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KNOCK-LIMITED PERFORMANCE OF PURE HYDROCARBONS BLENDED WITH A BASE FUEL IN A FULL-SCALE AIRCRAFT-ENGINE CYLINDER

III - FOUR AROMATICS, SIX ETHERS

By Anthony W. Jones, Arthur W. Bull, and Edmund R. Jonash

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ADVANCE RESTRICTED REPORT

KNOCK-LIMITED PERFORMANCE OF PURE HYDROCARBONS BLENDED WITH A BASE FUEL IN A FULL-SCALE AIRCRAFT-ENGINE CYLINDER

III - FOUR AROMATICS, SIX ETHERS

By Anthony W. Jones, Arthur W. Bull, and Edmund R. Jonash

SUMMARY

Knock-limited performance tests of leaded blends of four pure aromatic hydrocarbons and six pure ethers with a base fuel were conducted in a full-scale aircraft-engine cylinder at two operating conditions to determine the antiknock effectiveness of additions of pure compounds to aviation fuels. The following fuels were tested:

n-Butylbenzene
Isobutylbenzene
n-Propylbenzene
1-Isopropyl-4-methylbenzene (p-cymene)
Methyl tert-butyl ether
Ethyl tert-butyl ether
Isopropyl tert-butyl ether
Methyl phenyl ether (anisole)
Ethyl phenyl ether (phenetole)
Methyl p-tolyl ether

Each of these fuels was blended with a base fuel ($87\frac{1}{2}$ percent S-4 and $12\frac{1}{2}$ percent n-heptane plus 4 ml TEL/gal) and the final blend was leaded to 4.0 ml TEL per gallon. The four aromatics were blended to a concentration of 25 percent by volume and the ethers were blended to a concentration of 10 percent by volume in the base fuel. The base fuel and a fuel consisting of 85 percent S-4 and 15 percent M-4 plus 4.0 ml TEL per gallon were also tested separately. Curves of S-4 reference fuels having lead concentrations up to 4.0 ml TEL per gallon were obtained to bracket most of the test-fuel curves.

The data obtained from knock tests on a full-scale aircraft-engine cylinder indicate that:

1. The four aromatic hydrocarbons increased the knock limit of the base fuel at both operating conditions and p-cymene gave the greatest increase at all conditions with the exception of isobutylbenzene, which developed equivalent power in the lean region (0.06 to 0.075 fuel-air ratio) under the modified CRC cruise conditions.

2. The six ethers increased the knock-limited power of the base fuel at both operating conditions. Methyl tert-butyl ether gave the greatest increase throughout the normal fuel-air-ratio range at the CRC cruise conditions. Methyl tert-butyl ether also gave the greatest improvement at the modified cruise conditions except at fuel-air ratios leaner than 0.065 where ethyl tert-butyl ether gave an equivalent increase in knock-limited performance.

INTRODUCTION

A general investigation to determine the antiknock effectiveness of additions of pure hydrocarbons and other pure compounds to aircraft-engine fuels is being conducted by the NACA Cleveland laboratory. The program includes tests with 17.6, F-3 and F-4 small-scale engines, and a full-scale aircraft-engine cylinder. The knock-limited performance of 8 pure paraffins, 2 pure olefins, and 12 pure aromatics blended and leaded with a base fuel tested in a full-scale aircraft-engine cylinder are reported in references 1 and 2.

The present report gives the results of knock tests with leaded blends of four pure aromatic hydrocarbons and six pure ethers with a base fuel at two operating conditions. These tests were run between February and May 1945 in an aircraft-engine cylinder. F-3 ratings of all the blends and F-4 ratings of the aromatic blends are included in this report.

FUELS

The Organic Synthesis Section of the Cleveland laboratory prepared for the full-scale single-cylinder tests small quantities (5 gal of each of the aromatics, 3 gal of each of the ethers) of the following pure fuels leaded to a concentration of 4.0 ml TEL per gallon:

n-Butylbenzene
Isobutylbenzene
n-Propylbenzene
1-Isopropyl-4-methylbenzene (p-cymene)
Methyl tert-butyl ether
Ethyl tert-butyl ether
Isopropyl tert-butyl ether
Methyl phenyl ether (anisole)
Ethyl phenyl ether (phenetole)
Methyl p-tolyl ether

The four leaded aromatic hydrocarbons were mixed with the base fuel to form blends containing 25 percent by volume hydrocarbon and 75 percent by volume base fuel and the leaded ethers were mixed with the base fuel to form 10-percent blends by volume.

The base fuel consisted of $87\frac{1}{2}$ percent S-4 reference fuel and $12\frac{1}{2}$ percent n-heptane leaded to a concentration of 4.0 ml TEL per gallon and was inhibited with 0.09 pound of inhibitor per 500 gallons of fuel. The base fuel used in these tests differed from the base fuel used in previous tests (references 1 and 2) in that only pure paraffinic compounds were used. The original base fuel (references 1 and 2), which consisted of 85 percent S-4 reference fuel and 15 percent M-4 reference fuel leaded to a concentration of 4.0 ml TEL per gallon, was not used because the small amount of aromatics (about 8 percent by volume) present in the M-4 reference-fuel component of the blend might have some undesirable effect. A knock-limited power level equivalent to the original base fuel was desired and tests on an F-4 engine showed that the blend of $87\frac{1}{2}$ percent S-4 reference fuel and $12\frac{1}{2}$ percent n-heptane plus 4.0 ml TEL per gallon met this specification.

The reference fuels used to bracket most of the test fuels were:

S-4
S-4 plus 0.5 ml TEL per gallon
S-4 plus 1.25 ml TEL per gallon
S-4 plus 2.5 ml TEL per gallon
S-4 plus 4.0 ml TEL per gallon

APPARATUS AND METHODS

Apparatus. - The tests were conducted on a full-scale air-cooled cylinder mounted on a CUE crankcase. The auxiliary apparatus used in these tests was the same as that used in reference 1 except that a heat exchanger was installed in the cooling-air line to control the cooling-air temperature and the exhaust system was modified to permit engine operation at either atmospheric exhaust pressure or at a reduced exhaust pressure.

A full-scale aircraft-engine cylinder with a displacement of 202 cubic inches was used for the tests; the engine conditions were:

	CRC simulated cruise	Modified CRC simulated cruise
Inlet-air temperature, °F	210	250
Spark advance, deg B.T.C. (both plugs)	20	30
Exhaust pressure, inches of mercury absolute	29 ± 0.5	15 ± 0.2
Compression ratio	7.3	7.3
Engine speed, rpm	2000	2000
Oil flow to piston jets, pounds per minute	8	8
Fuel temperature at entrance to injection pump, °F	60 to 80	60 to 80
Cooling-air temperature, °F	80 ± 3	80 ± 3
Valve timing:		
Intake opens, deg B.T.C.	15	15
Intake closes, deg A.B.C.	44	44
Exhaust opens, deg B.B.C.	74	74
Exhaust closes, deg A.T.C.	25	25

The exhaust pressure of 15 inches of mercury was chosen because data from this laboratory show the existence of a critical relation between manifold and exhaust pressures and knock-limited power in the lean region where the manifold pressure is within +10 or -5 inches mercury of the exhaust pressure. The advanced spark and increased inlet-air temperature were chosen in an effort to obtain a more severe operating condition than the normal CRC cruise rating.

The cooling-air flow was determined for each test by operating the engine at a brake mean effective pressure of 140 pounds per square inch and a fuel-air ratio of 0.10 and by adjusting the damper valve in the cooling-air line until a rear spark-plug-bushing temperature of 365° F was reached. The cooling-air pressure drop across the cylinder thus determined was maintained constant for each test.

Knock was detected with a magnetostriction pickup unit inserted into the combustion chamber and used in conjunction with a cathode-ray oscillograph.

Test procedure. - In order to obtain complete mixture-response curves with the limited amount of fuel blends available, the special procedures described in reference 1 were used at both operating conditions.

Engine conditions were checked before each test-fuel run by obtaining four or five knock points with the blend of 85 percent S-4 reference fuel and 15 percent M-4 reference fuel plus 4.0 ml TEL per gallon.

Mixture-response curves for the reference fuels were determined at both operating conditions to bracket most of the test fuels. Friction runs were made after each test.

Precision of tests. - The variation of the knock-limited indicated mean effective pressure of the fuel blend (85 percent S-4 and 15 percent M-4 plus 4 ml TEL/gal) used for checking engine conditions from day to day is shown in figure 1. The daily variation in engine behavior was comparable with that observed in reference 1 and smaller than that observed in reference 2. The curves traced in figure 1 are the average of the data from several complete mixture-response curves at each set of operating conditions. The power variations among the several curves at each set of operating conditions were negligible. The data for the full mixture-response curves are not shown.

RESULTS AND DISCUSSION

The reference-fuel framework covering tests at both operating conditions is presented in figure 2. From these figures cross plots were made (fig. 3) to facilitate conversion of the knock-limited indicated mean effective pressures of the test fuels to lead ratings. Figure 3 shows a definite irregularity in the lead susceptibility of the S-4 reference fuel particularly at the CRC cruise conditions; the region of irregularity exists from about 0.8 to 1.6 ml TEL per gallon.. Because previous tests with almost the same equipment (references 1 and 2) had not shown the irregularity, a series of check tests were made with identical results. Numerous instances of this irregularity have been published, however, and a further investigation was not warranted at this time.

The knock-limited performance of the blends of the four aromatic hydrocarbons and the base fuel is presented in figure 4 and table I. All aromatic blends increased the knock-limited power of the base fuel at both operating conditions but the greatest improvement occurred at the CRC cruise conditions. The greatest increase in performance over the base fuel in the rich region at both operating conditions was obtained with the p-cymene blend. In the lean region at CRC cruise conditions (fig. 4(a)), p-cymene permitted the greatest improvement in knock-limited power over the base fuel whereas at the more severe conditions (fig. 4(b)), p-cymene and isobutylbenzene gave the best performance between fuel-air ratios of 0.06 and 0.075. At both operating conditions and all fuel-air ratios n-butylbenzene was the least effective of the four aromatics tested.

Figure 5 shows the knock-limited performance of the ether blends and the base fuel. All the ether blends show an improvement over the base fuel at both operating conditions. The methyl tert-butyl ether blend gave the greatest increase in knock-limited performance over the base fuel in the normal fuel-air-ratio range at both operating conditions; at fuel-air ratios leaner than 0.065 at the modified cruise conditions, however, ethyl tert-butyl ether gave an equal increase in knock-limited performance. At the CRC cruise conditions (fig. 5(a)) methyl phenyl ether was the least effective of the ethers tested in the fuel-air-ratio range from 0.062 to 0.11. At the more severe conditions (fig. 5(b)) methyl phenyl ether gave the smallest increase in knock-limited power over the base fuel between the fuel-air-ratio range from 0.0675 to 0.115 whereas in the extremely lean region (0.055 to 0.0675 fuel-air ratio) the blend of ethyl phenyl ether gave the smallest improvement in performance over the base fuel.

The tertiary butyl ethers gave higher ratings than the phenyl ethers except at very rich or very lean fuel-air ratios. The rating of methyl p-tolyl ether had a median value under the same conditions.

The data from figures 4 and 5 are incorporated in table I with the F-3, F-4, and full-scale cylinder ratings. The F-4 engine tests on the ether blends were incomplete and the data were unavailable for this report.

The correlation of the full-scale cylinder ratings of the aromatic blends with the F-4 ratings is shown in figure 6 on the basis of imep ratio (ratio of the imep of the test fuel to the imep of the base fuel). At either set of operating conditions the lean correlation is poor. The full-scale cylinder ratings are generally higher than the F-4 ratings especially at the CRC cruise conditions (fig. 6(a)). The correlation of rich (0.10 fuel-air ratio) ratings are good at both operating conditions (fig. 6).

The correlation of the full-scale cylinder ratings of the aromatic blends with the F-3 ratings on the basis of performance number are shown in figure 7. The correlation is poor at both operating conditions and indicates the well known tendency of the F-3 engine to give low ratings to aromatic fuels.

Figure 8 presents the correlation between the full-scale cylinder ratings of the ether blends and the F-3 ratings in terms of performance numbers. The correlation at the modified CRC cruise conditions (fig. 8(b)) is slightly better than at the normal CRC conditions although neither is good. It is interesting to note that in the rating of the ether blends the F-3 engine gave higher ratings than the full-scale cylinder, indicating that the ether blends are less sensitive to engine conditions than the reference fuels.

SUMMARY OF RESULTS

Results of the knock tests on an aircraft-engine cylinder at two operating conditions are given in table I. The data indicate that:

1. The four aromatic hydrocarbons increased the knock limit of the base fuel at both operating conditions and p-cymene gave the greatest increase at all conditions with the exception of isobutylbenzene, which developed equivalent power in the lean region (0.06 to 0.075 fuel-air ratio) under the modified CRC cruise conditions.

2. The six ethers increased the knock-limited power of the base fuel at both operating conditions. Methyl tert-butyl ether gave the greatest increase throughout the normal fuel-air-ratio range at the CRC cruise conditions. Methyl tert-butyl ether also gave the

greatest improvement at the modified cruise conditions except at fuel-air ratios leaner than 0.065 where ethyl tert-butyl ether gave an equivalent increase in knock-limited performance.

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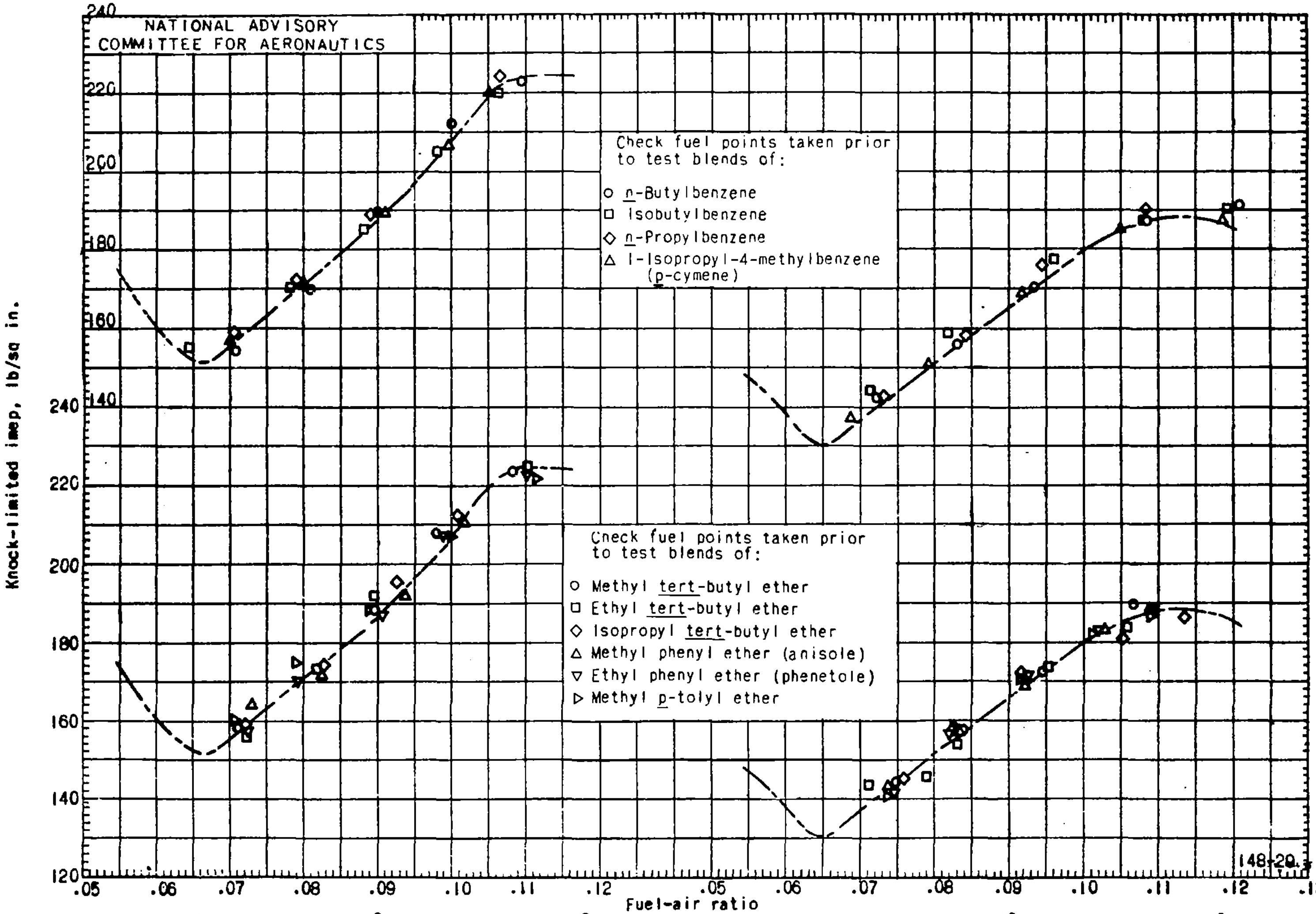
REFERENCES

1. 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.

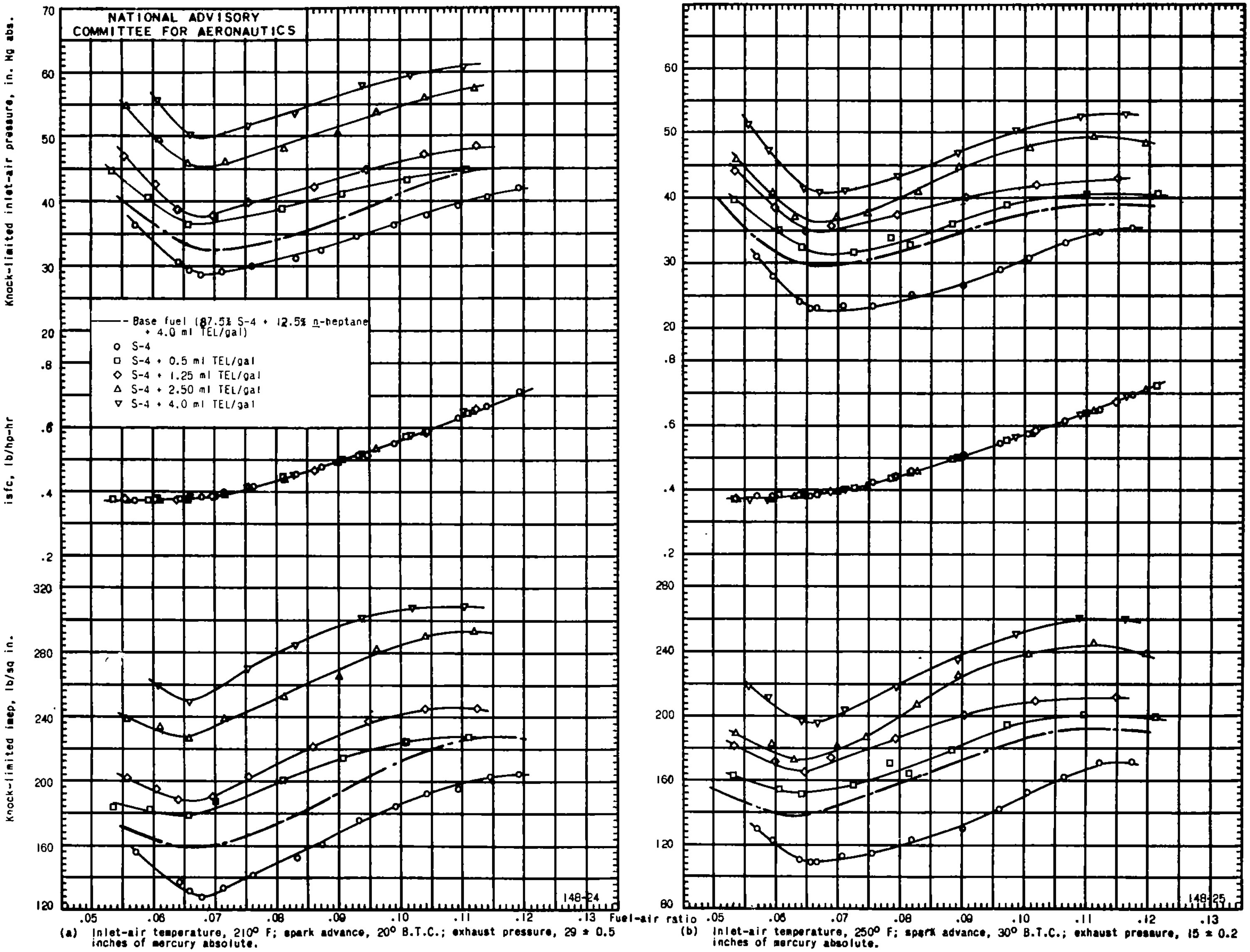
2. Bull, Arthur W., and Jones, Anthony W.: Knock-Limited Performance of Pure Hydrocarbons Blended with a Base Fuel in a Full-Scale Aircraft-Engine Cylinder. II - Twelve Aromatics. NACA ARR No. E4I09, 1944.



(a) Inlet-air temperature, 210° F; spark advance, 20° B.T.C.; exhaust pressure, 29 ± 0.5 inches of mercury absolute.

(b) Inlet-air temperature, 250° F; spark advance, 30° B.T.C.; exhaust pressure, 15 ± 0.2 inches of mercury absolute.

Figure 1. - Reproducibility of knock-limited indicated mean effective pressure with check fuel. Fuel, 85 percent S-4 and 15 percent M-4 plus 4 ml TEL per gallon; compression ratio, 7.3; engine speed, 2000 rpm. (Symbols represent check points for the various test fuels. The mixture-response curves shown are average curves in which the check runs are not included.)



(a) Inlet-air temperature, 210° F; spark advance, 20° B.T.C.; exhaust pressure, 29 ± 0.5 inches of mercury absolute.

(b) Inlet-air temperature, 250° F; spark advance, 30° B.T.C.; exhaust pressure, 15 ± 0.2 inches of mercury absolute.

Figure 2. - Reference-fuel framework. Compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

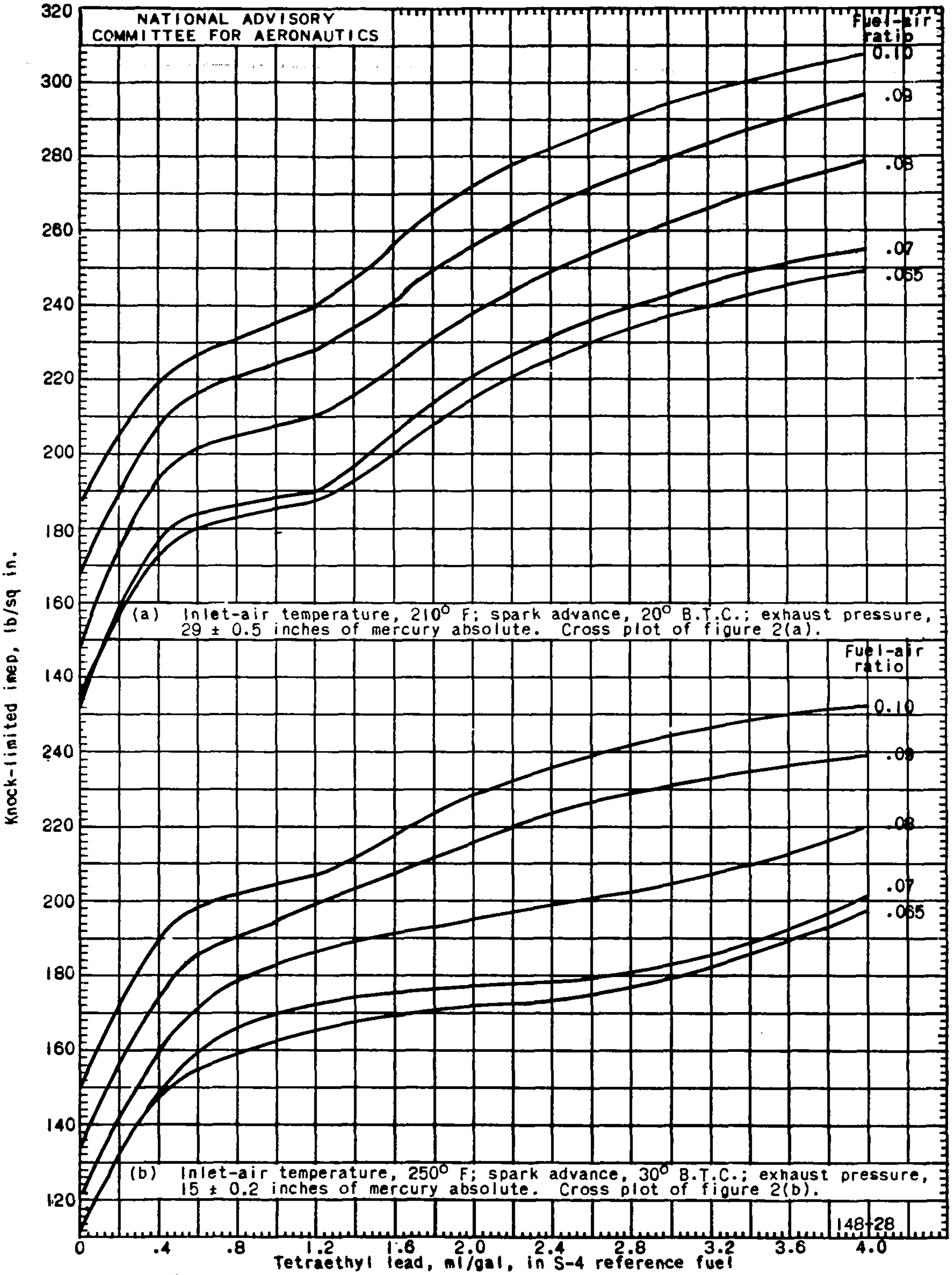
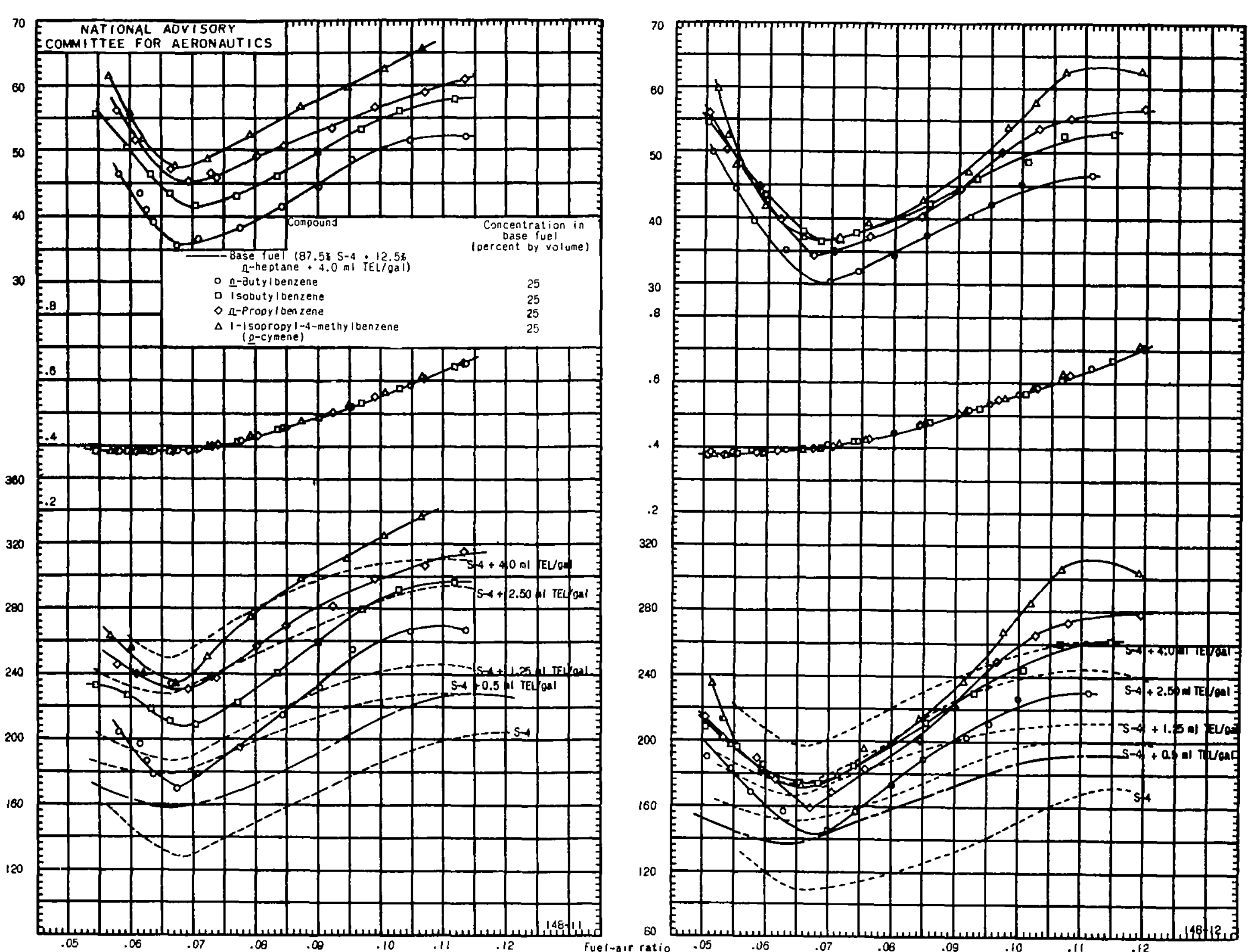


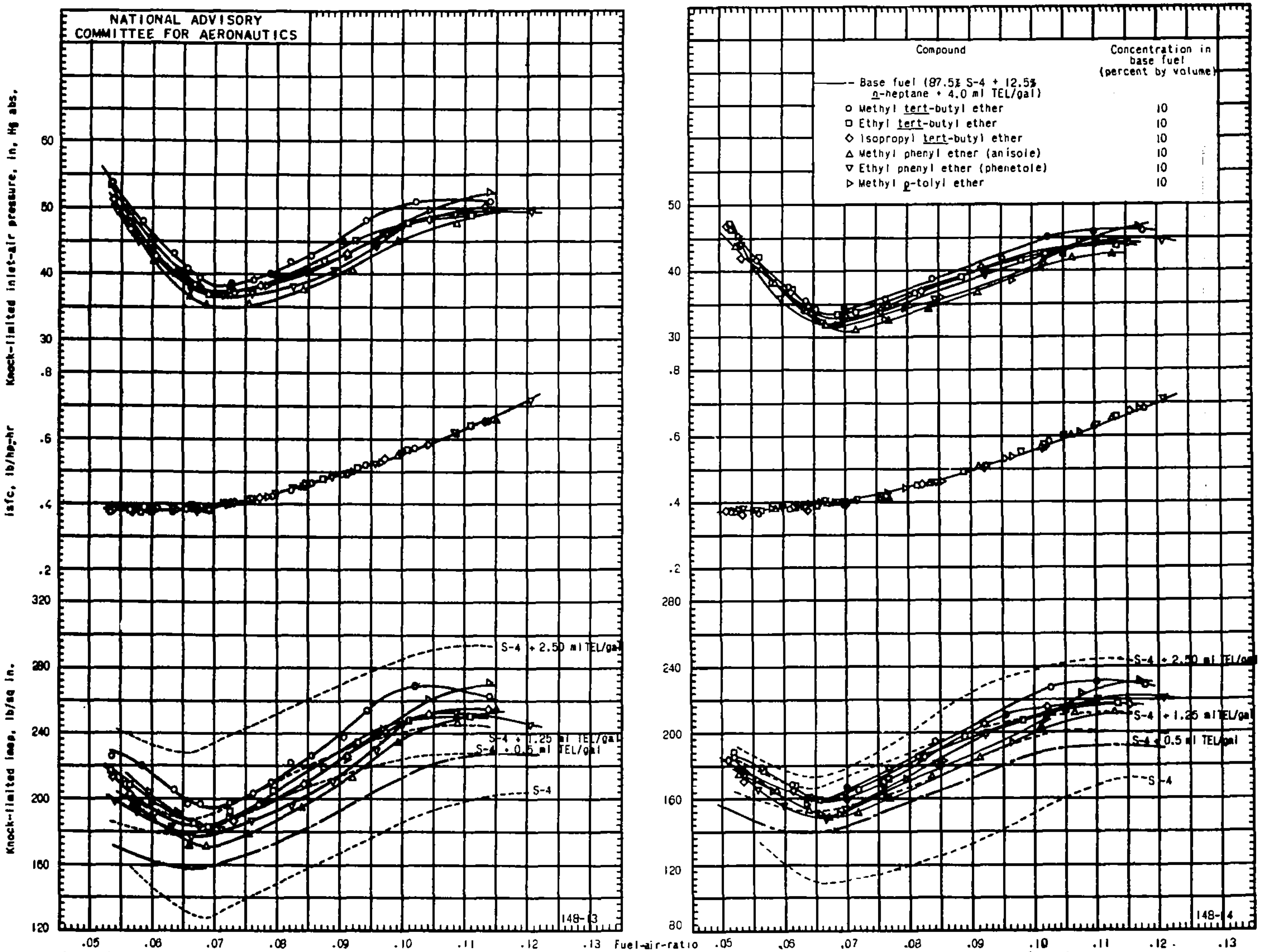
Figure 3. - Relation between knock-limited indicated mean effective pressure and lead concentration in S-4 reference fuel for different fuel-air ratios. Compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.



(a) Inlet-air temperature, 210° F; spark advance, 20° B.T.C.; exhaust pressure, 29 ± 0.5 inches of mercury absolute.

(b) Inlet-air temperature, 250° F; spark advance, 30° B.T.C.; exhaust pressure, 15 ± 0.2 inches of mercury absolute.

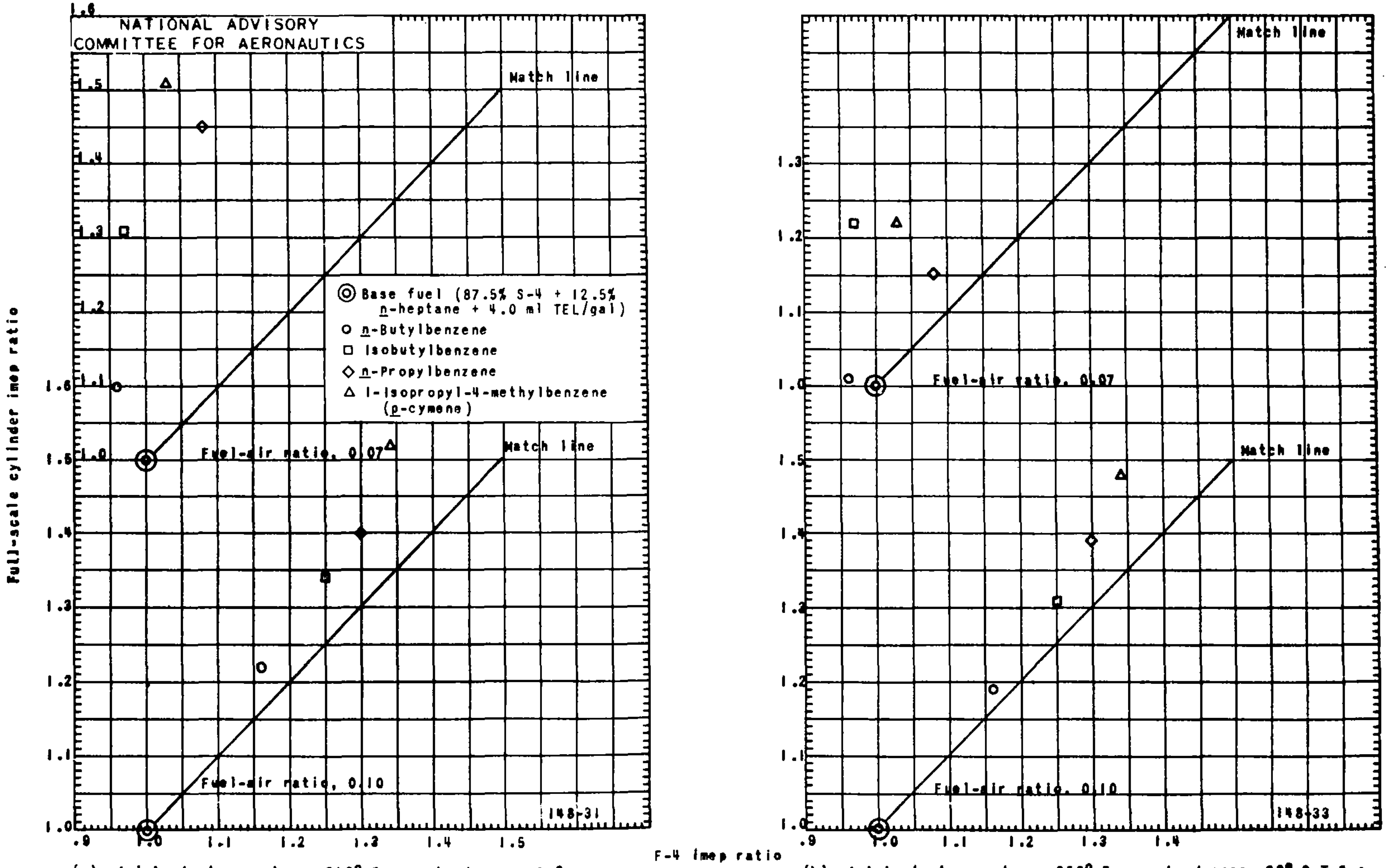
Figure 4. - Knock-limited performance of aromatic fuel blends. Compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 355° F.



(a) Inlet-air temperature, 210° F; spark advance, 20° B.T.C.; exhaust pressure, 29 ± 0.5 inches of mercury absolute.

(b) Inlet-air temperature, 250° F; spark advance, 30° B.T.C.; exhaust pressure, 15 ± 0.2 inches of mercury absolute.

Figure 5. - Knock-limited performance of ether fuel blends. Compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.



(a) Inlet-air temperature, 210° F; spark advance, 20° B.T.C.; exhaust pressure, 29 ± 0.5 inches of mercury absolute.

(b) Inlet-air temperature, 250° F; spark advance, 30° B.T.C.; exhaust pressure, 15 ± 0.2 inches of mercury absolute.

Figure 6. - Comparison of full-scale cylinder performance with F-4 engine performance. Compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

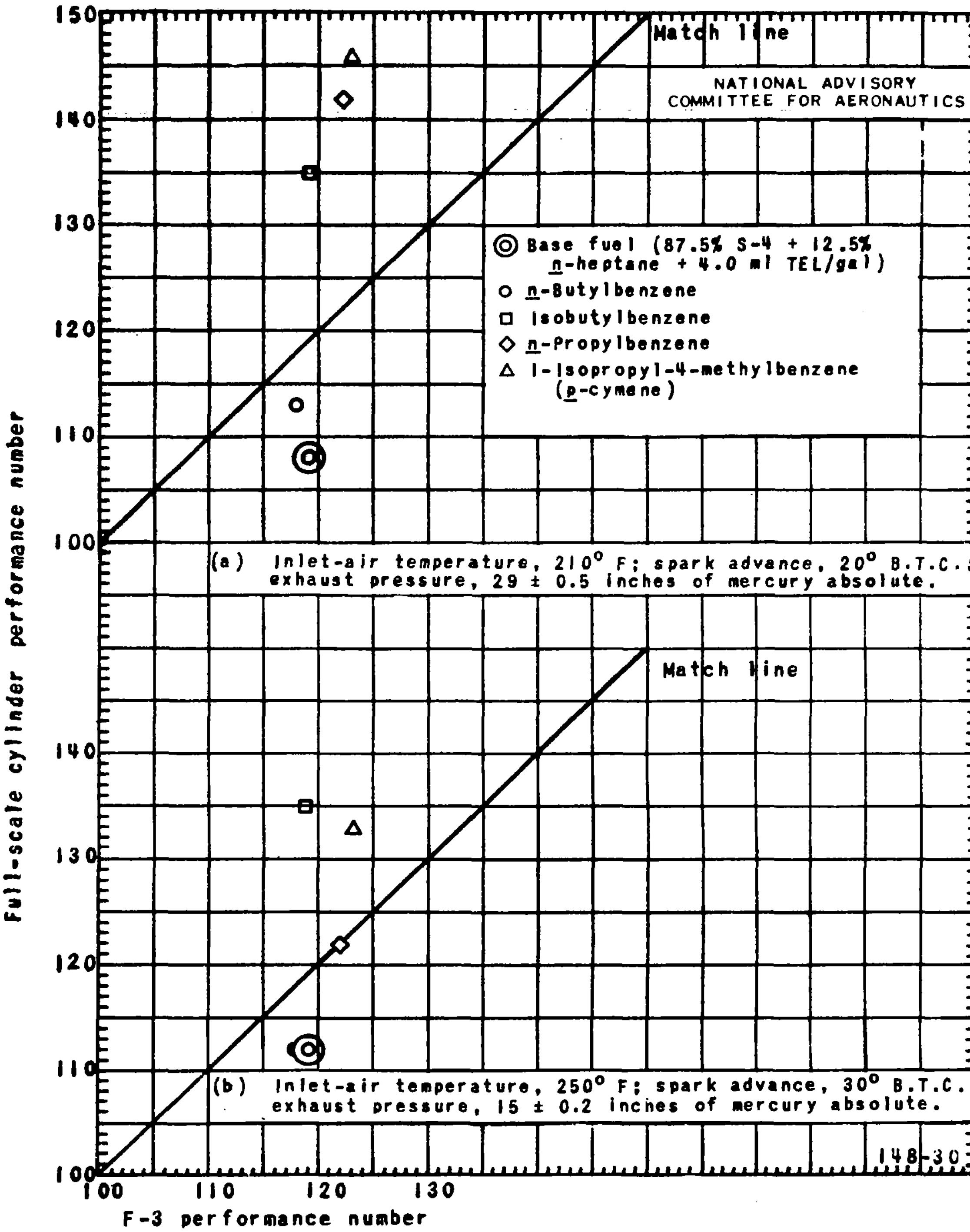


Figure 7. - Comparison of full-scale cylinder aromatic fuel-blend ratings with F-3 ratings. Fuel-air ratio, 0.07; compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

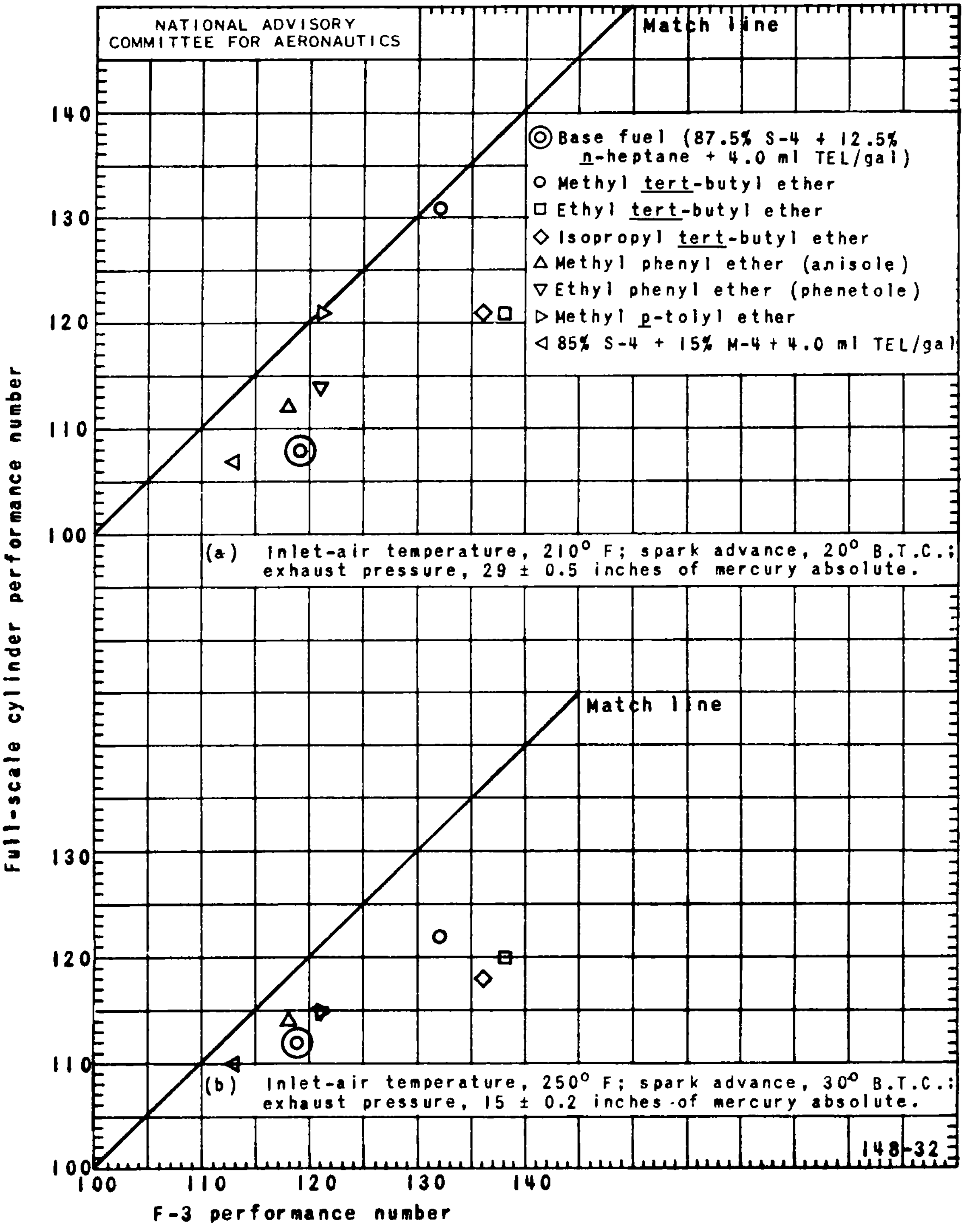


Figure 8. - Comparison of full-scale cylinder ether fuel-blend ratings with F-3 ratings. Fuel-air ratio, 0.07; compression ratio, 7.3; engine speed, 2000 rpm; cooling air adjusted at 140 bmep and 0.10 fuel-air ratio to give a rear spark-plug-bushing temperature of 365° F.

TABLE I.- COMPARISON OF RATINGS OBTAINED IN A FULL-SCALE CYLINDER WITH F-3 AND F-4 RATINGS

[For each compound there are four rows of values. The first row is imep, lb/sq in.; the second is tetraethyl lead in S reference fuel, ml/gal, except as noted; the third is performance number; and the fourth is ratio of imep of blend to imep of base fuel]

Compound	Concentration in base fuel (percent by volume)	F-3 ratings	F-4 ratings			Full-scale cylinder ratings (compression ratio, 7.3; engine speed, 2000 rpm)									
						Inlet-air temperature, 210° F; spark advance, 20° B.T.C.; exhaust pressure, 29 ±0.5 inches mercury					Inlet-air temperature, 250° F; spark advance, 30° B.T.C.; exhaust pressure, 15 ± 0.3 inches mercury				
			Fuel-air ratio			Fuel-air ratio					Fuel-air ratio				
			0.070	0.100	0.11	0.065	0.07	0.08	0.09	0.10	0.065	0.07	0.08	0.09	0.10
n-Butylbenzene	25	-------	120	200	204	176	176	203	233	260	147	146	175	202	222
		0.60	[a]85.5	[a]94.0	[a]94.3	0.46	0.40	0.66	1.37	1.69	0.41	0.37	0.69	1.34	1.75
		118	113	134	135	115	113	119	131	135	114	112	120	131	136
		-------	[b]0.96	[b]1.16	[b]1.18	1.11	1.10	1.17	1.21	1.22	1.07	1.01	1.11	1.17	1.19
Isobutylbenzene	25	-------	114	213	222	214	209	230	260	286	175	176	197	223	245
		0.64	[a]86.3	[a]96.5	[a]97.6	1.97	1.67	1.77	2.16	2.54	2.60	1.64	2.20	2.36	3.04
		119	114	141	145	138	135	136	140	143	144	135	140	142	147
		-------	[b]0.97	[b]1.25	[b]1.30	1.35	1.31	1.33	1.35	1.34	1.27	1.22	1.25	1.29	1.31
n-Propylbenzene	25	-------	136	227	240	232	232	256	281	299	165	166	192	223	259
		0.80	[a]90.8	[a]98.6	[a]99.8	2.70	2.41	2.68	3.07	3.29	1.15	0.79	1.72	2.36	>4.00
		122	124	149	152	144	142	144	147	148	128	122	135	142	> 153
		-------	[b]1.08	[b]1.30	[b]1.38	1.47	1.45	1.48	1.46	1.40	1.20	1.16	1.22	1.29	1.39
1-Isopropyl-4-methylbenzene (p-cymene)	25	-------	132	231	248	238	241	277	303	323	173	175	200	233	276
		0.82	[a]88.9	[a]99.4	>[a] 100	3.04	2.86	3.86	>4.00	>4.00	2.22	1.50	2.50	3.20	>4.00
		123	119	151	157	147	146	152	> 153	> 153	140	133	143	148	> 153
		-------	[b]1.03	[b]1.34	[b]1.43	1.51	1.51	1.60	1.58	1.52	1.25	1.22	1.27	1.35	1.48
Methyl tert-butyl ether	10	-------				200	194	212	239	267	160	166	185	204	223
		1.45				1.59	1.33	1.28	1.53	1.87	0.84	0.79	1.11	1.44	1.79
		132				134	131	130	133	137	123	122	128	132	136
		-------				1.27	1.21	1.23	1.24	1.25	1.16	1.15	1.17	1.18	1.19
Ethyl tert-butyl ether	10	-------				188	185	204	229	248	160	163	181	197	210
		1.96				1.24	0.72	0.74	1.25	1.43	0.84	0.69	0.90	1.10	1.34
		138				129	121	121	130	132	123	120	124	127	131
		-------				1.19	1.16	1.18	1.19	1.16	1.16	1.13	1.15	1.14	1.12
Isopropyl tert-butyl ether	10	-------				185	185	200	223	246	160	160	179	201	214
		1.75				1.02	0.72	0.53	0.94	1.38	0.84	0.60	0.82	1.30	1.49
		136				126	121	116	125	131	123	118	123	130	132
		-------				1.17	1.16	1.16	1.16	1.15	1.16	1.11	1.13	1.16	1.14
Methyl phenyl ether (anisole)	10	-------				176	172	187	209	237	151	150	166	183	200
		0.60				0.46	0.34	0.33	0.44	1.07	0.48	0.43	0.50	0.52	0.66
		118				115	112	111	114	127	115	114	116	116	119
		-------				1.11	1.08	1.08	1.09	1.11	1.09	1.04	1.05	1.06	1.07
Ethyl phenyl ether (phenetole)	10	-------				179	178	193	214	245	148	154	174	194	210
		0.75				0.54	0.43	0.40	0.53	1.36	0.42	0.48	0.66	0.96	1.34
		121				117	114	113	116	131	114	115	119	125	131
		-------				1.13	1.11	1.12	1.11	1.15	1.07	1.07	1.10	1.12	1.12
Methyl p-totyl ether	10	-------				189	185	200	223	250	151	153	172	187	205
		0.75				1.28	0.72	0.53	0.94	1.47	0.48	0.47	0.61	0.63	1.07
		121				130	121	116	125	132	115	115	118	119	127
		-------				1.20	1.16	1.16	1.16	1.17	1.09	1.06	1.09	1.08	1.10
Base fuel[c] (87½% S-4 + 12½% n-heptane + 4.0 ml TEL/gal)		-------	126	171	174	158	160	173	192	213	138	144	158	173	187
		0.63	[a]87.5	[a]87.5	[a]87.5	0.23	0.22	0.19	0.23	0.31	0.28	0.34	0.39	0.38	0.36
		119	116	112	111	108	108	107	108	111	110	112	113	113	112
		-------	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
85% S-4 + 15% M-4 + 4.0 ml TEL/gal[d]		-------				152	156	171	187	208	130	137	151	166	180
		0.39				0.17	0.19	0.17	0.18	0.24	0.19	0.27	0.31	0.30	0.28
		113				106	107	106	107	109	107	110	111	111	110
		-------				0.96	0.98	0.99	0.97	0.98	0.94	0.95	0.96	0.96	0.96

[a]Percentage S-4 reference fuel + 4.0 ml TEL/gal in n-heptane reference fuel + 4.0 ml TEL/gal.
[b]Based on imep data of base fuel check curves taken with each test fuel.
[c]Base fuel used for blending compounds.
[d]Base fuel used in references 1 and 2 and for checking engine conditions.

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