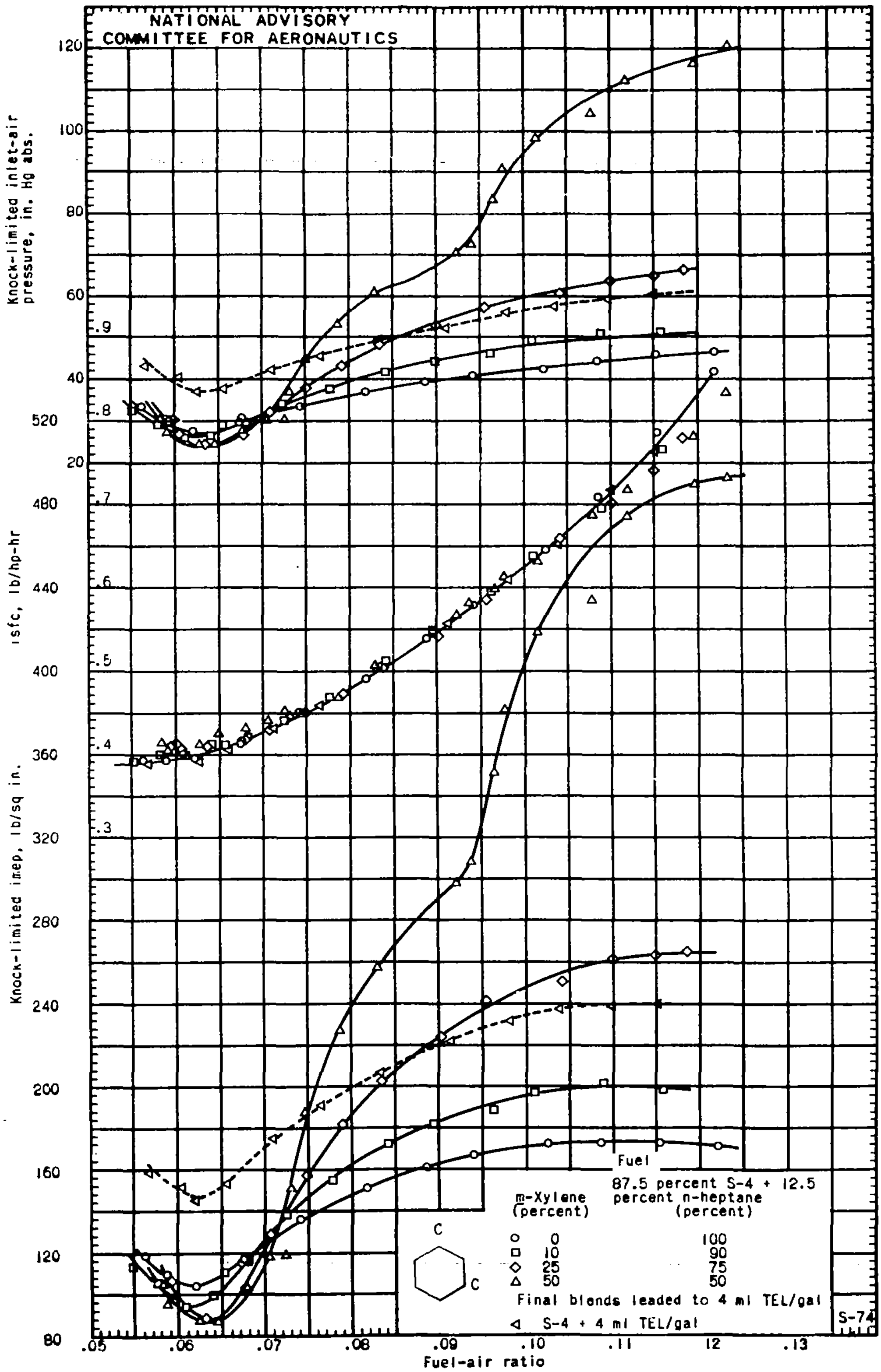


Figure 5. - The knock-limited performance of leaded blends of m-xylene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in an F-4 engine.

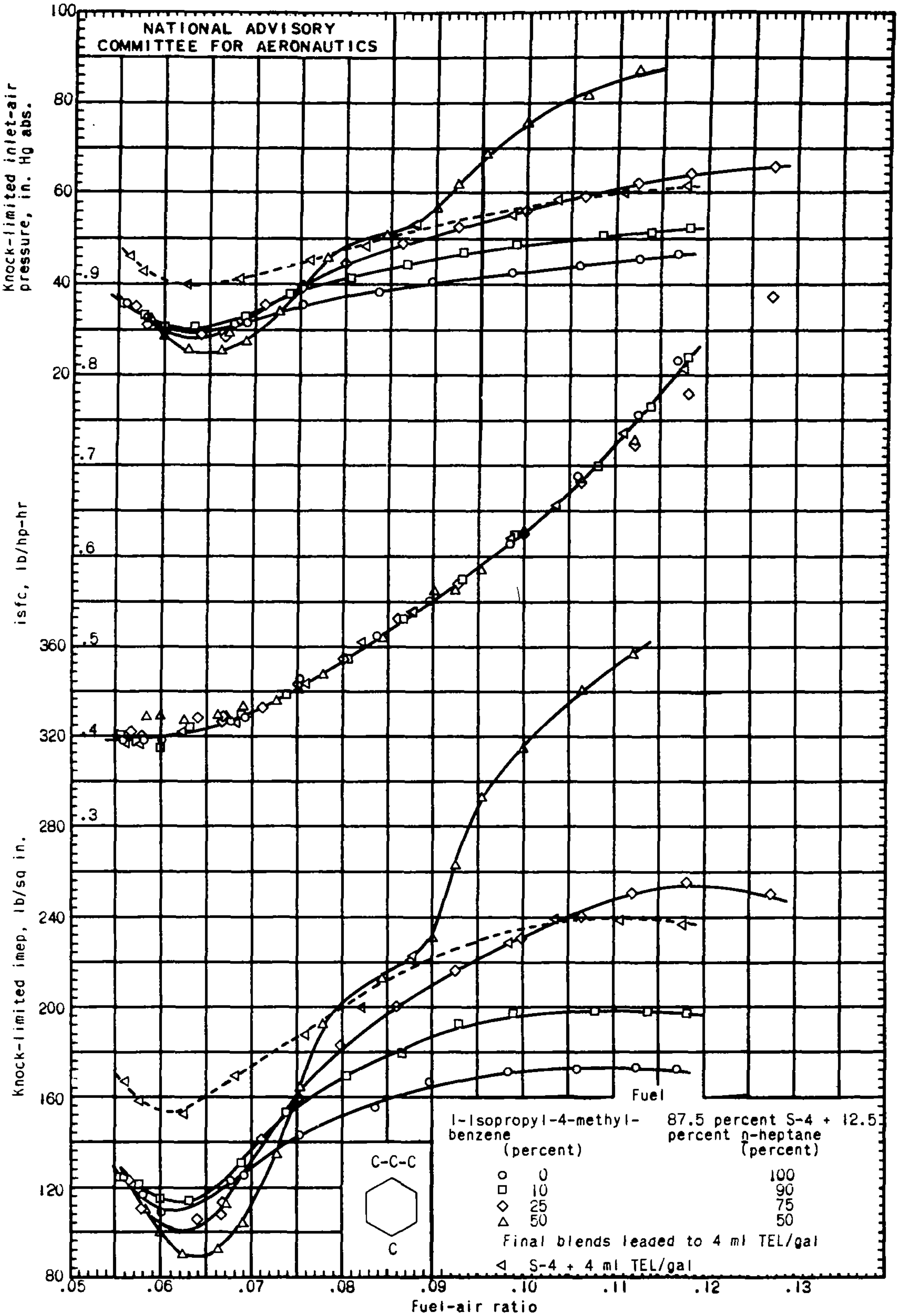


Figure 6. - The knock-limited performance of leaded blends of 1-isopropyl-4-methylbenzene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in an F-4 engine.

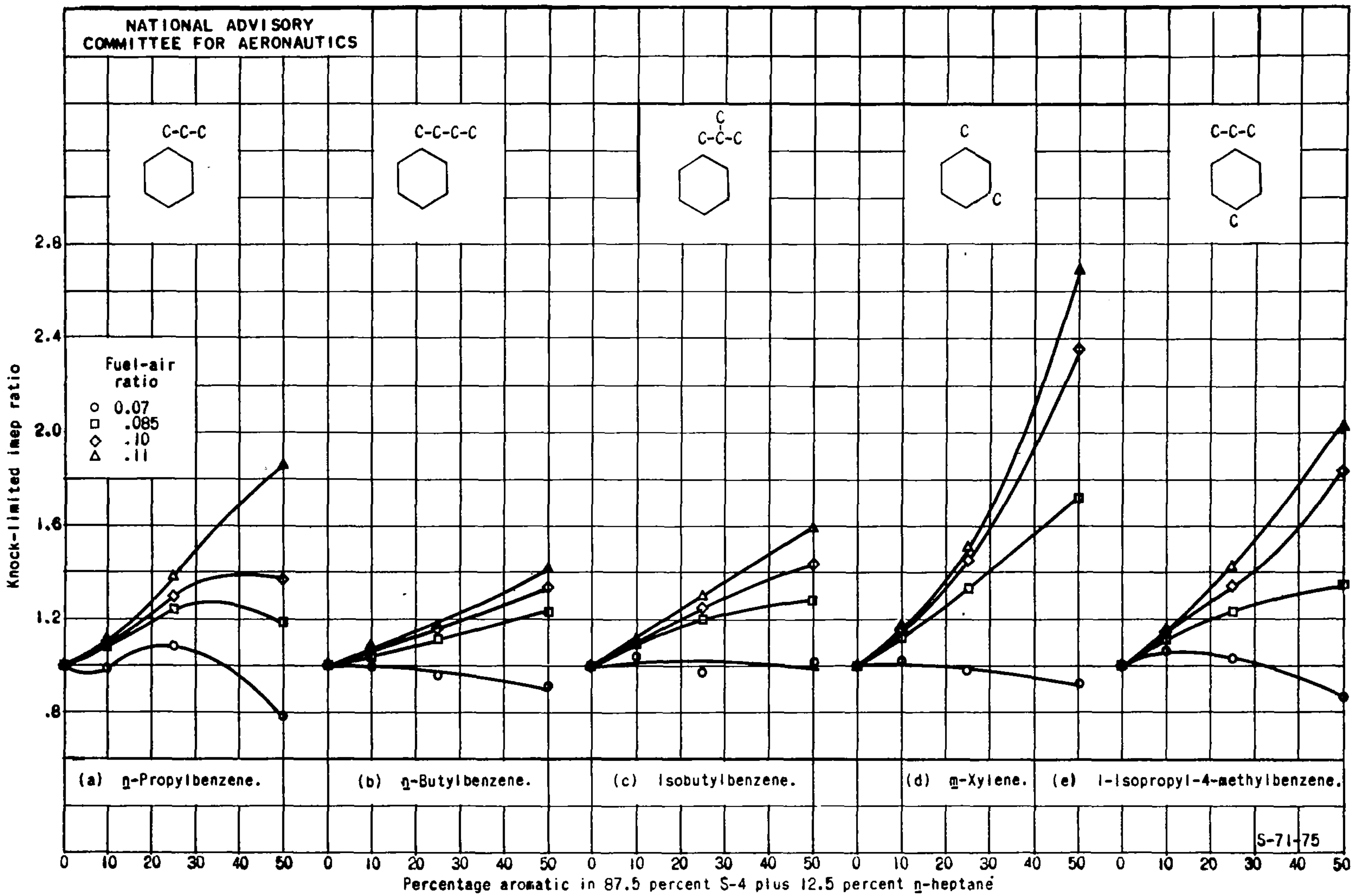


Figure 7. - The blending sensitivity of five aromatic hydrocarbons in 87.5 percent S-4 plus 12.5 percent n-heptane. F-4 engine; final blends leaded to 4 ml TEL per gallon.

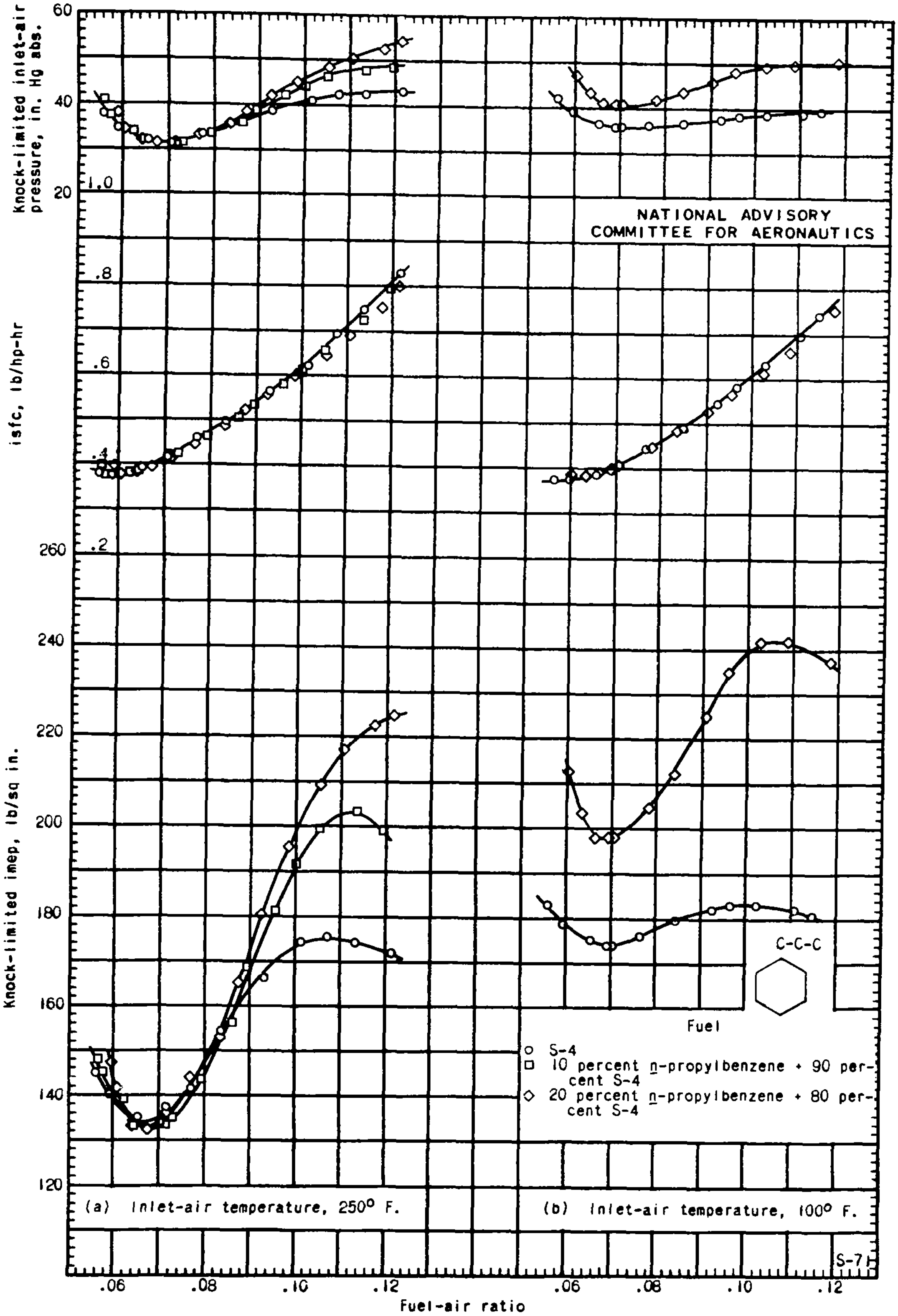


Figure 8. - The knock-limited performance of unleaded blends of n-propylbenzene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

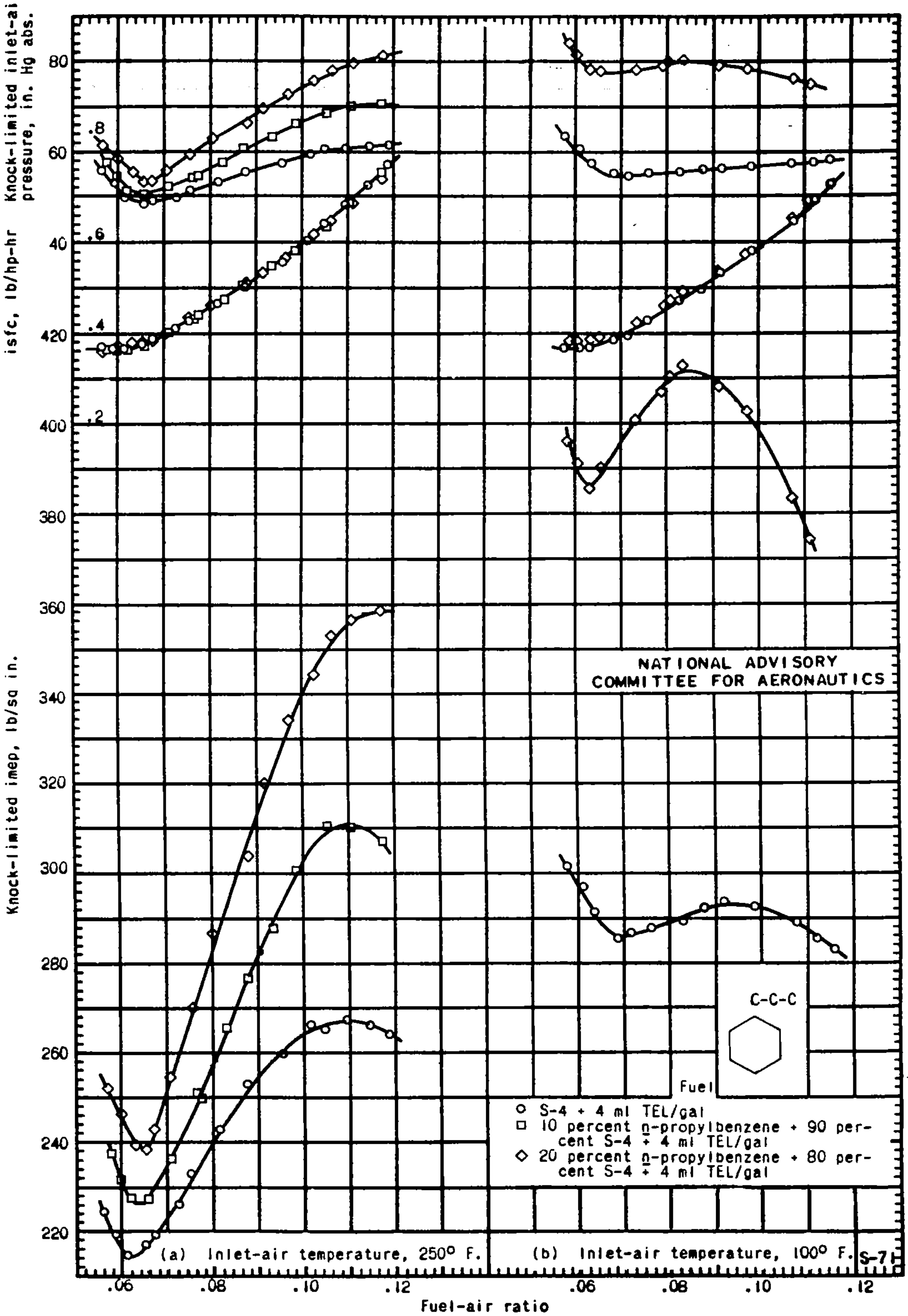


Figure 9. - The knock-limited performance of leaded blends of n-propylbenzene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

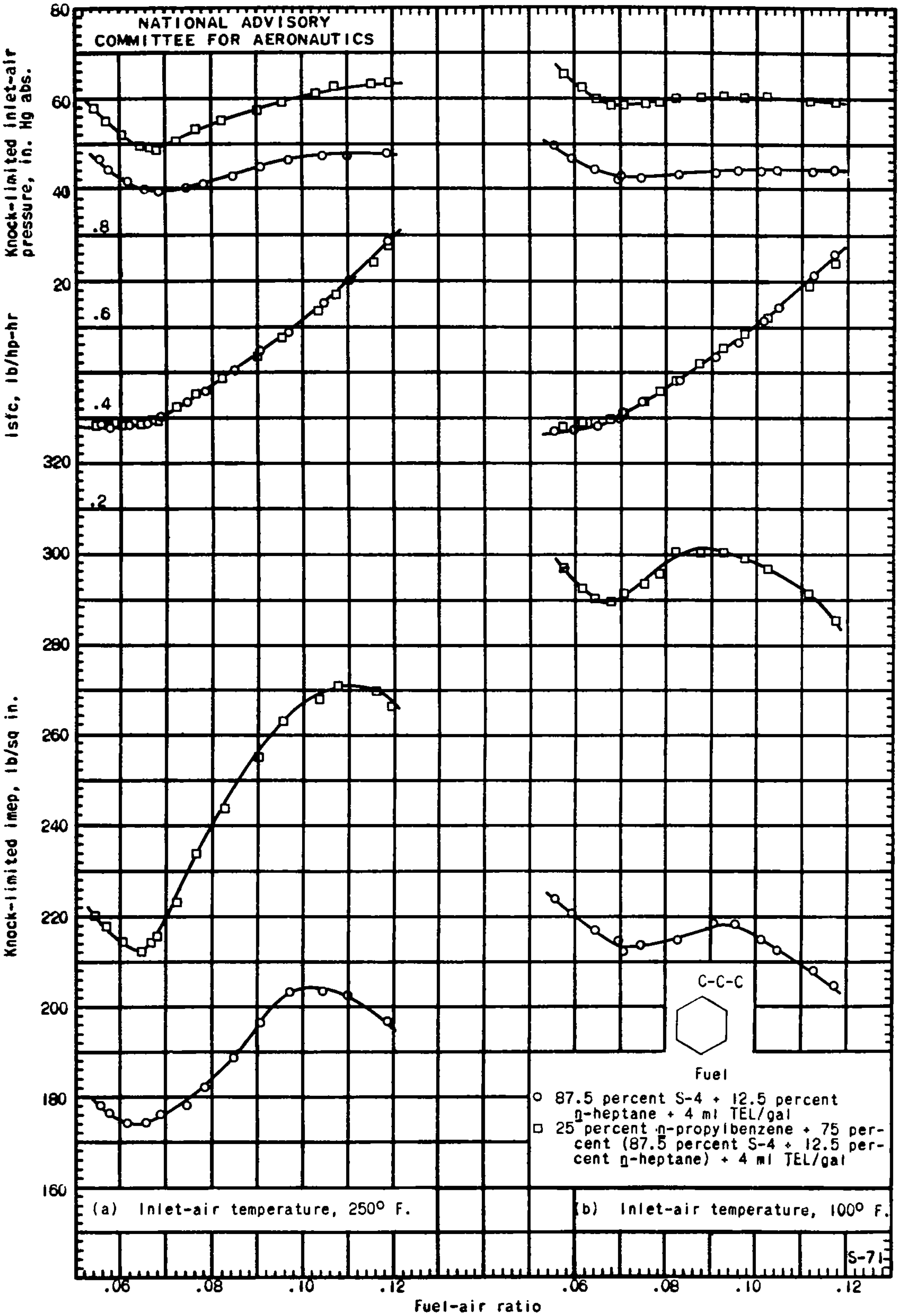


Figure 10. - The knock-limited performance of leaded blends of n-propylbenzene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

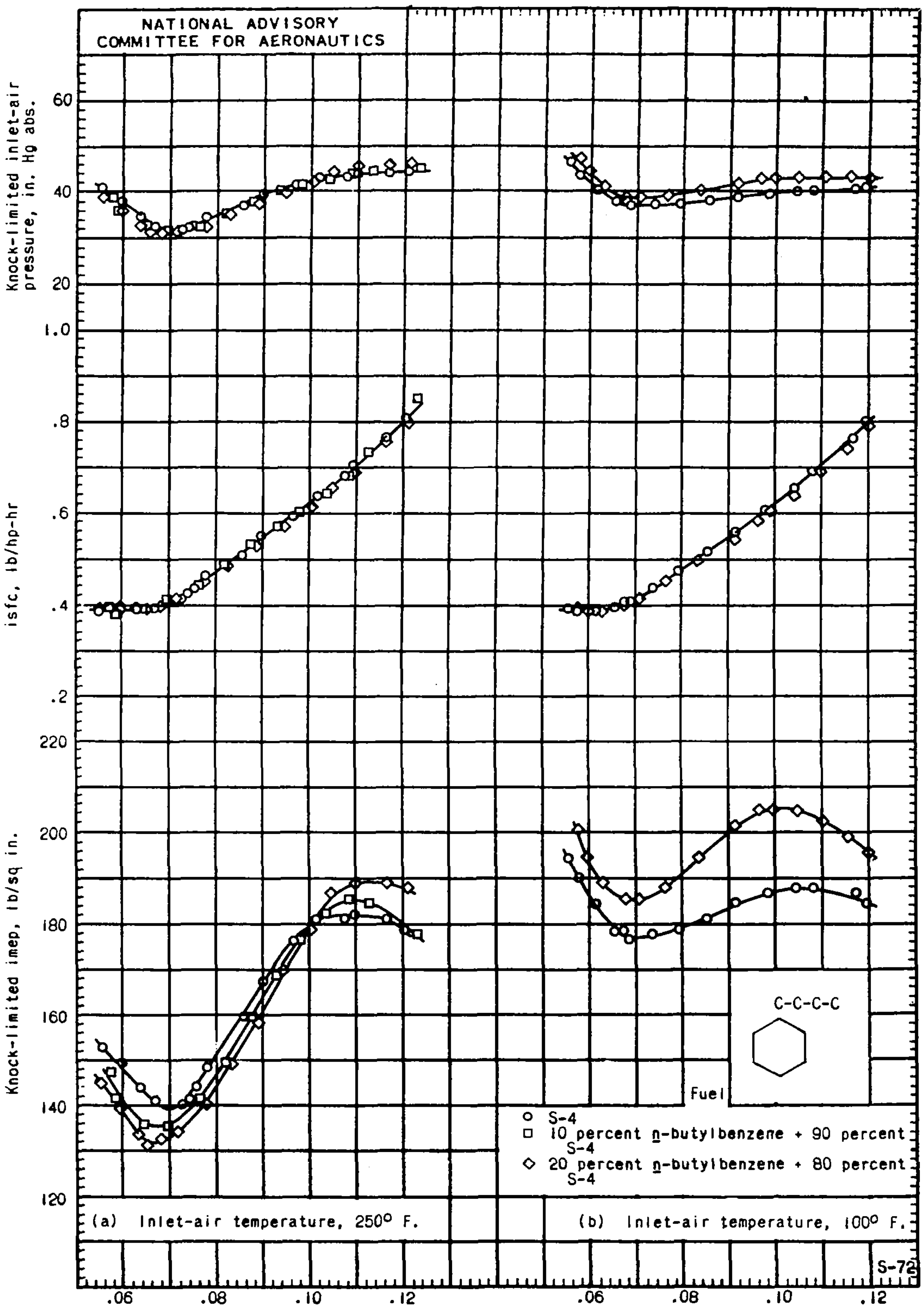


Figure 11. - The knock-limited performance of unleaded blends of n-butylbenzene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

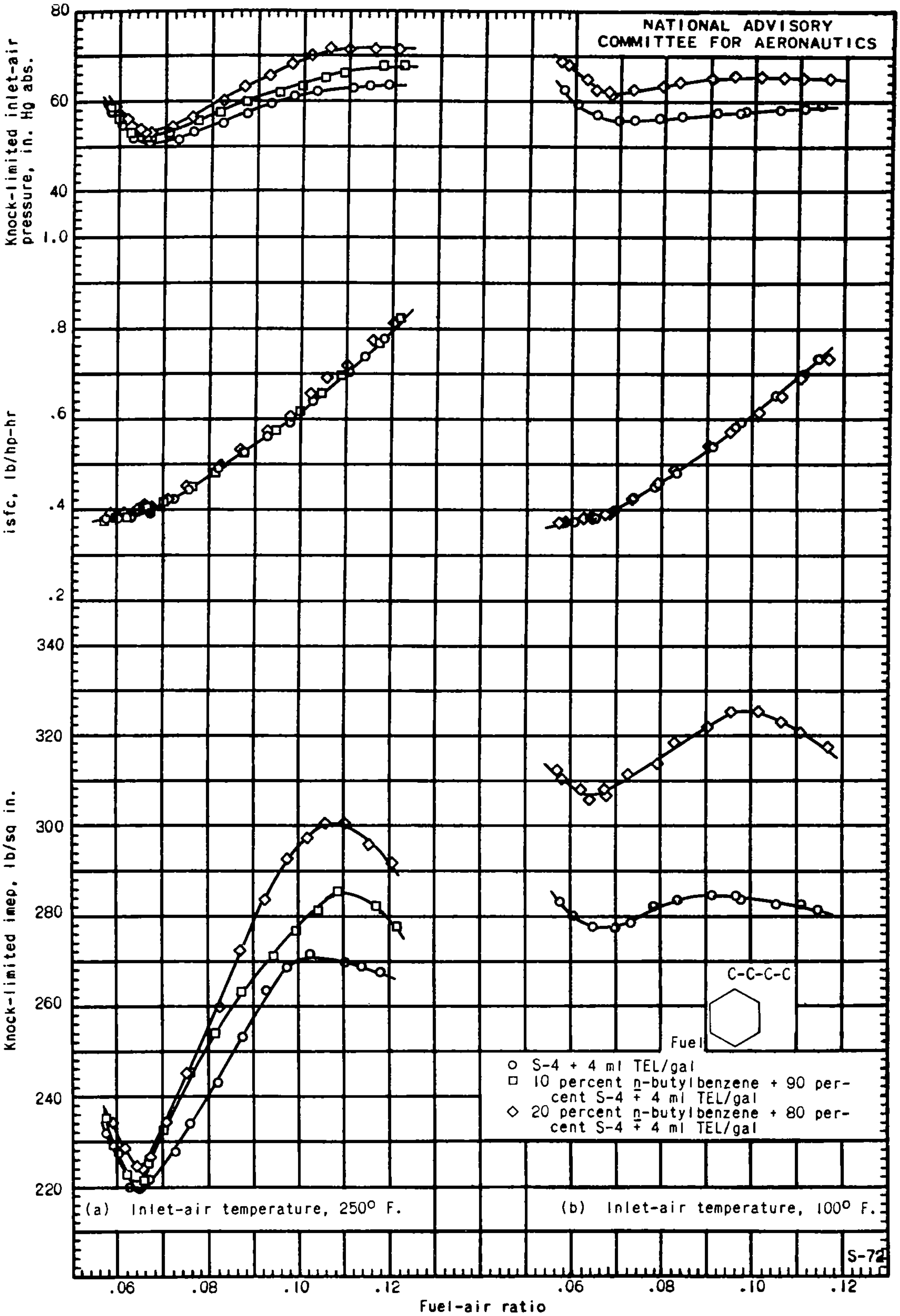


Figure 12. - The knock-limited performance of leaded blends of n-butylbenzene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

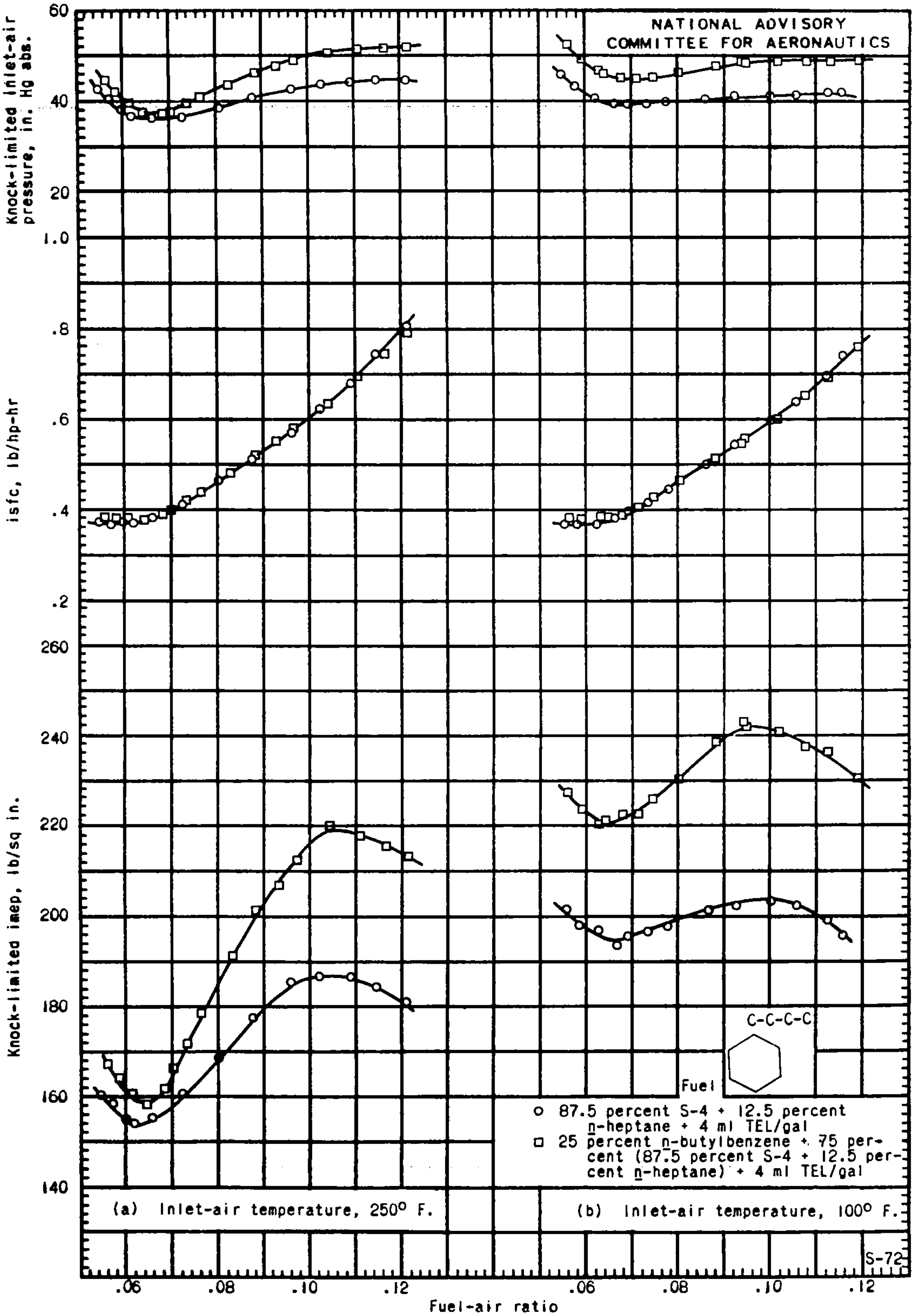


Figure 13. - The knock-limited performance of leaded blends of n-butylbenzene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

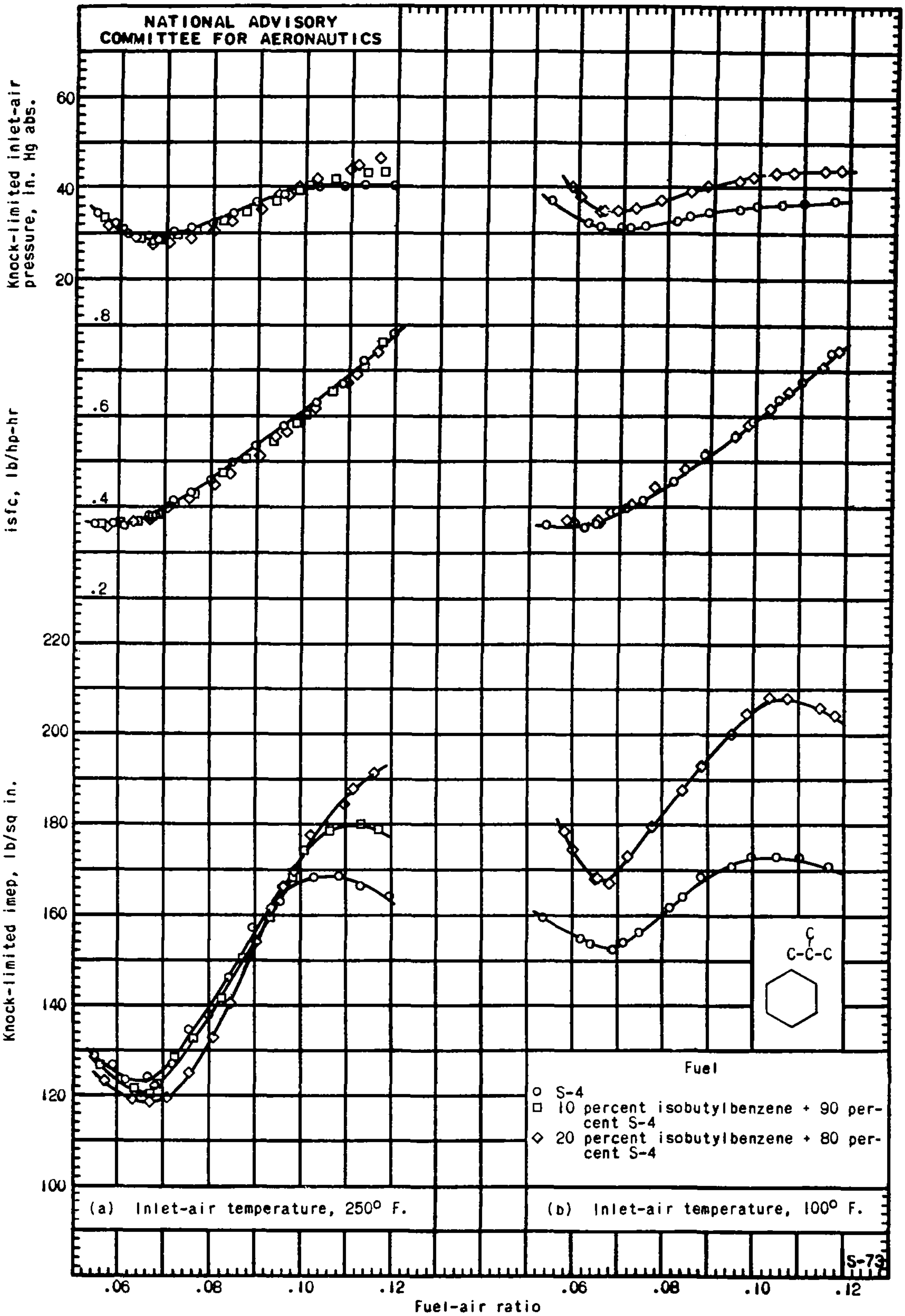


Figure 14. - The knock-limited performance of unleaded blends of isobutylbenzene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

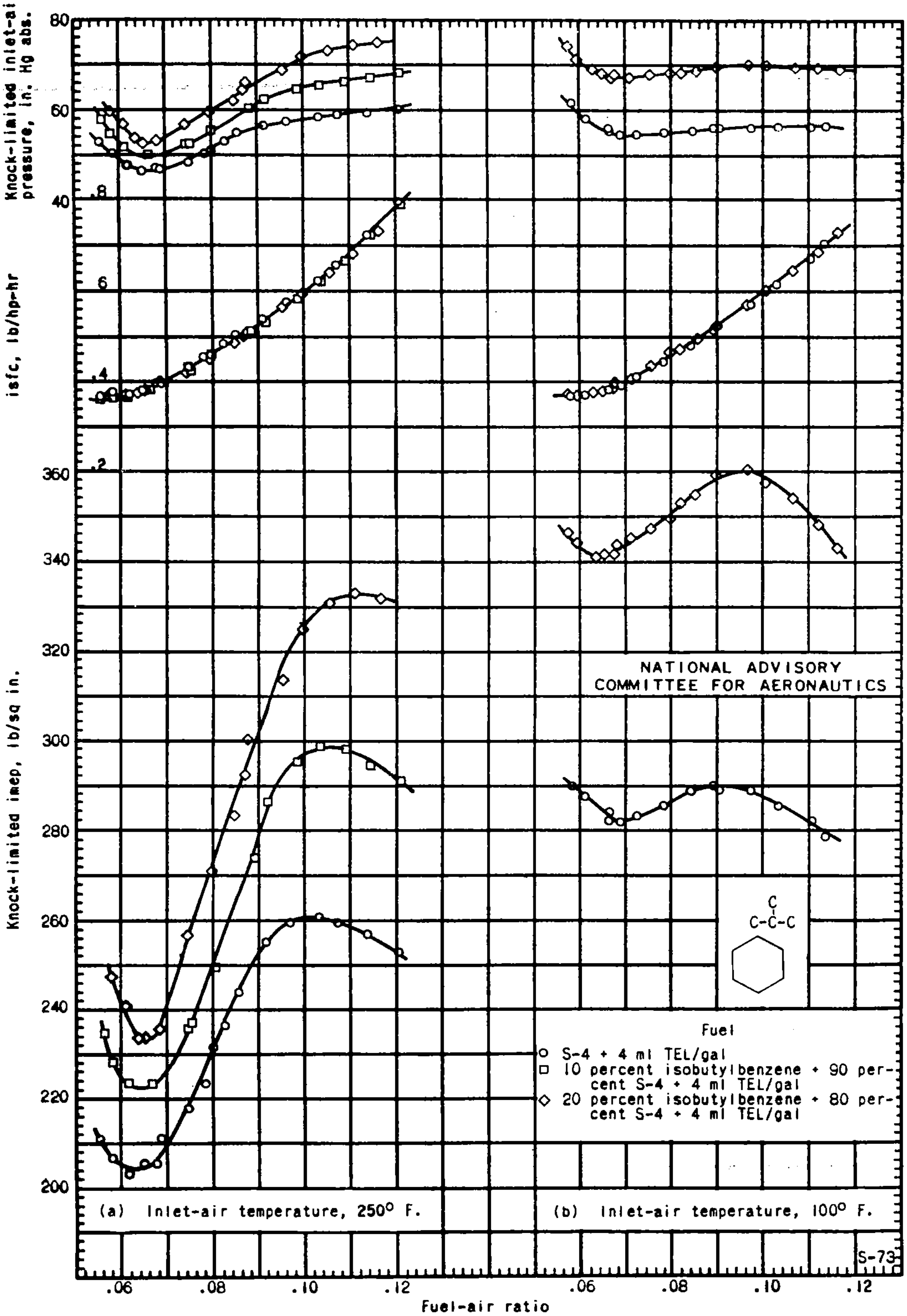


Figure 15. - The knock-limited performance of leaded blends of isobutylbenzene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

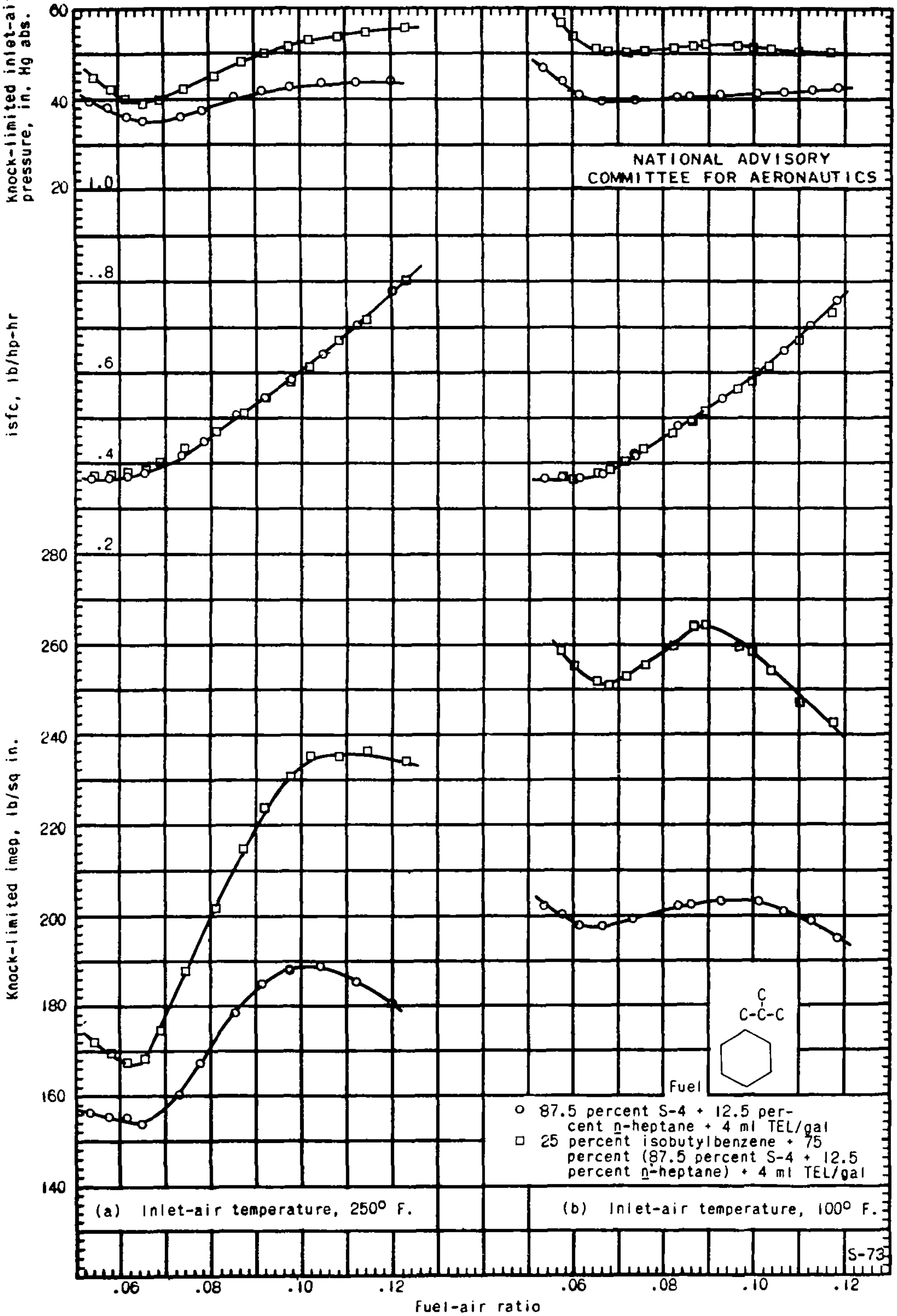


Figure 16. - The knock-limited performance of leaded blends of isobutylbenzene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

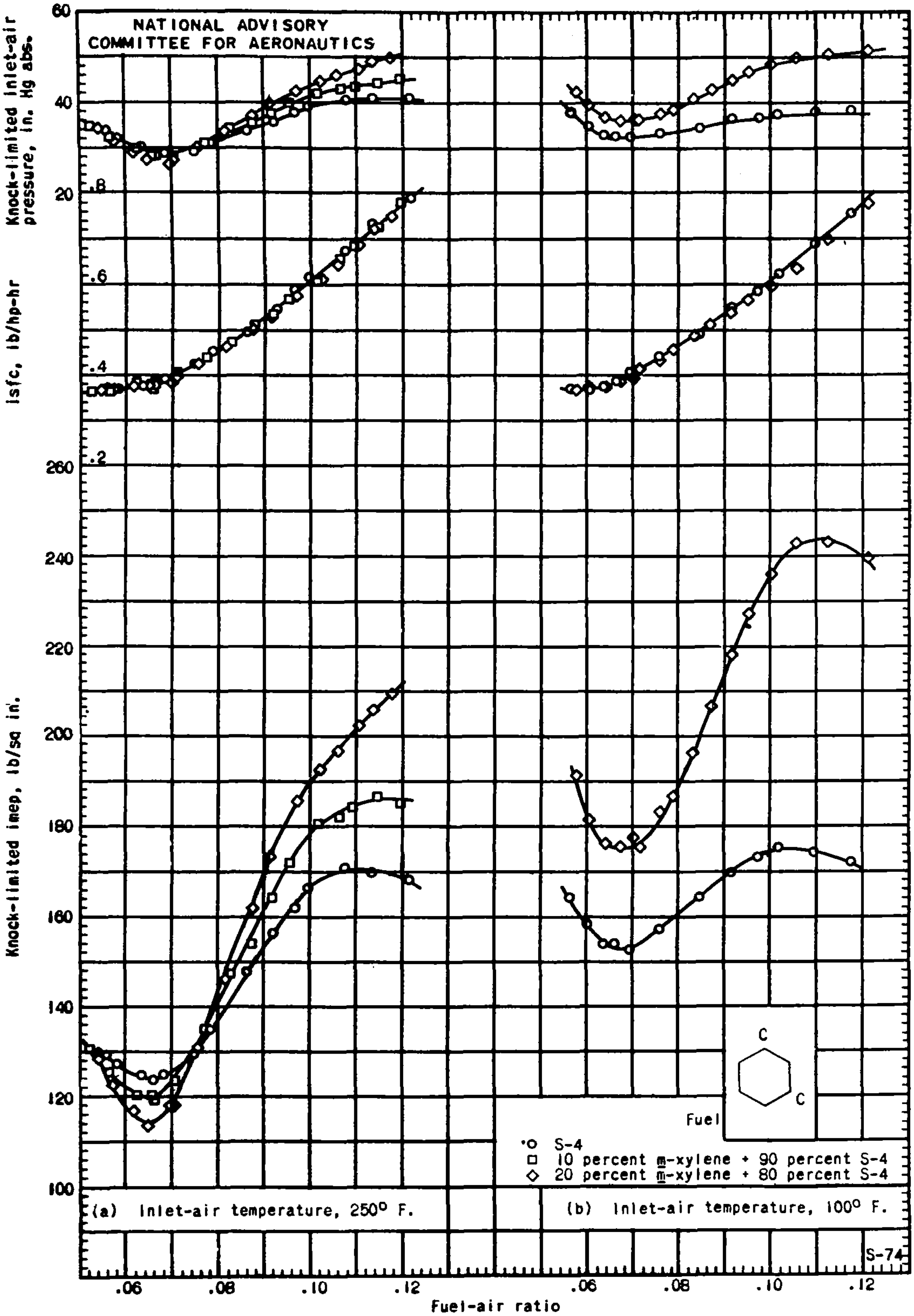


Figure 17. - The knock-limited performance of unleaded blends of m-xylene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

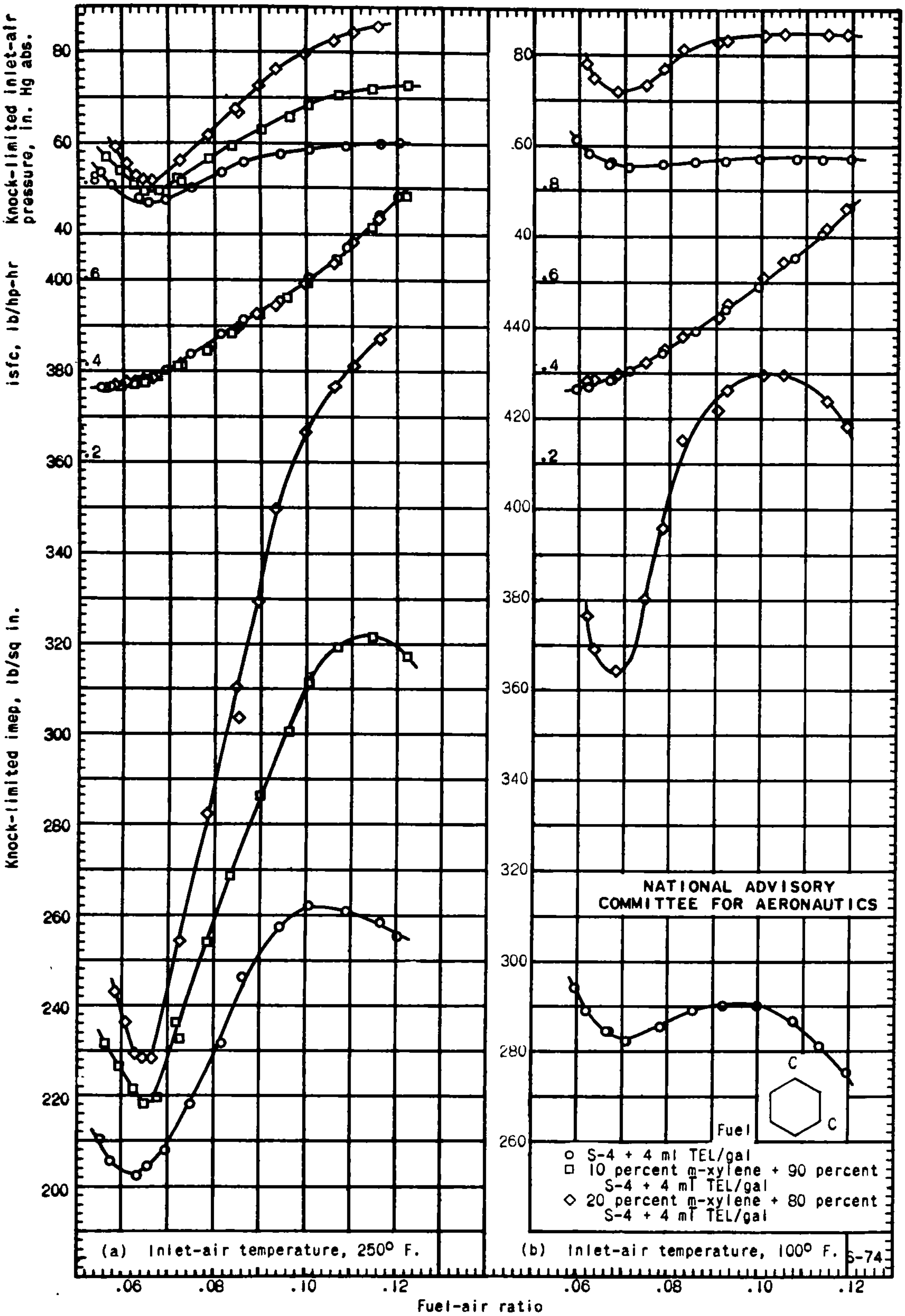


Figure 18. - The knock-limited performance of leaded blends of m-xylene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

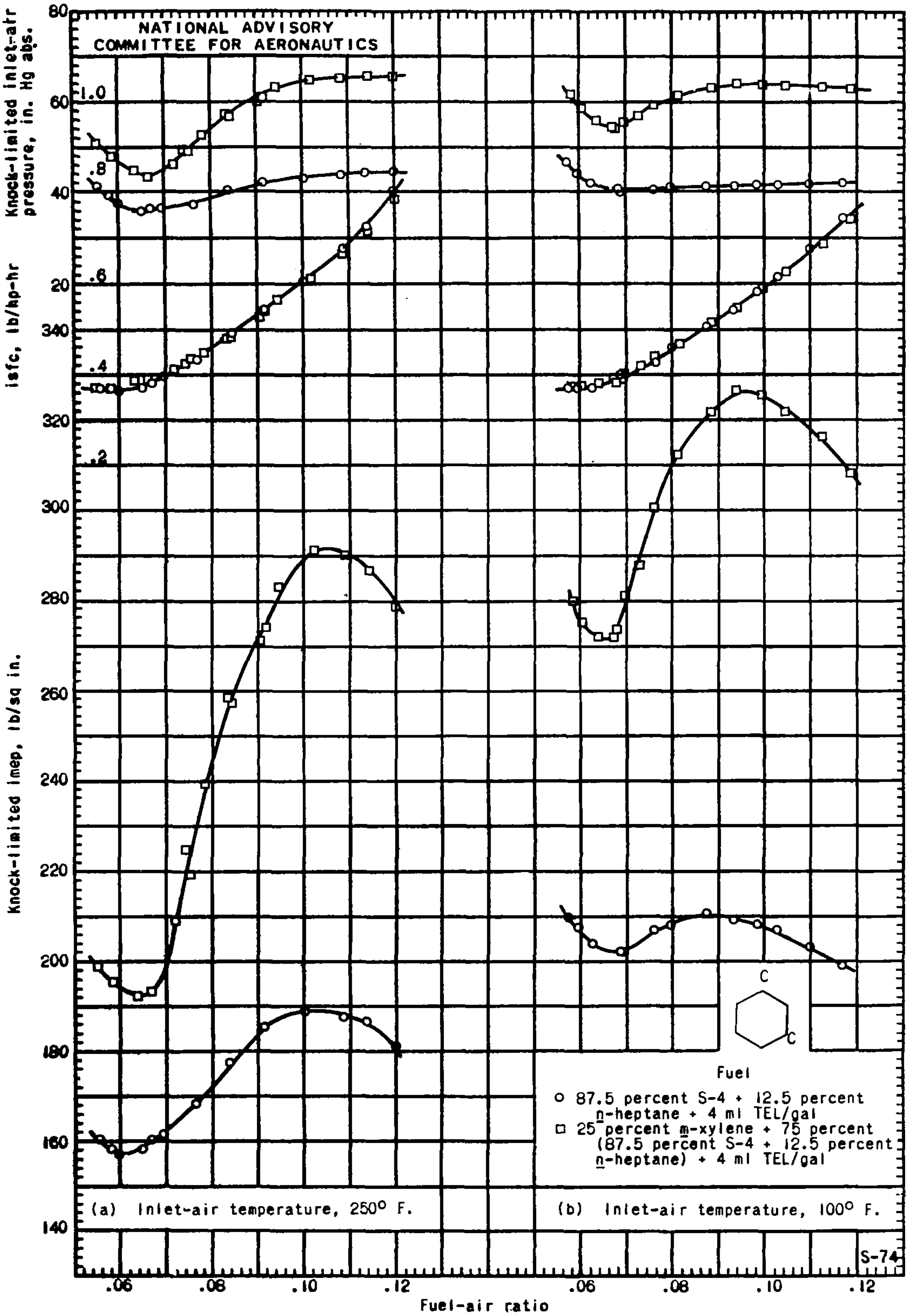


Figure 19. - The knock-limited performance of leaded blends of m-xylene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

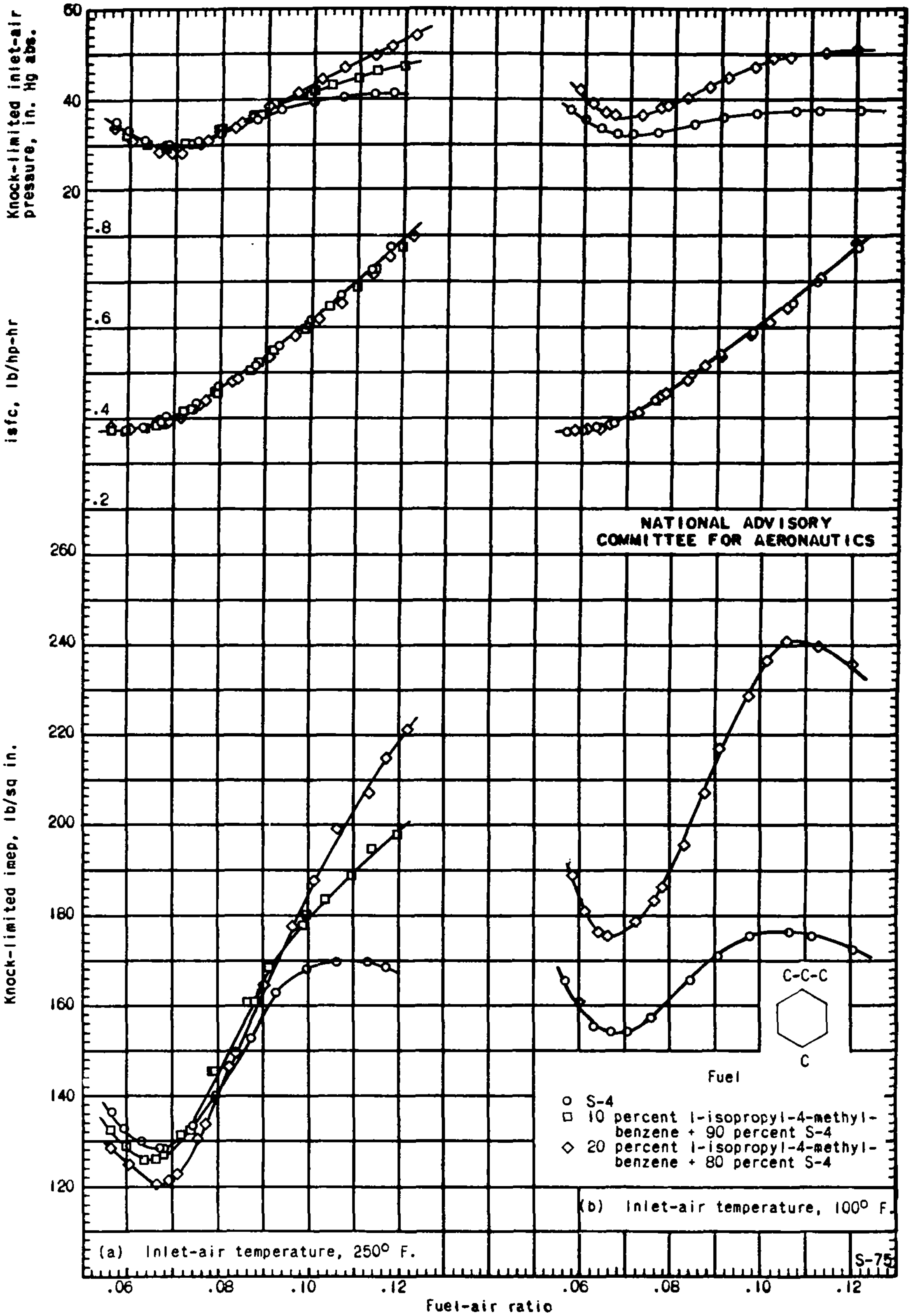


Figure 20. - The knock-limited performance of unleaded blends of 1-isopropyl-4-methylbenzene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

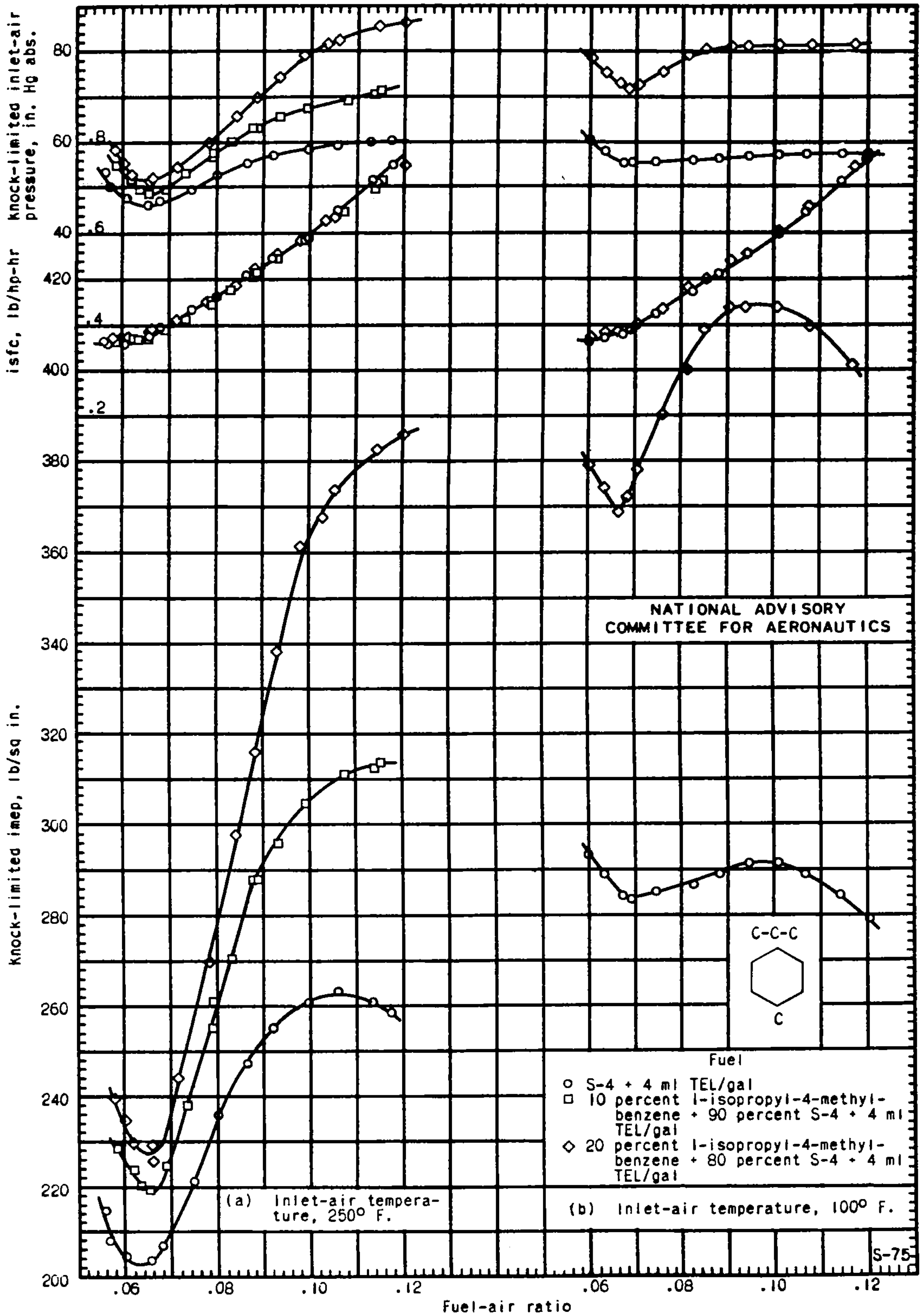


Figure 21. - The knock-limited performance of leaded blends of 1-isopropyl-4-methylbenzene and S-4 reference fuel in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

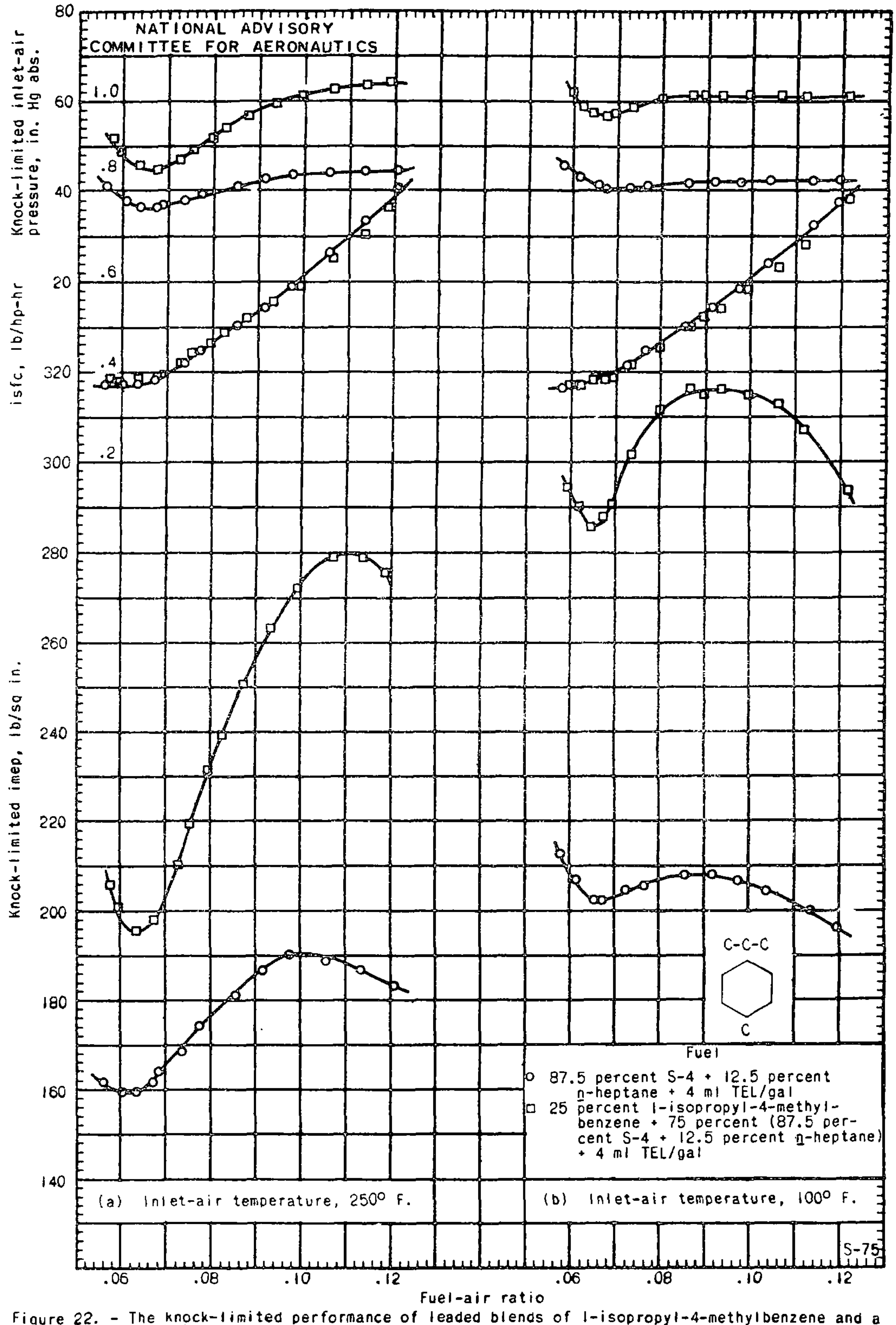


Figure 22. - The knock-limited performance of leaded blends of 1-isopropyl-4-methylbenzene and a base fuel consisting of 87.5 percent S-4 plus 12.5 percent n-heptane in a 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; outlet-coolant temperature, 212° F.

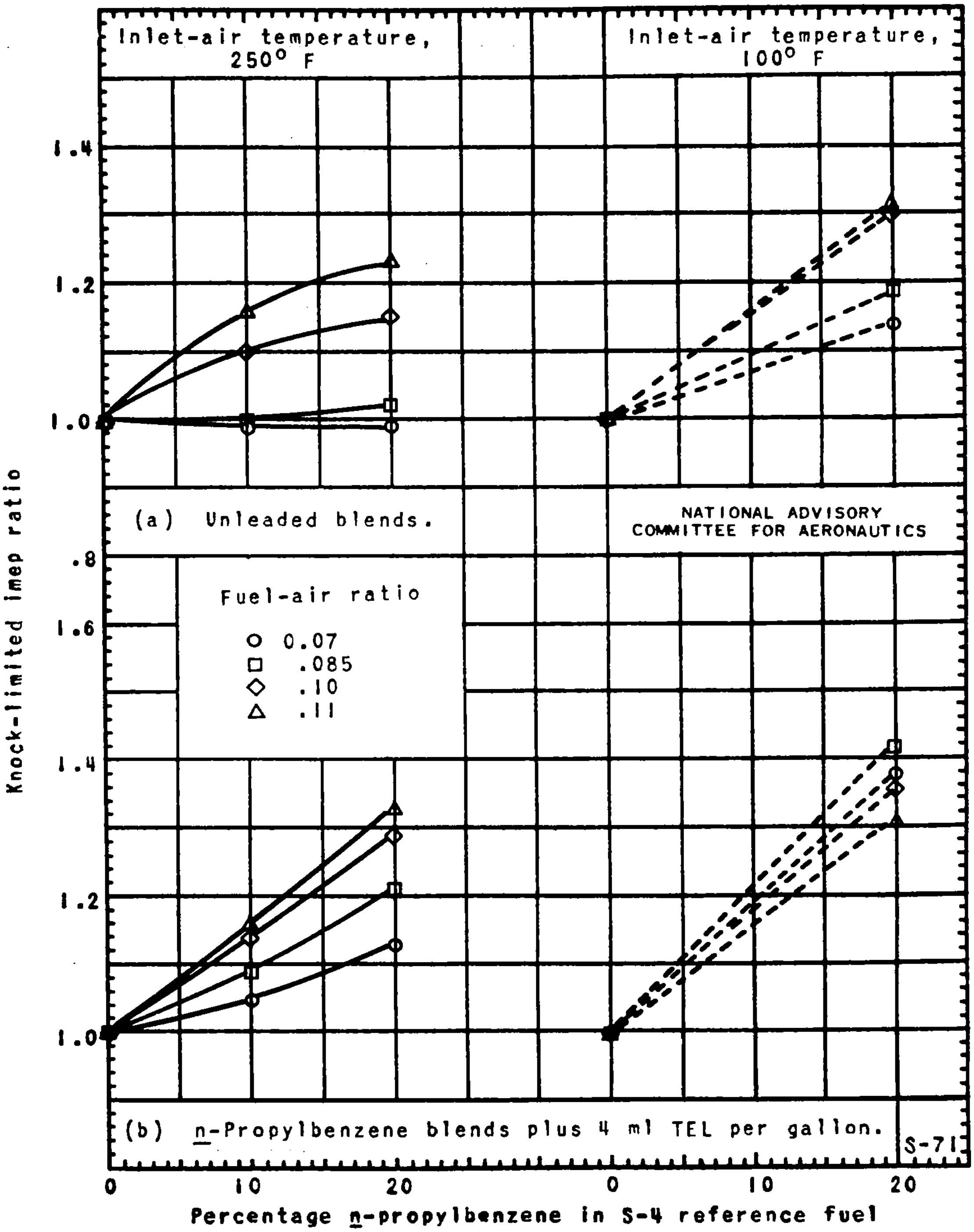


Figure 23. - The blending sensitivity of n-propylbenzene in S-4 reference fuel. 17.6 engine; data from figures 8 and 9.

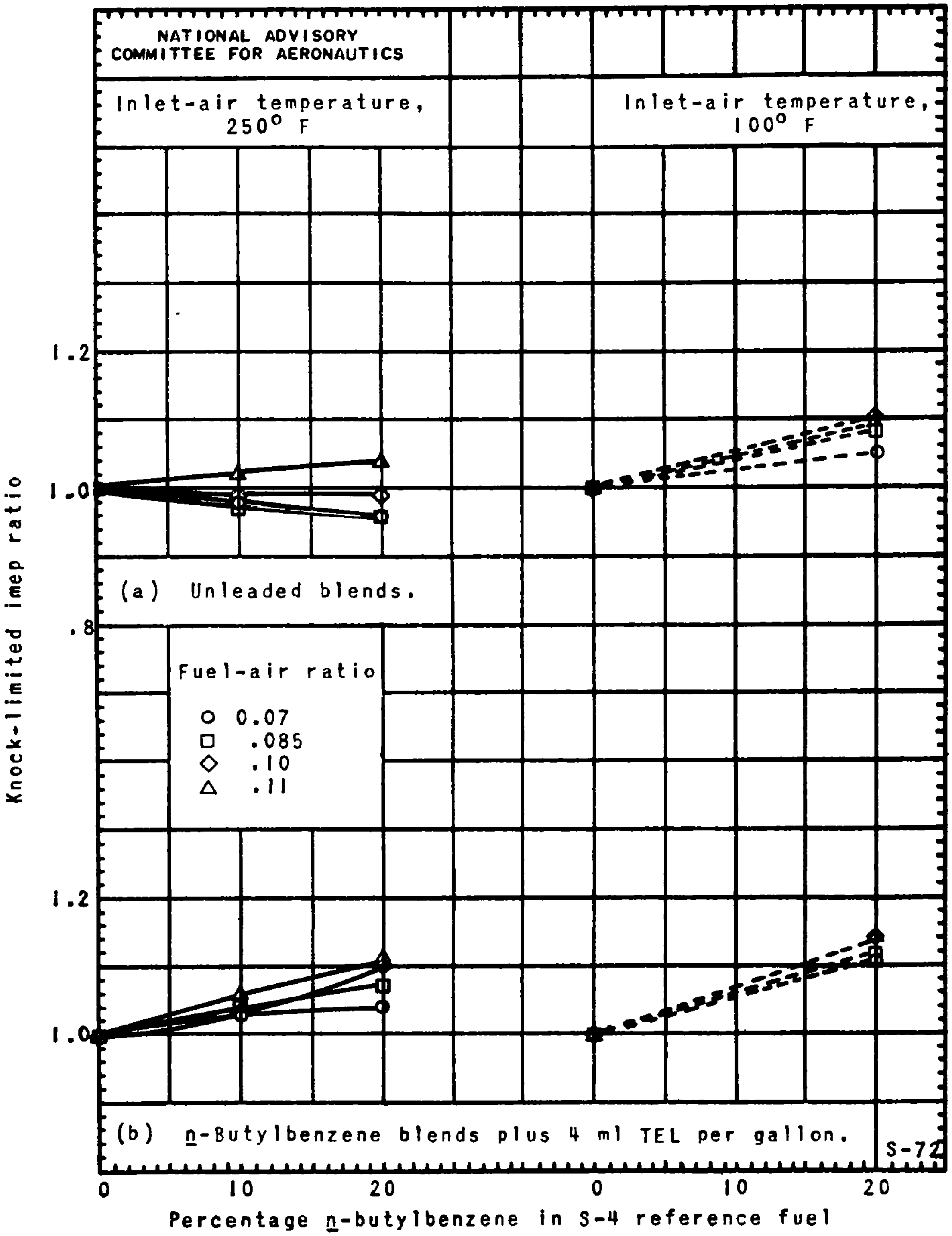


Figure 24. - The blending sensitivity of n-butylbenzene in S-4 reference fuel. 17.6 engine; data from figures 11 and 12.

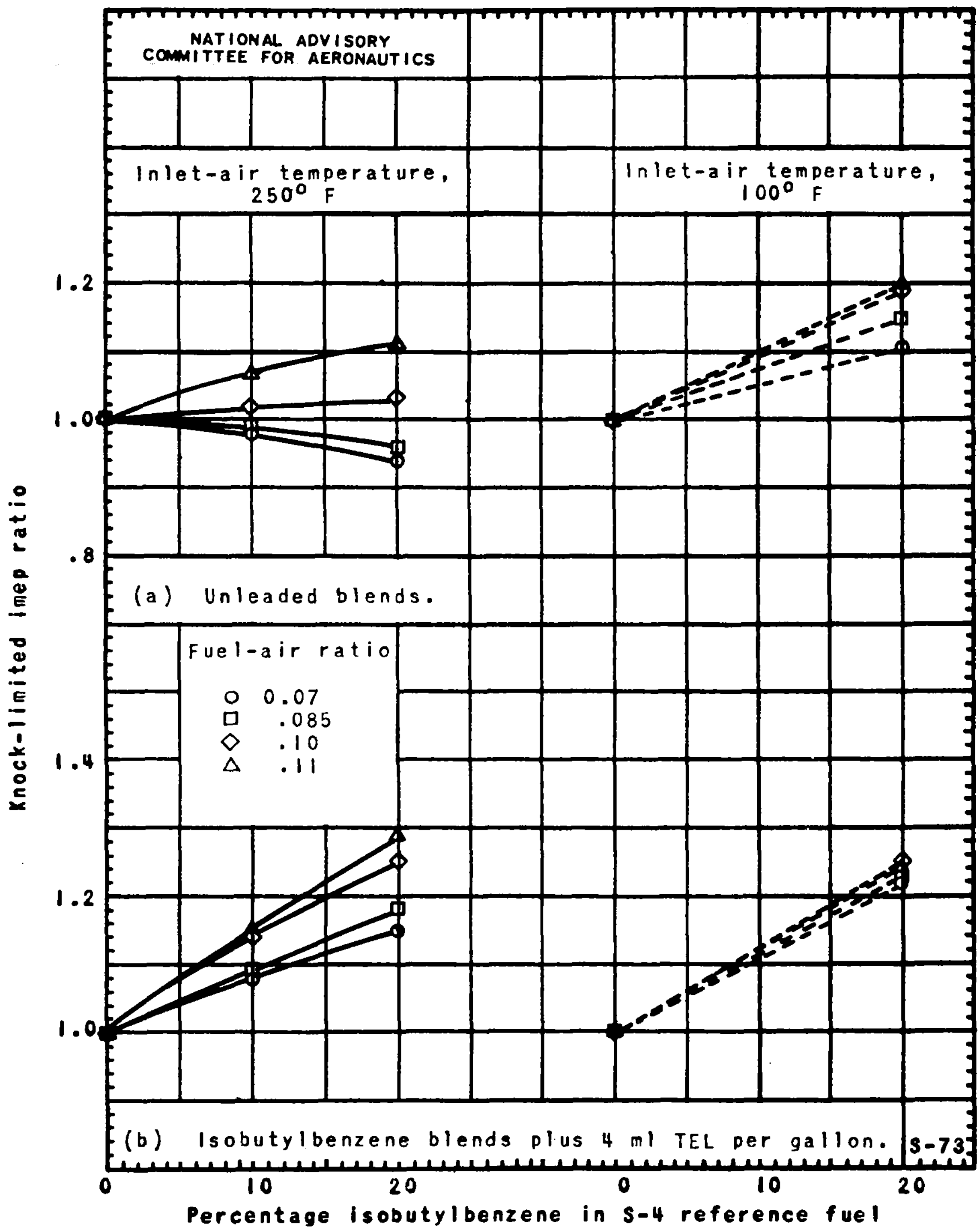


Figure 25. - The blending sensitivity of isobutylbenzene in S-4 reference fuel. 17.6 engine; data from figures 14 and 15.

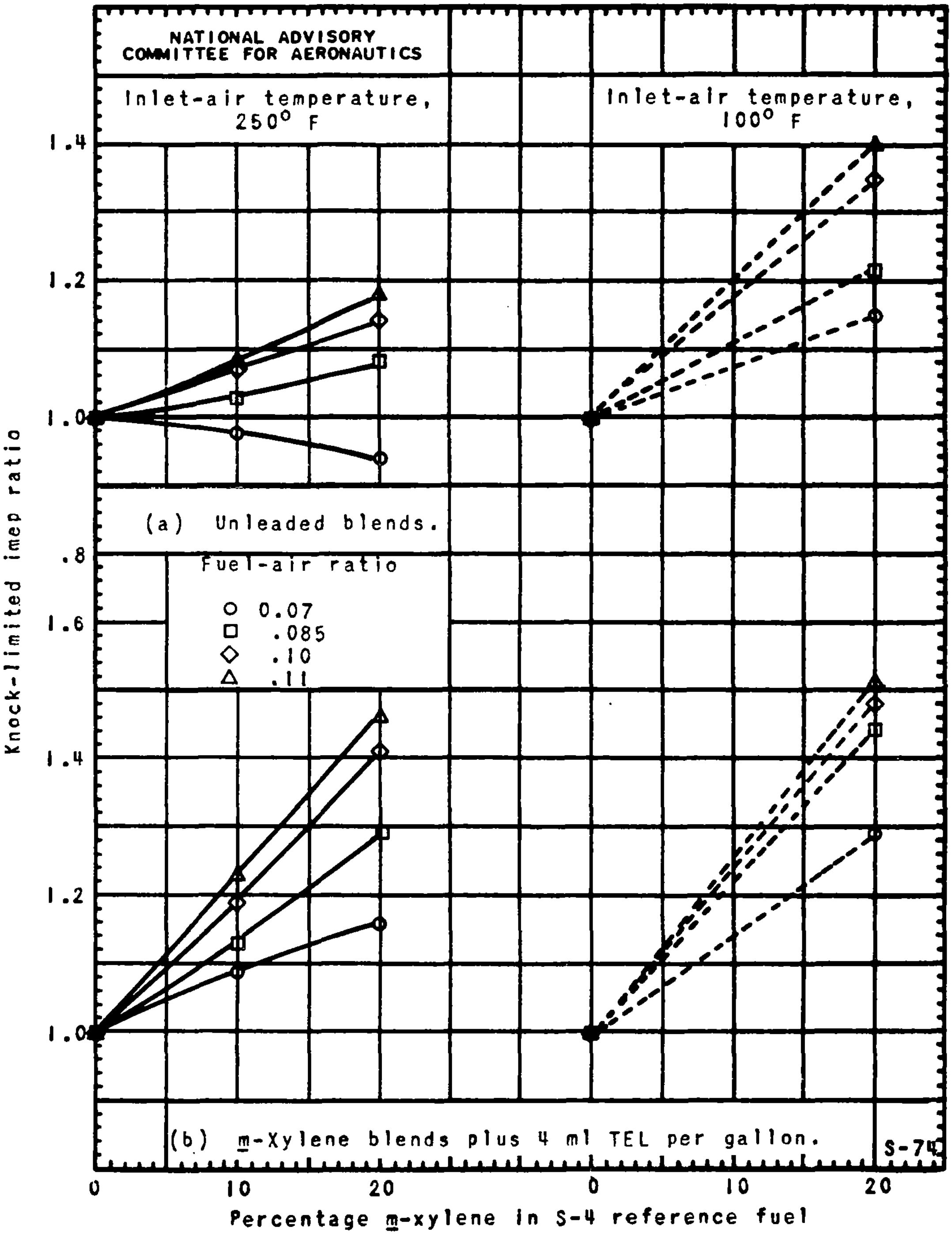


Figure 26. - The blending sensitivity of m-xylene in S-4 reference fuel. 17.6 engine; data from figures 17 and 18.

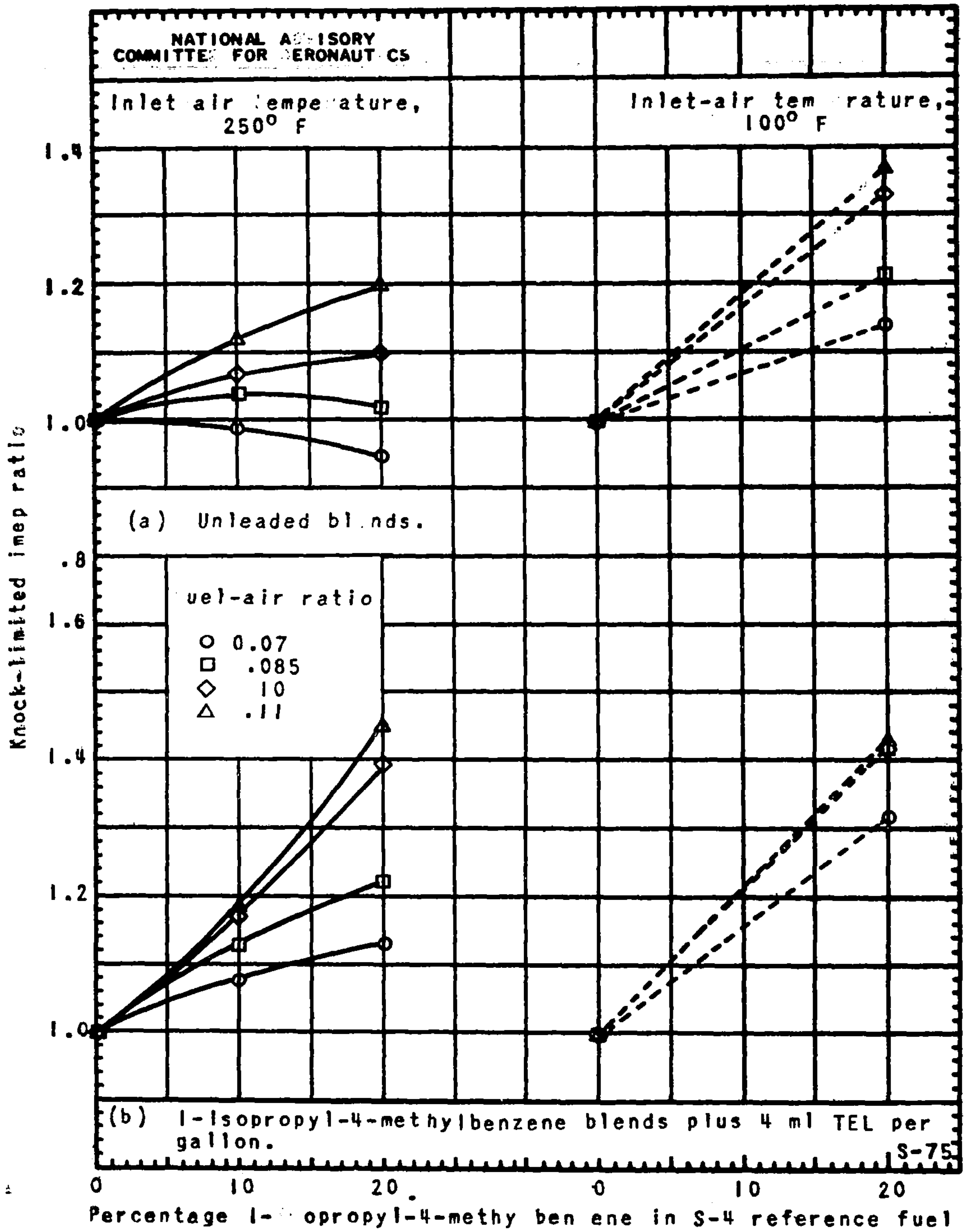
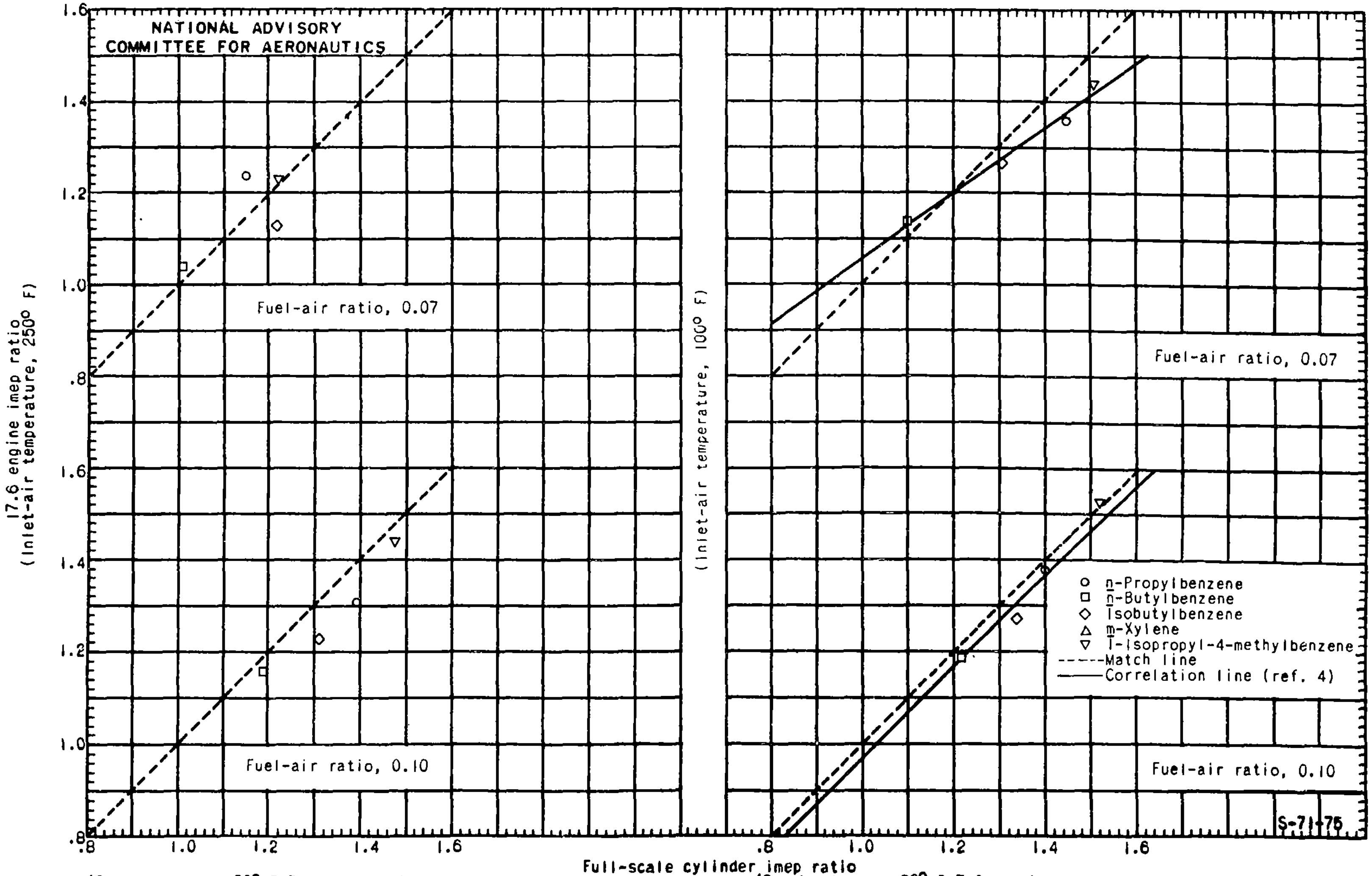


Figure 27. - The blending sensitivity of 1-isopropyl-4-methylbenzene in S-4 reference fuel. 17.6 engine data from figures 20 and 21.



(Spark advance, 30° B.T.C.; exhaust pressure, 15 in. Hg abs.; inlet-air temperature, 250° F.)

(Spark advance, 20° B.T.C.; exhaust pressure, 29 in. Hg abs.; inlet-air temperature, 210° F.)

Figure 28. - Comparison of the knock-limited performance of fuel blends containing 25 percent aromatic plus 75 percent (87.5 percent S-4 plus 12.5 percent n-heptane) plus 4 ml TEL per gallon as obtained with a 17.6 engine and a full-scale cylinder.

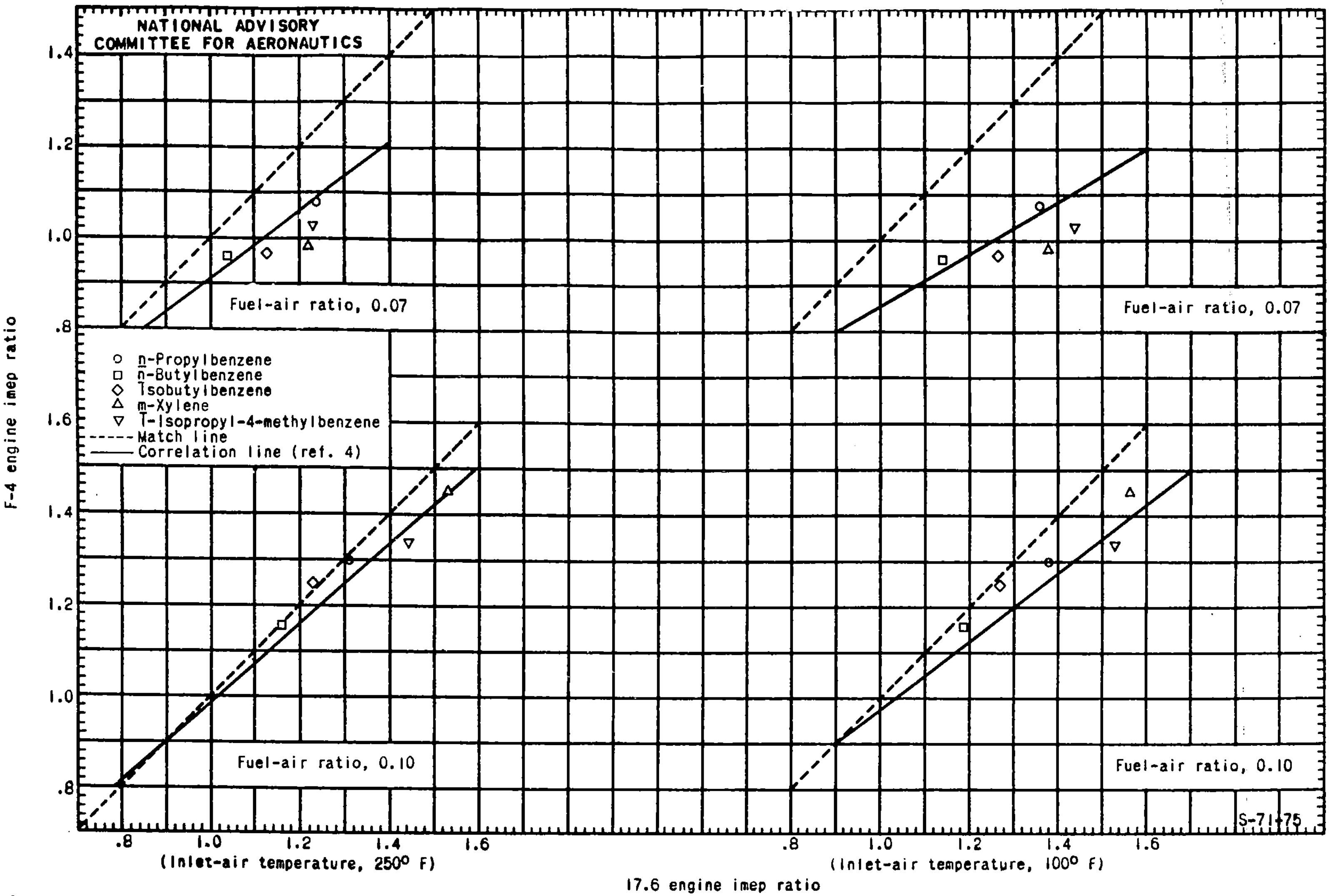


Figure 29. - Comparison of the knock-limited performance of fuel blends containing 25 percent aromatic plus 75 percent (87.5 percent S-4 plus 12.5 percent *n*-heptane) plus 4 ml TEL per gallon as obtained with an F-4 engine and a 17.6 engine.