NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2070

KNOCK-LIMITED PERFORMANCE OF FUEL BLENDS CONTAINING ETHERS

By I. L. Drell and J. R. Branstetter

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Washington
April 1950

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2070

KNOCK-LIMITED PERFORMANCE OF FUEL BLENDS CONTAINING ETHERS

By I. L. Drell and J. R. Branstetter

SUMMARY

Knock ratings are given for 23 ethers, each blended with base fuels. A.S.T.M. Aviation, A.S.T.M. Supercharge, aircraft single-cylinder, and 17.6 engine ratings are presented. Fuel consumption, blending characteristics, temperature sensitivity, and lead susceptibility are also briefly discussed.

Methyl tert-butyl ether appeared to have the best over-all antiknock effectiveness, considering all blend compositions and engine conditions investigated. In general, tert-butyl alkyl ethers gave the highest blend knock ratings, followed by aromatic alkyl ethers; ethers with olefinic, cycloparaffinic, and ortho-aromatic groups gave the lowest ratings.

INTRODUCTION

A general investigation of the antiknock value of selected compounds as blending agents for aviation fuels has been in progress at the NACA Lewis laboratory (references 1 to 18). An engine study of 23 ethers, each blended with base fuels, is reported herein.

The low knock limit of "ether" (diethyl ether) has long been known. Knock studies about two decades ago by Lovell, Campbell, and Boyd included di-n-propyl ether, di-n-butyl ether, diisobutyl ether, and ethyl n-butyl ether, in addition to diethyl ether. All gave low blending values (Kettering, reference 19). Over a decade ago, diisopropyl ether was reported to have a high knock rating (reference 20); practical interest was aroused and further studies were made of diisopropyl ether (reference 21 and unpublished reports). Ethyl tert-butyl ether was reported to have an even higher rating (reference 22). Motor-method blending values for 14 branched-paraffin ethers are given in reference 23.

During World War II, more knock studies (unpublished) of branched-paraffin ethers, particularly methyl tert-butyl ether, were made by United States industrial and military organizations; a German investigation of tert-butyl ethers was recently published (reference 24). Ether data obtained by the NACA are presented in references 1, 6, and 14-18. The current knock-testing program of the American Petroleum Institute has also included some ethers. Although ethers have lower heating values than hydrocarbons, the possibility remains that small concentrations of ethers in aviation fuels might be used with little increase in fuel consumption.

The NACA therefore undertook a systematic program of research on ethers that had not been previously investigated or that were considered worthy of further investigation. Blend knock ratings for some aromatic, olefinic, and cycloparaffinic ethers, for which no values are given in the literature, were determined at the NACA Lewis laboratory during 1945-1946 and are reported herein. Comparable data were also determined for blends containing methyl tert-butyl ether and other ethers for which few or no A.S.T.M. Aviation and A.S.T.M. Supercharge data exist.

Six of the ethers were more fully evaluated than the others; various blend compositions and engine conditions were used. Information is presented on knock-limited power, fuel consumption, blending characteristics, fuel-air-mixture response, temperature sensitivity, and lead susceptibility.

FUELS

Ethers: preparation, properties, and purity. - Synthesis and purification methods are described in reference 25. Table I lists the 23 ethers with structural formulas, heating values, stoichiometric fuel-air ratios, and physical constants of the engine samples. The first six ethers in the table were prepared in 10-gallon quantities and the others, in 1-liter quantities.

The purity of the engine samples was estimated at 99+ percent in most cases; at least 95-percent purity was attained in all cases except that of methyl cyclopropyl ether (number 20), which was the least pure of the 23 compounds.

A few ethers that form peroxides very rapidly were redistilled before the engine evaluation. The others were inhibited (0.0002 lb N-sec-butyl-p-aminophenol/gal) soon after preparation. Peroxide determinations on blends of the first six ethers were negative before and after the engine study.

1244

Blends: composition and tests. - The first six ethers were blended to concentrations of 10, 25, and 50 percent by volume with a mixed base fuel consisting of 87.5 percent S reference fuel and 12.5 percent n-heptane; all components were leaded to 4 ml TEL per gallon. These blends were studied in the A.S.T.M. Aviation, A.S.T.M. Supercharge, and 17.6 engines; the 10-percent blends were also run in a full-scale cylinder (reference 6).

The first six ethers were also blended to concentrations of 10 and 20 percent by volume with S reference fuel. These blends were evaluated with both 0 and 4 ml TEL per gallon in the A.S.T.M. Aviation and 17.6 engines.

The other 17 ethers were blended to 25 percent by volume with the mixed base fuel plus 4 ml TEL per gallon in final blends and were rated in the A.S.T.M. Aviation and A.S.T.M. Supercharge engines only.

All the S reference fuel (essentially isooctane) used for this investigation was S-4.

ENGINES

Apparatus and procedure. - The apparatus and the operating conditions for the A.S.T.M. Aviation, A.S.T.M. Supercharge, and supercharged 17.6 engines are described in references 7 and 8. References 4 and 6 describe apparatus and operating conditions for the full-scale air-cooled R-1820 G200 cylinder. The references use the CRC designations of F-3 and F-4 for A.S.T.M. Aviation and A.S.T.M. Supercharge, respectively.

In the A.S.T.M. Supercharge, 17.6, and the full-scale cylinder, an incipient-knock level was used, which was detected by a magnetostriction internal pickup and a cathode-ray oscilloscope. The 17.6 and full-scale cylinder were each operated at two sets of conditions, which are given in the data tables.

Severity of engine conditions. - In order to simplify the comparison of fuels, the engine conditions and the fuel-air ratios of this investigation were assigned various degrees of relative severity (fig. 1). These estimates of engine severity are based on comparisons of the relative order of knock ratings under these engine conditions for fuels of widely differing sensitivity; in passing from mild to severe conditions, the more sensitive fuels depreciate performancewise relative to less sensitive fuels. (See also reference 2.)

The use of a one-dimensional scale for engine severity is believed to be a considerable oversimplification of the actual situation. The inclusion of fuel-air ratio, on the assumption that it is primarily a temperature effect, is also of questionable validity. 1244
Nevertheless, if the roughness of the approximations is kept in mind, the concept of severity can be useful.

Precision of data. - Data for the fuel-air mixture-response curves for all blend concentrations of each ether with a given base fuel at given engine conditions were usually obtained on a single day; this procedure was followed in order to minimize effects of day-to-day variations in engine performance on the blending-characteristic data.

The 17.6 engine temperature-sensitivity and lead-susceptibility values each involve comparison of a given blend and base fuel at two conditions: at two inlet-air temperatures, or with and without lead. It was not feasible, however, to obtain data at both conditions on the same day except in a few cases; the precision of the temperature-sensitivity and lead-susceptibility values is therefore probably not so good as that of the blend data.

Base-fuel reproducibility is a rough index of the precision of the blend data. In the A.S.T.M. Supercharge engine, mixture-response curves were run eleven times on the mixed base fuel and eight times on S reference fuel plus 4 ml TEL per gallon. The following reproducibility was obtained:

	Fuel-air ratio				
	0.065	0.07	0.085	0.10	0.11
imep of mixed base fuel					
Average imep (lb/sq in.)	106	123	155	169	171
Average deviation (percent)	8	4	2	1	1
Maximum deviation (percent)	16	12	5	4	5
imep of S reference fuel + 4 ml TEL					
Average imep (lb/sq in.)	145	167	209	232	237
Average deviation (percent)	3	1	1	1	1
Maximum deviation (percent)	9	3	2	3	4
$\frac{\text{imep of S reference fuel + 4 ml TEL}}{\text{imep of mixed base fuel}}$					
Average imep ratio	1.41	1.37	1.34	1.37	1.38
Average deviation (percent)	6	4	2	1	1
Maximum deviation (percent)	12	8	4	2	2

The two values of indicated mean effective pressure (imep) used in computing each imep ratio in this table were obtained in a single day. At rich fuel-air ratios (0.10 and 0.11), imep ratios were more reproducible than the imep values; at lean fuel-air ratios in the A.S.T.M. Supercharge engine, however, the imep ratios seemed to be of little advantage.

In the 17.6 engine, three base fuels were each run six times at each of two inlet-air temperatures; an analysis at five fuel-air ratios showed that the average of all imep deviations was 2 percent and that the maximum was 6 percent.

RESULTS

A.S.T.M. Aviation Engine Data

Ratings in the A.S.T.M. Aviation engine for blends with the mixed base fuel are given in table II. The 25-percent blend ratings, which cover all 23 compounds, are also shown in figure 2 as a bar chart. For comparison, figure 2 includes values for corresponding blends of isooctane, n-heptane, and various high-performance hydrocarbons; some of these values were estimated and others have been corrected for slight differences in base fuel, as explained in the appendix. The tert-butyl alkyl ether blends (numbers 1 to 3) were outstanding under the severe A.S.T.M. Aviation conditions; these blends gave higher ratings than corresponding triptane blends.

Blending characteristics in the A.S.T.M. Aviation engine for the first six ethers are shown in figure 3. The first additions of the three tert-butyl alkyl ethers to the mixed base fuel gave larger increases in A.S.T.M. Aviation rating than did further additions. Ten-percent additions of the three aromatic ethers had little effect, but further additions caused a fairly regular drop in rating. The mixed base fuel had a fairly high A.S.T.M. Aviation rating to start with, 120 performance number.

Ratings in the A.S.T.M. Aviation engine for blends with S reference fuel are given in table III; the ratings are in about the same order as for blends with the mixed base fuel. Corresponding triptane blends (reference 26) had ratings approximately equal to the methyl tert-butyl ether blends; both were about equal to S reference fuel. Table III also defines and gives values of relative lead susceptibility in the A.S.T.M. Aviation engine for blends with S reference fuel. Relative lead susceptibility for the 10- and 20-percent tert-butyl alkyl ether blends was about the same as that for S reference fuel; it was lower for the aromatic ether blends, particularly at the 20-percent concentration.

1244

A.S.T.M. Supercharge Engine Data

Knock-limited power and mixture response. - Fuel-air mixture-response curves from the A.S.T.M. Supercharge engine are shown in figures 4 and 5. Each page of these figures gives results of a day's running. Two paraffin reference fuels are included: (1) the base fuel (87.5 percent S in n-heptane, plus 4 ml TEL per gallon), and (2) 100 percent S reference fuel plus 4 ml TEL per gallon. (Fuel flows for the data of figs. 5(a), (b), and (c) were measured with a rotameter instead of the usual weighing system. Some fuel-air ratios in these figures may be in error by as much as 10 percent at the lean end of the curves.)

Rich ratings in terms of percentage leaded S reference fuel in leaded n-heptane, derived from figures 4 and 5, are included in table II. The ratings were obtained from reciprocal imep plots and were converted to performance numbers, as described in reference 11. The 25-percent blend ratings, covering all the compounds, are also shown in bar-chart form (fig. 2). Under A.S.T.M. Supercharge rich conditions, methyl tert-butyl ether gave a considerably higher blend rating than the other ethers; only the best aromatic hydrocarbons of references 7 to 12 equaled it.

Table IV gives A.S.T.M. Supercharge engine imep ratios of blend relative to base fuel; they are given at five fuel-air ratios and at five percentage-of-stoichiometric-mixture values corresponding to the same five fuel-air ratios for the base fuel. The effect on knock-limited power of the higher stoichiometric fuel-air ratios for ether blends can thus be evaluated. Indicated specific fuel consumption (isfc) is, of course, affected at the same time.

Fuel consumption. - The ether blends generally had lower isfc values (in lb/hp-hr) than the paraffin reference fuels at fuel-air ratios richer than approximately 0.08; they had higher isfc values than the paraffins at fuel-air ratios less than about 0.08. The differences increased with greater ether concentration. (See figs. 4 and 5.)

The isfc values in the A.S.T.M. Supercharge engine are compared in figure 6 at constant percentage of stoichiometric mixture instead of the customary fuel-air weight basis. In pounds per horsepower-hour (fig. 6(a)), the isfc values of the 50-percent ether blends were higher than the base-fuel paraffins at all mixture ratios. In gallons per horsepower-hour (fig. 6(b)), isfc values for the 50-percent blends containing the three tert-butyl alkyl ethers were still somewhat higher than those for the paraffins; but for the 50-percent blends containing the aromatic alkyl ethers, the values were somewhat lower than for the paraffins. (The 50-percent blends were chosen to illustrate these points because they show larger effects than small concentrations; for small concentrations the effects are often of the order of the experimental error, but they are expected to be roughly proportional to the concentration.) In a volume-limited system, the high densities of the aromatic alkyl ethers tend to compensate for their low heating value.

Blending characteristics. - Rich A.S.T.M. Supercharge blending curves in terms of performance numbers are included in figure 3. The curves were determined at constant fuel-air ratio, which means a higher percentage rich for the paraffin reference fuels than for the ether blends. It is mainly for this reason that the curves show some drop at the higher concentrations of aromatic ethers; peak values occur at about 25 or 30 percent. The tert-butyl alkyl ethers, because of lower stoichiometric fuel-air ratios (and lower sensitivity relative to the aromatic ethers), are little affected; they exhibit nearly linear blending curves up to 50 percent.

The difference in shape of the blending curves when blend and reference base fuel are at the same percentage rich is shown in figure 7. The blending curves at a fuel-air ratio of 0.11 using imep ratio (fig. 7) have about the same shape as the curves using performance number (fig. 3), as expected. But when blend and base fuel are at the same percentage rich, corresponding to the base fuel-air ratio of 0.11, the curves for all six ethers have a similar shape – namely, rising more rapidly as concentration is increased up to 50 percent. At lean fuel-air ratios such as 0.07, the blending curves of the aromatic ethers fell off at the high concentrations no matter how compared; this effect can then be ascribed only to high sensitivity of the aromatic-ether content to the more severe conditions. No simple blending relation generally applicable to ether blends under all these conditions (such as is advanced for paraffins and other compounds in references 27 to 30) is immediately apparent from the shape of the curves in figures 3 and 7.

Full-Scale-Cylinder Data

Full-scale-cylinder imep ratios, derived from reference 6, for six ethers in 10-percent blends with the mixed base fuel at two sets of engine conditions are presented in table V. Methyl tert-butyl ether generally had the highest 10-percent-blend knock limit of the six ethers at all full-scale conditions. The ethyl and isopropyl tert-butyl ether blends were practically equal to the methyl tert-butyl ether blend at 250° F lean conditions; at less severe conditions, however, they had lower knock limits than the methyl tert-butyl ether blend.

The blend containing p-methylanisole showed high fuel-air-mixture response and engine sensitivity. At the most severe conditions, the values of imep ratio for this blend were close to the low values of the other two aromatic ethers; at the 250° F rich and 210° F lean conditions, p-methylanisole equaled or surpassed ethyl and isopropyl tert-butyl ethers; at very high fuel-air ratios, it became equal to methyl tert-butyl ether.

17.6 Engine Data

Table VI gives 17.6 engine imep ratios derived from the mixture-response curves of figure 8 for 10-, 25-, and 50-percent blends of the first six ethers with the mixed base fuel at two inlet-air temperatures. Some of the data of table VI are shown in figure 9 as blending-characteristic plots of imep ratio against percentage ether. Tables VII and VIII give 17.6 engine imep ratios derived from the mixture-response curves of figure 10 for 10- and 20-percent blends of the six ethers with S reference fuel, unleaded and leaded, respectively. In going from the severest (250° F air, lean) to the mildest (100° F air, rich) 17.6 engine conditions, the aromatic alkyl ethers showed a tendency to rise in order of rating relative to the tert-butyl alkyl ethers. At the mildest conditions, blends containing aromatic alkyl ethers generally had the highest knock ratings of the group; they were usually somewhat higher than methyl tert-butyl ether blends, much higher than triptane blends (reference 26), but not quite so high as the best aromatic hydrocarbon blends (references 7 to 12).

Lead susceptibility. - Data for relative lead susceptibility in the 17.6 engine for 10- and 20-percent ether blends with S reference fuel are presented in table IX. Values for the ether blends were, in general, a little higher than those for S reference fuel; methyl tert-butyl ether blends were generally slightly higher than the rest. The three aromatic ethers as a group tended to give lower lead susceptibility than the tert-butyl alkyl ethers at the severest 17.6 engine conditions (250° F air, lean). This trend parallels the A.S.T.M. Aviation results. Corresponding blends containing triptane (reference 26) or high-performance aromatic hydrocarbons (references 7 to 12) generally had lead susceptibilities as high as the best ethers.

Temperature sensitivity. - Values for relative inlet-air-temperature sensitivity in the 17.6 engine are given in table X. Within the estimated error, values for the six ethers in 10-percent blends with the mixed base fuel were about the same as for the base fuel. At the 25-percent concentration, the aromatic ethers showed greater temperature sensitivity than the tert-butyl alkyl ethers, which still gave about the same sensitivity as the base fuel. At the 50-percent concentration, the aromatic ethers were considerably more sensitive to temperature; even the tert-butyl alkyl ethers showed a definitely greater temperature sensitivity than the base fuel at lean mixtures. In blends with S reference fuel, unleaded and leaded, the tert-butyl alkyl ethers showed somewhat greater sensitivity than in blends with the mixed base fuel. Corresponding triptane blends (reference 26) had relative inlet-air temperature sensitivities in the 17.6 engine about the same as the tert-butyl alkyl ethers; corresponding blends containing the most sensitive aromatic hydrocarbons of references 7 to 12 were more sensitive than any of the six ethers.

Over-all Comparison of Ethers

Some rough generalizations providing an over-all comparison of the antiknock value of the 23 ethers in blends are included in this section. Fuel sensitivity to severity of engine conditions is one of the factors stressed. The 17.6 engine inlet-air temperature sensitivity is a measure of sensitivity to changes over a relatively mild part of the range of engine conditions. The sensitivity usually discussed in the following comments covers a wider range; it is obtained by comparing the order of knock ratings for the base fuel, the ether blends, and corresponding blends of other fuels at all engine conditions covered.

tert-Butyl alkyl ethers. - Methyl tert-butyl ether is slightly surpassed in blend performance at severe conditions by the other tert-butyl alkyl ethers and at mild conditions by some of the aromatic alkyl ethers (and even more by the best aromatic hydrocarbons of references 7 to 12). Nevertheless, for high antiknock value over a fairly wide range of engine severity, methyl tert-butyl ether is thought to be the best of the 23 ethers investigated. It is one of the best fuels known regardless of chemical class with respect to knock-limited power over a wide range of conditions.

At severe conditions, isopropyl tert-butyl ether gave the highest knock ratings of the 25-percent ether blends. (These relative ratings depend on concentration; ethyl tert-butyl ether gave slightly higher values in 10-percent blends and methyl tert-butyl ether, in 50-percent blends.) At milder conditions, the order of the three tert-butyl alkyl ethers was usually reversed, with isopropyl lowest, ethyl in between, and methyl highest. In other words, methyl tert-butyl was usually the most sensitive of the three with respect to changes in fuel-air ratio and engine severity in general; isopropyl tert-butyl ether was usually the least sensitive.

The sensitivity of methyl tert-butyl ether in blends was about the same as the least sensitive aromatic ethers; it was considered less than the least sensitive aromatic hydrocarbons of high performance (references 7 to 12) such as tert-butylbenzene and less than the most sensitive paraffins or olefins, but greater than triptane blends (references 2 to 4 and 26). The sensitivity of blends containing isopropyl tert-butyl ether was thought to be less than triptane blends but greater than isooctane blends (references 2 and 26).

Methyl tert-butyl ether generally showed greater response to changes in concentration than the other tert-butyl alkyl ethers, considering the entire range up to 50 percent; at low concentrations, however, ethyl tert-butyl ether often seemed to show greater response.

The three tert-butyl alkyl ethers investigated might be considered as members of a structural series in which the methyl hydrogens are successively replaced by methyl groups. If the antiknock trends discussed for the first three members could be extrapolated to the fourth member of the series, di-tert-butyl ether would be expected to be generally the least sensitive to engine severity of the four. For example, in the 25-percent blend with the mixed base fuel, di-tert-butyl ether might be expected to give higher knock ratings at the severe A.S.T.M. Aviation and lean Supercharge conditions than the other three tert-butyl ethers; and it might be expected to give slightly lower ratings than the other three at the moderate A.S.T.M. Supercharge rich conditions. Of course, experimental verification is needed.

1244

Reference 17 includes modified F-4 engine data for a 10-percent blend of di-tert-butyl ether with AN-F-28 fuel, and reference 18 includes 17.6 engine data for a leaded 20-percent blend of di-tert-butyl ether with S reference fuel. The modified F-4 engine conditions were probably less severe than standard A.S.T.M. Supercharge conditions but a little more severe than the 17.6 engine conditions with inlet air at 250° F. At the modified F-4 engine conditions, the di-tert-butyl ether blend gave slightly higher knock ratings at lean mixtures, but lower ratings at richer mixtures than corresponding blends of the three other tert-butyl alkyl ethers. At all the 17.6 engine conditions, di-tert-butyl ether gave lower blend knock ratings than the three tert-butyl alkyl ethers discussed herein; it was better than triptane (in corresponding blends) with inlet air at 100° F, but poorer at fuel-air ratios much above the minimum imep point with inlet air at 250° F. These data indicate that di-tert-butyl ether gave somewhat lower fuel-air mixture response but higher inlet-air-temperature sensitivity than the triptane blend at 17.6 engine conditions.

A relatively low motor octane number is reported in reference 24 for a blend containing 25 percent di-tert-butyl ether, lower than that for diisopropyl ether; no physical-property data are given, however, and some question as to purity seems to be indicated.

Aromatic alkyl ethers. - The best aromatic alkyl ethers gave much lower blend knock values than any of the tert-butyl alkyl ethers at severe lean conditions. At moderate conditions, they gave knock values about equal to ethyl or isopropyl tert-butyl ether, but still below methyl tert-butyl ether. At mild conditions, they surpassed even methyl tert-butyl ether and the superiority of these ethers tended to increase at higher blend concentrations. The aromatic alkyl ethers as a group showed greater sensitivity to engine severity and greater blending response at mild conditions than the dialkyl ethers investigated; a corresponding relation exists between aromatic and paraffinic hydrocarbons.

At all engine conditions, the best of the 11 aromatic alkyl ethers gave lower blend knock values and perhaps somewhat lower sensitivity than the best aromatic hydrocarbons of references 7 to 12.

Isopropyl benzyl ether, one of the better aromatic alkyl ethers at severe lean conditions, was one of the poorer ones at rich conditions; it seemed to be somewhat less sensitive than the ethers having the oxygen linked to a carbon in the ring. Methyl benzyl ether also gave poor fuel-air mixture response.

In the A.S.T.M. Supercharge engine, n-propyl phenyl ether was higher in blend knock value than ethyl phenyl ether (phenetole), which in turn was higher than methyl phenyl ether (anisole). This trend corresponds to the usual order of n-propyl-, ethyl-, and methylbenzene (references 7 and 11) at lean fuel-air ratios. Isopropyl phenyl ether gave lower blend A.S.T.M. Supercharge values than n-propyl phenyl ether at lean mixtures, but they were approximately equal at rich mixtures; this somewhat greater mixture response of isopropyl relative to n-propyl phenyl ether agrees with a similar effect noted for corresponding benzene derivatives (references 8 and 11). 1244

Of the other aromatic alkyl ethers, o-methylanisole gave the lowest blend knock values. The low knock limit of the ortho structure relative to meta or para apparently applies to aromatic ethers just as it does for aromatic hydrocarbons (references 8, 9, and 12).

Methallyl ethers. - Phenyl methallyl ether was much the lowest in blend knock value of the 23 ethers studied. Next poorest of the methallyl ethers was dimethallyl ether, which was near the level estimated for a corresponding n-heptane blend. The three methallyl alkyl ethers were somewhat better and generally ranked along with the two or three poorest aromatic alkyl ethers. A corresponding blend of 2,4,4-trimethyl-1-pentene (one of the better olefinic hydrocarbons) had about the same A.S.T.M. Aviation rating as the tert-butyl methallyl ether blend; in the A.S.T.M. Supercharge engine, however, the hydrocarbon was far superior (references 2 and 4).

Cycloalkyl methyl ethers. - Methyl cyclohexyl ether gave the lowest blend knock value of the three cycloalkyl ethers and was second lowest of the 23 compounds. Of the other two, methyl cyclopropyl ether had lower blend knock values than methyl cyclopentyl ether at A.S.T.M. Aviation and lean Supercharge conditions; the order was reversed, however, at the less severe A.S.T.M. Supercharge rich conditions. In other words, methyl cyclopropyl ether was more sensitive than methyl cyclopentyl ether.

Propylene oxide. - Propylene oxide ranked about in the middle of the group of 23 compounds in blend knock ratings; it had ratings of the order that might be expected if it behaved (in engines) like acetone (reference 14).

SUMMARY OF RESULTS

The highest knock ratings for 23 ethers investigated in various blends at several engine conditions were generally for the

1244

tert-butyl alkyl ethers, followed by most of the aromatic alkyl ethers; the lowest ratings were for ethers having olefinic, cycloparaffinic, or ortho-aromatic radicals. More specifically:

1. At severe engine conditions (A.S.T.M. Aviation or lean Supercharge), blends containing the *tert*-butyl alkyl ethers were outstanding. At concentrations of about 25 percent or less, methyl *tert*-butyl was not quite so good as ethyl *tert*-butyl or isopropyl *tert*-butyl ether; but all gave higher knock ratings than corresponding blends of triptane or other liquid hydrocarbons at severe conditions.

2. At moderate conditions (A.S.T.M. Supercharge rich or lean 17.6 engine conditions with inlet air at 250° F), blends containing methyl *tert*-butyl ether had the highest knock ratings, about equal to corresponding blends containing the best aromatic hydrocarbons. The other *tert*-butyl alkyl ethers and many of the aromatic alkyl ethers gave lower ratings in a class with triptane blends.

3. At mild conditions (17.6 engine with inlet air at 100° F), blends containing some of the aromatic alkyl ethers had the highest knock ratings. They were somewhat higher than methyl *tert*-butyl ether blends, much higher than triptane blends, but not quite so high as the best aromatic-hydrocarbon blends.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 15, 1949.

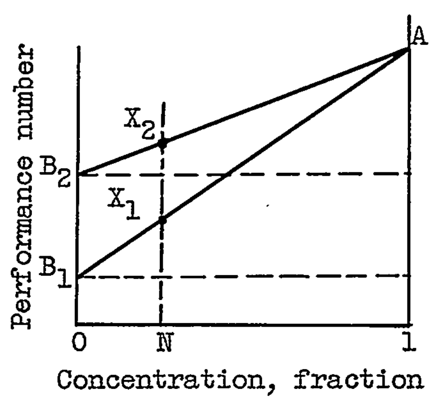
APPENDIX - ESTIMATION OF BLEND RATINGS

The A.S.T.M. Aviation rating of a 25-percent triptane blend was 130 performance number (reference 4); the base fuel (85 percent S-3 and 15 percent M-3) for this blend had a performance number of 114. The rating of a 25-percent triptane blend with a base fuel having a performance number of 120 was estimated to be 135.by the approximate method subsequently explained. Other 25-percent triptane blend data (derived from references 1, 26, and 31) gave estimated values ranging from 131 to 139. 1244

A 25-percent blend of isooctane in the mixed base fuel would be the same as 90.6 percent isooctane in n-heptane plus 4 ml TEL per gallon; the rating of this blend is estimated at approximately 128 on the basis of a plot of percentage composition against A.S.T.M. Aviation performance number derived from reference 30. A 25-percent n-heptane blend was similarly estimated to rate about 80.

The following approximate method was used to correct the performance number of a blend with one base fuel to that for a slightly different base fuel:

- A performance number of blending agent
- B_1 performance number of first base fuel
- B_2 performance number of slightly different base fuel
- X_1 performance number of blend with first base fuel at N fractional concentration
- X_2 performance number of blend with slightly different base fuel at N fractional concentration



If it is assumed that AB_1 and AB_2 in the accompanying figure are straight lines (this assumption is not true in general, but where the difference in base fuels is small, the resulting error would probably be small),

$$\frac{X_2-B_2}{N-0} = \frac{A-B_2}{1-0} \qquad \text{or} \qquad X_2-B_2 = NA-NB_2$$

Similarly,

$$X_1-B_1 = NA-NB_1$$

By subtraction and rearrangement,

$$X_2-X_1 = B_2-B_1-N(B_2-B_1)$$

or

$$X_2 = X_1 + (1-N)(B_2-B_1)$$

Thus, in order to correct the performance number of a 25-percent blend from a base-fuel value of 114 to one of 120, add $(1-0.25)(120-114) = 4.5$ to the original blend performance number.

REFERENCES

1. Imming, Harry S., Barnett, Henry C., and Genco, Russell S.: F-3 and F-4 Engine Tests of Several High-Antiknock Components of Aviation Fuel. NACA MR E4K27, 1944.

2. Genco, R. S., and Drell, I. L.: Knock-Limited Performance of Several Branched Paraffins and Olefins. NACA TN 1616, 1948.

3. Jonash, Edmund R., Meyer, Carl L., and Branstetter, J. Robert: Knock-Limited Performance Tests of 2,2,3,4-Tetramethylpentane, 2,3,3,4-Tetramethylpentane, 3,4,4-Trimethyl-2-pentene, and 2,3,4-Trimethyl-2-pentene in Small-Scale and Full-Scale Cylinders. NACA ARR E6C04, 1946.

4. 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 E4E25, 1944.

5. 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 E4I09, 1944.

6. Jones, Anthony W., Bull, Arthur W., and Jonash, Edmund R.: Knock-Limited Performance of Pure Hydrocarbons Blended with a Base Fuel in a Full-Scale Aircraft-Engine Cylinder. III - Four Aromatics, Six Ethers. NACA ARR E6B14, 1946.

7. Meyer, Carl L., and Branstetter, J. Robert: The Knock-Limited Performance of Fuel Blends Containing Aromatics. I - Toluene, Ethylbenzene, and p-Xylene. NACA ARR E4J05, 1944.

8. Branstetter, J. Robert, and Meyer, Carl L.: The Knock-Limited Performance of Fuel Blends Containing Aromatics. II - Isopropylbenzene, Benzene, and o-Xylene. NACA ARR E5A20, 1945.

9. Meyer, Carl L., and Branstetter, J. Robert: The Knock-Limited Performance of Fuel Blends Containing Aromatics. III - 1,3,5-Trimethylbenzene, tert-Butylbenzene, and 1,2,4-Trimethylbenzene. NACA ARR E5D16, 1945.

10. Meyer, Carl L., and Branstetter, J. Robert: The Knock-Limited Performance of Fuel Blends Containing Aromatics. IV - Data for m-Diethylbenzene, 1-Ethyl-4-methylbenzene, and sec-Butylbenzene Together with a Summarization of Data for 12 Aromatic Hydrocarbons. NACA ARR E5D16a, 1945.

11. Meyer, Carl L., and Branstetter, J. Robert: The Knock-Limited Performance of Fuel Blends Containing Aromatics. V - n-Propylbenzene, n-Butylbenzene, Isobutylbenzene, m-Xylene, and 1-Isopropyl-4-methylbenzene. NACA ARR E6C05, 1946.

12. Drell, I. L., and Alquist, H. E.: Knock-Limited Performance of Fuel Blends Containing Aromatics. VI - 10 Alkylbenzenes. NACA TN 1994, 1949.

13. Alquist, Henry E.: The Knock-Limited Performance of Several Fuels Blended with S-2 Reference Fuel. NACA RB E4K03, 1944.

14. Bellman, Donald R.: The Knock-Limited Performance of Several Miscellaneous Fuels Blended with a Base Fuel - I. NACA ACR E4G08, 1944.

15. Barnett, Henry C., Meyer, Carl L., and Jones, Anthony W.: Engine and Inspection Tests of Methyl tert-Butyl Ether as a Component of Aviation Fuel. NACA ACR E4H03, 1944.

16. Barnett, Henry C., and Slough, James W., Jr.: Supercharged-Engine Knock Tests of Methyl tert-Butyl Ether. NACA ACR E4H10, 1944.

17. Alquist, Henry E., and Tower, Leonard K.: Suitability of Ethers as Aviation Fuel Components. I - The Knock-Limited Performance of Several Ethers Blended with AN-F-28 Fuel. NACA CB E5A04, 1945.

18. Meyer, Carl L.: The Knock-Limited Performance of Fuel Blends Containing Spiropentane, Methylenecyclobutane, Di-tert-butyl Ether, Methyl tert-Butyl Ether, and Triptane. NACA RB E6D22, 1946.

19. Kettering, Charles F.: The Effect of the Molecular Structure of Fuels on the Power and Efficiency of Internal Combustion Engines. Ind. and Eng. Chem. (Ind. ed.), vol. 36, no. 12, Dec. 7, 1944, pp. 1079-1085.

20. Buc, H. E., and Aldrin, Edwin E.: A New High-Octane Blending Agent. SAE Jour. (Trans.), vol. 39, no. 3, Sept. 1936, pp. 333-340, 357.

21. Sokolik, A., and Voinov, A.: A Study of Isopropyl Ether as a Motor Fuel. Techn. Phys. USSR (Leningrad), vol. IV, no. 8, 1937, pp. 638-660.

22. Heron, S. D.: Branched-Chain Ethers Discussed. SAE Jour. (Trans.), vol. 39, no. 2, Aug. 1936, pp. 310-311.

23. Hofman, Erik, Lapeyrouse, M., and Sweeney, W.: New Blending Agents for Aviation Gasoline of 100 Octane Number. IId Congrés Mondial du Pètrole (Paris), T. III, 1937, pp. 812-819.

24. Nitschman: The Preparation, Properties and Utilization of Tertiary Butylethers. Trans. PC-89, Charles A. Meyer & Co., Inc. (New York), 1948.

25. Olson, Walter T., Hipsher, Harold F., Buess, Charles M., Goodman, Irving A., Hart, Isaac, Lamneck, John H., Jr., and Gibbons, Louis C.: The Synthesis and Purification of Ethers Jour. Am. Chem. Soc., vol. 69, no. 10, Oct. 1947, pp. 2451-2454.

26. Branstetter, J. Robert: Comparison of the Knock-Limited Performance of Triptane with 23 Other Purified Hydrocarbons. NACA MR E5E15, 1945.

27. Sanders, Newell D.: A Method of Estimating the Knock Rating of Hydrocarbon Fuel Blends. NACA Rep. 760, 1943.

28. Sanders, Newell D., Hensley, Reece V., and Breitwieser, Roland: Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels. I - Preliminary Tests in an Air-Cooled Cylinder. NACA ARR E4128, 1944.

29. Wear, Jerrold D., and Sanders, Newell D.: Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels. II - Investigation of Leaded Paraffinic Fuels in an Air-Cooled Cylinder. NACA TN 1374, 1947.

30. Drell, I. L., and Wear, J. D.: Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels. III - Aromatics and Cycloparaffins. NACA TN 1416, 1947.

31. Barnett, Henry C., and Clarke, Thomas C.: An Evaluation of Proposed Reference Fuel Scales for Knock Rating. NACA TN 1619, 1948.

32. Kharasch, M. S.: Heats of Combustion of Organic Compounds. Bur. Standards Jour. Res., vol. 2, no. 1, Jan. 1929, pp. 359-430.

TABLE I - PROPERTIES OF 23 ETHERS (ENGINE SAMPLES)

Number[a]	Name	Formula	Net heating value[b] (Btu/lb)	Stoichiometric fuel-air ratio	Freezing point (°C)	Boiling point (°C)	Density at 20° C (gram/ml)	Refractive index n_D^{20}
1	Methyl tert-butyl ether	$(CH_3)_3COCH_3$	15,100	0.0852	-109.00	54.63	0.7403	1.3689
2	Ethyl tert-butyl ether	$(CH_3)_3COC_2H_5$	15,600	.0823	-94.44	71.93	.7395	1.3756
3	Isopropyl tert-butyl ether	$(CH_3)_3COCH(CH_3)_2$	15,900	.0802	-88.10	87.42	.7413	1.3800
4	Anisole (Methyl phenyl ether)	$C_6H_5OCH_3$	14,400	.0922	-37.16	153.63	.9939	1.5170
5	Phenetole (Ethyl phenyl ether)	$C_6H_5OC_2H_5$	14,900	.0885	-29.49	169.95	.9651	1.5075
6	p-Methylanisole (Methyl p-tolyl ether)	p-$CH_3 \cdot C_6H_4OCH_3$	14,800	.0885	-32.20	176.69	.9701	1.5123
7	m-Methylanisole	m-$CH_3 \cdot C_6H_4OCH_3$	14,800	.0885	-56.05	176.53	.9716	1.5137
8	o-Methylanisole	o-$CH_3 \cdot C_6H_4OCH_3$	14,800	.0885	-34.21	171.81	.9796	1.5178
9	p-tert-Butylanisole	p-$(CH_3)_3C \cdot C_6H_4OCH_3$	15,800	.0821	19.11	223.18	.9383	1.5030
10	n-Propyl phenyl ether	$C_6H_5OC_3H_7$	15,300	.0858	-27.09	189.31	.9475	1.5012
11	Isopropyl phenyl ether	$C_6H_5OCH(CH_3)_2$	15,300	.0858	-33.05	176.73	.9405	1.4975
12	tert-Butyl phenyl ether	$C_6H_5OC(CH_3)_3$	15,600	.0837	-18.38	[c]187	.9247	1.4880
13	Methyl benzyl ether	$C_6H_5CH_2OCH_3$	14,800	.0885	-53.11	169.9	.9630	1.5019
14	Isopropyl benzyl ether	$C_6H_5CH_2OCH(CH_3)_2$	15,500	.0837	-67.18	[c]193	.9214	1.4859
15	Phenyl methallyl ether	$CH_2{:}C(CH_3)CH_2OC_6H_5$	15,400	.0859	-33.32	[c]210	.9634	1.5157
16	Methyl methallyl ether	$CH_2{:}C(CH_3)CH_2OCH_3$	14,800	.0892	-113.15	66.86	.7772	1.3941
17	Isopropyl methallyl ether	$CH_2{:}C(CH_3)CH_2OCH(CH_3)_2$	15,800	.0827	Glass[d]	103.20	.7753	1.4012
18	tert-Butyl methallyl ether	$CH_2{:}C(CH_3)CH_2OC(CH_3)_3$	16,100	.0808	-85.69	[c]114	.7853	1.4083
19	Dimethallyl ether	$[CH_2{:}C(CH_3)CH_2]_2O$	15,900	.0831	-57.72	134.40	.8131	1.4285
20	Methyl cyclopropyl ether	$\underbrace{CH_2CH_2CH}OCH_3$	13,700	.0950	---------	43.20	.7839	1.3799
21	Methyl cyclopentyl ether	$\underbrace{CH_2(CH_2)_3CH}OCH_3$	15,100	.0854	-135.03	105.39	.8625	1.4205
22	Methyl cyclohexyl ether	$\underbrace{CH_2(CH_2)_4CH}OCH_3$	15,600	.0827	-74.39	133.35	.8756	1.4346
23	Propylene oxide[e]	$CH_3\underbrace{CHCH_2O}$	13,000	.1052	-112.04	34.18	.8288	1.3659

[a]Compounds in all the tables are arranged in the same order, according to the nature of the two organic radicals linked to the oxygen atom.

[b]Calculated values (1 atmosphere; 18° C; liquid fuel burning to gaseous H_2O and CO_2), using method of reference 32, except in case of propylene oxide for which the experimental value in reference 32 was used.

[c]Approximate value (decomposed on atmospheric boiling).

[d]No definite melting point.

[e]Not strictly an ether but of related structure.

TABLE II - A.S.T.M. AVIATION AND A.S.T.M. SUPERCHARGE RATINGS FOR LEADED ETHERS BLENDED WITH BASE FUEL CONSISTING OF 87.5-PERCENT S REFERENCE FUEL AND 12.5-PERCENT n-HEPTANE PLUS 4 ML TEL PER GALLON

Ether in blend[a]				Blend stoichiometric fuel-air ratio	A.S.T.M. Aviation		A.S.T.M. Supercharge (fuel-air ratio, 0.11)	
Number	Name	Percent by volume	Percent by weight		TEL in S reference fuel (ml/gal)	Performance number	S + 4 ml TEL in heptane + 4 ml TEL (percent)	Performance number
0	Base fuel	0	0	0.0664	0.68	120	87.5	110
1	Methyl tert-butyl ether	10	10.6	0.0680	1.60	134	95.1	137
2	Ethyl tert-butyl ether		10.6	.0678	2.20	140	93.6	133
3	Isopropyl tert-butyl ether		10.6	.0676	1.90	137	91.9	127
4	Anisole		13.8	.0691	.60	118	91.6	126
5	Phenetole		13.4	.0687	.69	120	92.5	129
6	p-Methylanisole		13.5	.0687	.67	120	93.9	134
1	Methyl tert-butyl ether	25	26.3	0.0705	2.50	143	103.8	[b]174
2	Ethyl tert-butyl ether		26.3	.0700	2.60	144	99.2	150
3	Isopropyl tert-butyl ether		26.3	.0696	3.45	149	99.0	149
4	Anisole		32.4	.0730	.20	107	96.8	143
5	Phenetole		31.7	.0722	.32	111	97.9	146
6	p-Methylanisole		31.8	.0722	.35	112	97.6	145
7	m-Methylanisole		31.9	.0722	.28	110	98.2	147
8	o-Methylanisole		32.1	.0722	[c]94.0	82	79.3	92
9	p-tert-Butylanisole		31.1	.0706	.29	110	98.4	147
10	n-Propyl phenyl ether		31.3	.0715	.28	110	99.1	150
11	Isopropyl phenyl ether		31.2	.0715	.28	110	99.3	150
12	tert-Butyl phenyl ether		30.8	.0710	.20	107	95.2	138
13	Methyl benzyl ether		31.7	.0721	.11	104	87.2	109
14	Isopropyl benzyl ether		30.7	.0710	.63	119	96.0	140
15	Phenyl methallyl ether		31.7	.0716	[c]70±5	48	49.4	60
16	Methyl methallyl ether		27.2	.0714	[c]97.9	93	78.3	90
17	Isopropyl methallyl ether		27.2	.0702	.15	106	83.3	98
18	tert-Butyl methallyl ether		27.5	.0699	.16	106	86.1	106
19	Dimethallyl ether		28.1	.0704	[c]91.5	77	76.9	88
20	Methyl cyclopropyl ether		27.4	.0724	[c]91.2	76	79.4	92
21	Methyl cyclopentyl ether		29.4	.0711	[c]93.0	80	72.2	82
22	Methyl cyclohexyl ether		29.7	.0706	[c]86.6	68	67.9	77
23	Propylene oxide		28.5	.0742	.01	100	93.3	132
1	Methyl tert-butyl ether	50	51.7	0.0750	3.60	150	112.5	[b]254
2	Ethyl tert-butyl ether		51.7	.0738	3.50	150	105.3	[b]185
3	Isopropyl tert-butyl ether		51.7	.0730	5.60	160	105.7	[b]184
4	Anisole		58.9	.0796	[c]98.1	94	95.4	138
5	Phenetole		58.2	.0778	[c]100.0	100	95.4	138
6	p-Methylanisole		58.4	.0778	[c]100.0	100	94.8	136

[a]All contain 4 ml TEL/gal.

[b]Estimated performance number = $\frac{\text{imep of blend}}{\text{imep of S + 4 ml TEL}}$ x performance number of S + 4 ml TEL.

[c]Octane number.

NACA

TABLE III - A.S.T.M. AVIATION DATA FOR ETHERS BLENDED WITH S REFERENCE FUEL LEADED AND UNLEADED

Number	Ether in blend	A.S.T.M. Aviation rating								A.S.T.M. Aviation relative lead susceptibility[a]	
		TEL in S reference fuel (ml/gal)				Performance number					
		10-percent blends		20-percent blends		10-percent blends		20-percent blends		10-percent blends	20-percent blends
		Unleaded	Leaded	Unleaded	Leaded	Unleaded	Leaded	Unleaded	Leaded		
1	Methyl *tert*-butyl ether	[b]100	3.3	0.05	[c]4.0	100	149	102	[c]153	0.97	[c]0.98
2	Ethyl *tert*-butyl ether	[b]100	5.0	.10	6.0	100	157	104	161	1.03	1.01
3	Isopropyl *tert*-butyl ether	0.08	5.6	.10	5.9	103	160	104	161	1.01	1.01
4	Anisole	[b]97.9	2.25	[b]97.0	.75	93	141	90	121	.99	.88
5	Phenetole	[b]99.8	2.2	[b]99.2	.7	99	140	97	120	.93	.81
6	*p*-Methylanisole	[b]99.7	2.7	[b]99.7	1.5	99	144	99	133	.95	.88

$$^{a}\text{A.S.T.M. Aviation relative lead susceptibility} = \frac{\dfrac{\text{Performance number of blend leaded to 4 ml TEL/gal}}{\text{Performance number of blend unleaded}}}{\dfrac{\text{Performance number of S leaded to 4 ml TEL/gal}}{\text{Performance number of S unleaded}}}$$

[b]Octane number.

[c]Approximate value.

NACA

TABLE IV - A.S.T.M. SUPERCHARGE ENGINE IMEP RATIOS FOR LEADED ETHERS BLENDED WITH BASE FUEL CONSISTING OF 87.5-PERCENT S REFERENCE FUEL AND 12.5-PERCENT n-HEPTANE PLUS 4 ML TEL PER GALLON

Ether in blend[a]				Blend stoichiometric fuel-air ratio	Imep ratio of blend to base fuel[b]									
					Base fuel and blend at same fuel-air ratio					Base fuel and blend at same percentage of stoichiometric mixture				
					Fuel-air ratio of base fuel					Fuel-air ratio of base fuel				
Number	Name	Percent by volume	Percent by weight		0.065	0.07	0.085	0.10	0.11	0.065	0.07	0.085	0.10	0.11
1	Methyl tert-butyl ether	10	10.6	0.0680	1.07	1.01	1.11	1.18	1.21	1.08	1.10	1.15	1.19	1.21
2	Ethyl tert-butyl ether		10.6	.0678	1.13	1.12	1.14	1.16	1.17	1.17	1.19	1.16	1.17	1.17
3	Isopropyl tert-butyl ether		10.6	.0676	1.13	1.07	1.09	1.10	1.11	1.14	1.12	1.10	1.10	1.10
4	Anisole		13.8	.0691	.94	.93	1.03	1.07	1.10	.97	1.01	1.08	1.09	1.10
5	Phenetole		13.4	.0687	.97	.94	1.05	1.11	1.12	.98	1.05	1.09	1.13	1.13
6	p-Methylanisole		13.5	.0687	.99	.90	1.05	1.13	1.16	1.01	1.03	1.09	1.15	1.17
1	Methyl tert-butyl ether	25	26.3	0.0705	1.34	1.13	1.39	1.52	1.59	1.34	1.34	1.51	1.58	1.59
2	Ethyl tert-butyl ether		26.3	.0700	1.37	1.15	1.25	1.34	1.37	1.35	1.33	1.34	1.38	1.39
3	Isopropyl tert-butyl ether		26.3	.0696	1.34	1.26	1.24	1.29	1.33	1.43	1.37	1.29	1.32	1.34
4	Anisole		32.4	.0730	.87	.72	.96	1.13	1.25	.83	.92	1.15	1.26	1.34
5	Phenetole		31.7	.0722	.99	.81	1.05	1.21	1.30	.98	1.05	1.20	1.31	1.37
6	p-Methylanisole		31.8	.0722	.91	.74	.98	1.15	1.29	.95	.95	1.12	1.29	1.42
7	m-Methylanisole		31.9	.0722	.97	.90	1.07	1.21	1.31	1.06	1.07	1.20	1.32	1.41
8	o-Methylanisole		32.1	.0722	.60	.52	.57	.75	.85	.60	.56	.70	.85	.93
9	p-tert-Butylanisole		31.1	.0706	.95	.91	.94	1.10	1.32	1.00	1.02	1.02	1.25	1.40
10	n-Propyl phenyl ether		31.3	.0715	1.06	1.00	1.17	1.27	1.35	1.12	1.16	1.29	1.34	1.41
11	Isopropyl phenyl ether		31.2	.0715	.99	.90	1.05	1.26	1.35	1.04	1.02	1.21	1.35	1.42
12	tert-Butyl phenyl ether		30.8	.0710	.88	.81	.92	1.06	1.21	.90	.90	1.01	1.17	1.34
13	Methyl benzyl ether		31.7	.0721	.83	.89	.95	.96	.99	.98	1.04	1.01	1.00	1.01
14	Isopropyl benzyl ether		30.7	.0710	.95	.96	1.10	1.20	1.24	1.03	1.09	1.22	1.23	1.28
15	Phenyl methallyl ether		31.7	.0716	.48	.44	.38	.45	.54	.47	.44	.42	.52	.63
16	Methyl methallyl ether		27.2	.0714	.64	.66	.79	.81	.83	.71	.79	.84	.83	.84
17	Isopropyl methallyl ether		27.2	.0702	.77	.71	.85	.90	.92	.76	.77	.90	.93	.93
18	tert-Butyl methallyl ether		27.5	.0699	.68	.66	.81	.90	.97	.69	.77	.87	.95	1.01
19	Dimethallyl ether		28.1	.0704	.64	.58	.68	.78	.81	.63	.63	.74	.81	.83
20	Methyl cyclopropyl ether		27.4	.0724	.61	.57	.72	.82	.85	.65	.67	.82	.87	.88
21	Methyl cyclopentyl ether		29.4	.0711	.67	.61	.69	.75	.75	.67	.66	.76	.77	.75
22	Methyl cyclohexyl ether		29.7	.0706	.63	.55	.61	.67	.70	.62	.58	.66	.70	.72
23	Propylene oxide		28.5	.0742	.94	.87	1.01	1.12	1.15	1.06	1.05	1.18	1.17	1.17
1	Methyl tert-butyl ether	50	51.7	0.0750	2.22	1.44	1.85	2.08	2.34	1.81	2.11	2.14	2.43	[c]2.7
2	Ethyl tert-butyl ether		51.7	.0738	1.97	1.25	1.48	1.56	1.70	1.49	1.65	1.61	1.76	1.86
3	Isopropyl tert-butyl ether		51.7	.0730	[c]2.5	1.45	1.45	1.53	1.66	1.63	1.69	1.57	1.67	1.82
4	Anisole		58.9	.0796	.89	.63	.55	.92	1.21	.70	.68	1.06	1.52	2.18
5	Phenetole		58.2	.0778	.95	.65	.64	.96	1.21	.77	.75	1.05	1.53	1.97
6	p-Methylanisole		58.4	.0778	.94	.65	.56	.98	1.19	.77	.66	1.05	1.46	2.15

[a]All contain 4 ml TEL/gal.
[b]Average base-fuel imep values, lb/sq in., at five fuel-air ratios above: . . . 106 123 155 169 171
[c]Approximate value (extrapolated).

NACA

1244

TABLE V - FULL-SCALE-CYLINDER KNOCK DATA FOR LEADED ETHERS BLENDED WITH BASE FUEL CONSISTING OF 87.5-PERCENT S REFERENCE FUEL AND 12.5-PERCENT n-HEPTANE PLUS 4 ML TEL PER GALLON

[Compression ratio, 7.3; speed, 2000 rpm; cooling air adjusted at 140 BMEP and 0.10 fuel-air ratio to give rear spark-plug-bushing temperature of 365° F]

Ether in blend[a]				Blend stoichiometric fuel-air ratio	Imep ratio of blend to base fuel[b]									
					Base fuel and blend at same fuel-air ratio					Base fuel and blend at same percentage of stoichiometric mixture				
Number	Name	Percent by volume	Percent by weight		Fuel-air ratio of base fuel					Fuel-air ratio of base fuel				
					0.065	0.07	0.085	0.10	0.11	0.065	0.07	0.085	0.10	0.11
Inlet-air temperature, 210° F; spark advance, 20° B.T.C.; exhaust pressure, 29 ± 0.5 in. Hg abs.														
1	Methyl tert-butyl ether	10	10.6	0.0680	1.27	1.21	1.24	1.25	1.19	1.25	1.22	1.27	1.26	1.17
2	Ethyl tert-butyl ether		10.6	.0678	1.19	1.16	1.19	1.16	1.11	1.18	1.16	1.21	1.17	1.11
3	Isopropyl tert-butyl ether		10.6	.0676	1.17	1.16	1.15	1.15	1.14	1.16	1.16	1.18	1.17	1.13
4	Anisole		13.8	.0691	1.11	1.08	1.08	1.11	1.11	1.09	1.09	1.13	1.15	1.12
5	Phenetole		13.4	.0687	1.13	1.11	1.11	1.15	1.12	1.13	1.13	1.15	1.18	1.11
6	p-Methylanisole		13.5	.0687	1.20	1.16	1.15	1.17	1.19	1.17	1.18	1.20	1.21	1.20
Inlet-air temperature, 250° F; spark advance, 30° B.T.C.; exhaust pressure, 15 ± 0.2 in. Hg abs.														
1	Methyl tert-butyl ether	10	10.6	0.0680	1.16	1.15	1.17	1.19	1.20	1.16	1.17	1.19	1.21	1.20
2	Ethyl tert-butyl ether		10.6	.0678	1.16	1.13	1.14	1.12	1.13	1.15	1.15	1.16	1.13	1.14
3	Isopropyl tert-butyl ether		10.6	.0676	1.16	1.11	1.14	1.14	1.13	1.15	1.12	1.17	1.15	1.14
4	Anisole		13.8	.0691	1.09	1.04	1.05	1.07	1.10	1.08	1.07	1.08	1.10	1.10
5	Phenetole		13.4	.0687	1.07	1.07	1.11	1.12	1.15	1.08	1.10	1.15	1.14	1.16
6	p-Methylanisole		13.5	.0687	1.09	1.06	1.08	1.10	1.18	1.09	1.09	1.11	1.14	1.20

[a]All contain 4 ml TEL/gal.

[b]Average base-fuel imep values, lb/sq in., at five fuel-air ratios above:

Inlet-air temperature, 210° F	158	160	182	213	225
Inlet-air temperature, 250° F	138	144	166	187	192

TABLE VI - 17.6 ENGINE KNOCK DATA FOR LEADED ETHERS BLENDED WITH BASE FUEL CONSISTING OF 87.5-PERCENT S REFERENCE FUEL AND 12.5-PERCENT n-HEPTANE PLUS 4 ML TEL PER GALLON

[Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F]

Ether in blend[a]				Blend stoichiometric fuel-air ratio	Imep ratio of blend to base fuel[b]									
					Base fuel and blend at same fuel-air ratio					Base fuel and blend at same percentage of stoichiometric mixture				
					Fuel-air ratio of base fuel					Fuel-air ratio of base fuel				
Number	Name	Percent by volume	Percent by weight		0.065	0.07	0.085	0.10	0.11	0.065	0.07	0.085	0.10	0.11
Inlet-air temperature, 250° F														
1	Methyl tert-butyl ether	10	10.6	0.0680	1.14	1.14	1.15	1.15	1.13	1.14	1.14	1.17	1.15	1.13
2	Ethyl tert-butyl ether		10.6	.0678	1.11	1.12	1.13	1.13	1.13	1.11	1.13	1.14	1.13	1.12
3	Isopropyl tert-butyl ether		10.6	.0676	1.13	1.13	1.10	1.10	1.11	1.13	1.13	1.11	1.10	1.11
4	Anisole		13.8	.0691	1.11	1.11	1.12	1.15	1.16	1.11	1.13	1.15	1.15	1.15
5	Phenetole		13.4	.0687	1.15	1.14	1.11	1.12	1.15	1.15	1.15	1.12	1.12	1.15
6	p-Methylanisole		13.5	.0687	1.15	1.15	1.19	1.19	1.20	1.15	1.16	1.22	1.20	1.20
1	Methyl tert-butyl ether	25	26.3	0.0705	1.45	1.43	1.49	1.52	1.51	1.45	1.46	1.52	1.53	1.47
2	Ethyl tert-butyl ether		26.3	.0700	1.47	1.45	1.38	1.39	1.39	1.46	1.45	1.39	1.39	1.36
3	Isopropyl tert-butyl ether		26.3	.0696	1.33	1.33	1.31	1.31	1.31	1.33	1.34	1.32	1.31	1.30
4	Anisole		32.4	.0730	1.31	1.29	1.27	1.36	1.41	1.30	1.33	1.36	1.40	1.42
5	Phenetole		31.7	.0722	1.39	1.34	1.30	1.37	1.43	1.34	1.33	1.37	1.40	1.45
6	p-Methylanisole		31.8	.0722	1.38	1.33	1.37	1.44	1.52	1.34	1.36	1.45	1.51	1.59
1	Methyl tert-butyl ether	50	51.7	0.0750	2.07	1.84	2.28	2.46	2.44	2.00	2.21	2.50	2.45	2.33
2	Ethyl tert-butyl ether		51.7	.0738	1.99	1.88	1.76	1.90	2.01	1.88	1.87	1.86	2.00	1.98
3	Isopropyl tert-butyl ether		51.7	.0730	2.00	1.98	1.88	1.90	1.95	1.99	1.99	1.91	1.93	1.91
4	Anisole		58.9	.0796	1.71	1.50	1.41	1.74	2.07	1.46	1.55	1.89	2.25	2.51
5	Phenetole		58.2	.0778	1.77	1.64	1.52	1.99	2.22	1.59	1.62	2.04	2.30	2.53
6	p-Methylanisole		58.4	.0778	1.43	1.28	1.24	1.40	1.65	1.25	1.27	1.47	2.01	----

[a]All contain 4 ml TEL/gal.

[b]Average base-fuel imep values, lb/sq in., at five fuel-air ratios above:

Inlet-air temperature, 250° F	176	177	191	197	196
Inlet-air temperature, 100° F	213	211	214	213	211

TABLE VI - 17.6 ENGINE KNOCK DATA FOR LEADED ETHERS BLENDED WITH BASE FUEL CONSISTING OF 87.5-PERCENT S REFERENCE FUEL AND 12.5-PERCENT n-HEPTANE PLUS 4 ML TEL PER GALLON - Concluded

[Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F]

Ether in blend[a]				Blend stoichiometric fuel-air ratio	Imep ratio of blend to base fuel[b]									
					Base fuel and blend at same fuel-air ratio					Base fuel and blend at same percentage of stoichiometric mixture				
					Fuel-air ratio of base fuel					Fuel-air ratio of base fuel				
Number	Name	Percent by volume	Percent by weight		0.065	0.07	0.085	0.10	0.11	0.065	0.07	0.085	0.10	0.11
Inlet-air temperature, 100° F														
1	Methyl tert-butyl ether	10	10.6	0.0680	1.18	1.17	1.17	1.18	1.16	1.17	1.18	1.18	1.17	1.15
2	Ethyl tert-butyl ether		10.6	.0678	1.11	1.11	1.10	1.09	1.06	1.10	1.11	1.10	1.09	1.07
3	Isopropyl tert-butyl ether		10.6	.0676	1.11	1.11	1.11	1.10	1.11	1.11	1.11	1.11	1.10	1.11
4	Anisole		13.8	.0691	1.18	1.20	1.17	1.18	1.18	1.17	1.20	1.18	1.17	1.17
5	Phenetole		13.4	.0687	1.17	1.16	1.16	1.17	1.17	1.16	1.16	1.17	1.16	1.16
6	p-Methylanisole		13.5	.0687	1.18	1.15	1.18	1.19	1.20	1.17	1.16	1.18	1.19	1.19
1	Methyl tert-butyl ether	25	26.3	0.0705	1.51	1.50	1.50	1.53	1.51	1.49	1.49	1.52	1.51	1.48
2	Ethyl tert-butyl ether		26.3	.0700	1.44	1.43	1.41	1.36	1.32	1.42	1.42	1.40	1.35	1.30
3	Isopropyl tert-butyl ether		26.3	.0696	1.36	1.37	1.38	1.35	1.33	1.36	1.37	1.37	1.33	1.30
4	Anisole		32.4	.0730	1.46	1.48	1.45	1.50	1.54	1.42	1.45	1.47	1.50	1.52
5	Phenetole		31.7	.0722	1.57	1.55	1.54	1.55	1.56	1.53	1.53	1.55	1.54	1.53
6	p-Methylanisole		31.8	.0722	1.55	1.50	1.52	1.59	1.65	1.52	1.51	1.54	1.62	1.68
1	Methyl tert-butyl ether	50	51.7	0.0750	2.28	2.31	2.56	2.59	2.40	2.34	2.48	2.61	2.32	----
2	Ethyl tert-butyl ether		51.7	.0738	2.27	2.35	2.28	2.14	2.02	2.33	2.34	2.20	2.04	1.89
3	Isopropyl tert-butyl ether		51.7	.0730	2.14	2.16	2.10	2.00	1.98	2.14	2.16	2.04	1.96	1.95
4	Anisole		58.9	.0796	-----	----	-----	2.63	2.72	-----	----	2.59	2.74	----
5	Phenetole		58.2	.0778	-----	2.80	2.61	2.68	2.72	2.63	2.58	2.67	2.74	2.92
6	p-Methylanisole		58.4	.0778	-----	2.71	2.42	2.74	2.96	2.45	2.41	2.68	3.02	----

[a]All contain 4 ml TEL/gal.

[b]Average base-fuel imep values, lb/sq in., at five fuel-air ratios above:

Inlet-air temperature, 250° F	. . . .	176	177	191	197	196
Inlet-air temperature, 100° F	. . . .	213	211	214	213	211

NACA

TABLE VII - 17.6 ENGINE KNOCK DATA FOR UNLEADED ETHERS BLENDED WITH S REFERENCE FUEL

[Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F]

Ether in blend				Blend stoichiometric fuel-air ratio	Imep ratio of blend to base fuel[a]									
					Base fuel and blend at same fuel-air ratio					Base fuel and blend at same percentage of stoichiometric mixture				
					Fuel-air ratio of base fuel					Fuel-air ratio of base fuel				
Number	Name	Percent by volume	Percent by weight		0.065	0.07	0.085	0.10	0.11	0.065	0.07	0.085	0.10	0.11
					Inlet-air temperature, 250° F									
1	Methyl tert-butyl ether	10	10.6	0.0678	1.06	1.07	1.10	1.16	1.16	1.06	1.07	1.13	1.17	1.16
2	Ethyl tert-butyl ether		10.6	.0676	1.14	1.15	1.19	1.20	1.21	1.14	1.15	1.21	1.21	1.21
3	Isopropyl tert-butyl ether		10.6	.0674	1.11	1.11	1.12	1.15	1.14	1.11	1.11	1.13	1.15	1.14
4	Anisole		13.8	.0689	1.06	1.05	1.07	1.10	1.15	1.05	1.06	1.09	1.13	1.15
5	Phenetole		13.4	.0685	1.12	1.11	1.11	1.16	1.18	1.11	1.11	1.14	1.18	1.19
6	p-Methylanisole		13.5	.0685	1.12	1.09	1.12	1.18	1.21	1.10	1.09	1.15	1.20	1.22
1	Methyl tert-butyl ether	20	21.1	0.0695	1.15	1.14	1.20	1.34	1.38	1.13	1.14	1.26	1.38	1.39
2	Ethyl tert-butyl ether		21.1	.0691	1.24	1.25	1.28	1.37	1.45	1.23	1.25	1.32	1.41	1.45
3	Isopropyl tert-butyl ether		21.1	.0687	1.19	1.19	1.21	1.27	1.30	1.18	1.19	1.24	1.29	1.31
4	Anisole		26.4	.0715	1.13	1.10	1.09	1.20	1.32	1.10	1.11	1.18	1.30	1.37
5	Phenetole		25.8	.0708	1.27	1.24	1.17	1.31	1.40	1.23	1.21	1.25	1.39	1.43
6	p-Methylanisole		25.9	.0708	1.20	1.14	1.17	1.28	1.38	1.13	1.13	1.25	1.38	1.42
					Inlet-air temperature, 100° F									
1	Methyl tert-butyl ether	20	21.1	0.0695	1.26	1.28	1.35	1.37	1.35	1.23	1.27	1.38	1.37	1.34
2	Ethyl tert-butyl ether		21.1	.0691	1.33	1.32	1.31	1.35	1.37	1.31	1.32	1.32	1.35	1.36
3	Isopropyl tert-butyl ether		21.1	.0687	1.29	1.29	1.27	1.27	1.26	1.26	1.27	1.28	1.28	1.27
4	Anisole		26.4	.0715	1.28	1.27	1.26	1.31	1.34	1.24	1.26	1.29	1.33	1.34
5	Phenetole		25.8	.0708	1.40	1.37	1.33	1.41	1.41	1.35	1.33	1.38	1.42	1.40
6	p-Methylanisole		25.9	.0708	1.29	1.29	1.34	1.42	1.44	1.26	1.29	1.39	1.45	1.45

[a]Average imep in lb/sq in. of base fuel (S reference fuel) at five fuel-air ratios above:

Inlet-air temperature, 250° F	155	154	166	176	178
Inlet-air temperature, 100° F	188	182	185	188	189

NACA

TABLE VIII - 17.6 ENGINE KNOCK DATA FOR LEADED ETHERS BLENDED WITH S REFERENCE FUEL PLUS 4 ML TEL PER GALLON

[Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F]

Ether in blend[a]				Blend stoichiometric fuel-air ratio	Imep ratio of blend to base fuel[b]									
					Base fuel and blend at same fuel-air ratio					Base fuel and blend at same percentage of stoichiometric mixture				
					Fuel-air ratio of base fuel					Fuel-air ratio of base fuel				
Number	Name	Percent by volume	Percent by weight		0.065	0.07	0.085	0.10	0.11	0.065	0.07	0.085	0.10	0.11
Inlet-air temperature, 250° F														
1	Methyl tert-butyl ether	10	10.6	0.0680	1.14	1.15	1.19	1.21	1.22	1.14	1.16	1.20	1.21	1.21
2	Ethyl tert-butyl ether		10.6	.0678	1.15	1.13	1.12	1.15	1.15	1.15	1.13	1.13	1.15	1.15
3	Isopropyl tert-butyl ether		10.6	.0676	1.13	1.11	1.13	1.15	1.15	1.12	1.11	1.14	1.15	1.15
4	Anisole		13.8	.0691	1.07	1.07	1.07	1.13	1.16	1.06	1.07	1.10	1.15	1.17
5	Phenetole		13.4	.0687	1.11	1.09	1.15	1.18	1.18	1.09	1.09	1.17	1.18	1.17
6	p-Methylanisole		13.5	.0687	1.12	1.12	1.16	1.26	1.29	1.12	1.14	1.19	1.27	1.30
1	Methyl tert-butyl ether	20	21.1	0.0697	1.26	1.26	1.32	1.42	1.43	1.24	1.27	1.37	1.43	1.42
2	Ethyl tert-butyl ether		21.1	.0693	1.41	1.39	1.37	1.37	1.36	1.40	1.37	1.39	1.37	1.35
3	Isopropyl tert-butyl ether		21.1	.0689	1.32	1.27	1.24	1.27	1.27	1.31	1.27	1.25	1.27	1.27
4	Anisole		26.4	.0717	1.16	1.14	1.11	1.26	1.37	1.13	1.13	1.19	1.36	1.40
5	Phenetole		25.8	.0710	1.28	1.25	1.29	1.39	1.45	1.28	1.23	1.36	1.44	1.46
6	p-Methylanisole		25.9	.0710	1.16	1.17	1.25	1.36	1.43	1.17	1.21	1.32	1.41	1.48
Inlet-air temperature, 100° F														
1	Methyl tert-butyl ether	20	21.1	0.0697	1.41	1.43	1.45	1.47	1.46	1.41	1.43	1.47	1.46	1.43
2	Ethyl tert-butyl ether		21.1	.0693	1.41	1.42	1.40	1.37	1.33	1.40	1.41	1.41	1.35	1.30
3	Isopropyl tert-butyl ether		21.1	.0689	1.33	1.35	1.31	1.27	1.24	1.33	1.34	1.30	1.25	1.23
4	Anisole		26.4	.0717	1.34	1.33	1.33	1.39	1.40	1.30	1.32	1.36	1.39	1.39
5	Phenetole		25.8	.0710	1.44	1.43	1.43	1.44	1.45	1.41	1.43	1.44	1.43	1.44
6	p-Methylanisole		25.9	.0710	1.43	1.41	1.40	1.45	1.48	1.41	1.40	1.42	1.46	1.47

[a]All contain 4 ml TEL/gal.

[b]Average imep in lb/sq in. of base fuel (S + 4 ml TEL) at five fuel-air ratios above:

Inlet-air temperature, 250° F	244	244	260	268	268
Inlet-air temperature, 100° F	293	288	291	290	287

1244

TABLE IX - LEAD SUSCEPTIBILITY OF ETHER BLENDS RELATIVE TO S REFERENCE FUEL IN 17.6 ENGINE

[Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F; incipient knock]

Ether in blend		Relative lead susceptibility[a]									
		Base fuel and blend at same fuel-air ratio					Base fuel and blend at same percentage of stoichiometric mixture				
		Fuel-air ratio of base fuel					Fuel-air ratio of base fuel				
Number	Name	0.065	0.07	0.085	0.10	0.11	0.065	0.07	0.085	0.10	0.11
10-percent blends in S reference fuel; inlet-air temperature, 250° F											
1	Methyl *tert*-butyl ether	1.08	1.07	1.08	1.04	1.05	1.08	1.08	1.06	1.04	1.05
2	Ethyl *tert*-butyl ether	1.02	.98	.94	.96	.95	1.01	.98	.94	.95	.95
3	Isopropyl *tert*-butyl ether	1.01	1.00	1.01	1.00	1.01	1.01	1.00	1.00	1.00	1.00
4	Anisole	1.01	1.02	1.00	1.02	1.01	1.01	1.01	1.01	1.02	1.01
5	Phenetole	.99	.99	1.04	1.01	1.00	.98	.99	1.03	1.00	.99
6	*p*-Methylanisole	1.00	1.03	1.04	1.06	1.07	1.02	1.04	1.04	1.06	1.06
20-percent blends in S reference fuel; inlet-air temperature, 250° F											
1	Methyl *tert*-butyl ether	1.09	1.10	1.11	1.06	1.03	1.09	1.11	1.09	1.04	1.02
2	Ethyl *tert*-butyl ether	1.14	1.11	1.07	.99	.94	1.14	1.09	1.05	.97	.93
3	Isopropyl *tert*-butyl ether	1.11	1.07	1.02	1.01	.98	1.11	1.06	1.01	.99	.97
4	Anisole	1.03	1.04	1.02	1.05	1.04	1.02	1.02	1.01	1.04	1.02
5	Phenetole	1.01	1.01	1.11	1.07	1.04	1.04	1.01	1.09	1.04	1.03
6	*p*-Methylanisole	.97	1.03	1.06	1.07	1.04	1.04	1.07	1.06	1.02	1.04
20-percent blends in S reference fuel; inlet-air temperature, 100° F											
1	Methyl *tert*-butyl ether	1.13	1.11	1.08	1.07	1.08	1.15	1.13	1.06	1.07	1.07
2	Ethyl *tert*-butyl ether	1.06	1.07	1.07	1.01	.97	1.07	1.07	1.06	1.00	.96
3	Isopropyl *tert*-butyl ether	1.03	1.05	1.03	.99	.98	1.05	1.06	1.02	.98	.97
4	Anisole	1.04	1.04	1.05	1.06	1.05	1.05	1.05	1.05	1.04	1.03
5	Phenetole	1.03	1.04	1.08	1.02	1.02	1.05	1.08	1.04	1.01	1.02
6	*p*-Methylanisole	1.11	1.10	1.05	1.02	1.03	1.12	1.08	1.02	1.00	1.02

[a]Relative lead susceptibility = $\dfrac{\dfrac{\text{imep of blend (leaded to 4 ml TEL/gal)}}{\text{imep of blend (unleaded)}}}{\dfrac{\text{imep of S (leaded to 4 ml TEL/gal)}}{\text{imep of S (unleaded)}}}$

NACA

1244

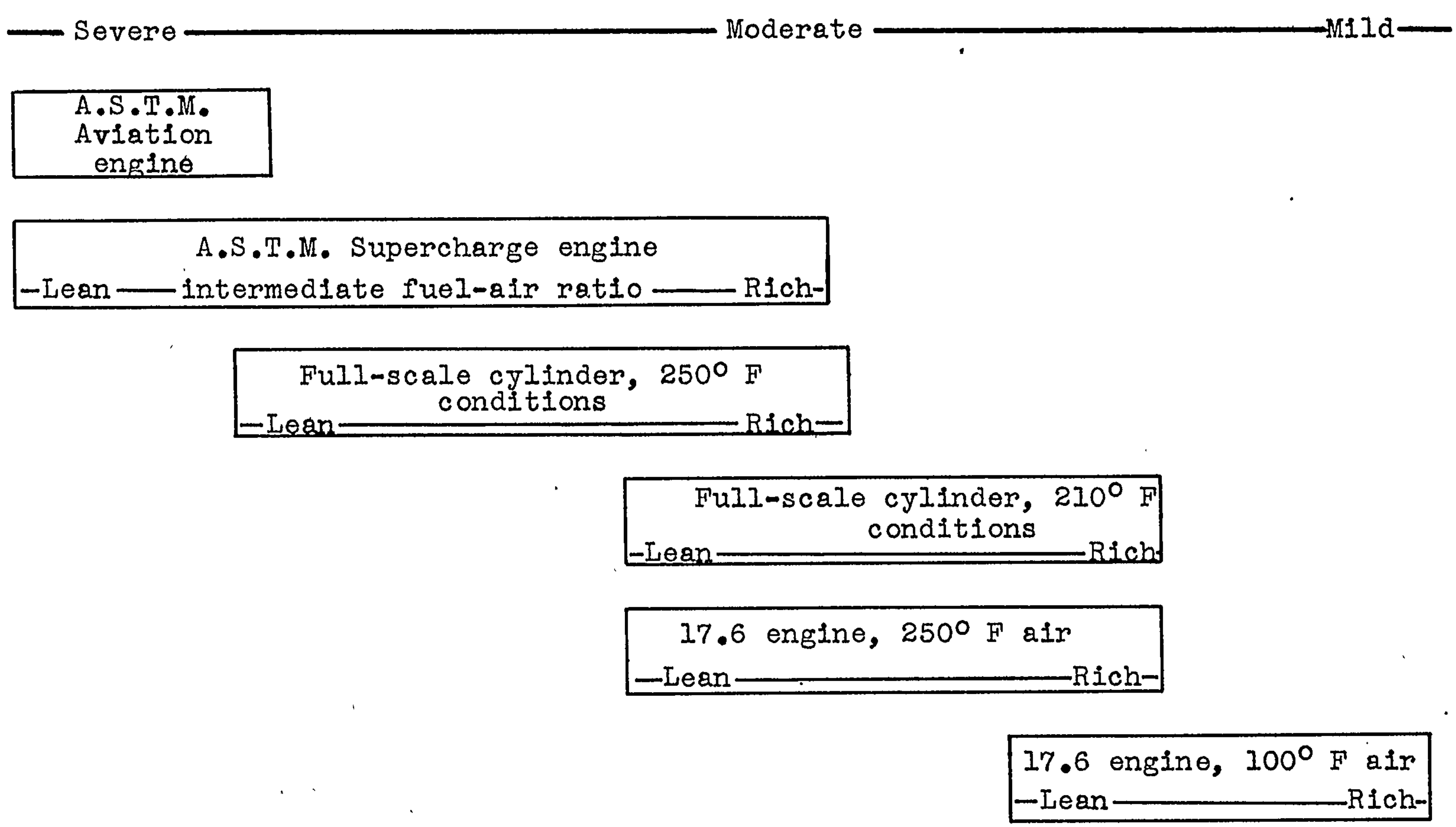
TABLE X - INLET-AIR-TEMPERATURE SENSITIVITY OF ETHER BLENDS RELATIVE TO BASE FUEL IN 17.6 ENGINE

[Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F; incipient knock]

Ether in blend		Relative temperature sensitivity[a]									
		Base fuel and blend at same fuel-air ratio					Base fuel and blend at same percentage of stoichiometric mixture				
Number	Name	Fuel-air ratio of base fuel					Fuel-air ratio of base fuel				
		0.065	0.07	0.085	0.10	0.11	0.065	0.07	0.085	0.10	0.11
	Leaded 10-percent blends in mixed base fuel										
1	Methyl *tert*-butyl ether	1.03	1.03	1.01	1.02	1.02	1.03	1.03	1.01	1.02	1.02
2	Ethyl *tert*-butyl ether	1.00	.99	.97	.97	.94	.99	.98	.97	.96	.95
3	Isopropyl *tert*-butyl ether	.98	.98	1.01	1.00	1.00	.98	.98	1.00	1.00	1.00
4	Anisole	1.05	1.08	1.04	1.03	1.02	1.05	1.06	1.02	1.02	1.02
5	Phenetole	1.02	1.02	1.05	1.04	1.02	1.01	1.01	1.04	1.03	1.01
6	*p*-Methylanisole	1.02	1.00	.99	1.00	1.00	1.02	1.00	.97	.99	.99
	Leaded 25-percent blends in mixed base fuel										
1	Methyl *tert*-butyl ether	1.04	1.05	1.01	1.00	1.00	1.03	1.02	1.00	0.99	1.01
2	Ethyl *tert*-butyl ether	.98	.99	1.02	.98	.95	.97	.98	1.00	.97	.96
3	Isopropyl *tert*-butyl ether	1.03	1.03	1.05	1.03	1.01	1.02	1.03	1.04	1.02	1.00
4	Anisole	1.12	1.14	1.14	1.10	1.09	1.09	1.09	1.09	1.07	1.07
5	Phenetole	1.13	1.16	1.18	1.13	1.09	1.14	1.15	1.13	1.10	1.06
6	*p*-Methylanisole	1.12	1.13	1.11	1.10	1.08	1.14	1.11	1.06	1.07	1.05
	Leaded 50-percent blends in mixed base fuel										
1	Methyl *tert*-butyl ether	1.10	1.26	1.12	1.05	0.98	1.17	1.12	1.04	0.95	-----
2	Ethyl *tert*-butyl ether	1.14	1.25	1.29	1.12	1.00	1.24	1.25	1.18	1.02	0.95
3	Isopropyl *tert*-butyl ether	1.07	1.09	1.12	1.05	1.02	1.08	1.08	1.07	1.02	1.02
4	Anisole	-----	----	-----	1.51	1.31	-----	----	1.37	1.22	-----
5	Phenetole	-----	1.71	1.71	1.35	1.22	1.65	1.59	1.31	1.19	1.15
6	*p*-Methylanisole	-----	2.11	1.95	1.95	1.79	1.96	1.89	1.83	1.50	-----
	Unleaded 20-percent blends in S reference fuel										
1	Methyl *tert*-butyl ether	1.09	1.12	1.13	1.03	0.98	1.08	1.11	1.10	0.99	0.96
2	Ethyl *tert*-butyl ether	1.07	1.06	1.02	.98	.94	1.07	1.05	1.00	.96	.94
3	Isopropyl *tert*-butyl ether	1.08	1.08	1.05	1.01	.97	1.07	1.06	1.03	.99	.97
4	Anisole	1.14	1.16	1.15	1.09	1.01	1.12	1.14	1.10	1.02	.98
5	Phenetole	1.09	1.11	1.14	1.08	1.01	1.10	1.10	1.11	1.03	.98
6	*p*-Methylanisole	1.07	1.13	1.14	1.11	1.04	1.11	1.14	1.12	1.06	1.02
	Leaded 20-percent blends in S reference fuel										
1	Methyl *tert*-butyl ether	1.12	1.14	1.10	1.03	1.02	1.13	1.12	1.07	1.02	1.01
2	Ethyl *tert*-butyl ether	1.00	1.02	1.02	1.00	.98	1.00	1.03	1.01	.99	.97
3	Isopropyl *tert*-butyl ether	1.01	1.06	1.06	.99	.97	1.02	1.06	1.04	.98	.97
4	Anisole	1.15	1.16	1.19	1.10	1.03	1.16	1.17	1.14	1.02	.99
5	Phenetole	1.13	1.15	1.11	1.03	1.00	1.10	1.17	1.05	1.00	.98
6	*p*-Methylanisole	1.23	1.21	1.12	1.07	1.03	1.20	1.15	1.08	1.03	1.00

[a]Relative temperature sensitivity = $$\frac{\dfrac{\text{imep of blend (inlet-air temperature, 100° F)}}{\text{imep of blend (inlet-air temperature, 250° F)}}}{\dfrac{\text{imep of base fuel (inlet-air temperature, 100° F)}}{\text{imep of base fuel (inlet-air temperature, 250° F)}}}$$

NACA



Lean - fuel-air ratio for lean minimum of mixture-response curve or slightly richer; usually near stoichiometric fuel-air ratio, or about 0.07

Rich - fuel-air ratio for rich peak (if any) of mixture-response curve or slightly leaner; often approximately 1.5 x stoichiometric fuel-air ratio, or about 0.10

Figure 1. - Comparison of engine conditions.

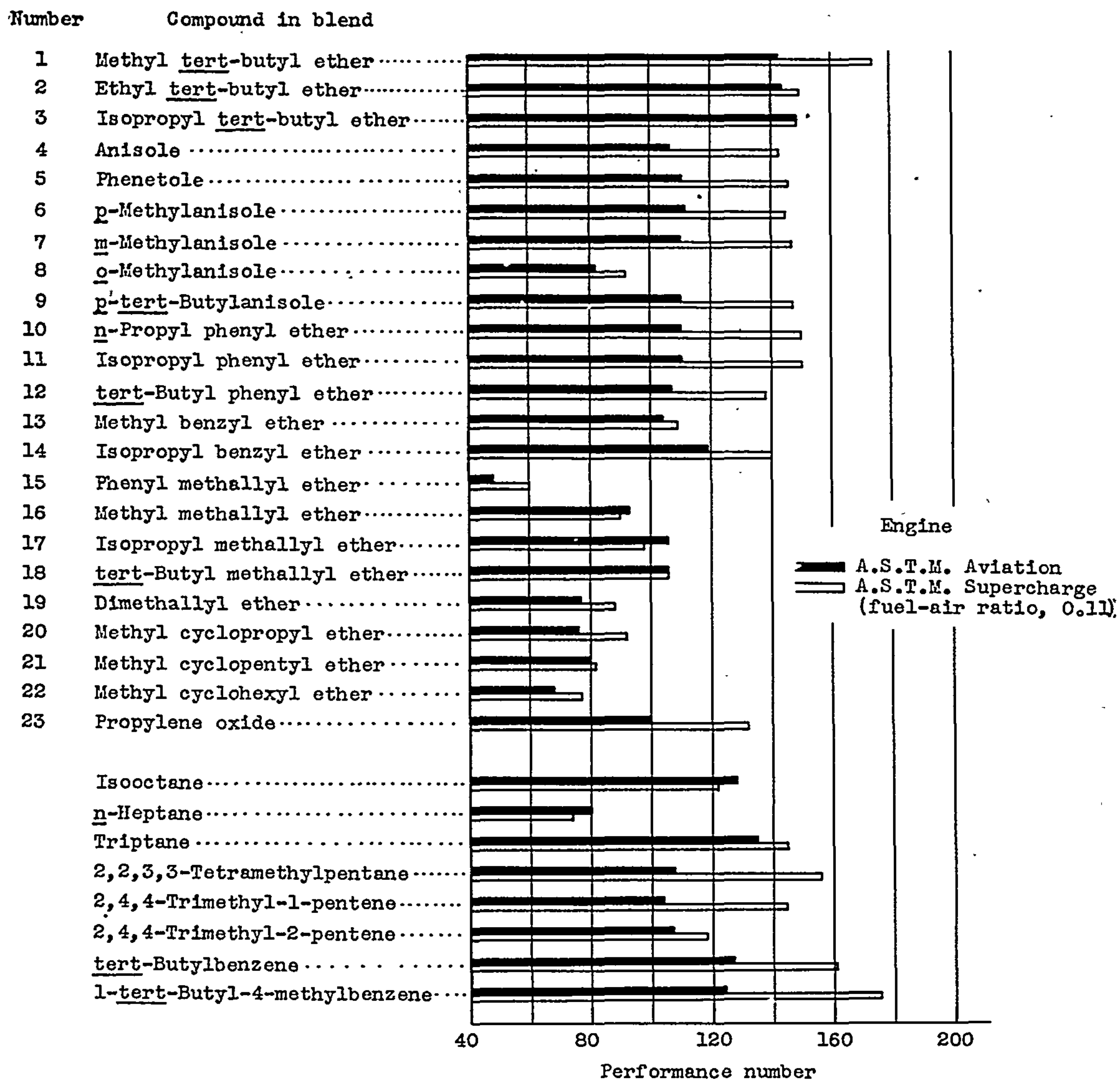


Figure 2. - Performance numbers in A.S.T.M. Aviation and Supercharge engines for 25-percent blends with a 120/110 base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane. All fuels leaded to 4 ml TEL per gallon.

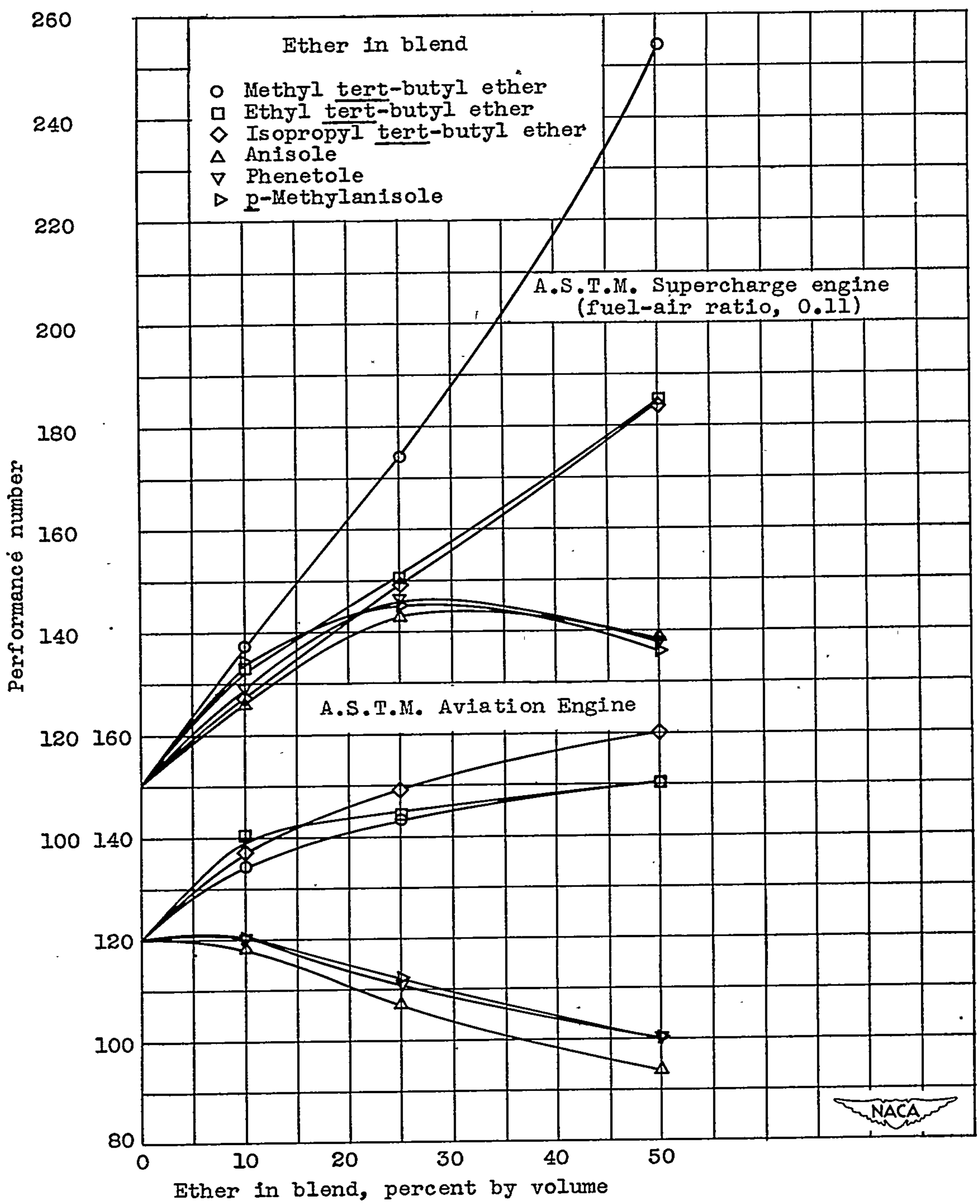
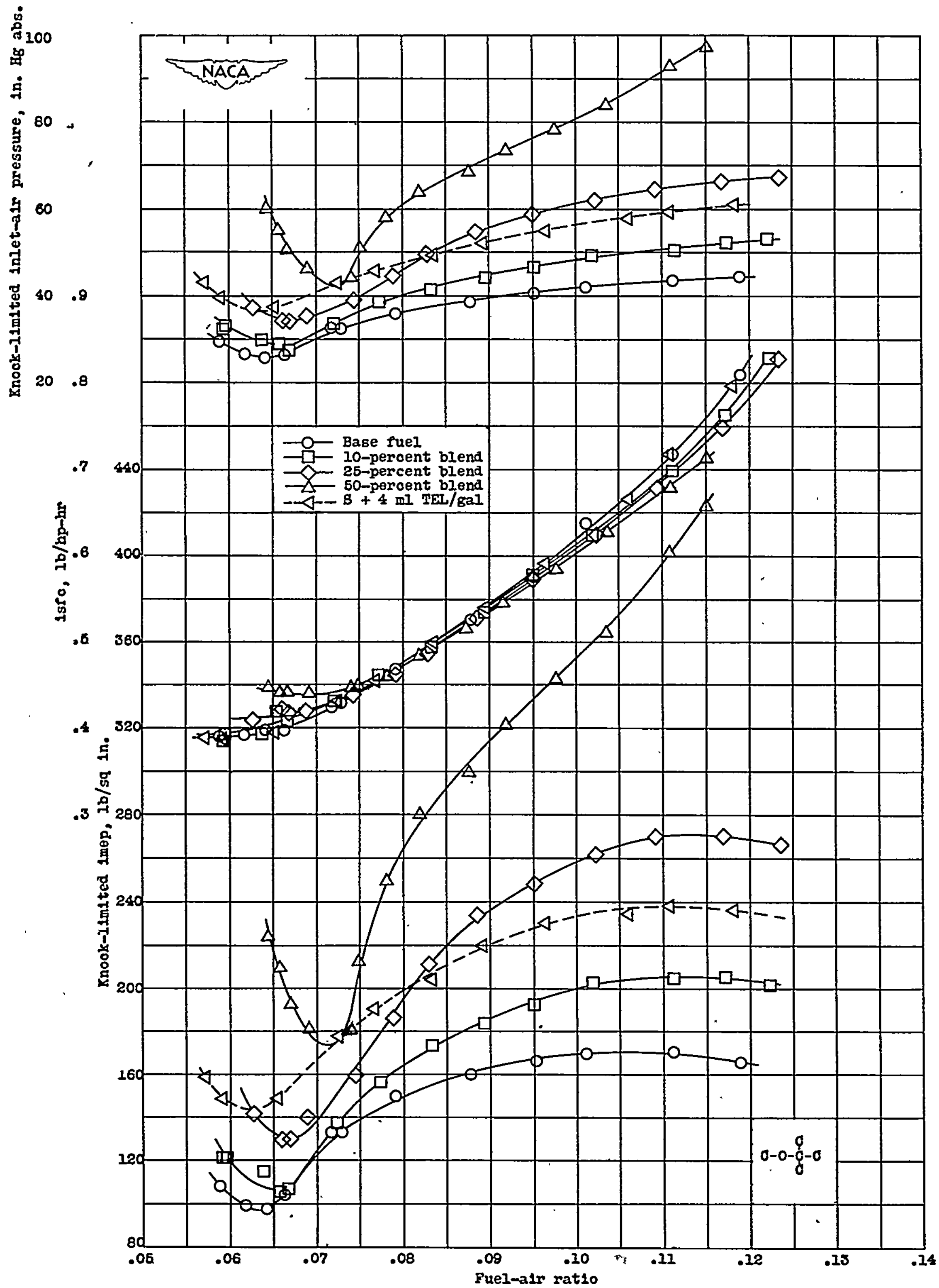
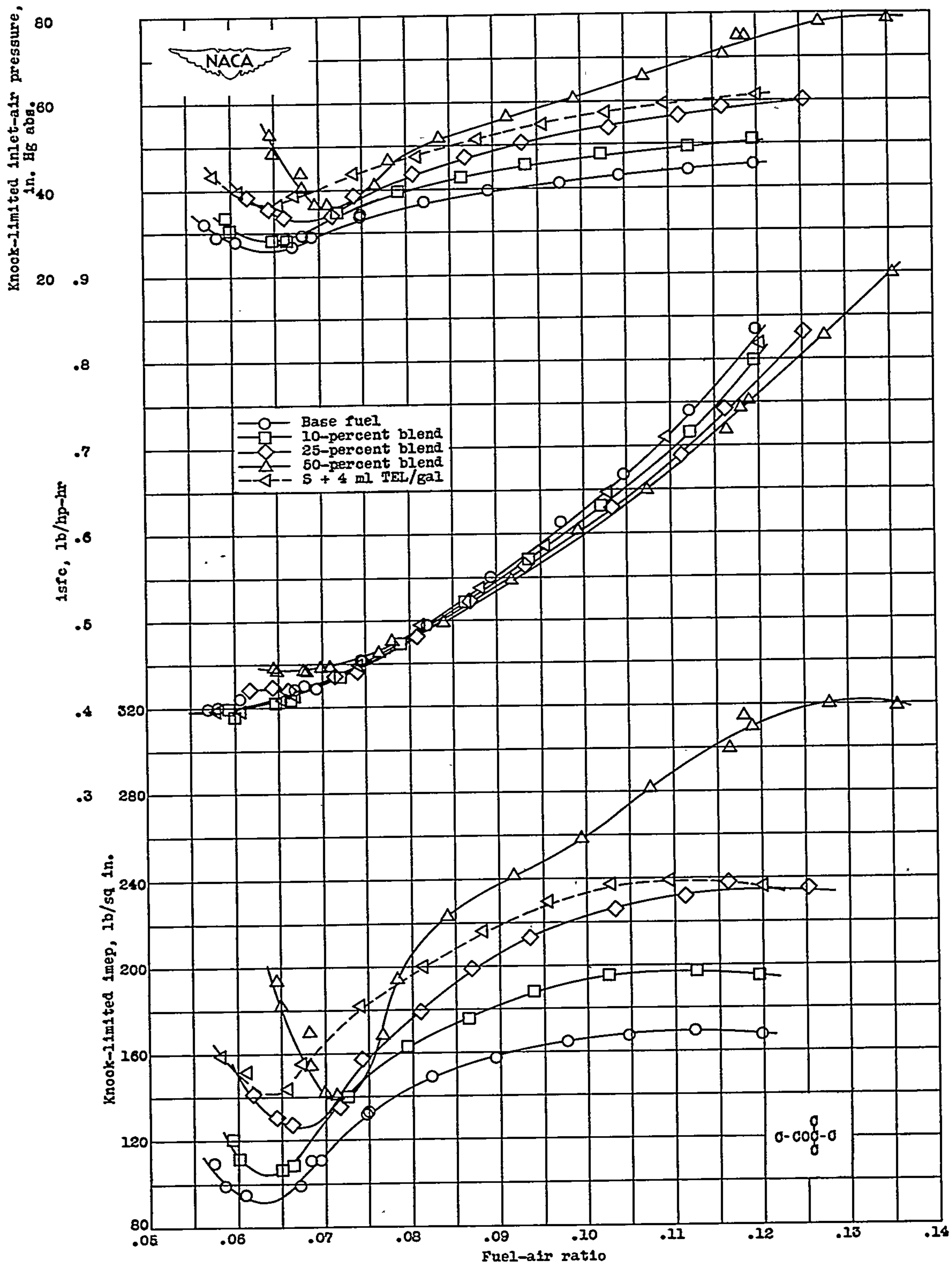


Figure 3. - Blending characteristics in A.S.T.M. Aviation and A.S.T.M. Supercharge engines for six ethers in leaded blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.



(a) Methyl tert-butyl ether.

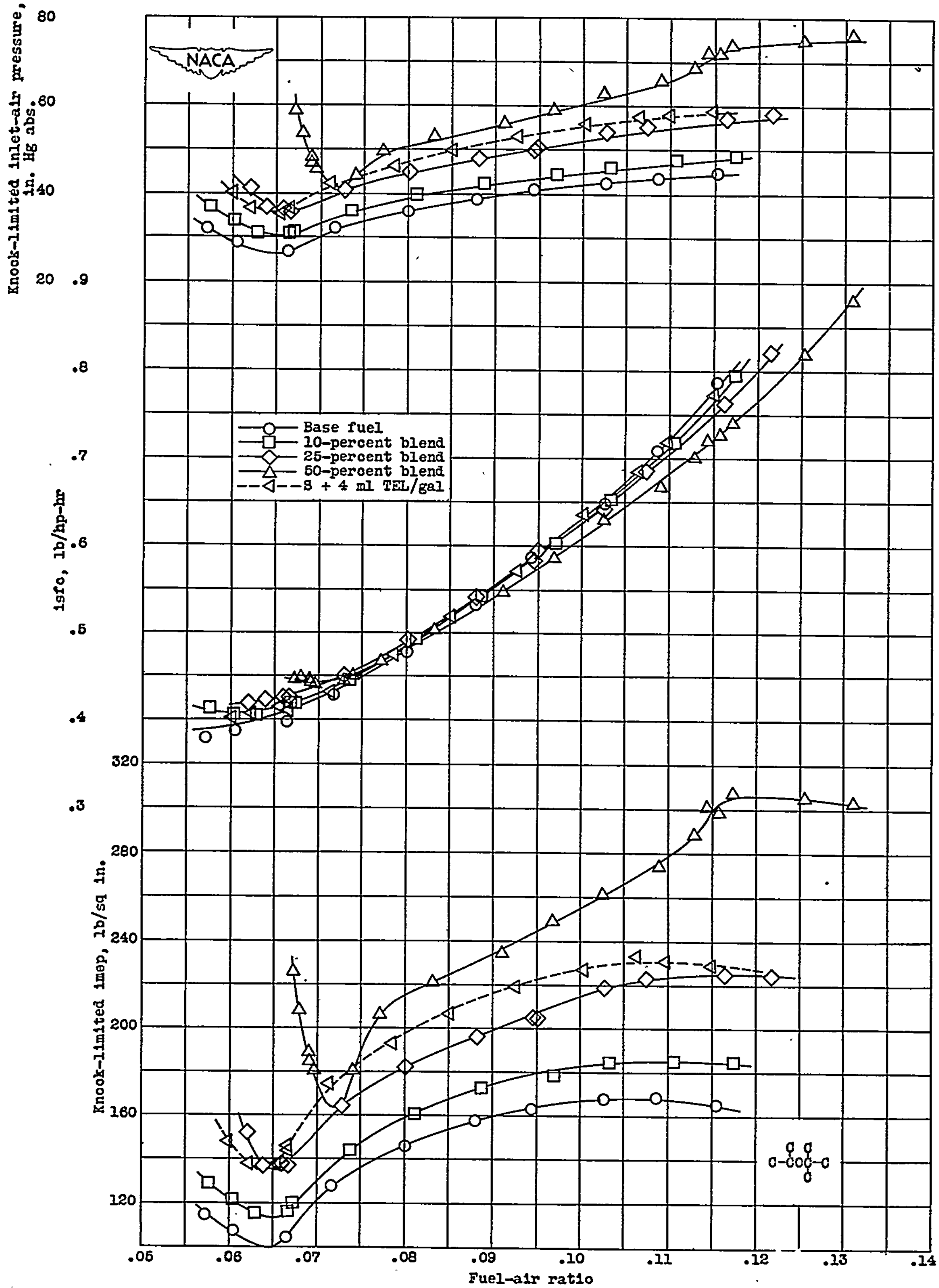
Figure 4. - Fuel-air mixture response in A.S.T.M. Supercharge engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.



(b) Ethyl *tert*-butyl ether.

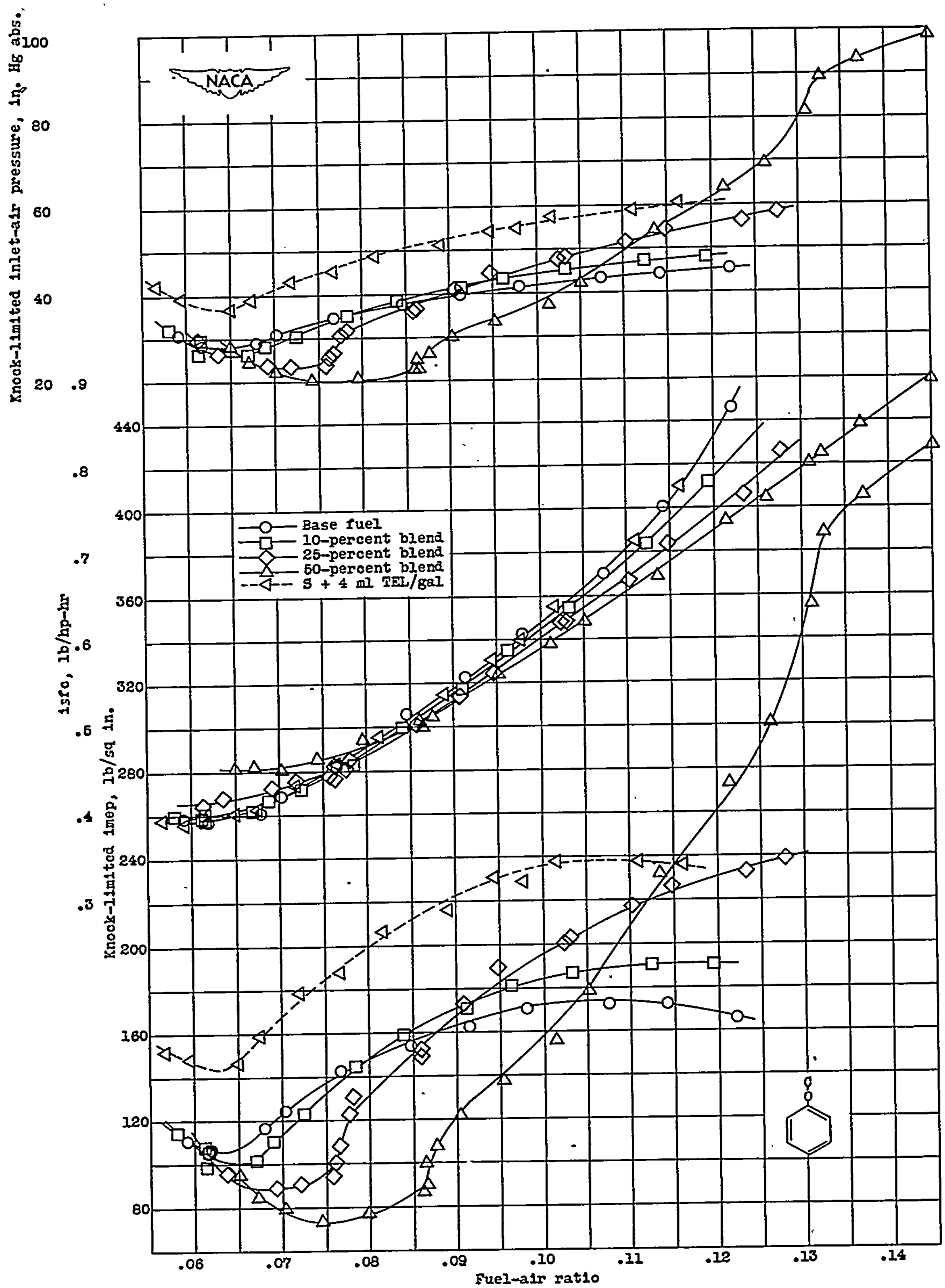
Figure 4. - Continued. Fuel-air mixture response in A.S.T.M. Supercharge engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent *n*-heptane plus 4 ml TEL per gallon.

1244



(c) Isopropyl tert-butyl ether.

Figure 4. - Continued. Fuel-air mixture response in A.S.T.M. Supercharge engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.

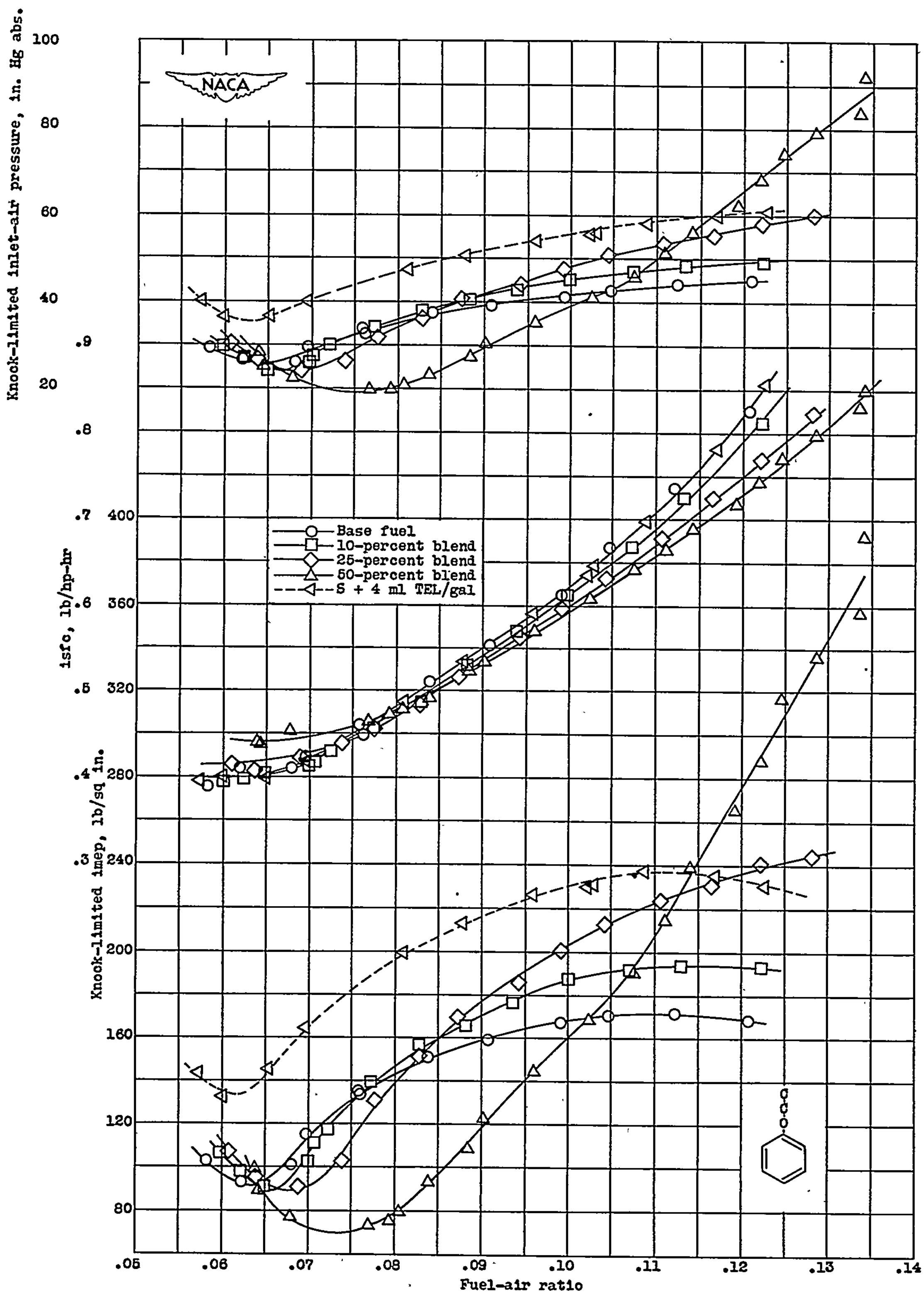


(d) Anisole.

Figure 4. - Continued. Fuel-air mixture response in A.S.T.M. Supercharge engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.

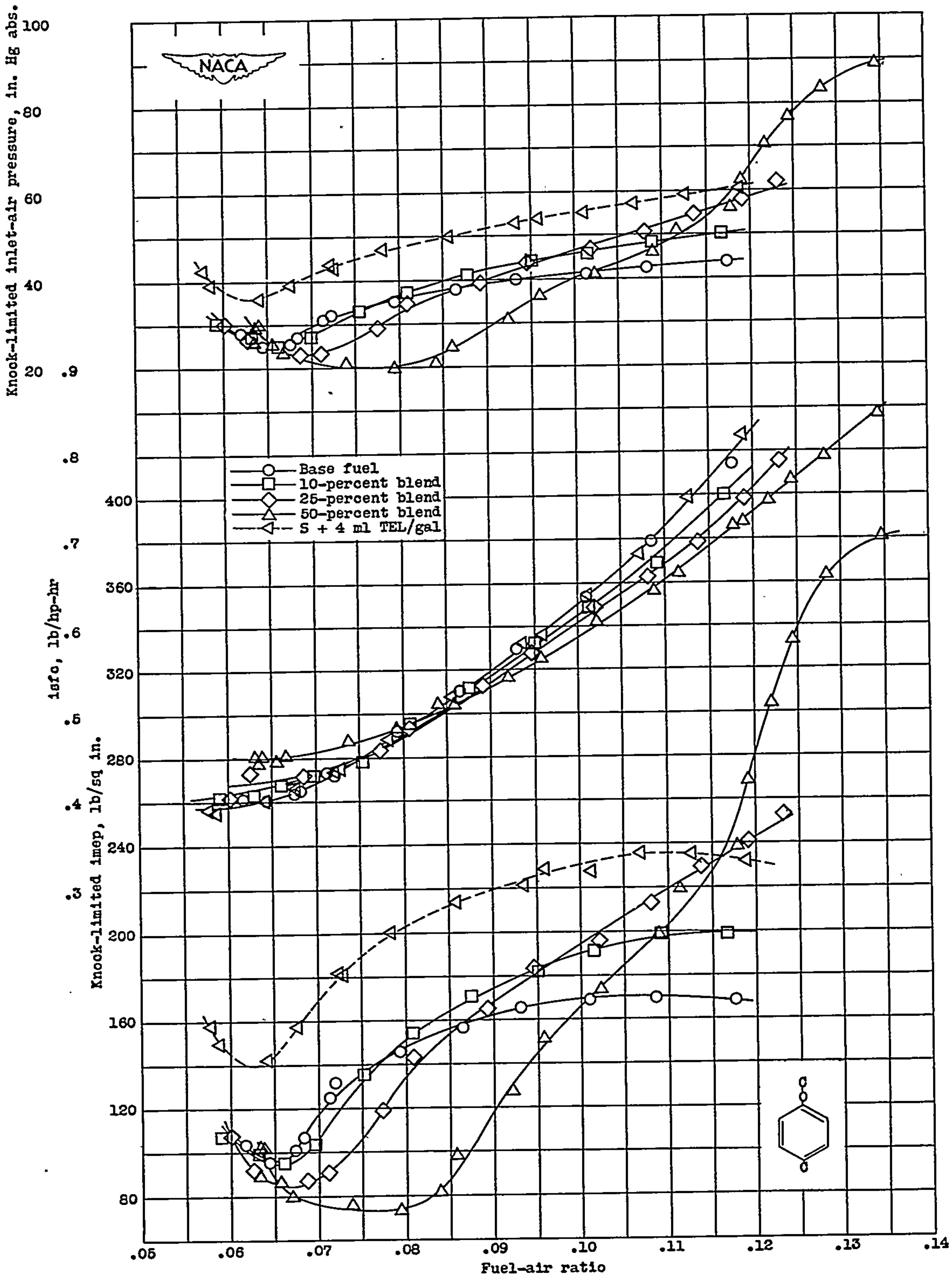
1244

1244



(e) Phenetole.

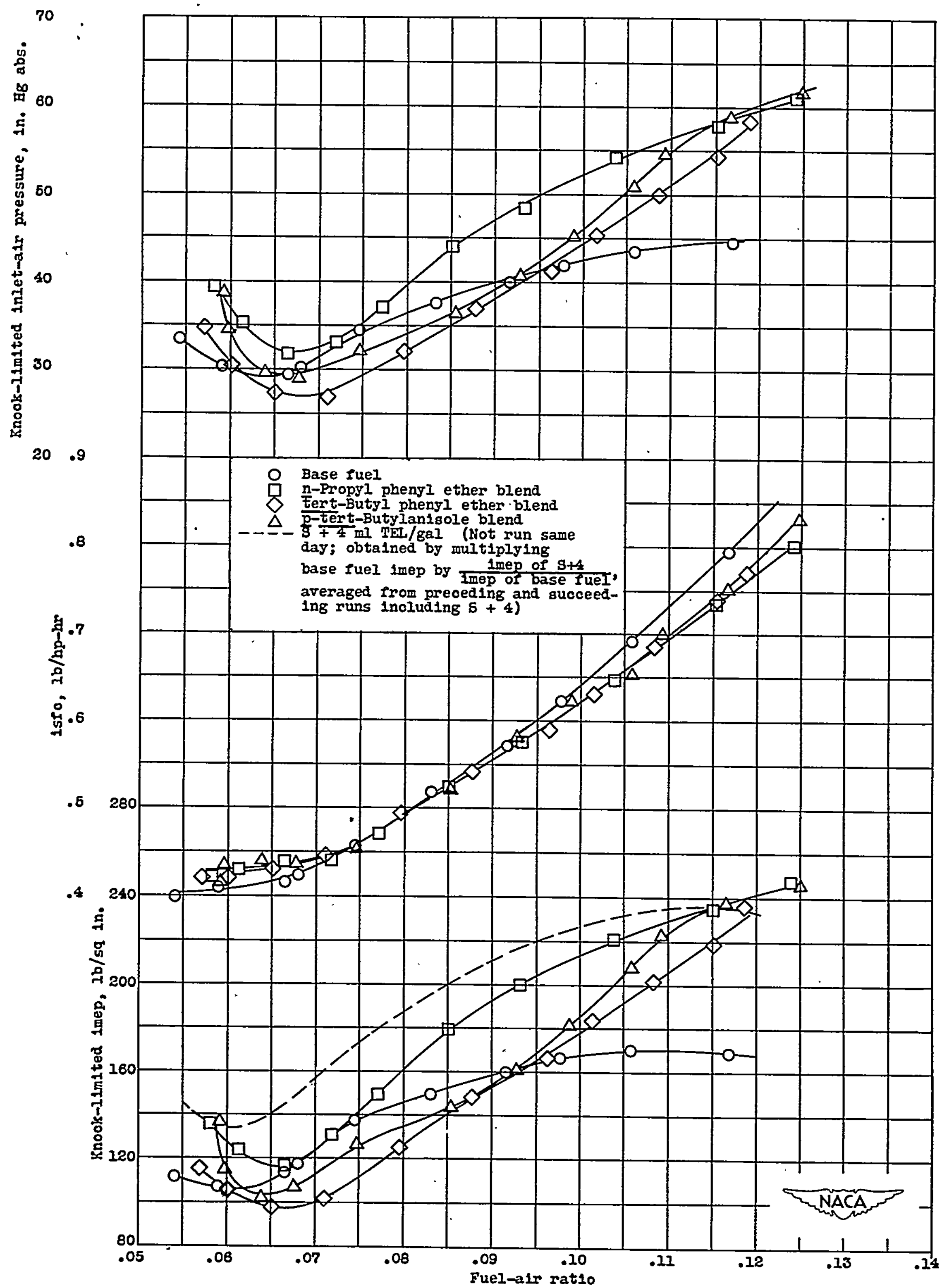
Figure 4. - Continued. Fuel-air mixture response in A.S.T.M. Supercharge engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.



(f) p-Methylanisole.

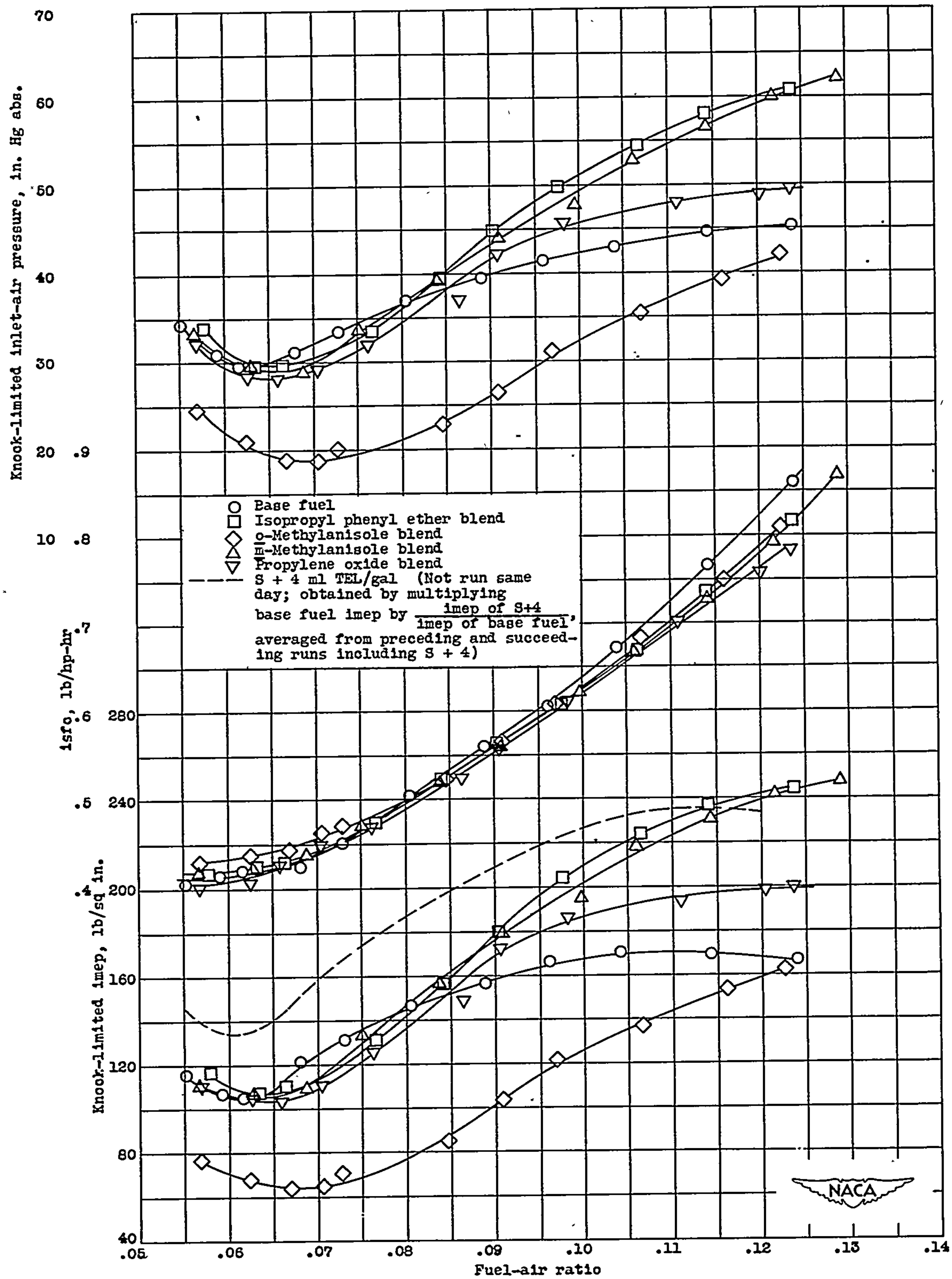
Figure 4. - Concluded. Fuel-air mixture response in A.S.T.M. Supercharge engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.

1244



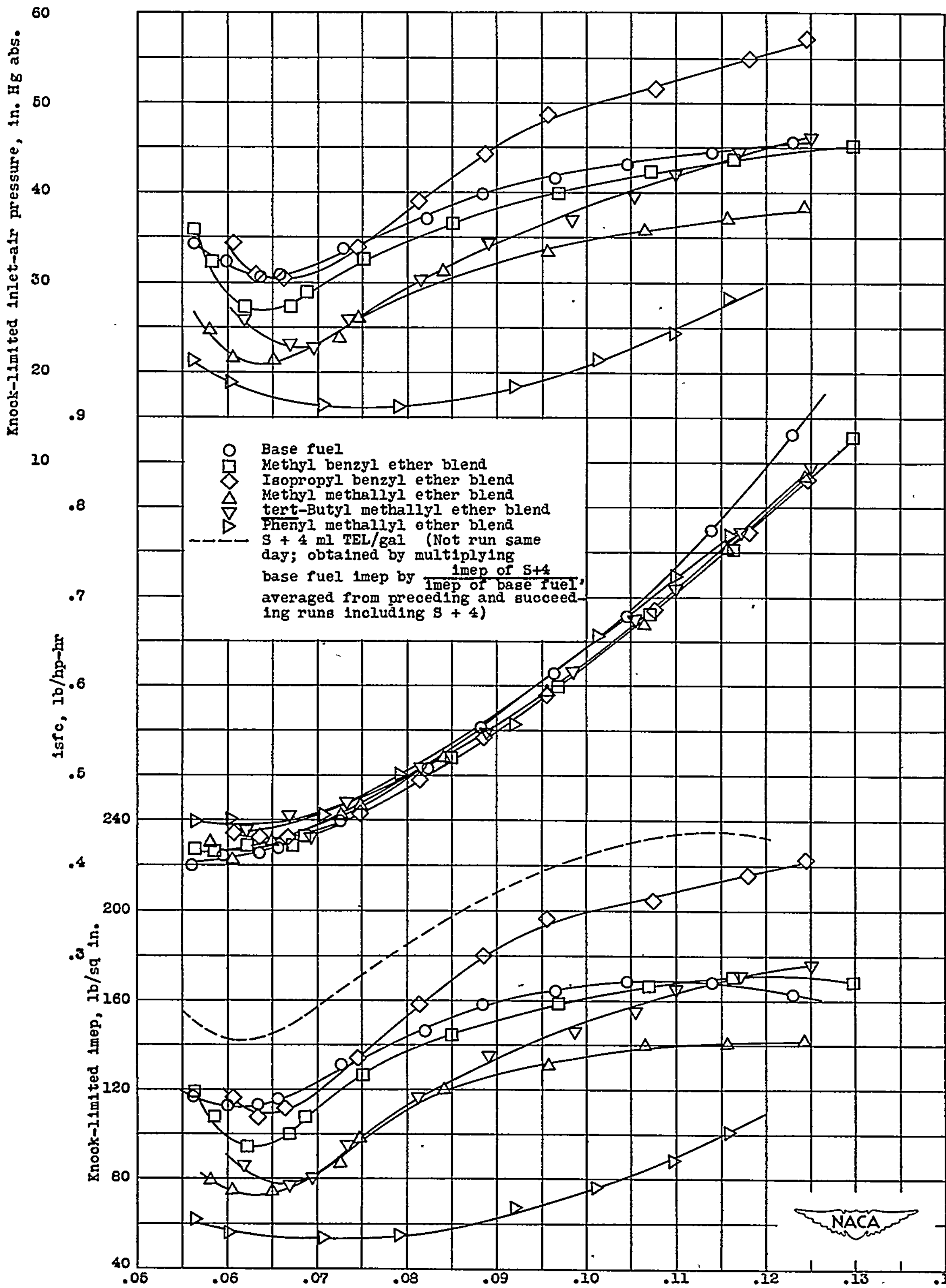
(a) Three ethers.

Figure 5. - Fuel-air mixture response in A.S.T.M. Supercharge engine for 17 ethers in leaded 25-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.



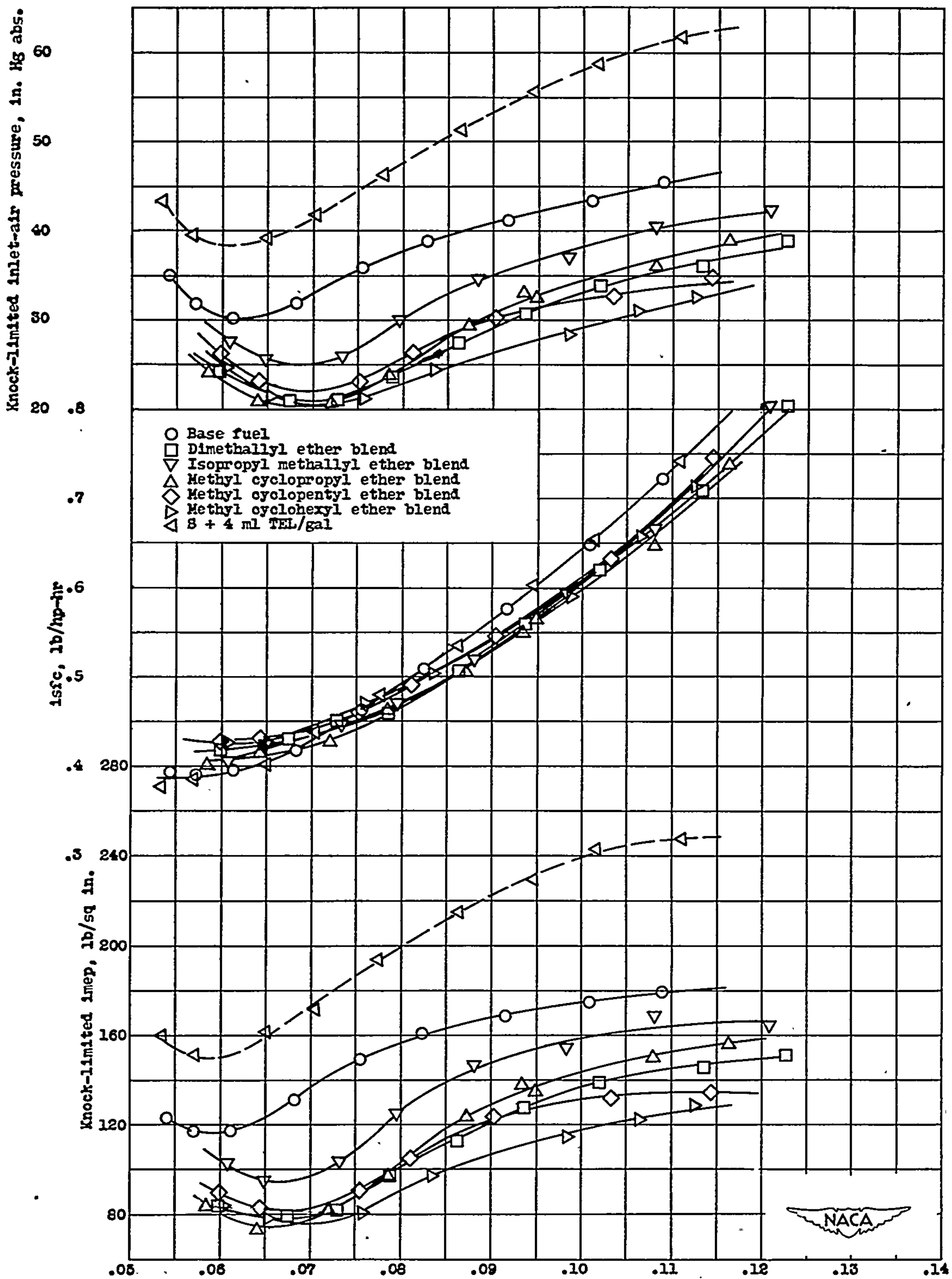
(b) Four ethers.

Figure 5. - Continued. Fuel-air mixture response in A.S.T.M. Supercharge engine for 17 ethers in leaded 25-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.



(c) Five ethers.

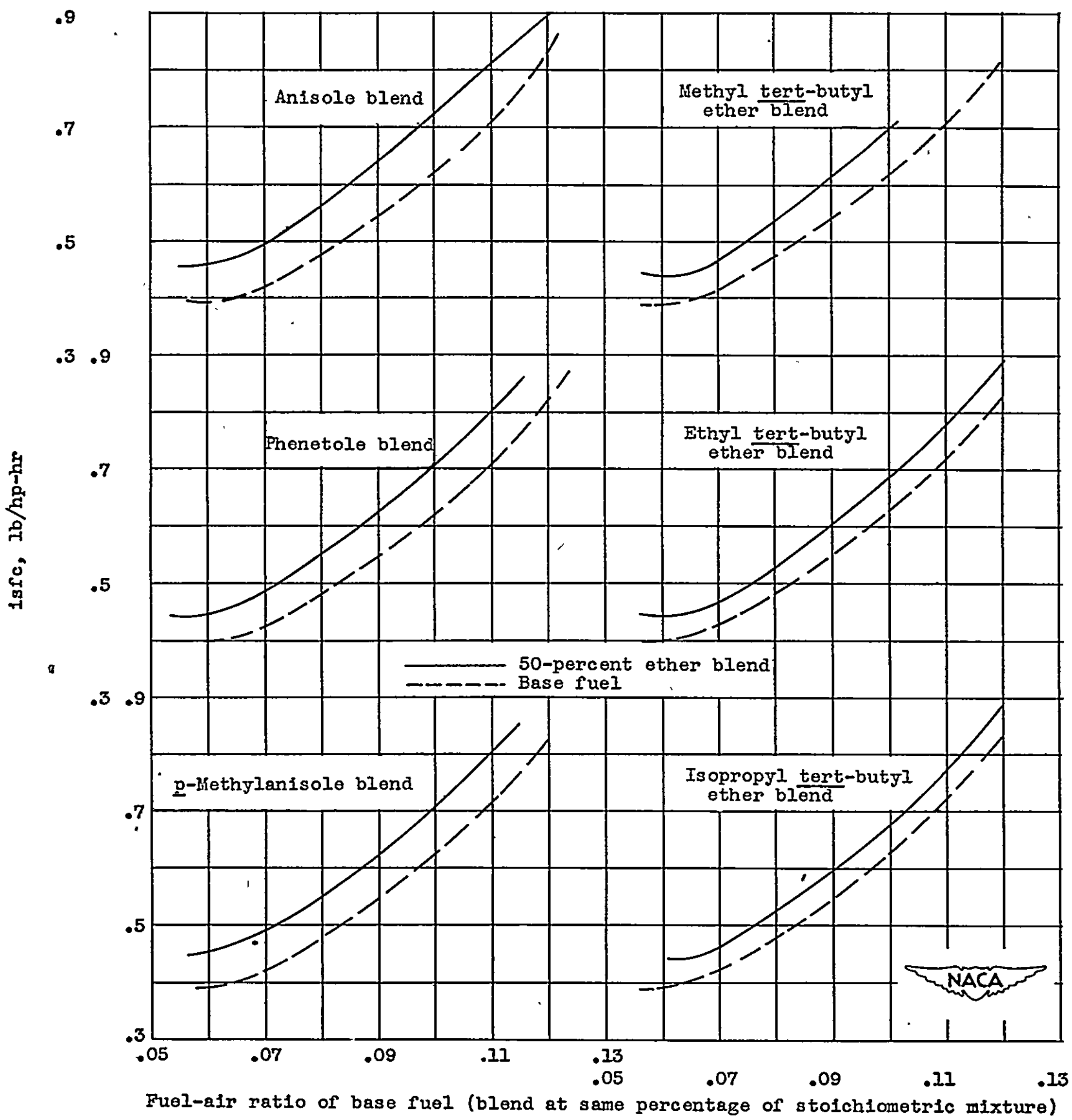
Figure 5. - Continued. Fuel-air mixture response in A.S.T.M. Supercharge engine for 17 ethers in leaded 25-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.



(d) Five ethers.

Figure 5. - Concluded. Fuel-air mixture response in A.S.T.M. Supercharge engine for 17 ethers in leaded 25-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.

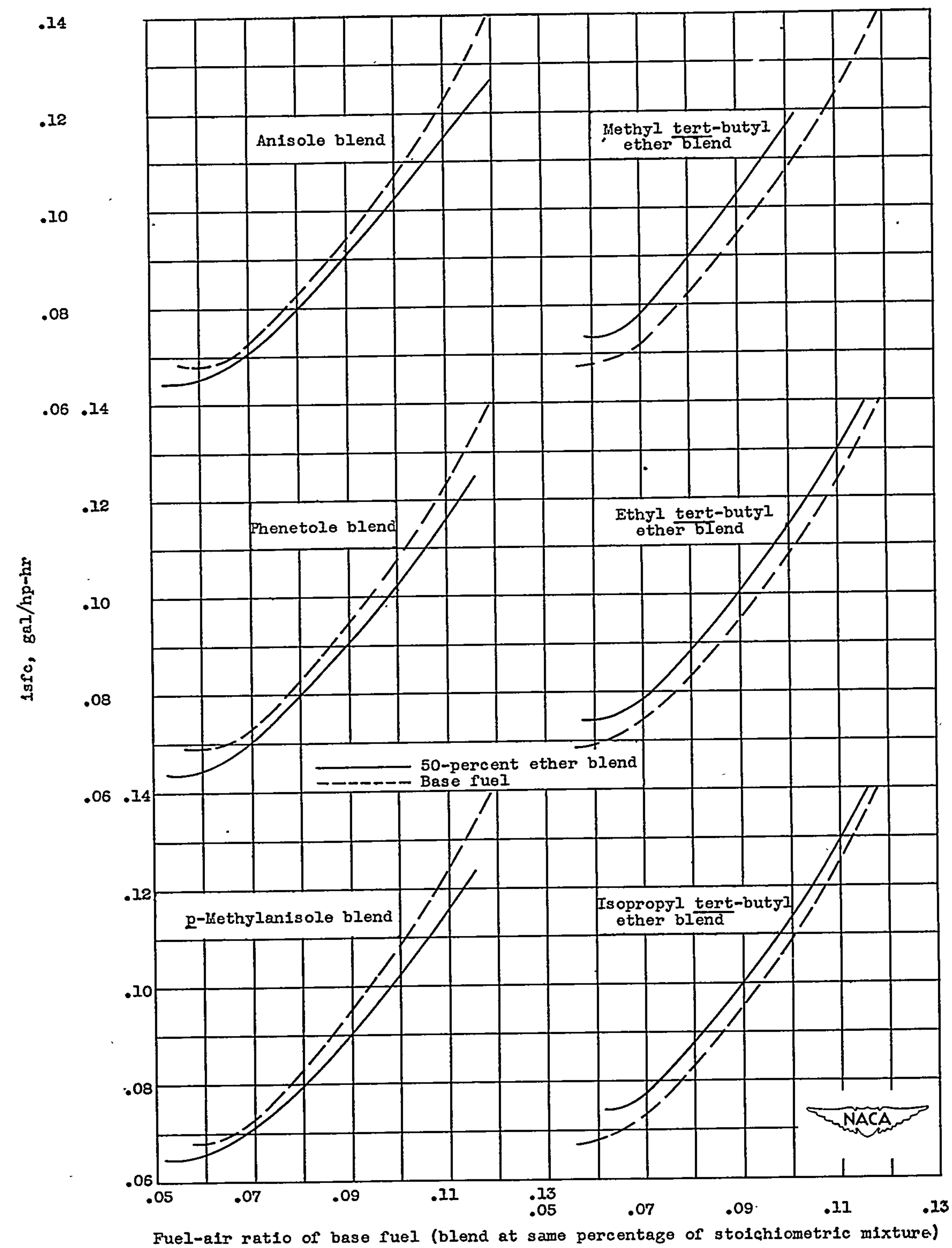
1244



(a) Pound per horsepower-hour.

Figure 6. - Indicated specific fuel consumption compared at same percentage of stoichiometric fuel-air mixture for base fuel and blend in A.S.T.M. Supercharge engine for first six ethers in leaded 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.

1244



(b) Gallon per horsepower-hour.

Figure 6. - Concluded. Indicated specific fuel consumption compared at same percentage of stoichiometric fuel-air mixture for base fuel and blend in A.S.T.M. Supercharge engine for first six ethers in leaded 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.

1244

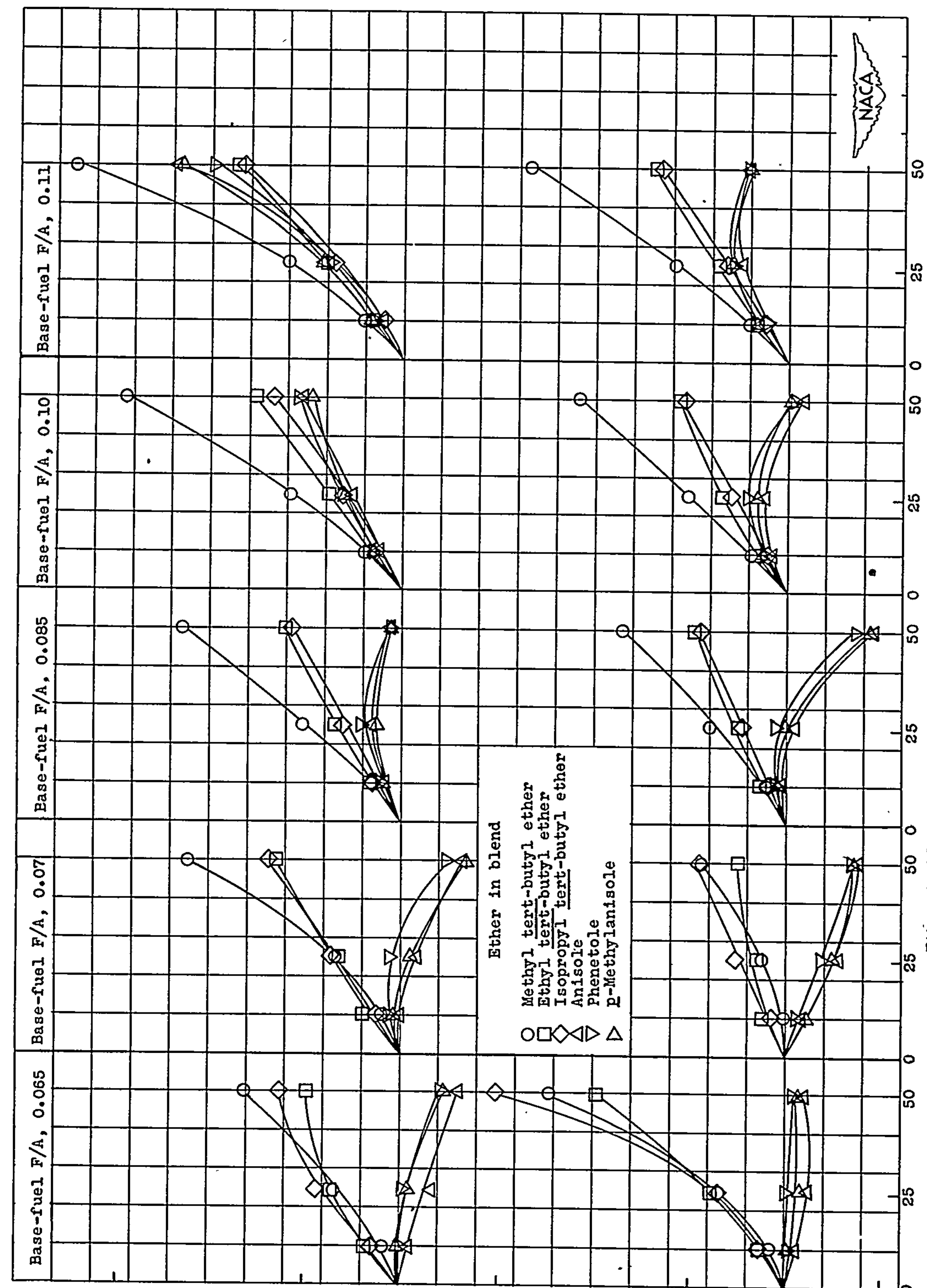
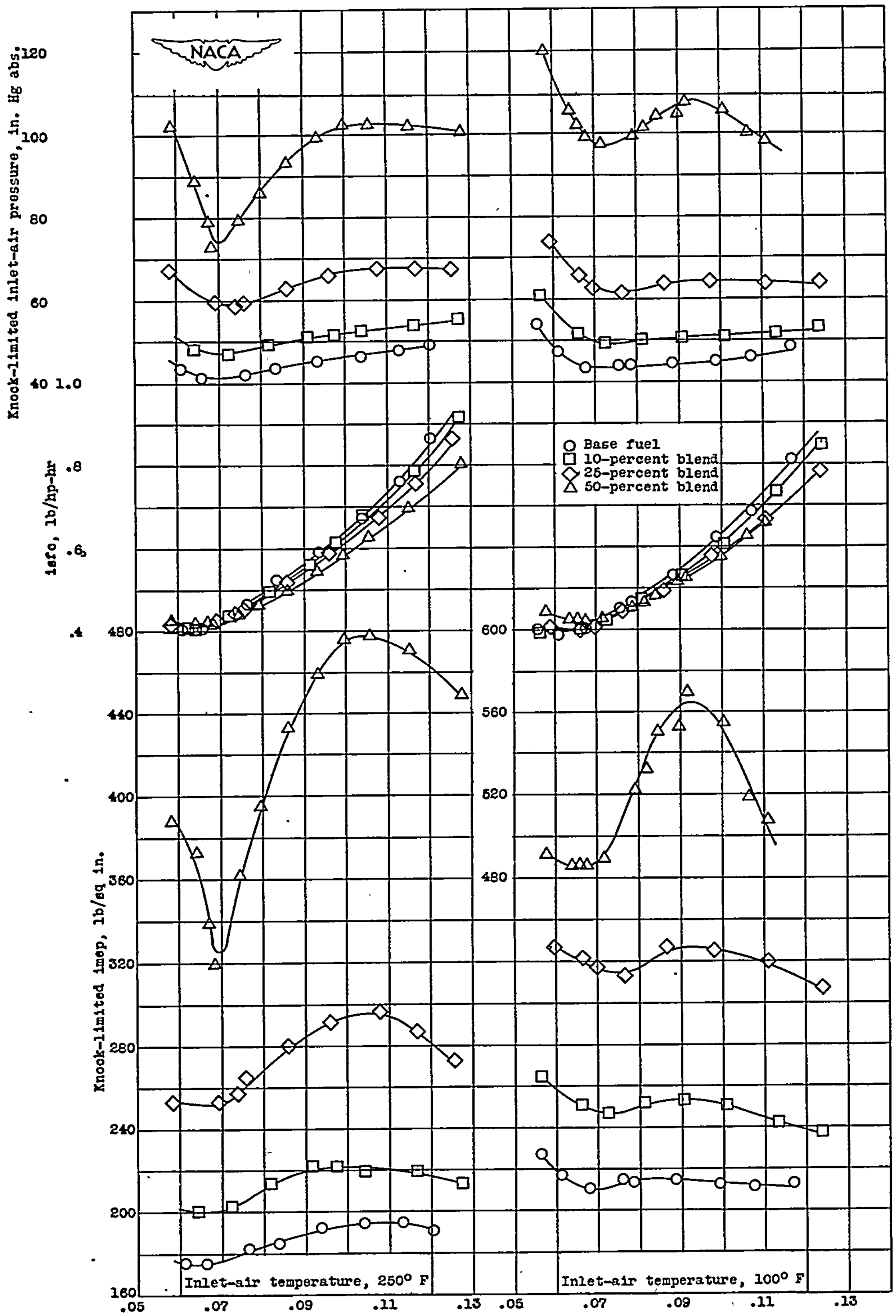


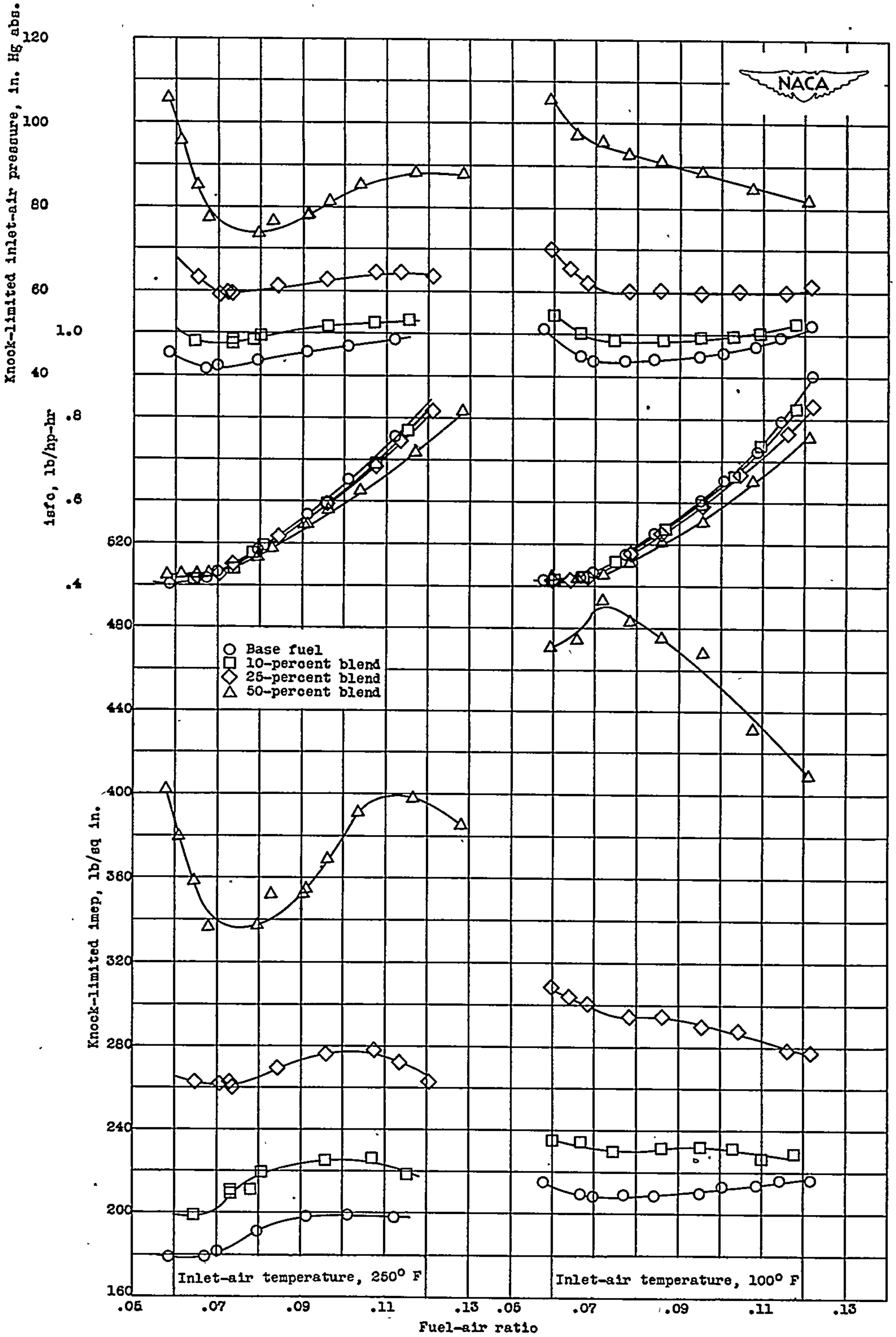
Figure 7. - Blending characteristics in A.S.T.M.-Supercharge engine for first six ethers in leaded blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon.

1244



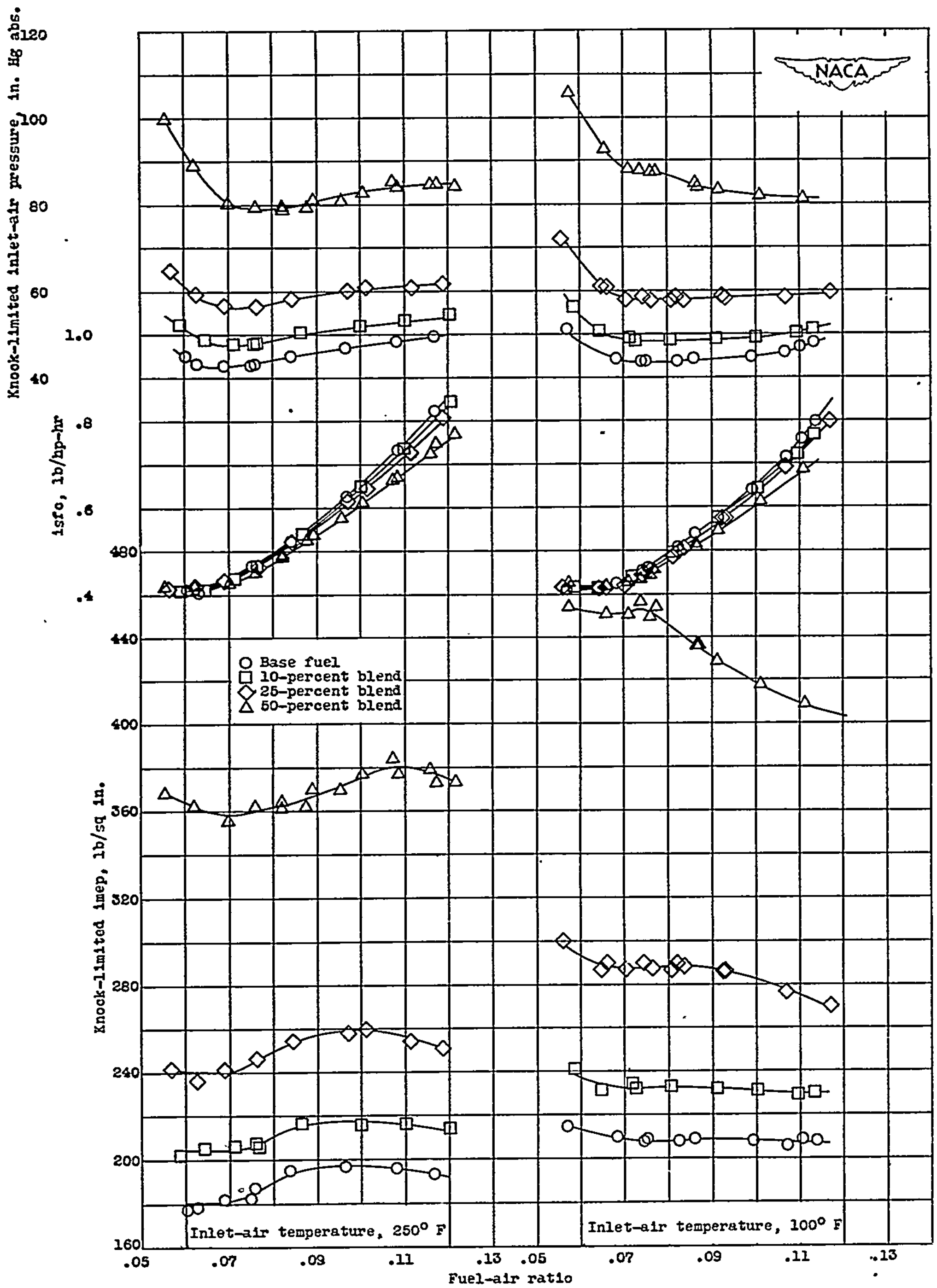
(a) Methyl tert-butyl ether.

Figure 8. - Fuel-air mixture response in 17.6 engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.



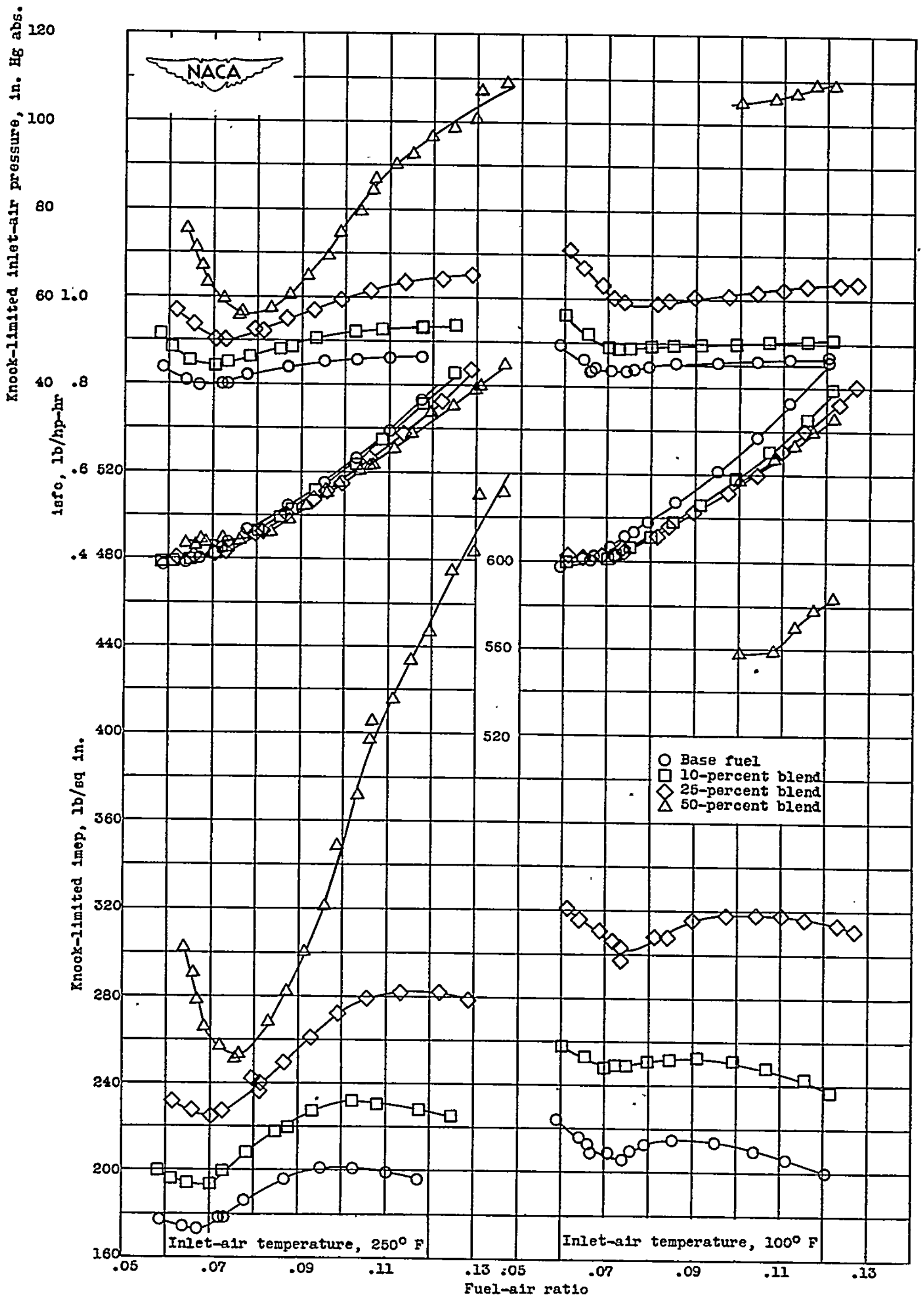
(b) Ethyl tert-butyl ether.

Figure 8. - Continued. Fuel-air mixture response in 17.6 engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.



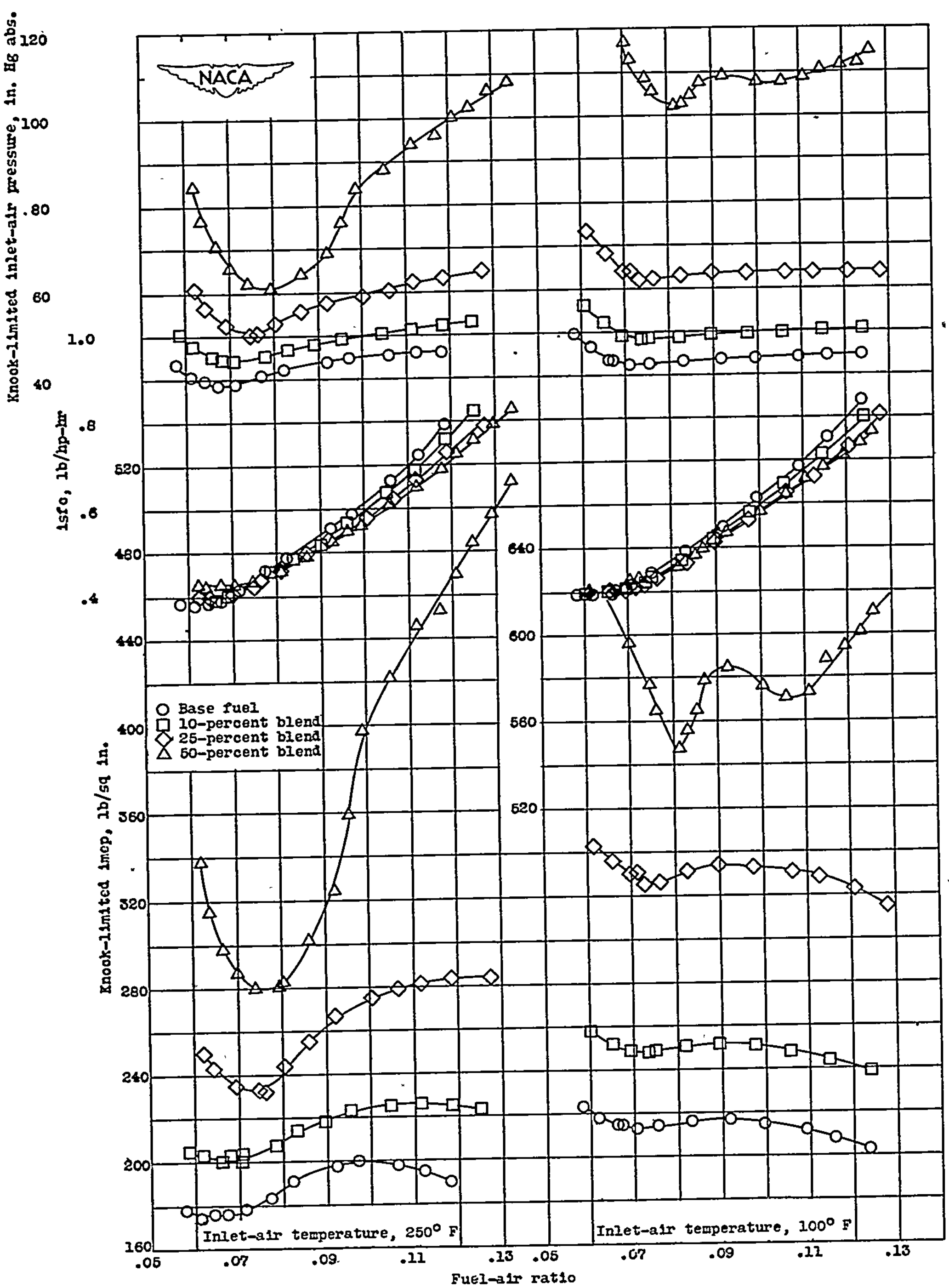
(c) Isopropyl tert-butyl ether.

Figure 8. - Continued. Fuel-air mixture response in 17.6 engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.



(d) Anisole.

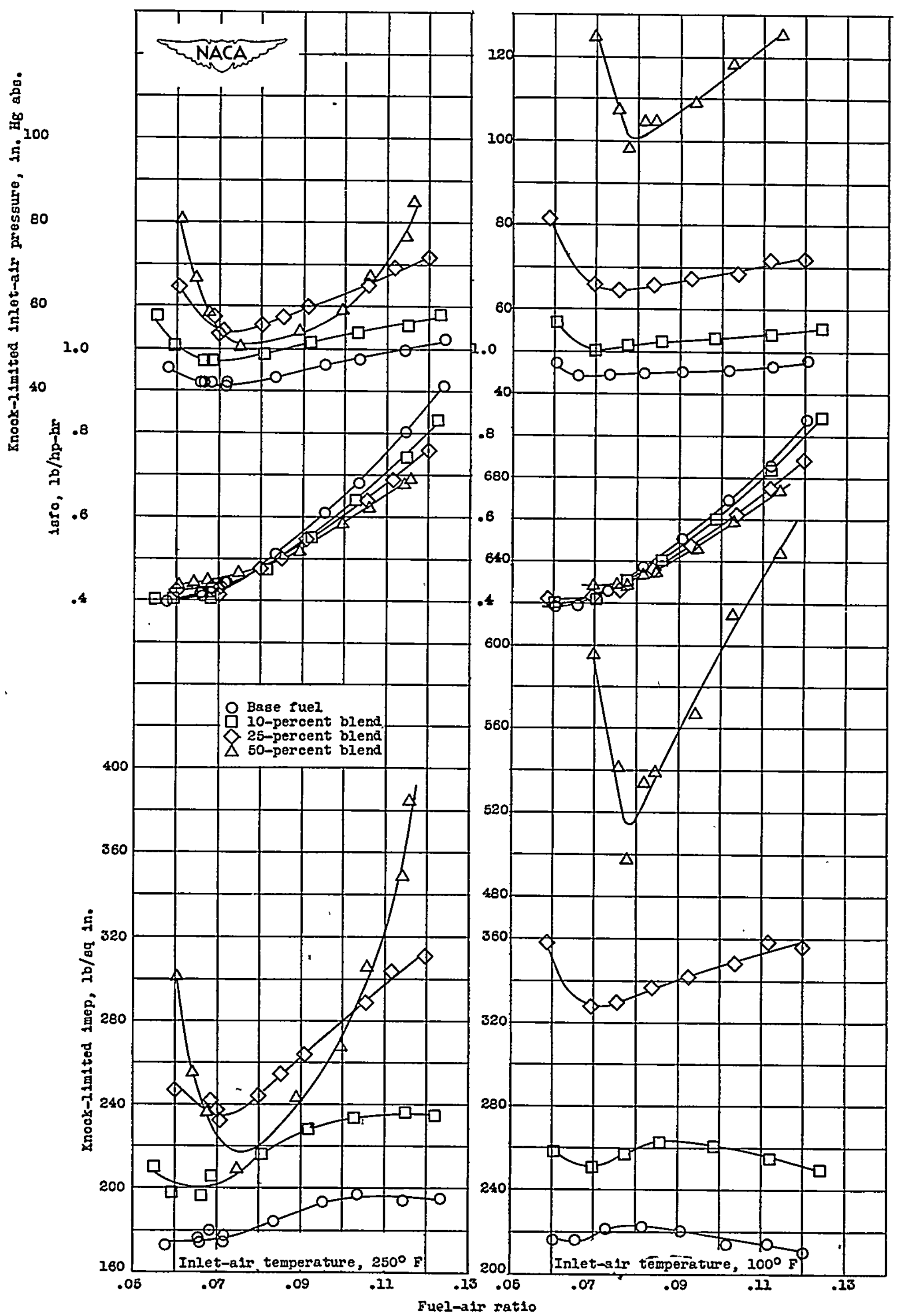
Figure 8. - Continued. Fuel-air mixture response in 17.6 engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.



(e) Phenetole.

Figure 8. - Continued. Fuel-air mixture response in 17.6 engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.

1244



(f) p-Methylanisole.

Figure 8. - Concluded. Fuel-air mixture response in 17.6 engine for first six ethers in leaded 10-, 25-, and 50-percent (volume) blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.

1244

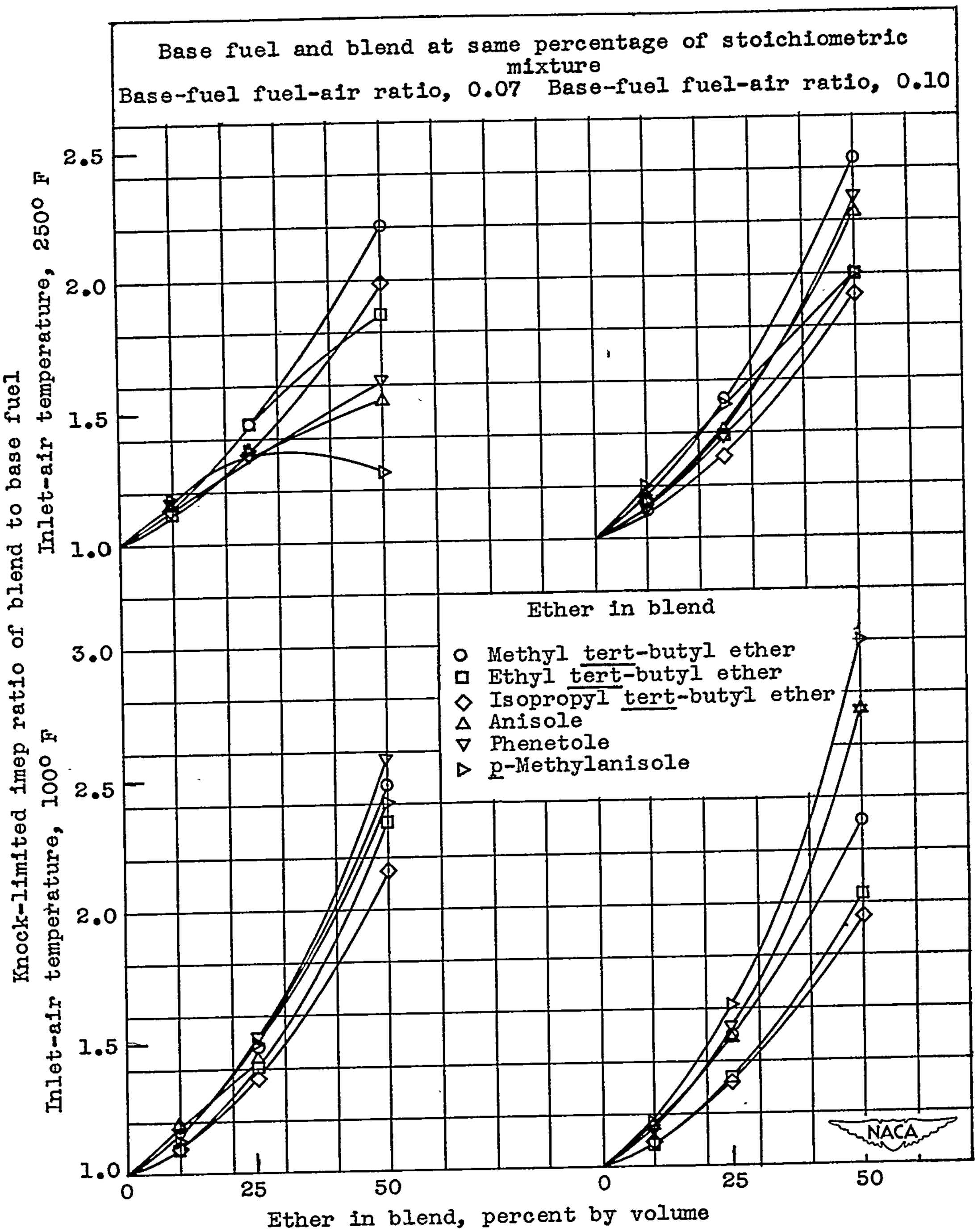
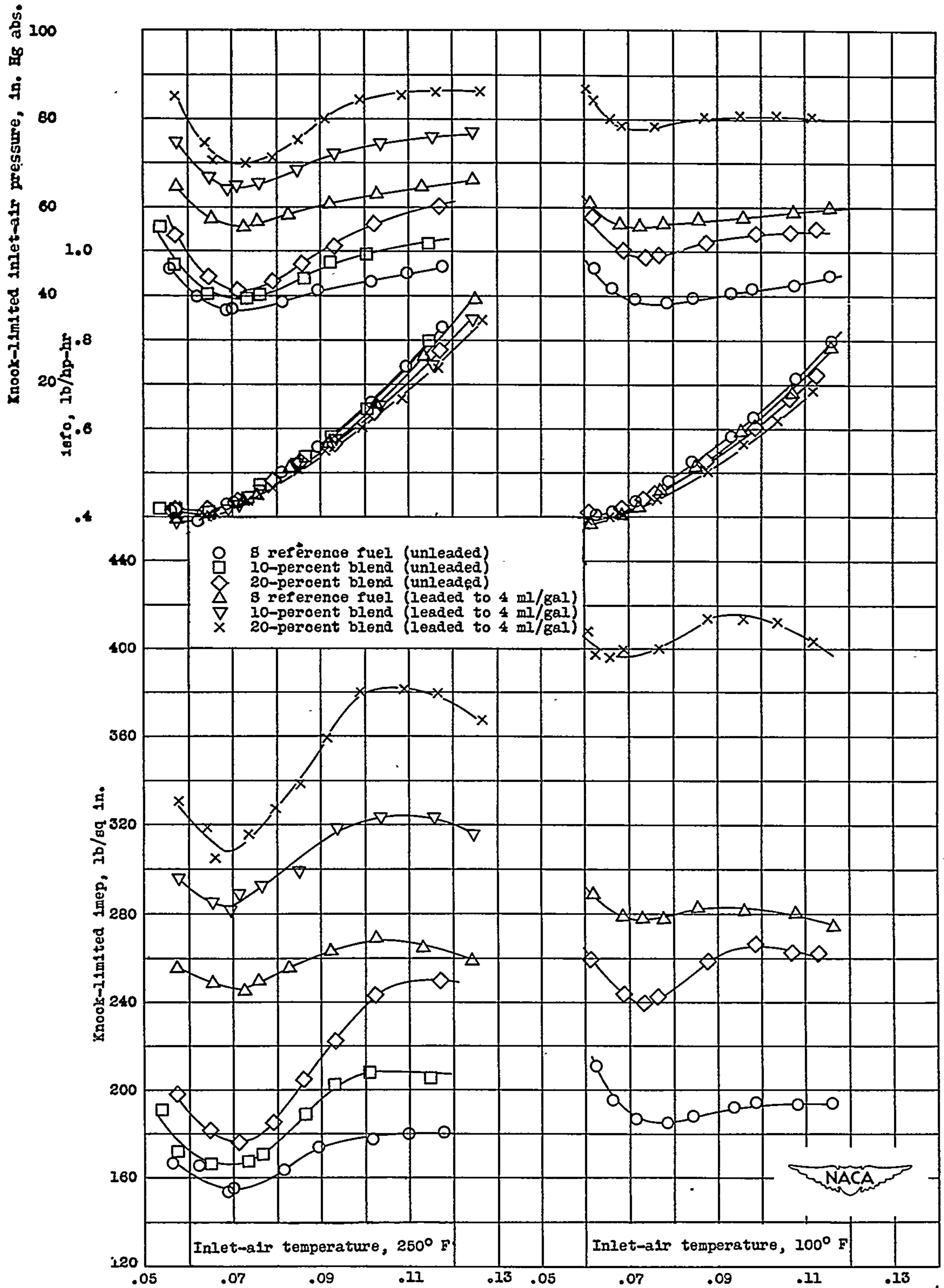


Figure 9. - Blending characteristics in 17.6 engine for first six ethers in leaded blends with base fuel consisting of 87.5-percent S reference fuel and 12.5-percent n-heptane plus 4 ml TEL per gallon. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.

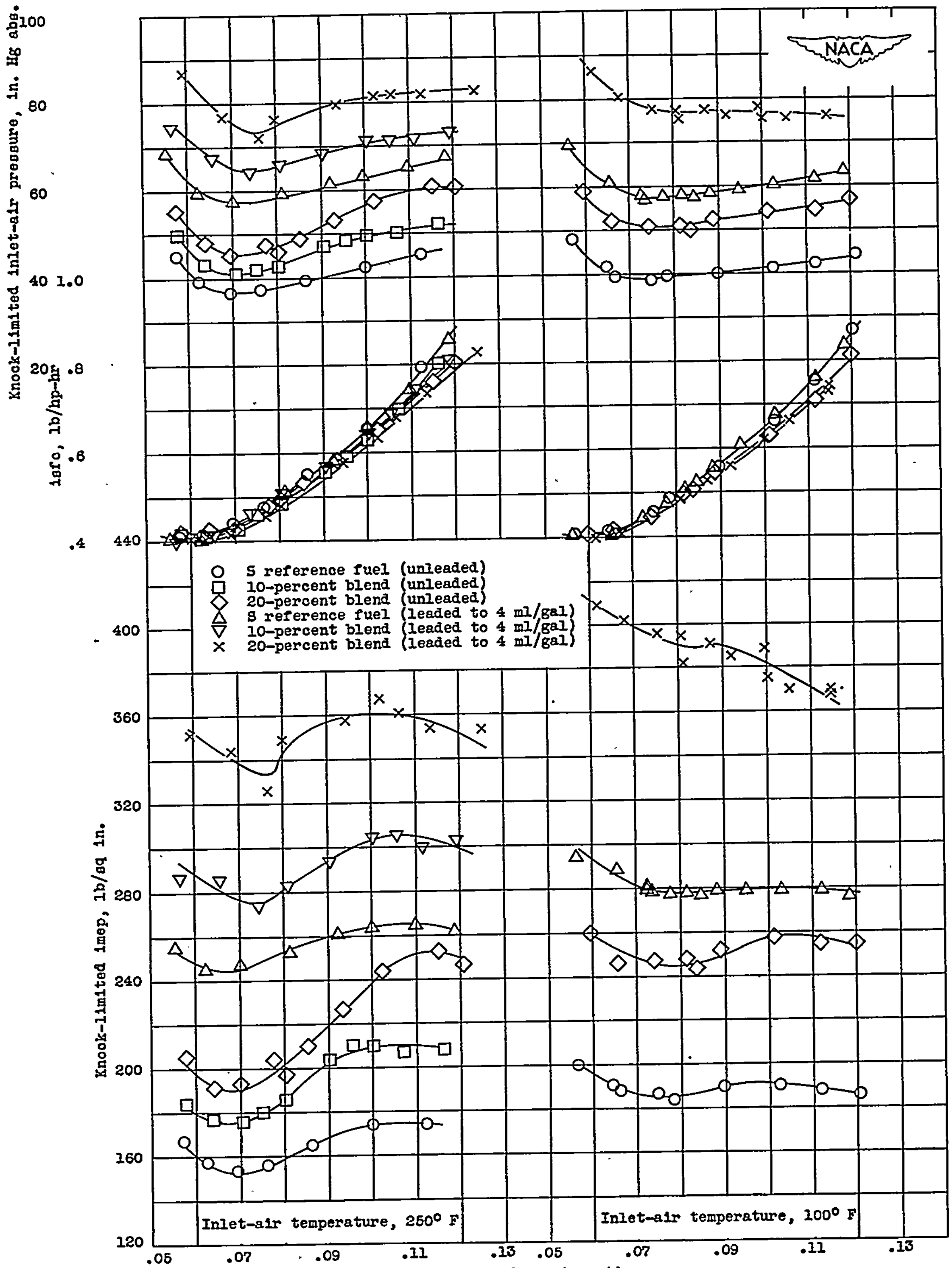
1244



(a) Methyl tert-butyl ether.

1244

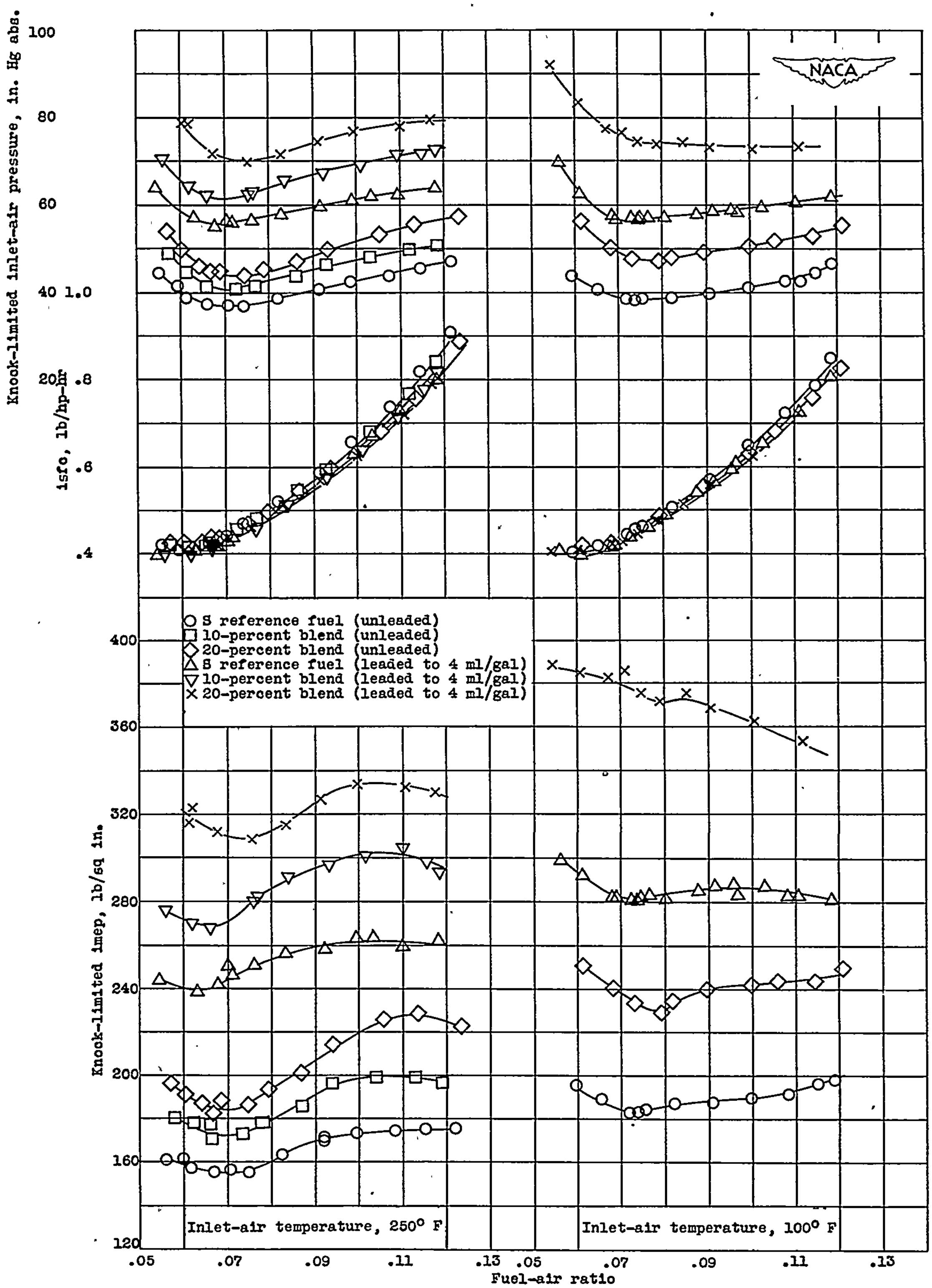
Figure 10. - Fuel-air mixture response in 17.6 engine for first six ethers in unleaded and leaded 10- and 20-percent (volume) blends with S reference fuel. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.



(b) Ethyl tert-butyl ether.

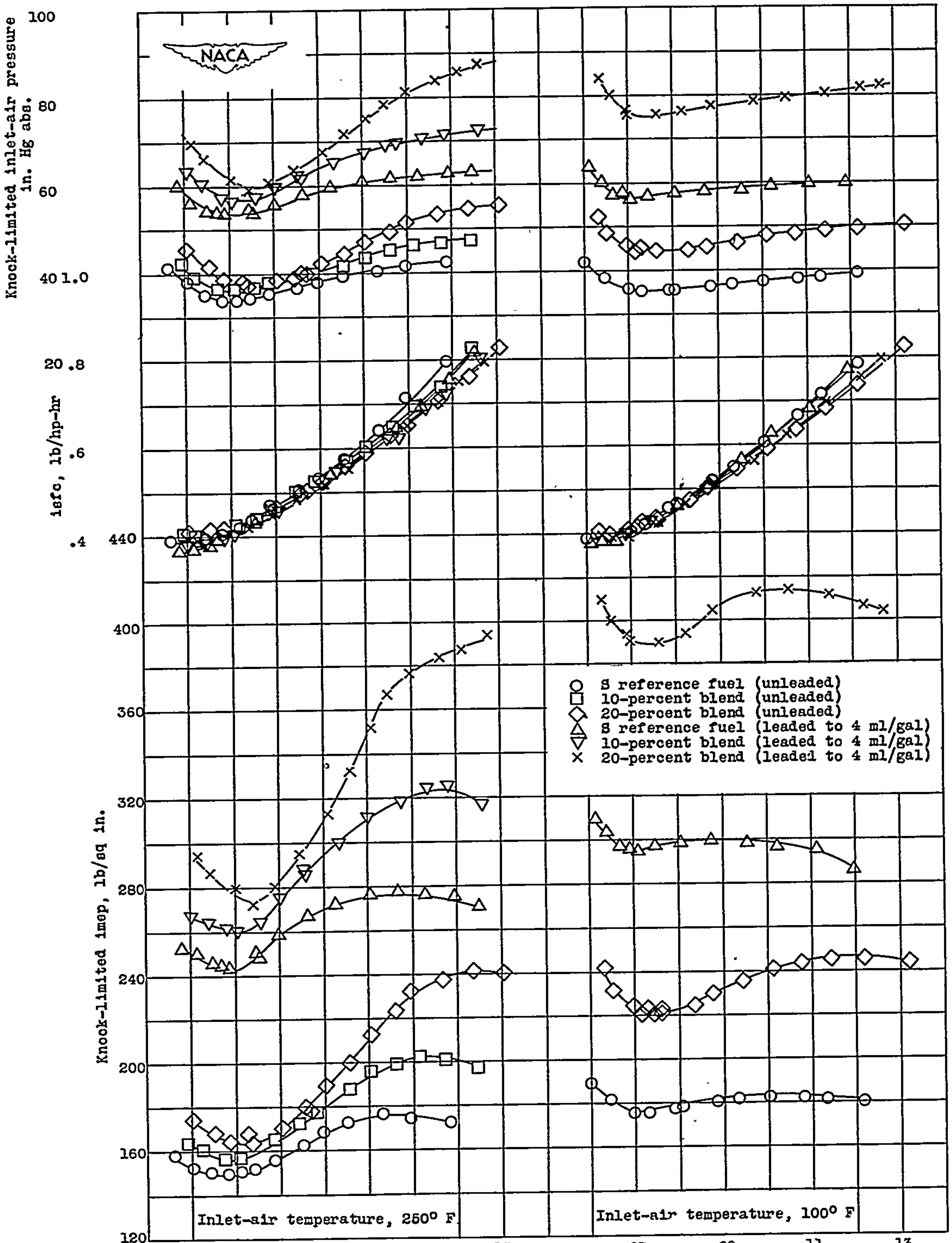
Figure 10. - Continued. Fuel-air mixture response in 17.6 engine for first six ethers in unleaded and leaded 10- and 20-percent (volume) blends with S reference fuel. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.

1244



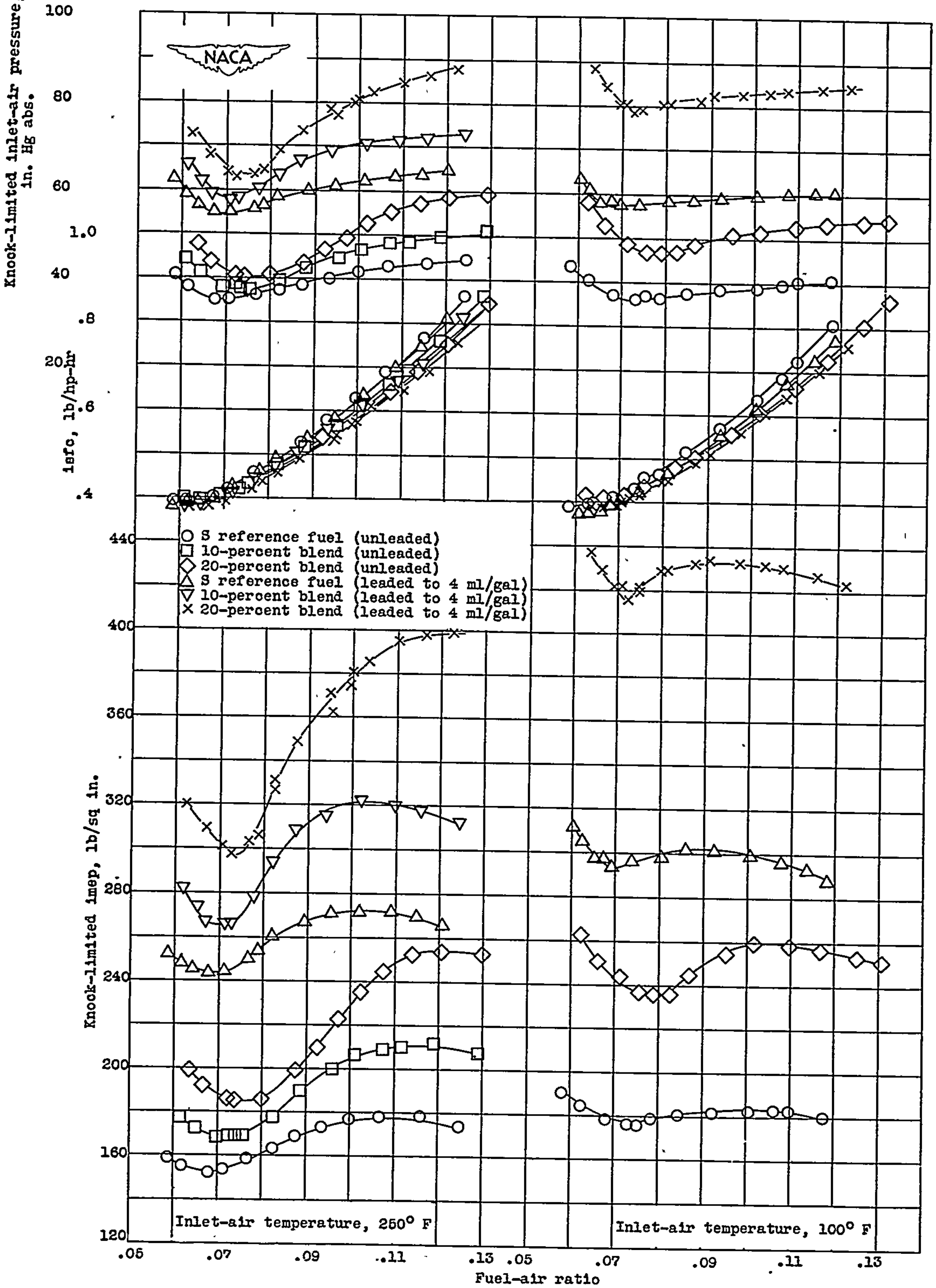
(c) Isopropyl tert-butyl ether.

Figure 10. - Continued. Fuel-air mixture response in 17.6 engine for first six ethers in unleaded and leaded 10- and 20-percent (volume) blends with S reference fuel. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.



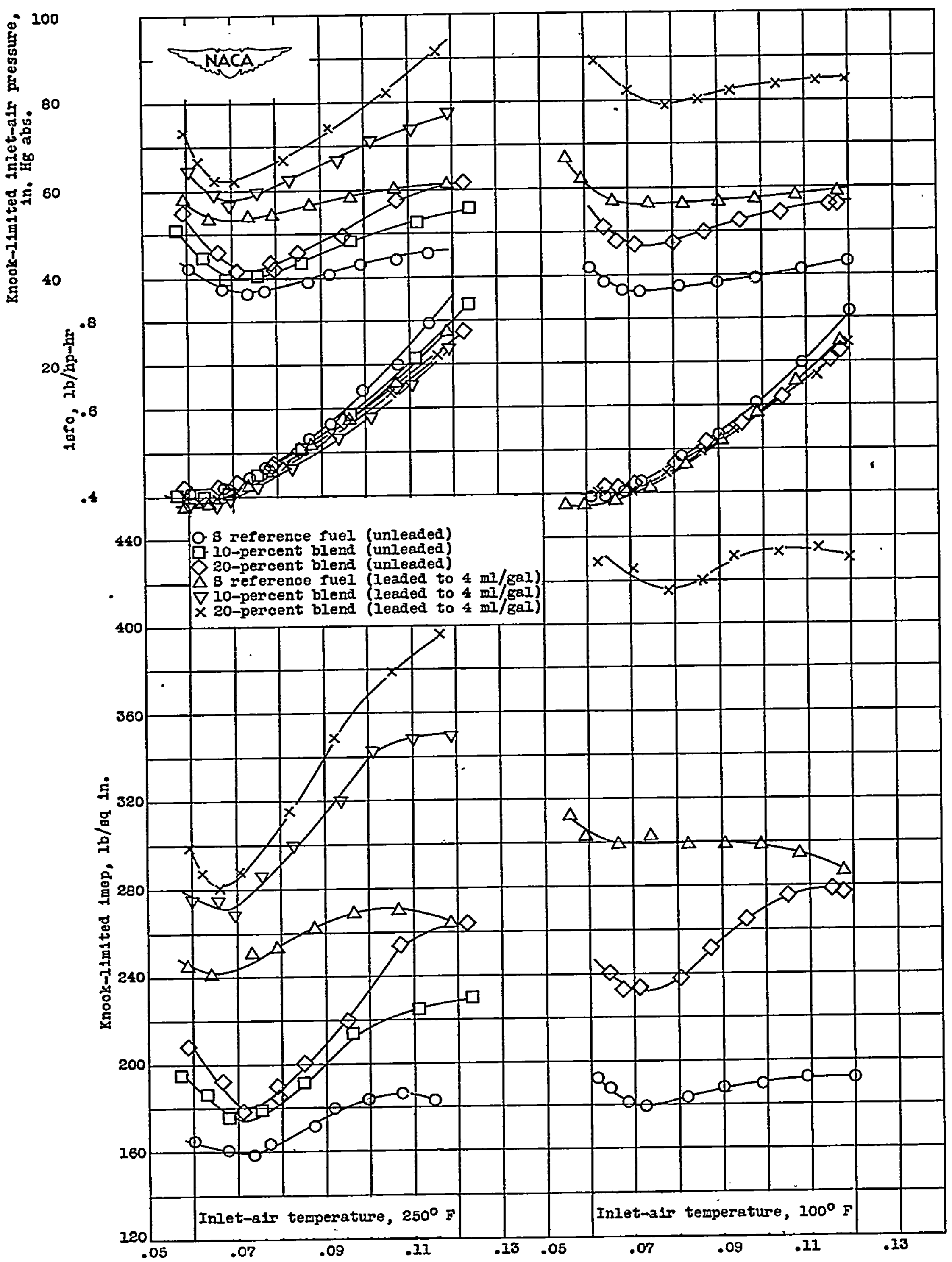
(d) Anisole.

Figure 10. - Continued. Fuel-air mixture response in 17.6 engine for first six ethers in unleaded and leaded 10- and 20-percent (volume) blends with S reference fuel. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.



(e) Phenetole.

Figure 10. - Continued. Fuel-air mixture response in 17.6 engine for first six ethers in unleaded and leaded 10- and 20-percent (volume) blends with S reference fuel. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.



(f) p-Methylanisole.

Figure 10. - Concluded. Fuel-air mixture response in 17.6 engine for first six ethers in unleaded and leaded 10- and 20-percent (volume) blends with S reference fuel. Compression ratio, 7.0; speed, 1800 rpm; spark advance, 30° B.T.C.; coolant, water at 212° F.