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# RESEARCH MEMORANDUM

## ANTIKNOCK EVALUATION OF HYDROCARBONS AND ETHERS AS AVIATION FUEL COMPONENTS

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# ANTIKNOCK EVALUATION OF HYDROCARBONS AND ETHERS AS AVIATION FUEL COMPONENTS

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## SUMMARY

The results of a NACA investigation conducted over a period of several years to evaluate the antiknock characteristics of organic compounds are summarized. Included are data for 18 branched paraffins and olefins, 27 aromatics, and 22 ethers.

The factors of performance investigated were blending characteristics, temperature sensitivity, lead response, and relation between molecular structure and antiknock ratings. Four engines were used in these studies.

## INTRODUCTION

Improvements in aircraft power plants during the past 30 years have resulted in demands for fuels of increasingly higher antiknock performance. This trend has necessitated a thorough investigation of possible high-antiknock compounds that may or may not occur naturally in petroleum. The task of surveying an endless procession of possible fuel-blending agents has fallen to the petroleum industry and interested research groups. Through the combined efforts of the organizations concerned, a large quantity of data has been amassed. These data permit an accurate appraisal of the merits of many chemical compounds heretofore given little more than cursory consideration as fuel-blending agents.

As a participant in this field of research, the NACA in 1937 sponsored a project by the National Bureau of Standards for the preparation of 1-liter quantities of selected paraffins and olefins. The engine evaluation of the antiknock qualities of these compounds was first conducted under the sponsorship of the American Petroleum Institute (API) and the results of this work have been reported by Lovell (reference 1). In addition, the API has sponsored a synthesis program conducted at the laboratories of Ohio State University. All these programs have been continued up to the present and were augmented during 1942-47 by additional synthesis and engine evaluation at the NACA Lewis laboratory.

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The synthesis project at the National Bureau of Standards has been devoted to compounds in the paraffinic and olefinic classes; the synthesis project at the NACA Lewis laboratory has been devoted to compounds in the aromatic and ether classes; and the synthesis program at Ohio State University has been devoted to compounds in these and other classes.

The engine evaluation of pure compounds sponsored by the API was conducted in laboratories of the General Motors Corporation and the Ethyl Corporation. The engine evaluation of blends reported herein was conducted at the NACA Lewis laboratory.

Results of the NACA study of paraffins, olefins, aromatics, and ethers are published in a number of reports (references 2 to 14); each report contains data for several compounds on factors such as blending characteristics, temperature sensitivity, lead response, and relation between molecular structure and antiknock ratings. No effort has been made, however, to prepare an integrated report covering the findings of these investigations. The data contained in references 2 to 14 are therefore summarized and the effect of the molecular structure of fuels on antiknock performance is shown herein.

## ENGINES AND EXPERIMENTAL CONDITIONS

The engine evaluation of the antiknock characteristics of organic compounds was conducted in four test engines: (1) a CFR engine conforming to specifications for the A.S.T.M. Aviation method (D 614-47 T) for rating fuels; (2) CFR engine conforming to specifications for the A.S.T.M. Supercharge method (D 909-47 T) for rating fuels; (3) an engine having a displacement of 17.6 cubic inches (about half that of a CFR engine) and popularly known as the 17.6 engine; and (4) a full-scale air-cooled aircraft cylinder mounted on a CUE crankcase.

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The 17.6 and A.S.T.M. Supercharge engines were equipped with dual fuel systems, one line for the "warm-up fuel" and one for the test fuel. Knocking was detected in both engines by means of a cathode-ray oscilloscope in conjunction with a magnetostriction pickup unit.

The full-scale single-cylinder test engine was fitted with baffles and cooling air was directed toward the cylinder in order to simulate cooling conditions in flight. Further details of the full-scale installation are given in reference 2.

Pertinent operating conditions for the various engines are presented in table I. The 17.6 engine was operated at two inlet-air temperatures, 100° and 250° F, in order to obtain an indication of the sensitivity of fuels to changes in temperature. When the inlet-air temperature was varied, all other conditions were held the same as shown in table I.

The conditions shown in table I for the A.S.T.M. Aviation and A.S.T.M. Supercharge engines are standard for these engines when antiknock ratings are being determined. As indicated in table I, the A.S.T.M. Aviation engine is a nonsupercharged engine in which the compression ratio is varied in order to determine the knock limit of a given fuel at a lean fuel-air ratio with all conditions other than compression ratio held reasonably constant. On the other hand, the A.S.T.M. Supercharge engine is operated with all conditions except inlet-air pressure and fuel-air ratio held constant. Knock limits are determined by varying the manifold pressure until knocking occurs. Although the fuel-air ratio can be varied for this engine, antiknock ratings are made at a rich fuel-air ratio, usually about 0.11. The A.S.T.M. Aviation method (lean ratings) may thus be indicative of fuel performance at cruise conditions; whereas the A.S.T.M. Supercharge method (rich ratings) may be indicative of take-off performance.

The full-scale engine conditions were proposed by the Coordinating Research Council in an effort to standardize full-scale single-cylinder experimental engine operation throughout the country. During the early stages of the NACA investigation, fuels were investigated in the full-scale single-cylinder engine (quantity permitting), but these methods were later abandoned when it became apparent that the small-scale engine adequately described the fuel performance.

## COMPOUNDS INVESTIGATED

The compounds investigated included 13 branched paraffins, 5 branched olefins, 27 aromatics, and 22 ethers. The paraffins and olefins examined were in the $C_5$ to $C_9$ molecular-weight range; the aromatics were in the $C_6$ to $C_{12}$ range; and the ethers were in the $C_4$ to $C_{11}$ range.

The individual compounds, together with physical properties determined by the National Bureau of Standards or the NACA Lewis laboratory, are listed in table II.

## BASE FUELS

Inasmuch as limited quantities of the compounds were available, all tests were conducted on blends rather than on the pure compound. By this procedure, considerable information could be obtained with a relatively small quantity of a given compound. The pure fuels were investigated in blends with two base fuels, one of which was S-reference fuel. The other was a blend of 85 percent (by volume) S-reference fuel and 15 percent M-reference fuel. This blend contained 4.0 ml TEL per gallon. For all practical purposes, S-reference fuel is pure isooctane and M-reference fuel is a straight-run stock of about 20 octane number (A.S.T.M. Motor method). Use of this base blend was discontinued during the investigation and a blend of $87\frac{1}{2}$ percent S-reference fuel and $12\frac{1}{2}$ percent n-heptane was substituted. This blend, too, contained 4.0 ml TEL per gallon.

The performance rating of the leaded blend of S- and M-reference fuels was about 113/108, whereas the rating of the leaded blend of S-reference fuel and n-heptane was about 120/112.

## PRESENTATION OF DATA

The antiknock performance data for all blends and base fuels are presented in tables III to X. In many cases the performance values have been adjusted to compensate for differences in the base blend used. (See section entitled "Base Fuels.") Where these adjustments have been made, the values will obviously disagree with values reported in references 2 to 14; however, for the purposes herein, the data as a whole have been placed on a more uniform basis.

The previously mentioned adjustments, in effect, permit treatment of the data as if only two base fuels had been used, namely, isooctane (leaded and unleaded) and a leaded blend of isooctane and n-heptane.

# RESULTS AND DISCUSSION

## Relation Between Molecular Structure and Antiknock Characteristics

A large part of past research relating to molecular structure and antiknock behavior has been summarized by Lovell (reference 1) and by Lovell and Campbell (reference 16). In both of these investigations, an attempt was made to secure generalizations that would assist in the prediction of relative antiknock values from molecular structures. The past studies have on the whole been very successful in this respect. As this particular phase of fuel research has progressed, however, the basic knowledge of engine performance has advanced; consequently, exceptions to these generalizations can and do exist by virtue of differences in engines and engine operating conditions. That is, the relative antiknock characteristics of a given group of fuels can be changed considerably by altering the engine or experimental conditions.

As a result, the concept of "severe" and "mild" engine conditions has been devised as an aid in evaluating the merits of different fuels. A severe condition is one in which controlled conditions such as inlet-air temperature, coolant temperature, compression ratio, spark advance, and engine speed combine in their effects to make a fuel knock more readily. (See reference 17.) In reference 14, the various engine operating conditions used in the NACA investigation of ethers are alined into a relative order of severity. This same order of severity is used in the present discussion and is presented in table XI.

Because of this so-called severity concept, any statement to the effect that one fuel performs better than another fuel has little significance unless it is true for all operating conditions or restricted to one operating condition. For this reason, the emphasis in an investigation of the type reported herein must be placed upon the trends in the relation between structure and knock rating that appear to apply under most conditions.

Paraffins. - Data were obtained for 13 paraffinic hydrocarbons in leaded blends with the mixed base fuel. Inasmuch as the quantities of hydrocarbon were somewhat limited, all the paraffins were compared only at the 25 percent (by volume) concentration level and only at standard A.S.T.M. Aviation and A.S.T.M. Supercharge conditions (table III(a)). The data for these blends are shown in figure 1.

These figures illustrate the relation between molecular structure and antiknock performance for the paraffins investigated. The lines joining the various data points are shown merely to define the paths followed by compounds in an homologous series. An increase of one carbon atom on the abscissa of these figures is equivalent to a molecular-weight increase equal to the molecular weight of a $CH_2$ group.

At the A.S.T.M. Aviation conditions (fig. 1(a)), seven of the paraffinic hydrocarbons raised the knock-limited performance of the base fuel. The increases varied between 2 and 15 performance numbers with 2,2,3-trimethylbutane (triptane) having the highest rating. This result indicates that under severe conditions, represented by the A.S.T.M. Aviation (lean) method, triptane has outstanding antiknock characteristics.

Insofar as the effect of molecular structure on antiknock characteristics is concerned, three trends have been emphasized (references 1 and 16). The first trend is concerned with centralization of the molecule. For example, 2,2,3,3-tetramethylbutane is a more centralized or compact molecule than 2,2,3-trimethylpentane and should therefore have a higher antiknock rating. The second trend shows the effect of adding methyl ($CH_3$) groups to a molecule in order to form successive members of an homologous series. The addition of a methyl group to increase the branching tends to produce a compound having a higher antiknock rating; however, the position in which the group is added to the molecule will influence the rating of the new compound. This effect based on A.S.T.M. Aviation antiknock ratings for the blends examined in the present investigation is illustrated as follows:

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```
                                        C C
                                        | |
                                      C-C-C-C-C(performance number, 130)
                                        |
                                        C
  C C                                   C C
  | |                                   | |
C-C-C-C-C(performance number, 118)-->C-C-C-C-C(performance number, 124)
                                        |
                                        C
                                        C C C
                                        | | |
                                      C-C-C-C-C(performance number, 122)
```

The third trend is concerned with the increase in length of a carbon side chain or the primary carbon chain of a molecule. The effect of such an addition is to decrease the antiknock rating as illustrated by the following examples:

```
                                        C
                                        |
  C C C                                 C C C
  | | |                               | | |
C-C-C-C-C(performance number, 122)-->C-C-C-C-C(performance number, 115)
  C C                                   C C
  | |                                   | |
C-C-C-C(performance number, 129)---->C-C-C-C-C(performance number, 118)
```

In general the trends reported in references 1 and 16 and discussed in the preceding paragraph (fig. 1(a)) appear to be valid at mild or moderate engine operating conditions. At severe operating conditions, however, exceptions do occur as regards centralization of the molecule or increased branching in the molecule.

At the A.S.T.M. Supercharge conditions, which, as indicated in table XI, are of moderate severity, the NACA data (fig. 1(b)) agree substantially with the results found by Lovell (reference 1). In this case (fig. 1(b)), 12 of the 13 paraffinic hydrocarbons investigated raised the knock-limited performance of the base fuel; the increases were in the range of 2 to 44 performance numbers. The antiknock rating of the blend containing 2,2,3,3-tetramethylpentane was the highest obtained and the triptane blend was next.

In order to illustrate the fact that increased centralization of the molecule does not always result in high antiknock values, the A.S.T.M. Aviation ratings are plotted against the A.S.T.M. Supercharge ratings for five nonanes blended with the mixed base fuel in figure 2. If, in this figure, 2,2,3,3-tetramethylpentane is considered the most compact molecule and 2,2,4,4-tetramethylpentane the least compact, then it is apparent (because the correlating line has a negative slope) that increasing compactness may improve antiknock performance under one set of conditions and depreciate antiknock performance at other conditions.

As previously mentioned, the addition of methyl groups, that is, increased branching, does not always result in improved performance. This fact is illustrated by the following A.S.T.M. Aviation ratings:

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```
                                                  C C C
                                                  | | |
                                                C-C-C-C-C(performance number, 118)
  C C C                                           |
  | | |                                           C
C-C-C-C-C(performance number, 122)
                                                  C C C
                                                  | | |
                                                C-C-C-C-C(performance number, 110)
                                                    |
                                                    C
```

It is emphasized, however, that these exceptions appear to exist at severe operating conditions as exemplified by the A.S.T.M. Aviation engine.

Olefins. - Five olefins were examined in leaded blends with the mixed base fuel at standard A.S.T M. Aviation and A.S.T.M. Supercharge conditions (table III(a)). The concentration of olefin in each blend was 25 percent by volume.

The data obtained are somewhat limited insofar as the relation between molecular structure and antiknock value is concerned; however, comparisons can be made with references 1 and 16 to determine further the consistency of trends noted by previous investigators. Lovell (reference 1) found that for branched aliphatic compounds if the parent paraffin hydrocarbon had a high antiknock value the introduction of a double bond would decrease the antiknock value. This trend is supported by the following data from the present investigation (table III(a)):

| Paraffin | Performance number of 25-percent blend[a] | | Olefin | Performance number of 25-percent blend[a] | |
|---|---|---|---|---|---|
| | A.S.T.M. Aviation | A.S.T.M. Supercharge | | A.S.T.M. Aviation | A.S.T.M. Supercharge |
| C C<br>\| \|<br>C-C-C-C-C | 118 | 114 | C C<br>\| \|<br>C-C=C-C-C | 100 | 117 |
| C C C<br>\| \| \|<br>C-C-C-C-C | 122 | 132 | C C C<br>\| \| \|<br>C-C=C-C-C | 101 | 104 |
| C C<br>\| \|<br>C-C-C-C-C<br>\|<br>C | 130 | 141 | C C<br>\| \|<br>C-C=C-C-C<br>\|<br>C | 106 | 108 |

[a]All blends were leaded to 4 ml TEL/gal.

In the foregoing examples, the double bond in the olefin appeared in the 2 position and, with one exception, the ratings for the olefins are lower than those of the corresponding paraffins. The one exception is shown for the A.S.T.M. Supercharge ratings of 2,3-dimethylpentane and 2,3-dimethyl-2-pentene where the olefin has an antiknock rating three performance numbers higher than the paraffin.

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Of the five olefins investigated only two, 2,4,4-trimethyl-1-pentene and 2,4,4-trimethyl-2-pentene, indicate the effect of the position of the double bond on antiknock performance. For the engines and the conditions examined (tables III(a) and VII(a)) the ratings of these two compounds appear to be the same at the more severe conditions. At milder conditions, the 2,4,4-trimethyl-2-pentene has lower ratings than 2,4,4-trimethyl-1-pentene This trend is contrary to the trend found for straight-chain olefins but is in agreement with data for branched-chain olefins (reference 1).

Aromatics. - The most complete set of antiknock performance data obtained in the present investigation resulted from engine studies made with 27 aromatic hydrocarbons in blends with selected base fuels. On the basis of these data, the relations between molecular structure and antiknock value and the influence of engine operating conditions on these relations for the aromatics can be readily seen.

The relation between structure and antiknock performance for a series of n-alkylbenzenes at a lean fuel-air ratio is shown in figure 3(a). In this figure it was necessary to use performance numbers for the A.S.T.M. Aviation engine, inasmuch as knock-limited indicated mean effective pressures are not measured on this engine. The first three carbon atoms added to the side chains of the aromatic compounds successively increased the blend knock limits. The addition of a fourth carbon atom to the side chain caused a sharp drop in performance at the full-scale single-cylinder cruise condition and a slight drop in the A.S.T.M. Aviation engine.

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More specifically, the data in figure 3(a) indicate that for the full-scale single-cylinder cruise condition the 25-percent benzene blend has a knock limit 20 percent higher than the base fuel; toluene is 28 percent higher; ethylbenzene, 35 percent higher; n-propylbenzene, 47 percent higher; whereas, n-butylbenzene is only 11 percent better than the base fuel. At the other experimental conditions (fig. 3(a)), the trends are the same but the magnitude of the increases is less. In fact, under simulated full-scale take-off conditions the benzene blend is lower in performance than the base fuel, which is represented by the ratio 1.0. In the A.S.T.M. Aviation engine, the base fuel has a performance number of 120 and, with the exception of n-propylbenzene, all the aromatic blends have performance numbers lower than 120. This depreciation in performance is characteristic of aromatics at conditions as severe as those encountered in the A.S.T.M. Aviation engine.

Figure 3(b) is similar to figure 3(a) except that the fuel-air ratio is rich and the A.S.T.M. Supercharge (rich) rating method has replaced the A.S.T.M. Aviation (lean) rating method. The trends shown are somewhat different from those in figure 3(a), but the similarity between the A.S.T.M. Supercharge data and the full-scale data is apparent. At the conditions investigated, the first addition of a carbon atom to the benzene ring produces a sharp improvement in performance; the next addition results in a decrease except for the A.S.T.M. Supercharge data, which are unchanged; the next addition slightly increases the performance; and the addition of the fourth carbon atom to the side chain results in a very sharp decrease in knock limit, as found at the lean conditions (fig. 3(a)).

The change in performance accompanying changes in molecular weight in an homologous series is illustrated in figures 3(a) and 3(b). The effect of different isomeric structures on performance when the molecular weight is unchanged is shown in figure 3(c). For this example, the four butylbenzenes, n-butylbenzene, isobutylbenzene, sec-butylbenzene, and tert-butylbenzene, were chosen. At the two 17.6 engine conditions and the A.S.T.M. Aviation condition, changing from the normal to the iso, the secondary, and the tertiary structures progressively improves the performance. Under simulated full-scale cruise conditions, the isobutylbenzene is slightly better than the sec-butylbenzene, but the small difference in antiknock value is probably insignificant.

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Data for the four butylbenzenes at a rich fuel-air ratio are presented in figure 3(d). The trends shown in this figure are similar to those found in figure 3(c).

Generally speaking, in figures 3(a) to 3(d), the trends in performance of the aromatic blends in the standard A.S.T.M. Aviation and A.S.T.M. Supercharge engines were similar to those in the other engines. This similarity among engines, however, is not always observed over wide ranges of operating conditions. Nevertheless, the comparison of performance characteristics of the organic compounds throughout the remainder of this report will be based primarily upon the A.S.T.M. Aviation and A.S.T.M. Supercharge engine data because these data were obtained in engines currently accepted as standards for rating fuels.

The knock-limited performance of dimethylbenzenes (xylenes) is illustrated in figure 3(e). In both engines, the 1,3-dimethylbenzene blend gave higher performance than either 1,2- or 1,4-dimethylbenzene. The 1,4-dimethylbenzene has an antiknock rating only slightly less than that of 1,3-dimethylbenzene but still considerably higher than that of 1,2-dimethylbenzene.

The trends shown in figure 3(f) for the methylethylbenzenes are the same as those shown in figure 3(e) for the dimethylbenzenes; that is, 1-methyl-3-ethylbenzene is appreciably better than 1-methyl-2-ethylbenzene and slightly better than the 1-methyl-4-ethylbenzene. A similar result was obtained for the diethylbenzenes (fig. 3(g)).

The antiknock performance of di-substituted compounds is illustrated in figures 3(e) to 3(g). Figure 3(h) illustrates antiknock trends for tri-substituted compounds. The 1,2,4-trimethylbenzene blend has a slightly higher knock limit than the 1,2,3-trimethylbenzene blend in the A.S.T.M. Supercharge engine but has a slightly lower knock limit in the A.S.T.M. Aviation engine. The 1,3,5-trimethylbenzene is considerably better than either of the other trimethylbenzenes.

The relative antiknock characteristics of all the aromatic hydrocarbons examined are presented in figure 3(i) at A.S.T.M. Aviation lean conditions. About 15 aromatics improved the knock-limited performance of the base fuel. These particular blends fall within a range about seven performance numbers above the base fuel. From these data at lean conditions, 1,3,5-trimethylbenzene and tert-butylbenzene appear to be the most desirable aromatics in the 25-percent blends investigated.

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The aromatic blends are compared at A.S.T.M. Supercharge rich conditions in figure 3(j). In contrast to the A.S.T.M. Aviation data (fig. 3(i)), the 25-percent additions of aromatics to the base fuel caused considerable improvement in A.S.T.M. Supercharge performance, from a performance number of 112 for the base fuel to about 176 for the best aromatic. These results are consistent with results obtained by other investigators in that aromatics in fuel blends generally offer considerable advantage at rich fuel-air ratios but only moderate improvement or even depreciation at lean fuel-air ratios under severe operating conditions. The 1,3,5-trimethylbenzene and tert-butylbenzene blends, which have good antiknock characteristics at A.S.T.M. Aviation conditions (fig. 3(i)), were still relatively high in performance at rich conditions (fig. 3(j)) but were exceeded by other aromatics. Among these high-performance aromatics were 1,3-dimethyl-5-ethylbenzene, 1-methyl-3,5-diethylbenzene, 1-methyl-4-tert-butylbenzene, and 1,3,5-triethylbenzene.

In the aromatic data just discussed, only one trend appears worthy of mention, namely, that meta structural arrangements are equal to or slightly better than para arrangements in antiknock performance and both arrangements are considerably better than the ortho structural arrangement. In one case (fig. 3(j)), however, the para arrangement was better than the meta arrangement as shown by comparison of 1-methyl-3-tert-butylbenzene and 1-methyl-4-tert-butylbenzene. Essentially the same trend is reported in reference 1 for the relation among ortho, meta, and para compounds.

For the paraffins (fig. 1) increasing the length of the primary carbon chain resulted in a decrease in the antiknock performance; however, for the aromatics (figs. 3(a) and 3(b)), an increase in length of a carbon side chain is beneficial up to a certain point, but further additions to the side chain are detrimental to the antiknock performance.

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Ethers. - The antiknock characteristics of three alkyl ethers are illustrated in figures 4(a) and 4(b) for lean and rich fuel-air ratios, respectively. At lean conditions (fig. 4(a)) in the A.S.T.M. Aviation engine, isopropyl tert-butyl ether was appreciably higher in antiknock value than either methyl or ethyl tert-butyl ether. Ethyl tert-butyl ether appears to be slightly higher than methyl tert-butyl ether in this engine. In the 17.6 engine (fig. 4(a)) at both conditions, the results obtained for the three alkyl ethers were directly opposite to those found in the A.S.T.M. Aviation engine. Methyl tert-butyl ether was equal to or better than ethyl tert-butyl ether and both were appreciably better than isopropyl tert-butyl ether. This trend was found also at the rich conditions shown in figure 4(b).

The antiknock characteristics of five phenyl alkyl ethers are shown in figure 4(c). In both engines methyl phenyl ether and tert-butyl phenyl ether gave the lowest performance numbers. The remaining three ethers were about equal in performance in both engines. A comparison of figures 4(a) and 4(c) shows that the phenyl alkyl ethers investigated have considerably poorer antiknock characteristics than do the tert-butyl alkyl ethers at A.S.T.M. Aviation conditions.

The effects of ortho, meta, and para structural arrangements on the antiknock performance of phenyl alkyl ethers are illustrated in figure 4(d). The basic ether for this particular example is methyl phenyl ether (anisole), which is shown on the left side of the figure. The addition of a carbon atom to the benzene ring to form o-methylanisole caused a decrease in performance. Adding a carbon atom in the meta or para position to form m-methylanisole and p-methylanisole slightly increased the antiknock performance. In each engine, m-methylanisole and p-methylanisole were about equal in performance number and both were considerably better than o-methylanisole. This result was similar to that obtained for the aromatics (figs. 3(e) to 3(g)).

Several ethers containing olefinic radicals are shown in figure 4(e). Isopropyl methallyl ether and tert-butyl methallyl ether blends had the highest performance numbers of this group of compounds and phenyl methallyl ether the lowest. At A.S.T.M. Aviation and A.S.T.M. Supercharge conditions, phenyl methallyl ether was the poorest of the 22 ethers examined.

Hydrogenating the benzene nucleus of anisole to give methyl cyclohexyl ether is shown in figure 4(f) to produce a large drop in performance number. Of the three methyl cycloalkyl ethers shown, all of which were relatively low, methyl cyclopropyl ether was the highest at A.S.T.M. Supercharge conditions and methyl cyclopentyl ether was highest at A.S.T.M. Aviation conditions.

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The relative antiknock characteristics of all the ethers investigated are presented in figure 4(g) at A.S.T.M. Aviation (lean) conditions. Under these conditions only the three tert-butyl alkyl ethers raised the knock limit of the base fuels. The maximum improvement in performance number was 29 and was obtained with isopropyl tert-butyl ether.

The antiknock characteristics of all the ethers investigated are compared in figure 4(h) at A.S.T.M. Supercharge rich conditions. Twelve of the ethers improved the performance of the base fuel; the greatest increase in knock-limited performance, about 63 performance numbers, was obtained with methyl tert-butyl ether. Comparison of figures 4(g) and 4(h) clearly shows that nine of the phenyl alkyl ethers have much better antiknock characteristics at rich mixtures than at lean mixtures. It is also apparent that the methyl cycloalkyl ethers show little promise as antiknock blending agents at the A.S.T.M. Aviation and A.S.T.M. Supercharge conditions.

Comparison of classes of compounds. - As a matter of interest, the isomers having the highest antiknock ratings in figures 1, 3(i), 3(j), 4(g), and 4(h) have been plotted in figure 5. The performance numbers have been plotted against boiling points in order to illustrate the most promising antiknock compounds in the boiling range of commercial gasolines. Comparison of the curves in figure 5 is not strictly valid, inasmuch as all the isomers in a given group of compounds have not been studied. Within the limitations of the investigation, however, these two figures do illustrate how the antiknock characteristics of the better paraffins, aromatics, and ethers compare.

By assuming the boiling range of aviation gasoline to be $100^{\circ}$ to $338^{\circ}$ F, it is seen (fig. 5(a)) that for A.S.T.M. Aviation lean conditions the $C_5$ and $C_6$ paraffins have the highest performance numbers in the boiling range from $80^{\circ}$ to $120^{\circ}$ F. In the boiling range between $130^{\circ}$ and about $300^{\circ}$ F, the ethers have the highest performance numbers. Above $300^{\circ}$ F the highest performance numbers were obtained with the aromatic blends.

At A.S.T.M. Supercharge conditions (fig. 5(b)), the paraffin blends had the highest performance numbers in the range of boiling temperatures from $80^{\circ}$ to $120^{\circ}$ F. Above $120^{\circ}$ F the ethers had the highest antiknock ratings up to a boiling temperature of $220^{\circ}$ F. At higher boiling temperatures the aromatics exhibited superior antiknock characteristics.

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## Blending Characteristics

In the preceding section, the discussion of structural trends was based on studies in which 25 percent of a given compound was blended with a selected base fuel. On the basis of such studies, it can be concluded that one compound is better than another or that all compounds aline themselves in an order of antiknock performance that is influenced by engine operating conditions. This situation is complicated, however, in that the relative order of antiknock value of a series of compounds at a fixed engine condition is influenced by the concentration of the compound in the blends upon which such an investigation is based. In other words, one compound could be better than another if both were compared in 25-percent blends but the reverse could be true if both were compared in 50-percent blends.

Blending characteristics of various potential aviation-fuel blending agents have been the subject of considerable investigation. A portion of the more recent findings in such studies is reported in references 18 to 21. The results of these investigations show conclusively that compounds differ radically in their blending behavior as regards antiknock performance.

In order to extend the current knowledge of blending characteristics of fuels, data obtained in the present investigation are discussed in the succeeding paragraphs.

Paraffins. - The blending characteristics of paraffinic fuels at rich fuel-air ratios may be expressed by the following equation: (references 18 and 19):

$$\frac{1}{P_b} = \frac{N_1}{P_1} + \frac{N_2}{P_2} + \frac{N_3}{P_3} + \ldots \tag{1}$$

where

$P_b$ knock-limited indicated mean effective pressure of blend

$P_1, P_2, P_3, \ldots$ knock-limited indicated mean effective pressures of components 1,2,3,..., respectively

$N_1, N_2, N_3, \ldots$ mass fractions of components 1,2,3,..., respectively, in blend

The application of this equation to data in the present investigation is illustrated in figure 6(a) for the A.S.T.M. Supercharge engine. The ordinate of this figure is a reciprocal scale and the abscissa is linear. For the fuels shown, 2,2,3,4-tetramethylpentane, 2,3,3,4-tetramethylpentane, and 2,2,3-trimethylbutane, the blending relation with the base fuel is linear up to a concentration of 50-percent added paraffin. Knock-limited indicated mean effective pressures (fig. 6(a)) for 2,2,3,4-tetramethylpentane and 2,3,3,4-tetramethylpentane are from reference 12. Similar data for 2,2,3-trimethylbutane are from reference 11.

Although data for these fuels at lean fuel-air ratios are not shown herein, an examination of such data indicated that the blending relation is nonlinear. The authors of reference 18 attribute this fact to the variation of the end gas temperature from one blend to another. That is, for a system in which a paraffinic blending agent is blended with a paraffinic base stock, the relation between the reciprocal of the knock-limited performance and the composition will be linear if the end gas temperature, or a wall temperature closely related to the end gas temperature, is held constant for each blend tested.

Olefins. - Blending data for two olefins (reference 12) are shown in figure 6(b) for the A.S.T.M. Supercharge engine operating at a rich fuel-air ratio. In this case, olefinic blending agents are blended with a paraffinic base fuel and the resulting relation between the reciprocal of the knock-limited performance and composition is nonlinear. The blending equation (1) is based upon one assumption, that for the equation to apply the blends should be tested at a constant percentage of excess of fuel or air. The differences between stoichiometric fuel-air ratios for olefins and paraffins, however, do not appear sufficiently great to explain the nonlinearity of this blending curve.

Aromatics. - The blending relations for the aromatic hydrocarbons (fig. 6(c)), like those of the olefins (fig. 6(b)), were found to be nonlinear in the A.S.T.M. Supercharge engine at rich mixtures. With the exception of 1,2-dimethylbenzene and 1,2,4-trimethylbenzene, all the aromatics increased the knock-limited performance of the base fuel at the concentration investigated.

It has previously been mentioned that the concentration level at which compounds are examined may have considerable effect on the relative order of antiknock rating, as shown in figure 6(c) for isopropylbenzene. For example, a blend of 50 percent by volume of isopropylbenzene has the second highest antiknock rating of the aromatics investigated; at concentrations below 35 percent by volume, however, the performance of isopropylbenzene is exceeded by that of 1,3-dimethylbenzene, 1,3-diethylbenzene, 1-ethyl-4-methylbenzene, and n-propylbenzene.

This result can perhaps be seen a little more clearly in figure 7(b), in which the blending data for the A.S.T.M. Supercharge engine are illustrated by a bar chart. The hydrocarbons are listed on this chart in order of decreasing antiknock rating, as determined by the 50-percent blends. At lower concentrations, however, the bars indicate a different order of rating.

At A.S.T.M. Aviation conditions (fig. 7(a)), the variation of knock-limited performance with composition was found to be different from that obtained at A.S.T.M. Supercharge conditions (figs. 6(c) and 7(b)). For example, the data presented in figure 7(a) indicate that the knock-limited performance of the base fuel is decreased as the concentration of aromatic is increased. Moreover, in figure 7(a) the aromatics do not rate in the same order at all concentrations.

Ethers. - Blending data for six ethers determined at A.S.T.M. Supercharge conditions are shown in figure 8(b). Methyl *tert*-butyl ether and ethyl *tert*-butyl ether have the highest antiknock characteristics of the six ethers at all concentrations. Isopropyl *tert*-butyl ether is also better than the three aromatic ethers at a concentration of 50 percent; however, at concentrations below about 20 percent isopropyl *tert*-butyl ether is lower than any of the other ethers.

The ethers shown in figure 8(b), like the olefins and aromatics, do not follow the reciprocal blending relation defined by equation (1).

The blending relations for the ethers in figure 8(b) were investigated at A.S.T.M. Aviation conditions and the results obtained are presented in figure 8(a). At these conditions, the three tert-butyl alkyl ethers all improved the knock-limited performance of the base fuel; the improvement became greater as concentration was increased. On the other hand, the three aromatic ethers decreased the performance of the base fuel; the decrease became greater as the concentration was increased.

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## Temperature Sensitivity

In order to determine the effects of changes of inlet-air temperature on knock-limited performance, most of the hydrocarbons and ethers were evaluated in the 17.6 engine at inlet-air temperatures of 100° and 250° F. These tests were made with each compound in 20-percent-by-volume blends with isooctane. The final blends were evaluated at both temperatures in the unleaded state and with 4 ml TEL per gallon. (See tables V and VI, respectively.) The greatest portion of the temperature-sensitivity studies of this investigation were conducted on blends with isooctane. A few experiments, however, were made in which the compounds were blended with the mixed base fuel. (See table VII.)

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The term "temperature sensitivity" has been given several definitions by investigators in the field of fuel research; however, none of these definitions has been wholly satisfactory. Perhaps the data offering the most scientific approach to such a definition are reported in references 17 and 22 to 24, but the emphasis in these references is placed upon engine severity rather than the more restricted idea of temperature sensitivity; that is, engine severity is a more inclusive term that considers other factors of engine performance such as compression ratio, spark advance, engine speed, and cooling, as well as inlet-air temperature.

Considerable experimental data are required in order to evaluate fully the engine severity as described in references 17 and 22 to 24 and in most cases during the present investigation the available quantities of the pure fuels were too small for extensive studies. For this reason, the sensitivity studies of these fuels to changes of engine conditions were restricted merely to measurements of the effect of inlet-air temperature on knock-limited performance. In so doing it was necessary to establish arbitrarily a definition for temperature sensitivity. This term is defined by the following equation:

$$\text{Relative temperature sensitivity} = \frac{\dfrac{\text{knock-limited imep of blend (inlet air at } 100^\circ \text{ F)}}{\text{knock-limited imep of base fuel (inlet air at } 100^\circ \text{ F)}}}{\dfrac{\text{knock-limited imep of blend (inlet air at } 250^\circ \text{ F)}}{\text{knock-limited imep of base fuel (inlet air at } 250^\circ \text{ F)}}}$$

The term "relative" is used in this definition inasmuch as the equation essentially describes the temperature sensitivity of the blend relative to that of the base fuel. This definition is the same as that used in references 5 to 11 and 13. The base fuels used in this study were paraffins and do not show high temperature sensitivity.

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Temperature sensitivities computed by this equation for all the compounds in the present investigation are presented in table VIII. In the discussion of temperature sensitivity in the following paragraphs and in the subsequent discussion of lead susceptibility, it should be remembered that the data were obtained over a long period of time and reproducibility errors therefore exist. Although no extensive reproducibility data were obtained, a few such runs indicated that relative temperature sensitivities computed by the equation and relative lead susceptibilities computed by a similar equation may be in error by $\pm$ 0.05.

Paraffins. - The temperature sensitivities of unleaded and leaded paraffinic fuel blends in the 17.6 engine at two fuel-air ratios are compared in figure 9(a) and 9(b). Of the paraffinic blending agents investigated (references 12 and 13), the three nonanes 2,3,3,4-tetramethylpentane, 2,2,3,4-tetramethylpentane, and 2,2,3,3-tetramethylpentane appear to be most sensitive to changes of inlet-air temperature at the lean fuel-air ratio in unleaded blends (fig. 9(a)). At the rich fuel-air ratio, however, the differences in temperature sensitivities among the paraffins are small.

In figures 9(a) and 9(b), the paraffins are listed in the same order. Inspection of these plots illustrates that tetraethyl lead affects temperature sensitivity. For example, in figure 9(a) and 9(b) the order of temperature sensitivities of the various paraffins are obviously different at both fuel-air ratios.

As previously mentioned, a few of the compounds in this investigation were examined in blends with the mixed base fuel. In the investigation of reference 13, paraffinic and olefinic blending agents in blends with the mixed base fuel were subjected to variations of compression ratio. By computing these data in the manner explained in references 23 and 24, it is possible to compare over a reasonably wide range the influence of engine severity on knock-limited performance. This effect is determined by computation of compression-air densities and compression temperatures at the knock limit; the main assumption is that these factors are related in some manner to end-gas densities and temperatures that cannot be directly measured (reference 17). The compression-air densities and temperatures are calculated by the following equations:

$$\rho = \frac{A\,(r-1)}{nv_d} \tag{2}$$

$$T = T_0 r^{(\gamma-1)} \tag{3}$$

Where

$\rho$ compression-air density, pound per cubic inch

A intake-air flow, pound per minute

r compression ratio

n intake cycles per minute

$v_d$ engine displacement volume, cubic inches

T compression-air temperature, $^{\circ}R$

$T_0$ intake-air temperature, $^{\circ}R$

$\gamma$ ratio of specific heat of charge at constant pressure to that at constant volume (assumed to be 1.4)

Although the data in reference 13 were determined by varying the compression ratio, it is apparent from the equation of compression temperature that the effect of varying the compression ratio is equivalent to that of varying the intake-air temperature.

The sensitivities of two paraffinic fuels (reference 13) are shown in figures 10(a) and 10(b) at two fuel-air ratios in a modified A.S.T.M. Supercharge engine. The two paraffin blends are more sensitive than the base fuel to changes of compression ratio or intake-air temperature, as indicated by the slopes of the curves in figures 10(a) and 10(b). The two paraffin blends had lower knock limits than the base fuel at severe conditions (high compression temperatures), but higher limits at mild conditions (low compression temperatures).

Olefins. - Plots similar to those in figures 10(a) and 10(b) are shown in figures 10(c) and 10(d) for three olefins in blends with the mixed base fuel (reference 13). At both fuel-air ratios, the three olefin blends were more sensitive to change of engine severity than the base fuel. At the severe conditions the three olefin blends had lower knock limits than did the base fuel, but at milder conditions the olefin blends had higher knock limits.

Aromatics. - The temperature sensitivities of aromatic blends determined in the 17.6 engine are shown in figures 9(c) and 9(d). The aromatics are listed in figure 9(c) in the order of decreasing sensitivity at the rich fuel-air ratio. As in the case of paraffins (figs. 9(a) and 9(b)), the sensitivities were inconsistent from one fuel-air ratio to another. Moreover, the sensitivities were influenced by tetraethyl lead.

The most sensitive aromatics at the rich fuel-air ratio (fig. 9(c)) were 1,3-dimethylbenzene, 1-methyl-4-isopropylbenzene, and tert-butylbenzene; whereas at the lean fuel-air ratio, a number of aromatics had high sensitivities. In leaded blends (fig. 9(d)), the differences in relative temperature sensitivity among the aromatics were not great at the rich fuel-air ratio, but at a lean fuel-air ratio appreciable differences occurred. At the lean fuel-air ratio, a number of the aromatics had sensitivities 20 to 25 percent greater than the sensitivity of the base fuel.

It has been shown herein that 1,3,5-trimethylbenzene and tert-butylbenzene had higher performance numbers than the other aromatics investigated at the lean condition of the A.S.T.M. Aviation method (fig. 3(i)). For this reason the temperature sensitivities of these two aromatics are of particular interest. These two aromatics in unleaded blends have temperature sensitivities equal to or greater than sensitivities of the other aromatics investigated at the lean fuel-air ratio (fig. 9(c)). On the other hand, the leaded blends shown in figure 9(d) indicate that the temperature sensitivity of tert-butylbenzene is reduced considerably, whereas 1,3,5-trimethylbenzene is still quite sensitive.

Similarly, among the better aromatics at A.S.T.M. Supercharge conditions (fig. 3(j)) were 1,3-dimethyl-5-ethylbenzene, 1-methyl-3,5-diethylbenzene, 1-methyl-4-tert-butylbenzene, and 1,3,5-triethylbenzene. As indicated in figure 9(c) for unleaded blends at a rich fuel-air ratio, these four aromatics show only moderate temperature sensitivity varying between 1.0 and 1.05. In leaded blends (fig. 9(d)) and at a rich fuel-air ratio, the four aromatics still exhibited only moderate temperature sensitivity varying between 1.0 and 1.05.

Compression-air density temperature relations were determined for several aromatics and are reported in reference 10. The relation obtained for three of the aromatics is presented in figures 10(e) and 10(f) in order to illustrate the nature of the results. As indicated by the slopes of the curves in these figures, the sensitivities of the aromatic blends are somewhat greater than the sensitivity of the base fuel.

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Ethers. - Temperature sensitivities determined for six ethers are shown in figures 9(e) and 9(f). The ethers (unleaded blends) are listed in figure 9(e) in the order of decreasing sensitivity at the rich fuel-air ratio (0.11); at this fuel-air ratio the three aromatic ethers appear to be more sensitive to temperature changes than do the tert-butyl alkyl ethers, with the possible exception of methyl tert-butyl ether. At the lean fuel-air ratio (0.065), anisole appears to be the most sensitive of the ethers; however, with consideration for the estimated reproducibility of these data there may be little real difference in the sensitivities of the six ethers shown.

In leaded blends (fig. 9(f)), the aromatic ethers are perhaps more temperature-sensitive than the tert-butyl alkyl ethers with the possible exception of methyl tert-butyl ether at the lean fuel-air ratio. At the rich fuel-air ratio, anisole and p-methylanisole show the highest sensitivities; however, the experimental accuracy may minimize the apparent differences shown on the figures.

Comparison of classes of compounds. - The temperature sensitivities of the various classes of compounds are compared in figure 11. The procedure used in preparing these plots was the same as that used for figure 5.

In figure 11 at two fuel-air ratios, the low-boiling ethers have the greatest temperature sensitivities in the boiling range of 100° to 175° F. Above 175° F the aromatics are more sensitive than the other classes examined. In the boiling range from 300° to 350° F, however, the ethers have temperature sensitivities comparable to those of the aromatics.

## Lead Susceptibility

Lead susceptibilities of the various organic compounds investigated were determined in the 17.6 engine by comparing unleaded blends (20 percent by volume) with blends containing 4 ml TEL per gallon. Data were obtained at two inlet-air temperatures, 100° and 250° F. (See table IX.)

Lead susceptibility, or lead response, is usually defined as the increase in octane number or power output resulting from the addition of a given quantity of tetraethyl lead to a fuel. For the present investigation, however, lead susceptibility is expressed in a manner similar to that used for temperature sensitivity:

$$\text{Relative lead susceptibility} = \frac{\dfrac{\text{knock-limited imep of blend + 4 ml TEL/gal}}{\text{knock-limited imep of base fuel + 4 ml TEL/gal}}}{\dfrac{\text{knock-limited imep of blend + 0 ml TEL/gal}}{\text{knock-limited imep of base fuel + 0 ml TEL/gal}}}$$

As in the foregoing discussion of temperature sensitivity, the estimated accuracy of these ratios is about $\pm 0.05$.

Paraffins. - The lead susceptibilities of six paraffinic blends are shown in figures 12(a) and 12(b). In figure 12(a) (inlet-air temperature, 100° F), the fuels are arranged in order of decreasing response at the rich mixture. At this condition 2,4-dimethyl-3-ethylpentane exhibits the greatest susceptibility to tetraethyl lead, but at the lean fuel-air ratio 2,3-dimethylpentane, 2,2,3-trimethylbutane, and 2,2,3,4-tetramethylpentane have the best response. The lead susceptibility is appreciably influenced by fuel-air ratio.

In figure 12(b) (inlet-air temperature, 250° F), the fuels are listed in the same order as that of figure 12(a), but little or no difference in lead susceptibility is apparent at the rich fuel-air ratio except in the case of 2,2,3-trimethylbutane. At the lean fuel-air ratio, 2,2,3,4-tetramethylpentane and 2,3,3,4-tetramethylpentane had the highest lead susceptibilities.

Olefins. - A limited amount of data was obtained in the 17.6 engine to show the lead susceptibility of olefins in 20-percent-by-volume blends with isooctane. (See table IX(a).) For convenience, a portion of these data is summarized in the following table:

| Olefin | Lead susceptibility of 20-percent olefinic blends relative to isooctane | | | |
|---|---|---|---|---|
| | Inlet-air temperature (°F) | | | |
| | 250 | | 100 | |
| | Fuel-air ratio | | | |
| | 0.065 | 0.11 | 0.065 | 0.11 |
| 2,3-dimethyl-2-pentene | 0.95 | 1.00 | 1.00 | 0.95 |
| 2,3,4-trimethyl-2-pentene | 1.05 | 1.05 | 1.05 | 1.05 |
| 3,4,4-trimethyl-2-pentene | 1.00 | 1.00 | 1.05 | 1.00 |

Aromatics. - In figures 12(c) and 12(d), the lead susceptibilities of aromatic blends are shown. The blends in figure 12(c) are listed in order of decreasing response at the rich fuel-air ratio. At this ratio, the data indicate that 1-methyl-4-ethylbenzene is the aromatic most susceptible to additions of tetraethyl lead. This particular aromatic also had the greatest response at the lean fuel-air ratio. From figures 12(c) and 12(d) lead susceptibility is obviously affected by fuel-air ratio.

At the higher inlet-air temperature (fig. 12(d)), the trend in lead susceptibility differs from that observed at 100° F (fig. 12(c)) for the aromatics. For the rich fuel-air ratio (fig. 12(d)), three of the aromatics, 1-methyl-4-ethylbenzene, 1,3-dimethylbenzene, and 1-methyl-4-isopropylbenzene, appear to be the most susceptible. At the lean fuel-air ratio, however, tert-butylbenzene is considerably more susceptible than the other aromatics.

Ethers. - Lead susceptibilities of the ether blends are presented in figures 12(e) and 12(f). At an inlet-air temperature of 100° F (fig. 12(e)), methyl tert-butyl ether and p-methylanisole have the greatest lead susceptibilities at the lean fuel-air ratio. At the rich fuel-air ratio, methyl tert-butyl ether has the highest susceptibility with anisole and p-methylanisole next.

At an inlet-air temperature of 250° F (fig. 12(f)), the three tert-butyl alkyl ethers have the highest susceptibilities at the lean fuel-air ratio. The three aromatic ethers and methyl tert-butyl ether exhibit the highest susceptibilities at the rich fuel-air ratio.

Comparison of classes of compounds. - In figure 13, the lead susceptibilities are plotted against boiling points for the isomers having highest lead susceptibilities in each class of compounds. At both lean (fig. 13(a)) and rich (fig. 13(b)) fuel-air ratio, the low-boiling ethers appear to be most susceptible to tetraethyl lead in the boiling range from 125° to 160° F. Above 160° F, the aromatics show the greatest lead response.

## CONCLUDING REMARKS

On the basis of an investigation of the type reported herein, it is difficult to draw any specific conclusions, inasmuch as antiknock characteristics are influenced by many factors. The relative order of antiknock ratings of a series of compounds is influenced by engine conditions, by the tetraethyl-lead content, and by the concentration of blending agent in the base fuel with which a comparison is made. With consideration for these factors, tert-butylbenzene, methyl and ethyl tert-butyl ethers, and 2,2,3-trimethylbutane and several nonanes were among the best compounds in their respective organic classes. This selection was based upon temperature sensitivity and lead susceptibility as well as antiknock value.

In an effort to generalize the data obtained in this investigation, the subsequent conclusions are expressed in terms of the relation of various performance factors to the gasoline boiling range as influenced by the classes of organic compounds investigated. Furthermore, these conclusions must necessarily be restricted to the limitations of this investigation and therefore cannot be applied without exception.

Antiknock ratings. - In the low-boiling gasoline range, the highest antiknock ratings are among the more volatile paraffins and ethers. In the intermediate gasoline range, the ethers excel; in the high-boiling range the aromatics have the highest antiknock ratings.

Temperature sensitivity. - In the low-boiling gasoline range, the data are incomplete as regards temperature sensitivity, but there are indications that the volatile ethers are more sensitive to temperature changes than are the paraffins or aromatics. In the intermediate and high-boiling ranges of gasoline, the aromatics are more sensitive to temperature than the paraffins and the ethers. Moreover, the aromatics that have the highest antiknock ratings are also sensitive to temperature.

Lead susceptibility. - In the low-boiling gasoline range, the data are incomplete as regards lead susceptibility, but there are indications that the more volatile ethers are more susceptibile to additions of tetraethyl lead than are the paraffins and the aromatics. In the intermediate and high-boiling ranges of gasoline, the aromatics show greater lead susceptibility than either the paraffins or the ethers.

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TABLE I - ENGINE OPERATING CONDITIONS

| Condition | Engine | | | | |
|---|---|---|---|---|---|
| | 17.6 | A.S.T.M. Aviation | A.S.T.M. Supercharge | Full-scale single cylinder | |
| | | | | Simulated take-off | Simulated cruise |
| Compression ratio | 7.0 | Variable | 7.0 | 7.3 | 7.3 |
| Inlet-air temperature, °F | 100<br>250 | 125 | 225 | 250 | 210 |
| Inlet-mixture temperature, °F | -------- | 220 | ---------- | --------- | --------- |
| Inlet-air pressure | Variable | Atmospheric | Variable | Variable | Variable |
| Fuel-air ratio | Variable | [a]0.07 | Variable | Variable | Variable |
| Speed, rpm | 1800 | 1200 | 1800 | 2500 | 2000 |
| Spark advance, deg B.T.C. | 30 | 35 | 45 | 20/20 | 20/20 |
| Coolant temperature, °F | 212 | 374 | 375 | --------- | --------- |
| Cooling-air temperature[b], °F | -------- | ---------- | ---------- | 85 | 85 |

[a]Approximate.

[b]Cooling-air flow was determined by running engine at brake mean effective pressure of 140 lb/sq in. and fuel-air ratio of 0.10 and by adjusting air flow until temperature of rear spark-plug bushing was 365° F.

TABLE II - PHYSICAL PROPERTIES

(a) Paraffins and olefins[a]

| Paraffins and olefins | Formula | Freezing point (°C) | Boiling point (°F) | Boiling point (°C) | Density at 20° C (gram/ml) | Refractive index $n_D^{20}$ |
|---|---|---|---|---|---|---|
| **Paraffins** | | | | | | |
| 2-Methylbutane | $C_5H_{12}$ | -159.890 | 82.14 | 27.854 | 0.61967 | 1.35373 |
| 2,2-Dimethylbutane | $C_6H_{14}$ | -99.73 | 121.54 | 49.743 | 0.64917 | 1.36876 |
| 2,3-Dimethylbutane | | -128.41 | 136.38 | 57.990 | .66164 | 1.37495 |
| 2,2,3-Trimethylbutane | $C_7H_{16}$ | -24.96 | 177.57 | 80.871 | 0.69002 | 1.38946 |
| 2,3-Dimethylpentane | | -------- | 193.62 | 89.79 | .69512 | 1.39200 |
| 2,2,3-Trimethylpentane | $C_8H_{18}$ | -112.27 | 229.72 | 109.844 | 0.71605 | 1.40295 |
| 2,3,3-Trimethylpentane | | -100.70 | 238.57 | 114.763 | .72620 | 1.40752 |
| 2,3,4-Trimethylpentane | | -109.210 | 236.25 | 113.470 | .71905 | 1.40422 |
| 2,2,3,3-Tetramethylpentane | $C_9H_{20}$ | -9.9 | 284.41 | 140.23 | 0.7566 | 1.4234 |
| 2,2,3,4-Tetramethylpentane | | -121.6 | 271.42 | 133.01 | .7390 | 1.4146 |
| 2,2,4,4-Tetramethylpentane | | -66.54 | 252.10 | 122.28 | .7196 | 1.4068 |
| 2,3,3,4-Tetramethylpentane | | -102.1 | 286.77 | 141.54 | .7547 | 1.4220 |
| 2,4-Dimethyl-3-ethyl-pentane | | -------- | 278.11 | 136.73 | .7379 | 1.4137 |
| **Olefins** | | | | | | |
| 2,3-Dimethyl-2-pentene | $C_7H_{14}$ | -119 | 207 | 97 | 0.728 | 1.421 |
| 2,3,4-Trimethyl-2-pentene | $C_8H_{16}$ | -------- | 241.27 | 116.26 | 0.7434 | 1.4275 |
| 2,4,4-Trimethyl-1-pentene | | -93.5 | 214.59 | 101.44 | .7150 | 1.4086 |
| 2,4,4-Trimethyl-2-pentene | | -106.4 | 220.84 | 104.91 | .7212 | 1.4160 |
| 3,4,4-Trimethyl-2-pentene | | -------- | 234 | 112 | .739 | 1.423 |

[a]Data from reference 15.

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TABLE II - PHYSICAL PROPERTIES - Continued

(b) Aromatics.

| Aromatic | Formula | Freezing point (°C) | Boiling point (°F) | Boiling point (°C) | Density at 20° C (gram/ml) | Refractive index $n_D^{20}$ |
|---|---|---|---|---|---|---|
| Benzene | $C_6H_6$ | 5.49 | 176.2 | 80.1 | 0.8789 | 1.5012 |
| Methylbenzene | $C_7H_8$ | -95.014 | 231.1 | 110.6 | 0.8670 | 1.4967 |
| Ethylbenzene | $C_8H_{10}$ | -95.025 | 276.8 | 136.0 | 0.8672 | 1.4960 |
| 1,2-Dimethylbenzene | | -25.34 | 291.9 | 144.4 | .8799 | 1.5052 |
| 1,3-Dimethylbenzene | | -48.31 | 282.4 | 139.1 | .8642 | 1.4971 |
| 1,4-Dimethylbenzene | | 13.25 | 281.1 | 138.4 | .8610 | 1.4960 |
| n-Propylbenzene | $C_9H_{12}$ | -99.61 | 318.7 | 159.3 | 0.8620 | 1.4920 |
| Isopropylbenzene | | -96.16 | 306.3 | 152.4 | .8621 | 1.4913 |
| 1-Methyl-2-ethylbenzene | | -80.94 | 329.2 | 165.1 | .8807 | 1.5045 |
| 1-Methyl-3-ethylbenzene | | -95.62 | 322.3 | 161.3 | .8645 | 1.4965 |
| 1-Methyl-4-ethylbenzene | | -63.60 | 323.6 | 162.0 | .8611 | 1.4951 |
| 1,2,3-Trimethylbenzene | | -25.97 | 349.0 | 176.1 | .8945 | 1.5137 |
| 1,2,4-Trimethylbenzene | | -44.23 | 336.7 | 169.3 | .8758 | 1.5048 |
| 1,3,5-Trimethylbenzene | | -44.85 | 328.8 | 164.9 | .8650 | 1.4990 |
| n-Butylbenzene | $C_{10}H_{14}$ | -88.19 | 361.8 | 183.2 | 0.8603 | 1.4898 |
| Isobutylbenzene | | -51.87 | 342.0 | 172.2 | .8527 | 1.4860 |
| sec-Butylbenzene | | -75.73 | 343.9 | 173.3 | .8620 | 1.4900 |
| tert-Butylbenzene | | -57.96 | 336.6 | 169.2 | .8665 | 1.4925 |
| 1-Methyl-4-isopropylbenzene | | -68.39 | 351.0 | 177.2 | .8568 | 1.4906 |
| 1,2-Diethylbenzene | | -32.05 | 361.8 | 183.2 | .8797 | 1.5032 |
| 1,3-Diethylbenzene | | -84.64 | 358.9 | 181.6 | .8643 | 1.4955 |
| 1,4-Diethylbenzene | | -43.31 | 362.7 | 183.7 | .8621 | 1.4948 |
| 1,3-Dimethyl-5-ethylbenzene | | -84.43 | 362.5 | 183.6 | .8647 | 1.4980 |
| 1-Methyl-3-tert-butylbenzene | $C_{11}H_{16}$ | -41.53 | 372.6 | 189.2 | 0.8658 | 1.4945 |
| 1-Methyl-4-tert-butylbenzene | | -52.73 | 378.7 | 192.6 | .8612 | 1.4919 |
| 1-Methyl-3,5-diethylbenzene | | -74.01 | 393.1 | 200.6 | .8633 | 1.4969 |
| 1,3,5-Triethylbenzene | $C_{12}H_{18}$ | -66.44 | 420.6 | 215.9 | 0.8620 | 1.4957 |

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TABLE II - PHYSICAL PROPERTIES - Concluded

(c) Ethers.

| Ether | Formula | Freezing point (°C) | Boiling point (°F) | Boiling point (°C) | Density at 20° C (gram/ml) | Refractive index $n_D^{20}$ |
|---|---|---|---|---|---|---|
| Methyl tert-butyl ether | $C_5H_{12}O$ | -109.00 | 130.3 | 54.63 | 0.7403 | 1.3689 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | -94.44 | 161.5 | 71.93 | .7395 | 1.3756 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | -88.10 | 189.4 | 87.42 | .7413 | 1.3800 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | -37.16 | 308.5 | 153.63 | .9939 | 1.5170 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | -29.49 | 337.9 | 169.95 | .9651 | 1.5075 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | -32.20 | 350.0 | 176.69 | .9701 | 1.5123 |
| o-Methylanisole | $C_8H_{10}O$ | -34.21 | 341.3 | 171.81 | .9796 | 1.5178 |
| m-Methylanisole | $C_8H_{10}O$ | -56.05 | 349.8 | 176.53 | .9716 | 1.5137 |
| p-tert-Butylanisole | $C_{11}H_{16}O$ | 19.11 | 433.7 | 223.18 | .9383 | 1.5030 |
| n-Propyl phenyl ether | $C_9H_{12}O$ | -27.09 | 372.8 | 189.31 | .9475 | 1.5012 |
| Isopropyl phenyl ether | $C_9H_{12}O$ | -33.05 | 350.1 | 176.73 | .9405 | 1.4975 |
| tert-Butyl phenyl ether | $C_{10}H_{14}O$ | -18.38 | [a]369 | [a]187 | .9247 | 1.4880 |
| Methyl benzyl ether | $C_8H_{10}O$ | -53.11 | 337.8 | 169.9 | .9630 | 1.5019 |
| Isopropyl benzyl ether | $C_{10}H_{14}O$ | -67.18 | 379 | [a]193 | .9214 | 1.4859 |
| Methyl methallyl ether | $C_5H_{10}O$ | -113.15 | 152.3 | 66.86 | .7772 | 1.3941 |
| Isopropyl methallyl ether | $C_7H_{14}O$ | -------- | 217.8 | 103.20 | .7753 | 1.4012 |
| tert-Butyl methallyl ether | $C_8H_{16}O$ | -85.69 | [a]237 | [a]114 | .7853 | 1.4083 |
| Dimethallyl ether | $C_8H_{14}O$ | -57.72 | 273.9 | 134.40 | .8131 | 1.4285 |
| Phenyl methallyl ether | $C_{10}H_{12}O$ | -33.32 | [a]410 | [a]210 | .9634 | 1.5157 |
| Methyl cyclopropyl ether | $C_4H_8O$ | -------- | 109.8 | 43.20 | .7839 | 1.3799 |
| Methyl cyclopentyl ether | $C_6H_{12}O$ | -135.03 | 221.7 | 105.39 | .8625 | 1.4205 |
| Methyl cyclohexyl ether | $C_7H_{14}O$ | -74.39 | 272.0 | 133.35 | .8756 | 1.4346 |

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

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TABLE III - A.S.T.M. AVIATION AND A.S.T.M. SUPERCHARGE PERFORMANCE NUMBERS OF LEADED AND UNLEADED BLENDS WITH ISOOCTANE AND WITH MIXED BASE FUEL CONSISTING OF 87.5-PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE[a]

(a) Paraffins and olefins.

| Paraffins and olefins | Formula | Performance number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A.S.T.M. Aviation method | | | | | | | A.S.T.M. Supercharge method (F/A=0.11) | | |
| | | Unleaded | | 4 ml TEL/gal | | 4 ml TEL/gal | | | | | |
| | | Volume percent paraffin or olefin in blend with isooctane | | | | Volume percent paraffin or olefin in blend with mixed base fuel[b] | | | | | |
| | | 10 | 20 | 10 | 20 | 10 | 25 | 50 | 10 | 25 | 50 |
| **Paraffins** | | | | | | | | | | | |
| 2-Methylbutane[c] | $C_5H_{12}$ | --- | ---- | ----- | ------ | --- | 128 | --- | 115 | 121 | 130 |
| 2,2-Dimethylbutane[c] | $C_6H_{14}$ | --- | ---- | ----- | ------ | --- | 129 | --- | 117 | 122 | 129 |
| 2,3-Dimethylbutane[c] | | --- | ---- | ----- | ------ | --- | 129 | --- | 117 | 130 | 147 |
| 2,2,3-Trimethylbutane[c] | $C_7H_{16}$ | 101 | 104 | 151 | 151 | 124 | 135 | 142 | 127 | 146 | 200 |
| 2,3-Dimethylpentane | | --- | 88 | ----- | 145 | --- | 118 | --- | --- | 114 | ---- |
| 2,2,3-Trimethylpentane[c] | $C_8H_{18}$ | --- | ---- | ----- | ------ | --- | 130 | --- | 123 | 141 | 174 |
| 2,3,3-Trimethylpentane[c] | | --- | ---- | ----- | ------ | --- | 124 | --- | 127 | 138 | 166 |
| 2,3,4-Trimethylpentane[c] | | --- | ---- | ----- | ------ | --- | 122 | --- | 118 | 132 | 147 |
| 2,2,3,3-Tetramethylpentane[c] | $C_9H_{20}$ | --- | 84 | ----- | 128 | --- | 107 | --- | 127 | 156 | >230 |
| 2,2,3,4-Tetramethylpentane | | 96 | 96 | 145 | 133 | 120 | 118 | 111 | 125 | 141 | 175 |
| 2,2,4,4-Tetramethylpentane[c] | | --- | ---- | ----- | ------ | --- | 118 | --- | 111 | 110 | 108 |
| 2,3,3,4-Tetramethylpentane | | 93 | 93 | 137 | 131 | 117 | 110 | 106 | 125 | 143 | 192 |
| 2,4-Dimethyl-3-ethylpentane | | --- | 86 | ----- | 140 | --- | 115 | --- | --- | 127 | ---- |
| **Olefins** | | | | | | | | | | | |
| 2,3-Dimethyl-2-pentene | $C_7H_{14}$ | --- | 78 | ----- | 108 | --- | 100 | --- | --- | 117 | ---- |
| 2,3,4-Trimethyl-2-pentene | $C_8H_{16}$ | 80 | 77 | 127 | 113 | 113 | 101 | 77 | 112 | 104 | 77 |
| 2,4,4-Trimethyl-1-pentene[c] | | --- | ---- | ----- | ------ | --- | 105 | --- | 131 | 146 | 159 |
| 2,4,4-Trimethyl-2-pentene[c] | | --- | ---- | ----- | ------ | --- | 108 | --- | 115 | 119 | 103 |
| 3,4,4-Trimethyl-2-pentene | | 96 | 92 | 133 | 120 | 114 | 106 | 88 | 118 | 108 | 93 |

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[a]Performance numbers greater than 161 were determined as follows:

$$\text{performance number} = 161\frac{\text{imep of blend}}{\text{imep of isooctane + 6 ml TEL/gal}}$$

[b]A.S.T.M. Aviation and A.S.T.M. Supercharge performance numbers of mixed base fuel, 120 and 112, respectively.

[c]A.S.T.M. Supercharge data for compound determined at a commercial laboratory; A.S.T.M. Aviation data determined at NACA Lewis laboratory.

TABLE III - A.S.T.M. AVIATION AND A.S.T.M. SUPERCHARGE PERFORMANCE NUMBERS OF LEADED AND UNLEADED BLENDS WITH ISOOCTANE AND WITH MIXED BASE FUEL CONSISTING OF 87.5-PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE[a] - Continued

(b) Aromatics.

| Aromatic | Formula | Performance number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A.S.T.M. Aviation method | | | | | | | A.S.T.M. Supercharge method (F/A=0.11) | | |
| | | Unleaded | | 4 ml TEL/gal | | 4 ml TEL/gal | | | | | |
| | | Volume percent aromatic in blend with isooctane | | | | Volume percent aromatic in blend with mixed base fuel[b] | | | | | |
| | | 10 | 20 | 10 | 20 | 10 | 25 | 50 | 10 | 25 | 50 |
| Benzene | $C_6H_6$ | 96 | 92 | ----- | ------ | 121 | 116 | 97±6 | 125 | 140 | 175 |
| Methylbenzene | $C_7H_8$ | ---- | 94 | ----- | 139 | 121 | 117 | 113 | 128 | 152 | >290 |
| Ethylbenzene | $C_8H_{10}$ | 97 | 95 | ----- | 138 | 120 | 119 | 106 | 130 | 155 | >260 |
| 1,2-Dimethylbenzene | | 93 | 86 | 136 | 118 | 113 | 105 | 84 | 104 | 101 | 112 |
| 1,3-Dimethylbenzene | | 100 | 98 | 150 | ------ | 125 | 123 | 122 | 131 | 166 | 297 |
| 1,4-Dimethylbenzene | | 98 | 99 | 148 | 138 | 125 | 122 | ---- | 130 | 164 | >300 |
| n-Propylbenzene | $C_9H_{12}$ | 96 | 93 | 146 | ------ | 126 | 122 | 118 | 127 | 152 | 205 |
| Isopropylbenzene | | 98 | --- | ----- | ------ | 122 | 122 | ---- | 133 | 153 | 284 |
| 1-Methyl-2-ethylbenzene | | ---- | 86 | ----- | 124 | ---- | 107 | ---- | --- | 124 | ---- |
| 1-Methyl-3-ethylbenzene | | ---- | 95 | ----- | 142 | ---- | 124 | ---- | --- | 168 | ---- |
| 1-Methyl-4-ethylbenzene | | 96 | 88 | ----- | ------ | 122 | 120 | ---- | 134 | 160 | 214 |
| 1,2,3-Trimethylbenzene | | ---- | 85 | ----- | 115 | ---- | 105 | ---- | --- | 104 | ---- |
| 1,2,4-Trimethylbenzene | | 91 | 87 | 141 | 121 | 113 | 101 | 97 | 107 | 113 | 147 |
| 1,3,5-Trimethylbenzene | | ---- | --- | 150 | ------ | 123 | 127 | ---- | 137 | 168 | >300 |
| n-Butylbenzene | $C_{10}H_{14}$ | 96 | 89 | ----- | ------ | 118 | 118 | 111 | 123 | 135 | 156 |
| Isobutylbenzene | | 97 | 93 | ----- | ------ | 120 | 119 | 116 | 125 | 144 | 174 |
| sec-Butylbenzene | | 96 | 93 | 146 | 138 | 123 | 122 | 112 | 125 | 147 | 177 |
| tert-Butylbenzene | | 98 | 99 | 151 | 142 | 125 | 127 | 126 | 135 | 162 | 287 |
| 1-Methyl-4-isopropylbenzene | | 98 | 95 | ----- | ------ | 126 | 123 | 113 | 130 | 158 | 223 |
| 1,2-Diethylbenzene | | ---- | 84 | ----- | 125 | ---- | 107 | ---- | --- | 124 | ---- |
| 1,3-Diethylbenzene | | 96 | 92 | 145 | ------ | ---- | 123 | ---- | 136 | 165 | 226 |
| 1,4-Diethylbenzene | | ---- | 94 | ----- | 136 | ---- | 119 | ---- | --- | 163 | ---- |
| 1,3-Dimethyl-5-ethylbenzene | | ---- | 95 | ----- | 140 | ---- | 124 | ---- | --- | 171 | ---- |
| 1-Methyl-3-tert-butylbenzene | $C_{11}H_{16}$ | ---- | 93 | ----- | 141 | ---- | 125 | ---- | --- | 169 | ---- |
| 1-Methyl-4-tert-butylbenzene | | ---- | 97 | ----- | 142 | ---- | 124 | ---- | --- | 176 | ---- |
| 1-Methyl-3,5-diethylbenzene | | ---- | 95 | ----- | 140 | ---- | 126 | ---- | --- | 171 | ---- |
| 1,3,5-Triethylbenzene | $C_{12}H_{18}$ | ---- | 93 | ----- | 140 | ---- | 122 | ---- | --- | 170 | ---- |

[a]Performance numbers greater than 161 were determined as follows:

$$\text{performance number} = 161\frac{\text{imep of blend}}{\text{imep of isooctane + 6 ml TEL/gal}}$$

[b]A.S.T.M. Aviation and A.S.T.M. Supercharge performance numbers of mixed base fuel, 120 and 112, respectively.

TABLE III - A.S.T.M. AVIATION AND A.S.T.M. SUPERCHARGE PERFORMANCE NUMBERS OF LEADED AND UNLEADED BLENDS WITH ISOOCTANE AND WITH MIXED BASE FUEL CONSISTING OF 87.5-PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE[a] - Concluded

(c) Ethers.

| Ether | Formula | Performance number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A.S.T.M. Aviation method | | | | | | | | A.S.T.M. Supercharge method (F/A=0.11) | |
| | | Unleaded | | 4 ml TEL/gal | | 4 ml TEL/gal | | | | | |
| | | Volume percent aromatic in blend with isooctane | | | | Volume percent ether in blend with mixed base fuel[b] | | | | | |
| | | 10 | 20 | 10 | 20 | 10 | 25 | 50 | 10 | 25 | 50 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 100 | 102 | 149 | [c]153 | 134 | 143 | 150 | 137 | 175 | 250 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | 100 | 104 | 157 | 161 | 140 | 144 | 150 | 132 | 150 | 185 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | 103 | 104 | 160 | 161 | 137 | 149 | 160 | 126 | 150 | 185 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | 93 | 90 | 141 | 121 | 118 | 107 | 94 | 125 | 142 | 137 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | 99 | 97 | 140 | 120 | 120 | 111 | 100 | 128 | 146 | 137 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | 99 | 99 | 144 | 133 | 120 | 112 | 100 | 133 | 145 | 136 |
| m-Methylanisole | $C_8H_{10}O$ | --- | ---- | ----- | ------ | --- | 110 | --- | --- | 147 | --- |
| o-Methylanisole | $C_8H_{10}O$ | --- | ---- | ----- | ------ | --- | 82 | --- | --- | 94 | --- |
| p-tert-Butylanisole | $C_{11}H_{16}O$ | --- | ---- | ----- | ------ | --- | 110 | --- | --- | 147 | --- |
| n-Propyl phenyl ether | $C_9H_{12}O$ | --- | ---- | ----- | ------ | --- | 110 | --- | --- | 149 | --- |
| Isopropyl phenyl ether | $C_9H_{12}O$ | --- | ---- | ----- | ------ | --- | 110 | --- | --- | 150 | --- |
| tert-Butyl phenyl ether | $C_{10}H_{14}O$ | --- | ---- | ----- | ------ | --- | 107 | --- | --- | 137 | --- |
| Methyl benzyl ether | $C_8H_{10}O$ | --- | ---- | ----- | ------ | --- | 104 | --- | --- | 111 | --- |
| Isopropyl benzyl ether | $C_{10}H_{14}O$ | --- | ---- | ----- | ------ | --- | 119 | --- | --- | 140 | --- |
| Phenyl methallyl ether | $C_{10}H_{12}O$ | --- | ---- | ----- | ------ | --- | 48 | --- | --- | 64 | --- |
| Methyl methallyl ether | $C_5H_{10}O$ | --- | ---- | ----- | ------ | --- | 93 | --- | --- | 92 | --- |
| Isopropyl methallyl ether | $C_7H_{14}O$ | --- | ---- | ----- | ------ | --- | 106 | --- | --- | 102 | --- |
| tert-Butyl methallyl ether | $C_8H_{16}O$ | --- | ---- | ----- | ------ | --- | 106 | --- | --- | 109 | --- |
| Dimethallyl ether | $C_8H_{14}O$ | --- | ---- | ----- | ------ | --- | 77 | --- | --- | 90 | --- |
| Methyl cyclopropyl ether | $C_4H_8O$ | --- | ---- | ----- | ------ | --- | 76 | --- | --- | 94 | --- |
| Methyl cyclopentyl ether | $C_6H_{12}O$ | --- | ---- | ----- | ------ | --- | 80 | --- | --- | 83 | --- |
| Methyl cyclohexyl ether | $C_7H_{14}O$ | --- | ---- | ----- | ------ | --- | 68 | --- | --- | 79 | --- |

[a]Performance numbers greater than 161 were determined as follows:

$$\text{performance number} = 161\frac{\text{imep of blend}}{\text{imep of isooctane + 6 ml TEL/gal}}$$

[b]A.S.T.M. Aviation and A.S.T.M. Supercharge performance numbers of mixed base fuel, 120 and 112, respectively.

TABLE IV - A.S.T.M. SUPERCHARGE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF BLENDS WITH MIXED BASE FUEL CONSISTING OF 87.5-PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE + 4 ML TEL PER GALLON

[Standard conditions]

(a) Paraffins and olefins.

| Paraffins and olefins | Formula | Imep ratio[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Volume percent added paraffin or olefin in blend with mixed base fuel | | | | | | | | | | | | | | |
| | | 10 | | | | | 25 | | | | | 50 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Paraffins | | | | | | | | | | | | | | | | |
| 2,2,3-Trimethylbutane | $C_7H_{16}$ | 1.02 | 1.05 | 1.08 | 1.09 | 1.11 | 1.12 | 1.21 | 1.26 | 1.29 | 1.30 | 1.49 | 1.51 | 1.66 | 1.73 | 1.74 |
| 2,3-Dimethylpentane | | ----- | ---- | ----- | ---- | ---- | .96 | .96 | .98 | 1.00 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 2,2,3,3-Tetramethylpentane | $C_9H_{20}$ | ----- | ---- | ----- | ---- | ---- | 0.83 | 0.83 | 1.06 | 1.31 | 1.39 | ----- | ---- | ----- | ---- | ---- |
| 2,2,3,4-Tetramethylpentane | | 0.90 | 0.93 | 1.04 | 1.08 | 1.10 | .85 | .88 | 1.05 | 1.19 | 1.24 | 0.80 | 0.75 | 0.88 | 1.46 | 1.59 |
| 2,3,3,4-Tetramethylpentane | | .95 | .94 | 1.03 | 1.09 | 1.11 | .87 | .84 | 1.06 | 1.23 | 1.28 | .75 | .70 | 1.06 | 1.50 | 1.76 |
| 2,4-Dimethyl-3-ethylpentane | | ----- | ---- | ----- | ---- | ---- | 1.05 | 1.05 | 1.07 | 1.09 | 1.10 | ----- | ---- | ----- | ---- | ---- |
| Olefins | | | | | | | | | | | | | | | | |
| 2,3-Dimethyl-2-pentene | $C_7H_{14}$ | ----- | ---- | ----- | ---- | ---- | 0.75 | 0.79 | 0.88 | 0.95 | 1.02 | ----- | ---- | ----- | ---- | ---- |
| 2,3,4-Trimethyl-2-pentene | $C_8H_{16}$ | 0.84 | 0.82 | 0.92 | 1.00 | 1.00 | 0.69 | 0.67 | 0.72 | 0.86 | 0.93 | 0.59 | 0.50 | 0.48 | 0.58 | 0.67 |
| 3,4,4-Trimethyl-2-pentene | | .87 | .87 | 1.00 | 1.02 | 1.03 | .75 | .73 | .79 | .91 | .97 | .66 | .59 | .59 | .72 | .84 |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of mixed base fuel with 4 ml TEL/gal}}$

TABLE IV - A.S.T.M. SUPERCHARGE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF BLENDS WITH MIXED BASE FUEL CONSISTING OF 87.5-PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE + 4 ML TEL PER GALLON - Continued

[Standard conditions]

(b) Aromatics.

| Aromatic | Formula | Imep ratio[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Volume percent aromatic in blend with mixed base fuel | | | | | | | | | | | | | | |
| | | 10 | | | | | 25 | | | | | 50 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Benzene | $C_6H_6$ | 1.03 | 1.01 | 1.04 | 1.05 | 1.07 | 1.06 | 1.10 | 1.12 | 1.15 | 1.19 | 0.74 | 0.73 | 1.23 | 1.39 | 1.51 |
| Methylbenzene | $C_7H_8$ | 1.01 | 1.05 | 1.08 | 1.10 | 1.13 | 1.00 | 1.04 | 1.18 | 1.29 | 1.37 | 0.84 | 0.99 | 1.27 | 2.43 | ---- |
| Ethylbenzene | $C_8H_{10}$ | 1.06 | 1.07 | 1.11 | 1.12 | 1.14 | 1.02 | 1.08 | 1.21 | 1.29 | 1.37 | 0.99 | 1.07 | 1.44 | 1.71 | ---- |
| 1,2-Dimethylbenzene | | .95 | .94 | .95 | .92 | .91 | .78 | .80 | .89 | .91 | .91 | .68 | .73 | .87 | .95 | 1.00 |
| 1,3-Dimethylbenzene | | .95 | 1.02 | 1.12 | 1.15 | 1.16 | .82 | .98 | 1.33 | 1.45 | 1.51 | .80 | .92 | 1.72 | 2.36 | 2.70 |
| 1,4-Dimethylbenzene | | 1.04 | 1.07 | 1.10 | 1.10 | 1.11 | 1.01 | 1.09 | 1.28 | 1.39 | 1.50 | .94 | 1.03 | 1.57 | 2.83 | ---- |
| n-Propylbenzene | $C_9H_{12}$ | 0.94 | 0.99 | 1.08 | 1.10 | 1.11 | 0.94 | 1.08 | 1.24 | 1.30 | 1.38 | 0.73 | 0.78 | 1.18 | 1.37 | 1.86 |
| Isopropylbenzene | | 1.14 | 1.13 | 1.13 | 1.11 | 1.12 | 1.05 | 1.07 | 1.14 | 1.25 | 1.30 | .93 | 1.03 | 1.41 | 1.92 | 2.58 |
| 1-Methyl-2-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | .86 | .91 | 1.03 | 1.08 | 1.09 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-3-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.11 | 1.14 | 1.28 | 1.40 | 1.47 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-4-ethylbenzene | | 1.01 | 1.04 | 1.11 | 1.15 | 1.16 | .98 | 1.01 | 1.21 | 1.34 | 1.43 | .93 | .98 | 1.27 | 1.51 | 1.93 |
| 1,2,3-Trimethylbenzene | | ----- | ---- | ----- | ---- | ---- | .82 | .85 | .90 | .93 | .94 | ----- | ---- | ----- | ---- | ---- |
| 1,2,4-Trimethylbenzene | | .92 | .95 | .98 | .98 | .97 | .81 | .85 | 1.02 | 1.03 | 1.08 | .81 | .83 | 1.04 | 1.21 | 1.34 |
| 1,3,5-Trimethylbenzene | | 1.09 | 1.10 | 1.13 | 1.16 | 1.18 | .94 | .95 | 1.26 | 1.39 | 1.49 | 1.02 | 1.04 | 1.61 | 2.86 | ---- |
| n-Butylbenzene | $C_{10}H_{14}$ | 0.95 | 1.00 | 1.04 | 1.07 | 1.08 | 0.87 | 0.96 | 1.12 | 1.16 | 1.18 | 0.77 | 0.91 | 1.23 | 1.34 | 1.42 |
| Isobutylbenzene | | .95 | 1.04 | 1.09 | 1.09 | 1.11 | .81 | .97 | 1.20 | 1.25 | 1.30 | .90 | 1.02 | 1.28 | 1.44 | 1.59 |
| sec-Butylbenzene | | 1.01 | .99 | 1.03 | 1.07 | 1.09 | 1.03 | 1.01 | 1.14 | 1.25 | 1.31 | .98 | .97 | 1.17 | 1.43 | 1.63 |
| tert-Butylbenzene | | 1.06 | 1.06 | 1.10 | 1.14 | 1.16 | 1.12 | 1.17 | 1.31 | 1.42 | 1.47 | 1.06 | 1.13 | 1.46 | 2.28 | 2.58 |
| 1-Methyl-4-isopropylbenzene | | 1.01 | 1.06 | 1.12 | 1.15 | 1.15 | .91 | 1.03 | 1.23 | 1.34 | 1.43 | .77 | .87 | 1.35 | 1.84 | 2.03 |
| 1,2-Diethylbenzene | | ----- | ---- | ----- | ---- | ---- | .93 | .96 | 1.01 | 1.04 | 1.07 | ----- | ---- | ----- | ---- | ---- |
| 1,3-Diethylbenzene | | 1.04 | 1.09 | 1.18 | 1.18 | 1.19 | .99 | 1.07 | 1.28 | 1.42 | 1.51 | .82 | .86 | 1.23 | 1.81 | 2.09 |
| 1,4-Diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.10 | 1.13 | 1.22 | 1.34 | 1.43 | ----- | ---- | ----- | ---- | ---- |
| 1,3-Dimethyl-5-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.07 | 1.11 | 1.28 | 1.41 | 1.49 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-3-tert-butylbenzene | $C_{11}H_{16}$ | ----- | ---- | ----- | ---- | ---- | 1.10 | 1.15 | 1.28 | 1.40 | 1.49 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-4-tert-butylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.11 | 1.14 | 1.28 | 1.43 | 1.53 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-3,5-diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.10 | 1.15 | 1.27 | 1.39 | 1.50 | ----- | ---- | ----- | ---- | ---- |
| 1,3,5-Triethylbenzene | $C_{12}H_{18}$ | ----- | ---- | ----- | ---- | ---- | 1.07 | 1.11 | 1.25 | 1.40 | 1.51 | ----- | ---- | ----- | ---- | ---- |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of mixed base fuel with 4 ml TEL/gal}}$

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TABLE IV - A.S.T.M. SUPERCHARGE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF BLENDS WITH MIXED BASE FUEL CONSISTING OF 87.5-PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE + 4 ML TEL PER GALLON - Concluded

[Standard conditions]

(c) Ethers.

| Ether | Formula | Imep ratio[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Volume percent ether in blend with mixed base fuel | | | | | | | | | | | | | | |
| | | 10 | | | | | 25 | | | | | 50 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 1.07 | 1.01 | 1.11 | 1.18 | 1.21 | 1.34 | 1.13 | 1.39 | 1.52 | 1.59 | 2.22 | 1.44 | 1.85 | 2.08 | 2.34 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | 1.13 | 1.12 | 1.14 | 1.16 | 1.17 | 1.37 | 1.15 | 1.25 | 1.34 | 1.37 | 1.97 | 1.25 | 1.48 | 1.56 | 1.70 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | 1.13 | 1.07 | 1.09 | 1.10 | 1.11 | 1.34 | 1.26 | 1.24 | 1.29 | 1.33 | [b]2.3 | 1.45 | 1.45 | 1.53 | 1.66 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | .94 | .93 | 1.03 | 1.07 | 1.10 | .87 | .72 | .96 | 1.13 | 1.25 | .89 | .63 | .55 | .92 | 1.21 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | .97 | .94 | 1.05 | 1.11 | 1.12 | .99 | .81 | 1.05 | 1.21 | 1.30 | .95 | .65 | .64 | .96 | 1.21 |
| Methyl p-tolyl ether (p-methylanisole) | $C_9H_{10}O$ | .99 | .90 | 1.05 | 1.13 | 1.16 | .91 | .74 | .98 | 1.15 | 1.29 | .94 | .65 | .56 | .98 | 1.19 |
| m-Methylanisole | $C_8H_{10}O$ | ----- | ---- | ----- | ---- | ---- | .97 | .90 | 1.07 | 1.21 | 1.31 | ----- | ---- | ----- | ---- | ---- |
| o-Methylanisole | $C_8H_{10}O$ | ----- | ---- | ----- | ---- | ---- | .60 | .52 | .57 | .75 | .85 | ----- | ---- | ----- | ---- | ---- |
| p-tert-Butylanisole | $C_{11}H_{16}O$ | ----- | ---- | ----- | ---- | ---- | .95 | .91 | .94 | 1.10 | 1.32 | ----- | ---- | ----- | ---- | ---- |
| n-Propyl phenyl ether | $C_9H_{12}O$ | ----- | ---- | ----- | ---- | ---- | 1.06 | 1.00 | 1.17 | 1.27 | 1.35 | ----- | ---- | ----- | ---- | ---- |
| Isopropyl phenyl ether | $C_9H_{12}O$ | ----- | ---- | ----- | ---- | ---- | .99 | .90 | 1.05 | 1.26 | 1.35 | ----- | ---- | ----- | ---- | ---- |
| tert-Butyl phenyl ether | $C_{10}H_{14}O$ | ----- | ---- | ----- | ---- | ---- | .88 | .81 | .92 | 1.06 | 1.21 | ----- | ---- | ----- | ---- | ---- |
| Methyl benzyl ether | $C_8H_{10}O$ | ----- | ---- | ----- | ---- | ---- | .83 | .89 | .95 | .96 | .99 | ----- | ---- | ----- | ---- | ---- |
| Isopropyl benzyl ether | $C_{10}H_{14}O$ | ----- | ---- | ----- | ---- | ---- | .95 | .95 | 1.10 | 1.20 | 1.24 | ----- | ---- | ----- | ---- | ---- |
| Phenyl methallyl ether | $C_{10}H_{12}O$ | ----- | ---- | ----- | ---- | ---- | .48 | .44 | .38 | .45 | .54 | ----- | ---- | ----- | ---- | ---- |
| Methyl methallyl ether | $C_5H_{10}O$ | ----- | ---- | ----- | ---- | ---- | .64 | .66 | .79 | .81 | .83 | ----- | ---- | ----- | ---- | ---- |
| Isopropyl methallyl ether | $C_7H_{14}O$ | ----- | ---- | ----- | ---- | ---- | .77 | .71 | .85 | .90 | .92 | ----- | ---- | ----- | ---- | ---- |
| tert-Butyl methallyl ether | $C_8H_{16}O$ | ----- | ---- | ----- | ---- | ---- | .68 | .66 | .81 | .90 | .97 | ----- | ---- | ----- | ---- | ---- |
| Dimethallyl ether | $C_8H_{14}O$ | ----- | ---- | ----- | ---- | ---- | .64 | .58 | .68 | .78 | .81 | ----- | ---- | ----- | ---- | ---- |
| Methyl cyclopropyl ether | $C_4H_8O$ | ----- | ---- | ----- | ---- | ---- | .61 | .57 | .72 | .82 | .85 | ----- | ---- | ----- | ---- | ---- |
| Methyl cyclopentyl ether | $C_6H_{12}O$ | ----- | ---- | ----- | ---- | ---- | .67 | .61 | .69 | .75 | .75 | ----- | ---- | ----- | ---- | ---- |
| Methyl cyclohexyl ether | $C_7H_{14}O$ | ----- | ---- | ----- | ---- | ---- | .63 | .65 | .61 | .67 | .70 | ----- | ---- | ----- | ---- | ---- |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of mixed base fuel with 4 ml TEL/gal}}$

[b]Approximate value.

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TABLE V - 17.6 ENGINE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF UNLEADED BLENDS WITH ISOOCTANE

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

(a) Paraffins and olefins.

| Paraffins and olefins | Formula | Imep ratio[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inlet-air temperature, 250° F | | | | | | | | | | Inlet-air temperature, 100° F | | | | |
| | | Volume percent added paraffin or olefin in blend with isooctane | | | | | | | | | | | | | | |
| | | 10 | | | | | 25 | | | | | 50 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Paraffins | | | | | | | | | | | | | | | | |
| 2,2,3-Trimethylbutane | $C_7H_{16}$ | 1.02 | 1.02 | 1.03 | 1.09 | 1.10 | 1.08 | 1.07 | 1.09 | 1.17 | 1.20 | 1.16 | 1.15 | 1.21 | 1.20 | 1.20 |
| 2,3-Dimethylpentane | | ----- | ---- | ----- | ---- | ---- | .95 | .96 | .94 | .94 | .94 | .93 | .93 | .95 | .94 | .93 |
| 2,2,3,3-Tetramethylpentane | $C_9H_{20}$ | ----- | ---- | ----- | ---- | ---- | 1.12 | 1.14 | 1.20 | 1.32 | 1.31 | 1.23 | 1.22 | 1.27 | 1.27 | 1.27 |
| 2,2,3,4-Tetramethylpentane | | 0.96 | 0.96 | 1.01 | 1.11 | 1.13 | .91 | .91 | 1.00 | 1.15 | 1.22 | 1.09 | 1.10 | 1.15 | 1.21 | 1.22 |
| 2,3,3,4-Tetramethylpentane | | .97 | .98 | 1.03 | 1.06 | 1.13 | .95 | .96 | 1.07 | 1.16 | 1.27 | 1.17 | 1.19 | 1.22 | 1.27 | 1.27 |
| 2,4-Dimethyl-3-ethylpentane | | ----- | ---- | ----- | ---- | ---- | .99 | 1.00 | 1.00 | 1.01 | 1.00 | 1.03 | 1.02 | 1.02 | .98 | .97 |
| Olefins | | | | | | | | | | | | | | | | |
| 2,3-Dimethyl-2-pentene | $C_7H_{14}$ | ----- | ---- | ----- | ---- | ---- | 0.99 | 0.99 | 1.01 | 1.09 | 1.15 | 1.14 | 1.12 | 1.17 | 1.23 | 1.27 |
| 2,3,4-Trimethyl-2-pentene | $C_8H_{16}$ | 0.90 | 0.90 | 0.89 | 0.91 | 0.96 | 0.79 | 0.79 | 0.78 | 0.82 | 0.89 | 0.95 | 0.95 | 0.96 | 0.99 | 1.02 |
| 3,4,4-Trimethyl-2-pentene | | .96 | .98 | .99 | 1.00 | 1.05 | .93 | .94 | .94 | .98 | 1.06 | 1.05 | 1.04 | 1.08 | 1.16 | 1.20 |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend}}{\text{knock-limited imep of isooctane}}$

TABLE V - 17.6 ENGINE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF UNLEADED BLENDS WITH ISOOCTANE - Continued

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

(b) Aromatics.

| Aromatic | Formula | Imep ratio[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inlet-air temperature, 250° F | | | | | | | | | | Inlet-air temperature, 100° F | | | | |
| | | Volume percent aromatic in blend with isooctane | | | | | | | | | | | | | | |
| | | 10 | | | | | 25 | | | | | 50 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Benzene | $C_6H_6$ | 1.00 | 1.01 | 1.02 | 1.03 | 1.04 | 1.00 | 1.01 | 1.02 | 1.10 | 1.17 | 1.08 | 1.06 | 1.08 | 1.12 | 1.15 |
| Methylbenzene | $C_7H_8$ | 1.04 | 1.02 | 1.05 | 1.08 | 1.11 | 1.04 | 1.02 | 1.11 | 1.21 | 1.26 | 1.05 | 1.07 | 1.18 | 1.21 | 1.24 |
| Ethylbenzene | $C_8H_{10}$ | 1.02 | 1.02 | 1.04 | 1.11 | 1.16 | 1.02 | 1.00 | 1.07 | 1.21 | 1.31 | 1.19 | 1.21 | 1.28 | 1.35 | 1.36 |
| 1,2-Dimethylbenzene | | .95 | .95 | .93 | .97 | 1.00 | .90 | .89 | .87 | .93 | .99 | .97 | .98 | 1.00 | 1.02 | 1.06 |
| 1,3-Dimethylbenzene | | .97 | .98 | 1.03 | 1.07 | 1.08 | .93 | .94 | 1.08 | 1.14 | 1.18 | 1.14 | 1.15 | 1.22 | 1.35 | 1.40 |
| 1,4-Dimethylbenzene | | 1.01 | 1.01 | 1.10 | 1.12 | 1.14 | 1.04 | 1.04 | 1.16 | 1.28 | 1.38 | 1.15 | 1.20 | 1.29 | 1.34 | 1.40 |
| n-Propylbenzene | $C_9H_{12}$ | 0.99 | 0.99 | 1.00 | 1.10 | 1.16 | 0.99 | 0.99 | 1.02 | 1.15 | 1.23 | 1.14 | 1.14 | 1.19 | 1.30 | 1.32 |
| Isopropylbenzene | | 1.01 | 1.00 | 1.09 | 1.14 | 1.16 | 1.05 | .98 | 1.07 | 1.20 | 1.29 | 1.15 | 1.20 | 1.29 | 1.32 | 1.34 |
| 1-Methyl-2-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.03 | 1.01 | 1.03 | 1.07 | 1.10 | 1.03 | 1.04 | 1.09 | 1.08 | 1.10 |
| 1-Methyl-3-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.11 | 1.11 | 1.21 | 1.29 | 1.33 | 1.28 | 1.31 | 1.39 | 1.41 | 1.43 |
| 1-Methyl-4-ethylbenzene | | 1.00 | 1.00 | 1.05 | 1.08 | 1.09 | 1.00 | 1.00 | 1.11 | 1.14 | 1.18 | 1.01 | 1.03 | 1.11 | 1.17 | 1.21 |
| 1,2,3-Trimethylbenzene | | ----- | ---- | ----- | ---- | ---- | .97 | .97 | .99 | 1.00 | 1.02 | 1.04 | 1.03 | 1.05 | 1.07 | 1.09 |
| 1,2,4-Trimethylbenzene | | .91 | .93 | .93 | .99 | 1.01 | .87 | .86 | .91 | .95 | 1.05 | .95 | .95 | 1.02 | 1.07 | 1.10 |
| 1,3,5-Trimethylbenzene | | .96 | .98 | 1.03 | 1.15 | 1.21 | .91 | .95 | 1.08 | 1.27 | 1.42 | 1.15 | 1.16 | 1.31 | 1.48 | 1.51 |
| n-Butylbenzene | $C_{10}H_{14}$ | 0.95 | 0.98 | 0.97 | 0.99 | 1.02 | 0.93 | 0.96 | 0.96 | 0.99 | 1.04 | 1.04 | 1.05 | 1.08 | 1.10 | 1.09 |
| Isobutylbenzene | | .98 | .98 | .99 | 1.02 | 1.07 | .97 | .94 | .96 | 1.03 | 1.11 | 1.10 | 1.11 | 1.15 | 1.19 | 1.20 |
| sec-Butylbenzene | | .98 | 1.00 | 1.05 | 1.08 | 1.10 | .98 | .99 | 1.08 | 1.16 | 1.26 | 1.14 | 1.12 | 1.19 | 1.23 | 1.23 |
| tert-Butylbenzene | | .98 | 1.00 | 1.03 | 1.12 | 1.19 | .95 | .95 | 1.09 | 1.15 | 1.27 | 1.24 | 1.23 | 1.32 | 1.41 | 1.43 |
| 1-Methyl-4-isopropylbenzene | | .98 | .99 | 1.04 | 1.07 | 1.12 | .94 | .95 | 1.02 | 1.10 | 1.20 | 1.14 | 1.14 | 1.21 | 1.33 | 1.37 |
| 1,2-Diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.03 | 1.01 | 1.03 | 1.08 | 1.11 | 1.04 | 1.06 | 1.11 | 1.11 | 1.12 |
| 1,3-Diethylbenzene | | 1.01 | 1.01 | 1.05 | 1.12 | 1.19 | 1.05 | 1.04 | 1.11 | 1.24 | 1.38 | 1.27 | 1.27 | 1.39 | 1.46 | 1.49 |
| 1,4-Diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.11 | 1.12 | 1.23 | 1.34 | 1.41 | 1.32 | 1.33 | 1.41 | 1.44 | 1.41 |
| 1,3-Dimethyl-5-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.10 | 1.07 | 1.17 | 1.24 | 1.29 | 1.24 | 1.26 | 1.31 | 1.35 | 1.32 |
| 1-Methyl-3-tert-butylbenzene | $C_{11}H_{16}$ | ----- | ---- | ----- | ---- | ---- | 1.16 | 1.16 | 1.28 | 1.36 | 1.37 | 1.30 | 1.33 | 1.37 | 1.39 | 1.38 |
| 1-Methyl-4-tert-butylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.12 | 1.14 | 1.22 | 1.31 | 1.37 | 1.31 | 1.32 | 1.37 | 1.40 | 1.38 |
| 1-Methyl-3,5-diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.10 | 1.11 | 1.23 | 1.36 | 1.44 | 1.30 | 1.36 | 1.48 | 1.51 | 1.51 |
| 1,3,5-Triethylbenzene | $C_{12}H_{18}$ | ----- | ---- | ----- | ---- | ---- | 1.09 | 1.09 | 1.19 | 1.31 | 1.42 | 1.35 | 1.37 | 1.46 | 1.50 | 1.48 |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend}}{\text{knock-limited imep of isooctane}}$

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TABLE V - 17.6 ENGINE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF UNLEADED BLENDS WITH ISOOCTANE - Concluded

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

(c) Ethers.

| Ether | Formula | Imep ratio[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inlet-air temperature, 250° F | | | | | | | | | | Inlet-air temperature, 100° F | | | | |
| | | Volume percent ether in blend with isooctane | | | | | | | | | | | | | | |
| | | 10 | | | | | 20 | | | | | 20 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 1.06 | 1.07 | 1.10 | 1.16 | 1.16 | 1.15 | 1.14 | 1.20 | 1.34 | 1.38 | 1.26 | 1.28 | 1.35 | 1.37 | 1.35 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | 1.14 | 1.15 | 1.19 | 1.20 | 1.21 | 1.24 | 1.25 | 1.28 | 1.37 | 1.45 | 1.33 | 1.32 | 1.31 | 1.35 | 1.37 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | 1.11 | 1.11 | 1.12 | 1.15 | 1.14 | 1.19 | 1.19 | 1.21 | 1.27 | 1.30 | 1.29 | 1.29 | 1.27 | 1.27 | 1.26 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | 1.06 | 1.05 | 1.07 | 1.10 | 1.15 | 1.13 | 1.10 | 1.09 | 1.20 | 1.32 | 1.28 | 1.27 | 1.26 | 1.31 | 1.34 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | 1.12 | 1.11 | 1.11 | 1.16 | 1.18 | 1.27 | 1.24 | 1.17 | 1.31 | 1.40 | 1.40 | 1.37 | 1.33 | 1.41 | 1.41 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | 1.12 | 1.09 | 1.12 | 1.18 | 1.21 | 1.20 | 1.14 | 1.17 | 1.28 | 1.38 | 1.29 | 1.29 | 1.34 | 1.42 | 1.44 |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend}}{\text{knock-limited imep of isooctane}}$

TABLE VI - 17.6 ENGINE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF BLENDS WITH ISOOCTANE + 4 ML TEL PER GALLON

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

(a) Paraffins and olefins.

| Paraffins and olefins | Formula | Imep ratio[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inlet-air temperature, 250° F | | | | | | | | | | Inlet-air temperature, 100° F | | | | |
| | | Volume percent added paraffin or olefin in blend with isooctane | | | | | | | | | | | | | | |
| | | 10 | | | | | 20 | | | | | 20 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Paraffins | | | | | | | | | | | | | | | | |
| 2,2,3-Trimethylbutane | $C_7H_{16}$ | 1.05 | 1.06 | 1.09 | 1.10 | 1.10 | 1.13 | 1.16 | 1.22 | 1.23 | 1.24 | 1.20 | 1.18 | 1.22 | 1.20 | 1.19 |
| 2,3-Dimethylpentane | | ----- | ---- | ----- | ---- | ---- | .96 | .97 | .98 | .96 | .95 | .96 | .97 | .97 | .96 | .95 |
| 2,2,3,3-Tetramethylpentane | $C_9H_{20}$ | ----- | ---- | ----- | ---- | ---- | 1.19 | 1.18 | 1.31 | 1.34 | 1.32 | 1.23 | 1.25 | 1.28 | 1.29 | 1.29 |
| 2,2,3,4-Tetramethylpentane | | 1.02 | 1.03 | 1.04 | 1.09 | 1.11 | 1.04 | 1.06 | 1.10 | 1.19 | 1.23 | 1.17 | 1.18 | 1.21 | 1.21 | 1.19 |
| 2,3,3,4-Tetramethylpentane | | 1.05 | 1.05 | 1.09 | 1.14 | 1.17 | 1.10 | 1.10 | 1.15 | 1.24 | 1.27 | 1.17 | 1.18 | 1.20 | 1.20 | 1.19 |
| 2,4-Dimethyl-3-ethylpentane | | ----- | ---- | ----- | ---- | ---- | 1.01 | 1.01 | 1.02 | 1.01 | .99 | 1.00 | 1.01 | 1.01 | 1.01 | 1.00 |
| Olefins | | | | | | | | | | | | | | | | |
| 2,3-Dimethyl-2-pentene | $C_7H_{14}$ | ----- | ---- | ----- | ---- | ---- | 0.95 | 0.95 | 1.00 | 1.13 | 1.16 | 1.14 | 1.14 | 1.19 | 1.24 | 1.23 |
| 2,3,4-Trimethyl-2-pentene | $C_8H_{16}$ | 0.91 | 0.91 | 0.89 | 0.94 | 0.97 | 0.81 | 0.81 | 0.78 | 0.85 | 0.92 | 0.99 | 1.00 | 1.00 | 1.05 | 1.09 |
| 3,4,4-Trimethyl-2-pentene | | .96 | .96 | .97 | 1.01 | 1.05 | .93 | .92 | .92 | .99 | 1.07 | 1.10 | 1.10 | 1.10 | 1.15 | 1.18 |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of isooctane with 4 ml TEL/gal}}$

TABLE VI - 17.6 ENGINE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF BLENDS WITH ISOOCTANE + 4 ML TEL PER GALLON - Continued

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

(b) Aromatics.

| Aromatic | Formula | Imep ratio[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inlet-air temperature, 250° F | | | | | | | | | | Inlet-air temperature, 100° F | | | | |
| | | Volume percent aromatic in blend with isooctane | | | | | | | | | | | | | | |
| | | 10 | | | | | 20 | | | | | 20 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Benzene | $C_6H_6$ | 1.00 | 1.02 | 1.06 | 1.08 | 1.09 | 0.99 | 1.04 | 1.10 | 1.14 | 1.17 | 1.11 | 1.11 | 1.17 | 1.21 | 1.23 |
| Methylbenzene | $C_7H_8$ | 1.01 | 1.03 | 1.04 | 1.05 | 1.10 | 1.05 | 1.07 | 1.11 | 1.19 | 1.26 | 1.13 | 1.17 | 1.23 | 1.29 | 1.31 |
| Ethylbenzene | $C_8H_{10}$ | 1.07 | 1.07 | 1.08 | 1.10 | 1.13 | 1.14 | 1.17 | 1.22 | 1.31 | 1.36 | 1.29 | 1.33 | 1.36 | 1.37 | 1.38 |
| 1,2-Dimethylbenzene | | .89 | .91 | .88 | .87 | .86 | .77 | .82 | .84 | .83 | .82 | .81 | .82 | .84 | .86 | .87 |
| 1,3-Dimethylbenzene | | 1.07 | 1.09 | 1.13 | 1.19 | 1.23 | 1.12 | 1.16 | 1.29 | 1.41 | 1.46 | 1.28 | 1.29 | 1.44 | 1.48 | 1.51 |
| 1,4-Dimethylbenzene | | 1.04 | 1.08 | 1.12 | 1.14 | 1.16 | 1.05 | 1.13 | 1.23 | 1.34 | 1.41 | 1.23 | 1.28 | 1.42 | 1.47 | 1.48 |
| n-Propylbenzene | $C_9H_{12}$ | 1.05 | 1.05 | 1.09 | 1.14 | 1.16 | 1.11 | 1.13 | 1.21 | 1.29 | 1.33 | 1.34 | 1.38 | 1.42 | 1.36 | 1.31 |
| Isopropylbenzene | | 1.04 | 1.10 | 1.12 | 1.16 | 1.20 | 1.10 | 1.12 | 1.19 | 1.31 | 1.38 | 1.33 | 1.35 | 1.35 | 1.38 | 1.41 |
| 1-Methyl-2-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | .96 | 1.00 | 1.05 | 1.01 | .98 | 1.00 | 1.00 | 1.01 | 1.00 | .99 |
| 1-Methyl-3-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.26 | 1.32 | 1.39 | 1.46 | 1.46 | 1.42 | 1.46 | 1.52 | 1.48 | 1.47 |
| 1-Methyl-4-ethylbenzene | | 1.03 | 1.04 | 1.14 | 1.17 | 1.20 | 1.11 | 1.12 | 1.21 | 1.33 | 1.41 | 1.34 | 1.35 | 1.45 | 1.48 | 1.41 |
| 1,2,3-Trimethylbenzene | | ----- | ---- | ----- | ---- | ---- | .83 | .87 | .90 | .89 | .91 | .87 | .88 | .90 | .93 | .94 |
| 1,2,4-Trimethylbenzene | | .91 | .94 | .97 | .95 | .94 | .85 | .88 | .95 | .94 | .94 | .88 | .90 | .94 | .94 | .95 |
| 1,3,5-Trimethylbenzene | | 1.00 | 1.03 | 1.12 | 1.16 | 1.17 | 1.02 | 1.07 | 1.24 | 1.40 | 1.47 | 1.26 | 1.29 | 1.49 | 1.55 | 1.55 |
| n-Butylbenzene | $C_{10}H_{14}$ | 1.01 | 1.03 | 1.04 | 1.03 | 1.06 | 1.02 | 1.04 | 1.07 | 1.10 | 1.11 | 1.10 | 1.11 | 1.12 | 1.14 | 1.14 |
| Isobutylbenzene | | 1.09 | 1.08 | 1.09 | 1.14 | 1.15 | 1.14 | 1.15 | 1.18 | 1.25 | 1.29 | 1.20 | 1.22 | 1.23 | 1.25 | 1.24 |
| sec-Butylbenzene | | 1.09 | 1.08 | 1.08 | 1.14 | 1.17 | 1.16 | 1.13 | 1.20 | 1.29 | 1.35 | 1.26 | 1.28 | 1.30 | 1.31 | 1.31 |
| tert-Butylbenzene | | 1.12 | 1.12 | 1.12 | 1.16 | 1.18 | 1.32 | 1.30 | 1.31 | 1.36 | 1.41 | 1.37 | 1.36 | 1.39 | 1.41 | 1.42 |
| 1-Methyl-4-isopropylbenzene | | 1.08 | 1.08 | 1.13 | 1.17 | 1.19 | 1.12 | 1.13 | 1.22 | 1.39 | 1.45 | 1.30 | 1.32 | 1.42 | 1.42 | 1.43 |
| 1,2-Diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.00 | 1.03 | 1.07 | 1.11 | 1.10 | 1.11 | 1.10 | 1.11 | 1.10 | 1.08 |
| 1,3-Diethylbenzene | | 1.08 | 1.11 | 1.18 | 1.22 | 1.25 | 1.17 | 1.25 | 1.32 | 1.48 | 1.54 | 1.45 | 1.47 | 1.53 | 1.53 | 1.53 |
| 1,4-Diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.25 | 1.27 | 1.32 | 1.42 | 1.45 | 1.40 | 1.47 | 1.53 | 1.49 | 1.47 |
| 1,3-Dimethyl-5-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.17 | 1.24 | 1.35 | 1.38 | 1.38 | 1.39 | 1.46 | 1.53 | 1.46 | 1.43 |
| 1-Methyl-3-tert-butylbenzene | $C_{11}H_{16}$ | ----- | ---- | ----- | ---- | ---- | 1.22 | 1.24 | 1.32 | 1.41 | 1.42 | 1.36 | 1.40 | 1.45 | 1.47 | 1.45 |
| 1-Methyl-4-tert-butylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.23 | 1.25 | 1.32 | 1.36 | 1.36 | 1.37 | 1.40 | 1.44 | 1.45 | 1.45 |
| 1-Methyl-3,5-diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.22 | 1.25 | 1.35 | 1.44 | 1.50 | 1.47 | 1.54 | 1.59 | 1.56 | 1.54 |
| 1,3,5-Triethylbenzene | $C_{12}H_{18}$ | ----- | ---- | ----- | ---- | ---- | 1.20 | 1.24 | 1.36 | 1.49 | 1.51 | 1.49 | 1.58 | 1.59 | 1.53 | 1.53 |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of isooctane with 4 ml TEL/gal}}$

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TABLE VI - 17.6 ENGINE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF BLENDS WITH ISOOCTANE + 4 ML TEL PER GALLON - Concluded

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

(c) Ethers.

| Ether | Formula | Imep ratio[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inlet-air temperature, 250° F | | | | | | | | | | Inlet-air temperature, 100° F | | | | |
| | | Volume percent ether in blend with isooctane | | | | | | | | | | | | | | |
| | | 10 | | | | | 20 | | | | | 20 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 1.14 | 1.15 | 1.19 | 1.21 | 1.22 | 1.26 | 1.26 | 1.32 | 1.42 | 1.43 | 1.41 | 1.43 | 1.45 | 1.47 | 1.46 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | 1.15 | 1.13 | 1.12 | 1.15 | 1.15 | 1.41 | 1.39 | 1.37 | 1.37 | 1.36 | 1.41 | 1.42 | 1.40 | 1.37 | 1.33 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | 1.13 | 1.11 | 1.13 | 1.15 | 1.15 | 1.32 | 1.27 | 1.24 | 1.27 | 1.27 | 1.33 | 1.35 | 1.31 | 1.27 | 1.24 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | 1.07 | 1.07 | 1.07 | 1.13 | 1.16 | 1.16 | 1.14 | 1.11 | 1.26 | 1.37 | 1.34 | 1.33 | 1.33 | 1.39 | 1.40 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | 1.11 | 1.09 | 1.15 | 1.18 | 1.18 | 1.28 | 1.25 | 1.29 | 1.39 | 1.45 | 1.44 | 1.43 | 1.43 | 1.44 | 1.45 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | 1.12 | 1.12 | 1.16 | 1.26 | 1.29 | 1.16 | 1.17 | 1.25 | 1.36 | 1.43 | 1.43 | 1.41 | 1.40 | 1.45 | 1.48 |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of isooctane with 4 ml TEL/gal}}$

TABLE VII - KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF BLENDS WITH MIXED BASE FUEL CONSISTING OF 87.5-PERCENT-(BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE + 4 ML TEL PER GALLON

(a) Paraffins and olefins; 25 volume percent blends.

[For 17.6 engine: compression ratio, 7.0; engine speed, 1800 rpm; coolant temperature, 212° F; spark advance, 30° B.T.C. For full-scale single-cylinder at simulated take-off: compression ratio, 7.3; engine speed, 2500 rpm; inlet-air temperature, 250° F; spark advance, 20° B.T.C.; cooling-air flow such that rear-spark-plug-bushing temperature equals 385° F at 140 bmep and 0.10 fuel-air ratio. For full-scale single-cylinder engine at simulated cruise: same conditions as for take-off except for engine speed, 2000 rpm; inlet-air temperature, 210° F.]

| Paraffins and olefins | Formula | Imep ratio[a] | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 17.6 engine | | | | | | | | | | Full-scale single-cylinder engine | | | | | | | | | |
| | | Inlet-air temperature, 250° F | | | | | Inlet-air temperature, 100° F | | | | | Simulated take-off conditions | | | | | Simulated cruise conditions | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Paraffins | | | | | | | | | | | | | | | | | | | | | |
| 2-Methylbutane | $C_5H_{12}$ | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.07 | 1.05 | 1.14 | 1.10 | 1.09 | 1.10 | 1.12 | 1.14 | 1.11 | 1.07 |
| 2,2-Dimethylbutane | $C_6H_{14}$ | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.13 | 1.10 | 1.08 | 1.07 | 1.05 | 1.10 | 1.13 | 1.10 | 1.07 | 1.07 |
| 2,3-Dimethylbutane | | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.27 | 1.25 | 1.19 | 1.12 | 1.10 | 1.27 | 1.26 | 1.19 | 1.13 | 1.08 |
| 2,2,3-Trimethylbutane | $C_7H_{16}$ | 1.24 | 1.24 | 1.32 | 1.30 | 1.28 | 1.28 | 1.29 | 1.31 | 1.31 | 1.28 | 1.39 | 1.31 | 1.34 | 1.28 | 1.27 | 1.35 | 1.31 | 1.26 | 1.30 | 1.25 |
| 2,3-Dimethylpentane | | 1.03 | 1.03 | 1.06 | 1.04 | 1.02 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 2,2,3-Trimethylpentane | $C_8H_{18}$ | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.26 | 1.22 | 1.27 | 1.25 | 1.23 | 1.27 | 1.26 | 1.26 | 1.28 | 1.24 |
| 2,3,3-Trimethylpentane | | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.26 | 1.21 | 1.22 | 1.21 | 1.20 | 1.19 | 1.20 | 1.18 | 1.22 | 1.21 |
| 2,3,4-Trimethylpentane | | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.15 | 1.06 | 1.16 | 1.17 | 1.15 | 1.17 | 1.16 | 1.17 | 1.18 | 1.14 |
| 2,2,3,3-Tetramethylpentane | $C_9H_{20}$ | 1.26 | 1.26 | 1.35 | 1.39 | 1.37 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 2,2,3,4-Tetramethylpentane | | 1.18 | 1.10 | 1.16 | 1.23 | 1.26 | 1.20 | 1.21 | 1.24 | 1.24 | 1.24 | ----- | ----- | ----- | ----- | ----- | 1.22 | 1.20 | 1.26 | 1.29 | 1.22 |
| 2,2,4,4-Tetramethylpentane | | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.14 | 1.06 | 0.99 | 0.99 | 1.02 | 1.05 | 1.03 | .98 | 1.00 | 1.00 |
| 2,3,3,4-Tetramethylpentane | | 1.13 | 1.11 | 1.19 | 1.29 | 1.30 | 1.22 | 1.22 | 1.27 | 1.30 | 1.28 | ----- | ----- | ----- | ----- | ----- | 1.21 | 1.15 | 1.21 | 1.27 | 1.28 |
| 2,4-Dimethyl-3-ethylpentane | | 1.04 | 1.06 | 1.08 | 1.08 | 1.07 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| Olefins | | | | | | | | | | | | | | | | | | | | | |
| 2,3-Dimethyl-2-pentene | $C_7H_{14}$ | 1.03 | 1.07 | 1.12 | 1.16 | 1.20 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 2,3,4-Trimethyl-2-pentene | $C_8H_{16}$ | 0.94 | 0.94 | 0.94 | 0.99 | 1.05 | 1.12 | 1.11 | 1.11 | 1.14 | 1.16 | ----- | ----- | ----- | ----- | ----- | 0.95 | 0.96 | 1.05 | 1.00 | 1.04 |
| 2,4,4-Trimethyl-1-pentene | | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.04 | 1.01 | 1.14 | 1.32 | 1.37 | 1.26 | 1.23 | 1.31 | 1.35 | 1.33 |
| 2,4,4-Trimethyl-2-pentene | | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.06 | 1.01 | 1.08 | 1.12 | 1.21 | 1.25 | 1.20 | 1.17 | 1.12 | 1.15 |
| 3,4,4-Trimethyl-2-pentene | | .99 | 1.01 | 1.04 | 1.10 | 1.13 | 1.25 | 1.22 | 1.20 | 1.23 | 1.25 | ----- | ----- | ----- | ----- | ----- | 1.18 | 1.12 | 1.17 | 1.13 | 1.12 |

[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of mixed base fuel with 4 ml TEL/gal}}$

TABLE VII - KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF BLENDS WITH MIXED BASE FUEL CONSISTING OF 87.5 PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE + 4 ML TEL PER GALLON - Continued

(b) Aromatics; 25 volume percent blends.

[For 17.6 engine: compression ratio, 7.0; engine speed, 1800 rpm; coolant temperature, 212° F; spark advance, 30° B.T.C. For full-scale single-cylinder at simulated take-off: compression ratio, 7.3; engine speed, 2500 rpm; inlet-air temperature, 250° F; spark advance, 20° B.T.C.; cooling-air flow such that rear-spark-plug-bushing temperature equals 365° F at 140 bmep and 0.10 fuel-air ratio. For full-scale single-cylinder engine at simulated cruise: same conditions as for take-off except for engine speed, 2000 rpm; inlet-air temperature, 210° F]

| Aromatic | Formula | Imep ratio[a] | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 17.6 engine | | | | | | | | | | Full-scale single-cylinder engine | | | | | | | | | |
| | | Inlet-air temperature, 250° F | | | | | Inlet-air temperature, 100° F | | | | | Simulated take-off conditions | | | | | Simulated cruise conditions | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Benzene | $C_6H_6$ | 1.04 | 1.08 | 1.15 | 1.22 | 1.28 | 1.18 | 1.21 | 1.23 | 1.27 | 1.28 | 0.97 | 0.93 | 1.14 | 1.19 | 1.20 | 1.20 | 1.19 | 1.17 | 1.23 | 1.25 |
| Methylbenzene | $C_7H_8$ | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.10 | 1.18 | 1.41 | 1.40 | 1.38 | 1.28 | 1.30 | 1.41 | 1.49 | 1.42 |
| Ethylbenzene | $C_8H_{10}$ | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.18 | 1.22 | 1.35 | 1.36 | 1.34 | 1.35 | 1.39 | 1.45 | 1.39 | 1.35 |
| 1,2-Dimethylbenzene | | 0.81 | 0.84 | 0.89 | 0.91 | 0.92 | 0.89 | 0.90 | 0.91 | 0.92 | 0.94 | .77 | .71 | .98 | .99 | .92 | .77 | .82 | .98 | .99 | .98 |
| 1,3-Dimethylbenzene | | 1.21 | 1.22 | 1.46 | 1.53 | 1.54 | 1.34 | 1.38 | 1.51 | 1.56 | 1.57 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1,4-Dimethylbenzene | | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 1.19 | 1.21 | 1.55 | 1.64 | 1.54 | 1.25 | 1.31 | 1.68 | 1.62 | 1.58 |
| n-Propylbenzene | $C_9H_{12}$ | 1.22 | 1.24 | 1.31 | 1.31 | 1.34 | 1.34 | 1.36 | 1.39 | 1.38 | 1.40 | ----- | ----- | ----- | ----- | ----- | 1.47 | 1.45 | 1.48 | 1.40 | 1.38 |
| Isopropylbenzene | | 1.25 | 1.27 | 1.40 | 1.45 | 1.48 | ----- | ----- | ----- | ----- | ----- | 1.25 | 1.27 | 1.39 | 1.47 | 1.43 | 1.40 | 1.36 | 1.52 | 1.48 | 1.41 |
| 1-Methyl-2-ethylbenzene | | 1.02 | 1.06 | 1.09 | 1.06 | 1.06 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1-Methyl-3-ethylbenzene | | 1.34 | 1.43 | 1.54 | 1.56 | 1.57 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1-Methyl-4-ethylbenzene | | 1.08 | 1.09 | 1.25 | 1.41 | 1.48 | 1.33 | 1.33 | 1.59 | 1.59 | 1.58 | 1.19 | 1.18 | 1.59 | 1.62 | 1.58 | 1.53 | 1.52 | 1.65 | 1.66 | 1.56 |
| 1,2,3-Trimethylbenzene | | .94 | .94 | .99 | .98 | .99 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1,2,4-Trimethylbenzene | | .86 | .92 | 1.01 | 1.03 | 1.03 | .96 | .99 | 1.04 | 1.04 | 1.06 | .88 | .87 | 1.11 | 1.10 | 1.10 | .74 | .87 | 1.05 | 1.08 | 1.07 |
| 1,3,5-Trimethylbenzene | | 1.13 | 1.22 | 1.45 | 1.58 | 1.66 | ----- | ----- | ----- | ----- | ----- | 1.19 | 1.23 | 1.63 | 1.72 | ----- | 1.34 | 1.39 | 1.54 | 1.62 | 1.64 |
| n-Butylbenzene | $C_{10}H_{14}$ | 1.03 | 1.04 | 1.12 | 1.16 | 1.18 | 1.13 | 1.14 | 1.17 | 1.18 | 1.19 | ----- | ----- | ----- | ----- | ----- | 1.11 | 1.10 | 1.20 | 1.22 | 1.19 |
| Isobutylbenzene | | 1.09 | 1.13 | 1.18 | 1.23 | 1.26 | 1.27 | 1.27 | 1.29 | 1.27 | 1.25 | ----- | ----- | ----- | ----- | ----- | 1.35 | 1.31 | 1.35 | 1.34 | 1.31 |
| sec-Butylbenzene | | 1.22 | 1.22 | 1.27 | 1.33 | 1.41 | 1.31 | 1.32 | 1.36 | 1.40 | 1.40 | 1.16 | 1.11 | 1.41 | 1.33 | 1.38 | 1.34 | 1.34 | 1.37 | 1.38 | 1.35 |
| tert-Butylbenzene | | 1.24 | 1.22 | 1.34 | 1.41 | 1.44 | 1.46 | 1.52 | 1.54 | 1.54 | 1.54 | 1.24 | 1.30 | 1.50 | 1.53 | 1.52 | 1.49 | 1.49 | 1.57 | 1.55 | 1.49 |
| 1-Methyl-4-isopropylbenzene | | 1.23 | 1.25 | 1.36 | 1.44 | 1.49 | 1.41 | 1.44 | 1.51 | 1.53 | 1.53 | ----- | ----- | ----- | ----- | ----- | 1.51 | 1.51 | 1.60 | 1.58 | 1.58 |
| 1,2-Diethylbenzene | | 1.07 | 1.11 | 1.14 | 1.14 | 1.13 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1,3-Diethylbenzene | | 1.25 | 1.26 | 1.43 | 1.48 | 1.51 | 1.47 | 1.48 | 1.57 | 1.60 | 1.60 | 1.26 | 1.41 | 1.71 | 1.62 | 1.54 | 1.67 | 1.71 | 1.78 | 1.63 | 1.55 |
| 1,4-Diethylbenzene | | 1.43 | 1.50 | 1.57 | 1.55 | 1.52 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1,3-Dimethyl-5-ethylbenzene | | 1.36 | 1.45 | 1.49 | 1.49 | 1.47 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1-Methyl-3-tert-butylbenzene | $C_{11}H_{16}$ | 1.40 | 1.44 | 1.52 | 1.55 | 1.50 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1-Methyl-4-tert-butylbenzene | | 1.44 | 1.49 | 1.57 | 1.59 | 1.57 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1-Methyl-3,5-diethylbenzene | | 1.44 | 1.50 | 1.65 | 1.71 | 1.69 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 1,3,5-Triethylbenzene | $C_{12}H_{18}$ | 1.44 | 1.51 | 1.62 | 1.63 | 1.60 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |

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[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of mixed base fuel with 4 ml TEL/gal}}$

TABLE VII - KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF BLENDS WITH MIXED BASE FUEL CONSISTING OF 87.5-PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE + 4 ML TEL PER GALLON - Concluded

(c) Ethers.

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

| Ether | Formula | Volume percent ether in blend | 17.6 Engine imep ratio[a] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Inlet-air temperature (°F) | | | | | | | | | |
| | | | 100 | | | | | 250 | | | | |
| | | | Fuel-air ratio | | | | | | | | | |
| | | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 10 | 1.18 | 1.17 | 1.17 | 1.18 | 1.16 | 1.14 | 1.14 | 1.15 | 1.15 | 1.13 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | | 1.11 | 1.11 | 1.10 | 1.09 | 1.06 | 1.11 | 1.12 | 1.13 | 1.13 | 1.13 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | | 1.11 | 1.11 | 1.11 | 1.10 | 1.11 | 1.13 | 1.13 | 1.10 | 1.10 | 1.11 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | | 1.18 | 1.20 | 1.17 | 1.18 | 1.18 | 1.11 | 1.11 | 1.12 | 1.15 | 1.16 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | | 1.17 | 1.16 | 1.16 | 1.17 | 1.17 | 1.15 | 1.14 | 1.11 | 1.12 | 1.15 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | | 1.18 | 1.15 | 1.18 | 1.19 | 1.20 | 1.15 | 1.15 | 1.19 | 1.19 | 1.20 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 25 | 1.51 | 1.50 | 1.50 | 1.53 | 1.51 | 1.45 | 1.43 | 1.49 | 1.52 | 1.51 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | | 1.44 | 1.43 | 1.41 | 1.36 | 1.32 | 1.47 | 1.45 | 1.38 | 1.39 | 1.39 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | | 1.36 | 1.37 | 1.38 | 1.35 | 1.33 | 1.33 | 1.33 | 1.31 | 1.31 | 1.31 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | | 1.46 | 1.48 | 1.45 | 1.50 | 1.54 | 1.31 | 1.29 | 1.27 | 1.36 | 1.41 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | | 1.57 | 1.55 | 1.54 | 1.55 | 1.56 | 1.39 | 1.34 | 1.30 | 1.37 | 1.43 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | | 1.55 | 1.50 | 1.52 | 1.59 | 1.65 | 1.38 | 1.33 | 1.37 | 1.44 | 1.52 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 50 | 2.28 | 2.31 | 2.56 | 2.59 | 2.40 | 2.07 | 1.84 | 2.28 | 2.46 | 2.44 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | | 2.27 | 2.35 | 2.28 | 2.14 | 2.02 | 1.99 | 1.88 | 1.76 | 1.90 | 2.01 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | | 2.14 | 2.16 | 2.10 | 2.00 | 1.98 | 2.00 | 1.98 | 1.88 | 1.90 | 1.95 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | | ----- | ---- | ----- | 2.63 | 2.72 | 1.71 | 1.50 | 1.41 | 1.74 | 2.07 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | | ----- | 2.80 | 2.61 | 2.63 | 2.72 | 1.77 | 1.64 | 1.52 | 1.99 | 2.22 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | | ----- | 2.71 | 2.42 | 2.74 | 2.96 | 1.43 | 1.28 | 1.24 | 1.40 | 1.65 |

NACA

[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of mixed base fuel with 4 ml TEL/gal}}$

TABLE VIII - 17.6 ENGINE TEMPERATURE SENSITIVITY OF BLENDS RELATIVE TO ISOOCTANE AND MIXED BASE FUEL CONSISTING OF 87.5-PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE + 4 ML TEL PER GALLON

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

(a) Paraffins and olefins.

| Paraffins and olefins | Formula | Relative temperature sensitivity[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 volume percent added paraffin or olefin in blend with isooctane | | | | | | | | | | 25 volume percent added paraffin or olefin in blend with mixed base fuel | | | | |
| | | Unleaded | | | | | 4 ml TEL/gal | | | | | | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Paraffins | | | | | | | | | | | | | | | | |
| 2,2,3-Trimethylbutane | $C_7H_{16}$ | 1.05 | 1.05 | 1.10 | 1.05 | 1.00 | 1.05 | 1.00 | 1.00 | 1.00 | 0.95 | 1.05 | 1.05 | 1.00 | 1.00 | 1.00 |
| 2,3-Dimethylpentane | | 1.00 | .95 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 2,2,3,3-Tetramethylpentane | $C_9H_{20}$ | 1.10 | 1.05 | 1.05 | 0.95 | 0.95 | 1.05 | 1.05 | 1.00 | 0.95 | 0.95 | ----- | ---- | ----- | ---- | ---- |
| 2,2,3,4-Tetramethylpentane | | 1.20 | 1.20 | 1.15 | 1.05 | 1.00 | 1.10 | 1.10 | 1.10 | 1.00 | .95 | 1.05 | 1.10 | 1.05 | 1.00 | 1.00 |
| 2,3,3,4-Tetramethylpentane | | 1.25 | 1.25 | 1.15 | 1.10 | 1.00 | 1.05 | 1.05 | 1.05 | .95 | .95 | 1.10 | 1.10 | 1.05 | 1.00 | 1.00 |
| 2,4-Dimethyl-3-ethylpentane | | 1.05 | 1.00 | 1.00 | 1.00 | .95 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| Olefins | | | | | | | | | | | | | | | | |
| 2,3-Dimethyl-2-pentene | $C_7H_{14}$ | 1.15 | 1.15 | 1.15 | 1.15 | 1.10 | 1.20 | 1.20 | 1.20 | 1.10 | 1.05 | ----- | ---- | ----- | ---- | ---- |
| 2,3,4-Trimethyl-2-pentene | $C_8H_{16}$ | 1.20 | 1.20 | 1.25 | 1.20 | 1.15 | 1.20 | 1.25 | 1.30 | 1.25 | 1.20 | 1.20 | 1.20 | 1.20 | 1.15 | 1.10 |
| 3,4,4-Trimethyl-2-pentene | | 1.15 | 1.10 | 1.15 | 1.20 | 1.15 | 1.20 | 1.20 | 1.20 | 1.15 | 1.10 | 1.25 | 1.20 | 1.15 | 1.10 | 1.10 |

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

TABLE VIII - 17.6 ENGINE TEMPERATURE SENSITIVITY OF BLENDS RELATIVE TO ISOOCTANE AND MIXED BASE FUEL CONSISTING OF 87.5 PERCENT (BY VOLUME) ISOOCTANE AND 12.5 PERCENT n-HEPTANE + 4 ML TEL PER GALLON - Continued

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

(b) Aromatics.

| Aromatic | Formula | Relative temperature sensitivity[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 volume percent aromatic in blend with isooctane | | | | | | | | | | 25 volume percent aromatic in blend with mixed base fuel | | | | |
| | | Unleaded | | | | | 4 ml TEL/gal | | | | | | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Benzene | $C_6H_6$ | 1.10 | 1.05 | 1.05 | 1.00 | 1.00 | 1.10 | 1.05 | 1.05 | 1.05 | 1.05 | 1.15 | 1.10 | 1.05 | 1.05 | 1.00 |
| Methylbenzene | $C_7H_8$ | 1.00 | 1.05 | 1.05 | 1.00 | 1.00 | 1.10 | 1.10 | 1.10 | 1.10 | 1.05 | ----- | ---- | ----- | ---- | ---- |
| Ethylbenzene | $C_8H_{10}$ | 1.15 | 1.20 | 1.20 | 1.10 | 1.05 | 1.15 | 1.15 | 1.10 | 1.05 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 1,2-Dimethylbenzene | | 1.10 | 1.10 | 1.15 | 1.10 | 1.05 | 1.05 | 1.00 | 1.00 | 1.05 | 1.05 | 1.10 | 1.05 | 1.00 | 1.00 | 1.00 |
| 1,3-Dimethylbenzene | | 1.25 | 1.20 | 1.15 | 1.20 | 1.20 | 1.15 | 1.10 | 1.10 | 1.05 | 1.05 | 1.10 | 1.15 | 1.05 | 1.00 | 1.00 |
| 1,4-Dimethylbenzene | | 1.10 | 1.15 | 1.10 | 1.05 | 1.00 | 1.15 | 1.15 | 1.15 | 1.10 | 1.05 | ----- | ---- | ----- | ---- | ---- |
| n-Propylbenzene | $C_9H_{12}$ | 1.15 | 1.15 | 1.15 | 1.15 | 1.05 | 1.20 | 1.20 | 1.15 | 1.05 | 1.00 | 1.10 | 1.10 | 1.05 | 1.05 | 1.05 |
| Isopropylbenzene | | 1.10 | 1.20 | 1.20 | 1.10 | 1.05 | 1.20 | 1.20 | 1.15 | 1.05 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-2-ethylbenzene | | 1.00 | 1.05 | 1.05 | 1.00 | 1.00 | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-3-ethylbenzene | | 1.15 | 1.20 | 1.15 | 1.10 | 1.05 | 1.15 | 1.10 | 1.10 | 1.00 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-4-ethylbenzene | | 1.00 | 1.05 | 1.00 | 1.05 | 1.05 | 1.20 | 1.20 | 1.20 | 1.05 | 1.00 | 1.25 | 1.20 | 1.25 | 1.15 | 1.05 |
| 1,2,3-Trimethylbenzene | | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.00 | 1.00 | 1.05 | 1.05 | ----- | ---- | ----- | ---- | ---- |
| 1,2,4-Trimethylbenzene | | 1.10 | 1.10 | 1.10 | 1.10 | 1.05 | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | 1.10 | 1.10 | 1.05 | 1.00 | 1.00 |
| 1,3,5-Trimethylbenzene | | 1.25 | 1.20 | 1.20 | 1.15 | 1.05 | 1.25 | 1.20 | 1.20 | 1.10 | 1.05 | ----- | ---- | ----- | ---- | ---- |
| n-Butylbenzene | $C_{10}H_{14}$ | 1.10 | 1.10 | 1.10 | 1.10 | 1.05 | 1.10 | 1.05 | 1.05 | 1.05 | 1.05 | 1.10 | 1.10 | 1.05 | 1.00 | 1.00 |
| Isobutylbenzene | | 1.15 | 1.20 | 1.20 | 1.15 | 1.10 | 1.05 | 1.05 | 1.05 | 1.00 | .95 | 1.15 | 1.10 | 1.10 | 1.05 | 1.00 |
| sec-Butylbenzene | | 1.15 | 1.15 | 1.10 | 1.05 | 1.00 | 1.10 | 1.15 | 1.10 | 1.00 | .95 | 1.05 | 1.10 | 1.05 | 1.05 | 1.00 |
| tert-Butylbenzene | | 1.30 | 1.30 | 1.20 | 1.25 | 1.15 | 1.05 | 1.05 | 1.05 | 1.05 | 1.00 | 1.20 | 1.25 | 1.15 | 1.10 | 1.05 |
| 1-Methyl-4-isopropylbenzene | | 1.20 | 1.20 | 1.20 | 1.20 | 1.15 | 1.15 | 1.15 | 1.15 | 1.00 | 1.00 | 1.15 | 1.15 | 1.10 | 1.05 | 1.05 |
| 1,2-Diethylbenzene | | 1.00 | 1.05 | 1.10 | 1.00 | 1.00 | 1.10 | 1.05 | 1.05 | 1.00 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 1,3-Diethylbenzene | | 1.20 | 1.20 | 1.25 | 1.20 | 1.10 | 1.25 | 1.20 | 1.15 | 1.05 | 1.00 | 1.20 | 1.15 | 1.10 | 1.10 | 1.05 |
| 1,4-Diethylbenzene | | 1.20 | 1.20 | 1.15 | 1.10 | 1.00 | 1.10 | 1.15 | 1.15 | 1.05 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 1,3-Dimethyl-5-ethylbenzene | | 1.15 | 1.15 | 1.15 | 1.10 | 1.05 | 1.20 | 1.20 | 1.15 | 1.05 | 1.05 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-3-tert-butylbenzene | $C_{11}H_{16}$ | 1.10 | 1.15 | 1.10 | 1.00 | 1.00 | 1.10 | 1.15 | 1.10 | 1.05 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-4-tert-butylbenzene | | 1.15 | 1.15 | 1.10 | 1.05 | 1.00 | 1.10 | 1.10 | 1.10 | 1.05 | 1.05 | ----- | ---- | ----- | ---- | ---- |
| 1-Methyl-3,5-diethylbenzene | | 1.20 | 1.20 | 1.20 | 1.10 | 1.05 | 1.20 | 1.25 | 1.10 | 1.10 | 1.00 | ----- | ---- | ----- | ---- | ---- |
| 1,3-5-Triethylbenzene | $C_{12}H_{18}$ | 1.25 | 1.25 | 1.25 | 1.15 | 1.05 | 1.25 | 1.25 | 1.10 | 1.00 | 1.00 | ----- | ---- | ----- | ---- | ---- |

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

TABLE VIII - 17.6 ENGINE TEMPERATURE SENSITIVITY OF BLENDS RELATIVE TO ISOOCTANE AND PERCENT n-HEPTANE + 4 ML TEL PER

[Compression ratio, 7.0; engine speed, 1800 rpm; coolant

(c) Ethers.

| Ether | Formula | Relative temperature sensitivity[a] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ether in blend with isooctane, percent by volume | | | | | | | | | |
| | | 20 | | | | | | | | | |
| | | Unleaded | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 1.10 | 1.10 | 1.15 | 1.05 | 1.00 | 1.10 | 1.15 | 1.10 | 1.05 | 1.00 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | 1.05 | 1.05 | 1.00 | 1.00 | .95 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | 1.10 | 1.10 | 1.05 | 1.00 | .95 | 1.00 | 1.05 | 1.05 | 1.00 | .95 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | 1.15 | 1.15 | 1.15 | 1.10 | 1.00 | 1.15 | 1.15 | 1.20 | 1.10 | 1.05 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | 1.10 | 1.10 | 1.15 | 1.10 | 1.00 | 1.15 | 1.15 | 1.10 | 1.05 | 1.00 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | 1.05 | 1.15 | 1.15 | 1.10 | 1.05 | 1.25 | 1.20 | 1.10 | 1.05 | 1.05 |

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

MIXED BASE FUEL CONSISTING OF 87.5 PERCENT (BY VOLUME) ISOOCTANE AND 12.5 GALLON - Concluded

temperature, 212° F; spark advance, 30° B.T.C.]

| Relative temperature sensitivity[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ether in blend with mixed base fuel, percent by volume | | | | | | | | | | | | | | |
| 10 | | | | | 25 | | | | | 50 | | | | |
| 4 ml TEL/gal | | | | | | | | | | | | | | |
| Fuel-air ratio | | | | | | | | | | | | | | |
| 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| 1.05 | 1.05 | 1.00 | 1.00 | 1.00 | 1.05 | 1.05 | 1.00 | 1.00 | 1.00 | 1.10 | 1.25 | 1.10 | 1.05 | 1.00 |
| 1.00 | 1.00 | .95 | .95 | .95 | 1.00 | 1.00 | 1.00 | 1.00 | .95 | 1.15 | 1.25 | 1.30 | 1.10 | 1.00 |
| 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.05 | 1.05 | 1.05 | 1.05 | 1.00 | 1.05 | 1.10 | 1.10 | 1.05 | 1.00 |
| 1.05 | 1.10 | 1.05 | 1.05 | 1.00 | 1.10 | 1.15 | 1.15 | 1.10 | 1.10 | ----- | ---- | ----- | 1.50 | 1.30 |
| 1.00 | 1.00 | 1.05 | 1.05 | 1.00 | 1.15 | 1.15 | 1.20 | 1.15 | 1.10 | ----- | 1.70 | 1.70 | 1.35 | 1.20 |
| 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.10 | 1.15 | 1.10 | 1.10 | 1.10 | ----- | 2.10 | 1.95 | 1.95 | 1.80 |

TABLE IX - 17.6 ENGINE LEAD SUSCEPTIBILITY OF BLENDS RELATIVE TO ISOOCTANE

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

(a) Paraffins and olefins.

| Paraffins and olefins | Formula | Relative lead susceptibility[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inlet-air temperature, 250° F | | | | | | | | | | Inlet-air temperature, 100° F | | | | |
| | | Volume percent paraffin or olefin in blend with isooctane | | | | | | | | | | | | | | |
| | | 10 | | | | | 20 | | | | | 20 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Paraffins | | | | | | | | | | | | | | | | |
| 2,2,3-Trimethylbutane | $C_7H_{16}$ | 1.05 | 1.05 | 1.05 | 1.00 | 1.00 | 1.05 | 1.10 | 1.10 | 1.05 | 1.05 | 1.05 | 1.05 | 1.00 | 1.00 | 1.00 |
| 2,3-Dimethylpentane | | ----- | ---- | ----- | ---- | ---- | 1.00 | 1.00 | 1.05 | 1.05 | 1.00 | 1.05 | 1.05 | 1.05 | 1.00 | 1.00 |
| 2,2,3,3-Tetramethylpentane | $C_9H_{20}$ | ----- | ---- | ----- | ---- | ---- | 1.05 | 1.05 | 1.10 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 2,2,3,4-Tetramethylpentane | | 1.05 | 1.05 | 1.05 | 1.00 | 1.00 | 1.15 | 1.15 | 1.10 | 1.05 | 1.00 | 1.05 | 1.05 | 1.05 | 1.00 | 1.00 |
| 2,3,3,4-Tetramethylpentane | | 1.10 | 1.05 | 1.05 | 1.10 | 1.05 | 1.15 | 1.15 | 1.05 | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | .95 | .95 |
| 2,4-Dimethyl-3-ethylpentane | | ----- | ---- | ----- | ---- | ---- | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | .95 | 1.00 | .95 | 1.00 | 1.05 |
| Olefins | | | | | | | | | | | | | | | | |
| 2,3-Dimethyl-2-pentene | $C_7H_{14}$ | ----- | ---- | ----- | ---- | ---- | 0.95 | 0.95 | 1.00 | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.95 |
| 2,3,4-Trimethyl-2-pentene | $C_8H_{16}$ | 1.00 | 1.00 | 1.00 | 1.05 | 1.00 | 1.05 | 1.05 | 1.00 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| 3,4,4-Trimethyl-2-pentene | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.05 | 1.05 | 1.00 | 1.00 | 1.00 |

[a]Relative lead susceptibility = $\frac{\text{imep ratio of blend with 4 ml TEL/gal}}{\text{imep ratio of blend with 0 ml TEL/gal}}$

TABLE IX - 17.6 ENGINE LEAD SUSCEPTIBILITY OF BLENDS RELATIVE TO ISOOCTANE - Continued

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

(b) Aromatics.

| Aromatic | Formula | Relative lead susceptibility[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inlet-air temperature, 250° F | | | | | | | | | | Inlet-air temperature, 100° F | | | | |
| | | Volume percent aromatic in blend with isooctane | | | | | | | | | | | | | | |
| | | 10 | | | | | 20 | | | | | 20 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Benzene | $C_6H_6$ | 1.00 | 1.00 | 1.05 | 1.05 | 1.05 | 1.00 | 1.05 | 1.10 | 1.05 | 1.00 | 1.05 | 1.05 | 1.10 | 1.10 | 1.05 |
| Methylbenzene | $C_7H_8$ | 0.95 | 1.00 | 1.00 | 0.95 | 1.00 | 1.00 | 1.05 | 1.00 | 1.00 | 1.00 | 1.10 | 1.10 | 1.05 | 1.05 | 1.05 |
| Ethylbenzene | $C_8H_{10}$ | 1.05 | 1.05 | 1.05 | 1.00 | 0.95 | 1.10 | 1.15 | 1.15 | 1.10 | 1.05 | 1.10 | 1.10 | 1.05 | 1.00 | 1.00 |
| 1,2-Dimethylbenzene | | .95 | .95 | .95 | .90 | .85 | .85 | .90 | .95 | .90 | .85 | .85 | .85 | .85 | .85 | .80 |
| 1,3-Dimethylbenzene | | 1.10 | 1.10 | 1.10 | 1.10 | 1.15 | 1.20 | 1.25 | 1.20 | 1.25 | 1.25 | 1.10 | 1.10 | 1.20 | 1.10 | 1.10 |
| 1,4-Dimethylbenzene | | 1.05 | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | 1.10 | 1.05 | 1.05 | 1.00 | 1.05 | 1.05 | 1.10 | 1.10 | 1.05 |
| n-Propylbenzene | $C_9H_{12}$ | 1.05 | 1.05 | 1.10 | 1.05 | 1.00 | 1.10 | 1.15 | 1.20 | 1.10 | 1.10 | 1.20 | 1.20 | 1.20 | 1.05 | 1.00 |
| Isopropylbenzene | | 1.05 | 1.10 | 1.05 | 1.00 | 1.05 | 1.05 | 1.15 | 1.10 | 1.10 | 1.05 | 1.15 | 1.15 | 1.05 | 1.05 | 1.05 |
| 1-Methyl-2-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | .95 | 1.00 | 1.00 | .95 | .90 | .95 | .95 | .90 | .90 | .90 |
| 1-Methyl-3-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.15 | 1.20 | 1.15 | 1.15 | 1.10 | 1.10 | 1.10 | 1.10 | 1.05 | 1.05 |
| 1-Methyl-4-ethylbenzene | | 1.05 | 1.05 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.15 | 1.20 | 1.35 | 1.30 | 1.30 | 1.20 | 1.15 |
| 1,2,3-Trimethylbenzene | | ----- | ---- | ----- | ---- | ---- | .85 | .90 | .90 | .90 | .90 | .85 | .85 | .85 | .85 | .85 |
| 1,2,4-Trimethylbenzene | | 1.00 | 1.00 | 1.00 | .95 | .95 | 1.00 | 1.00 | 1.05 | 1.00 | .90 | .90 | .95 | .90 | .90 | .85 |
| 1,3,5-Trimethylbenzene | | 1.05 | 1.05 | 1.10 | 1.00 | .95 | 1.10 | 1.15 | 1.15 | 1.10 | 1.05 | 1.10 | 1.10 | 1.15 | 1.05 | 1.05 |
| n-Butylbenzene | $C_{10}H_{14}$ | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.10 | 1.10 | 1.10 | 1.10 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| Isobutylbenzene | | 1.10 | 1.10 | 1.10 | 1.10 | 1.05 | 1.20 | 1.20 | 1.25 | 1.20 | 1.15 | 1.10 | 1.10 | 1.05 | 1.05 | 1.05 |
| sec-Butylbenzene | | 1.10 | 1.10 | 1.05 | 1.05 | 1.05 | 1.20 | 1.15 | 1.10 | 1.10 | 1.05 | 1.10 | 1.15 | 1.10 | 1.05 | 1.05 |
| tert-Butylbenzene | | 1.15 | 1.10 | 1.05 | 1.05 | 1.00 | 1.40 | 1.35 | 1.20 | 1.20 | 1.10 | 1.10 | 1.10 | 1.05 | 1.00 | 1.00 |
| 1-Methyl-4-isopropylbenzene | | 1.10 | 1.10 | 1.10 | 1.10 | 1.05 | 1.20 | 1.20 | 1.20 | 1.25 | 1.20 | 1.15 | 1.15 | 1.15 | 1.05 | 1.05 |
| 1,2-Diethylbenzene | | ----- | ---- | ----- | ---- | ---- | .95 | 1.00 | 1.05 | 1.00 | 1.00 | 1.05 | 1.05 | 1.00 | 1.00 | .95 |
| 1,3-Diethylbenzene | | 1.05 | 1.10 | 1.10 | 1.10 | 1.05 | 1.10 | 1.20 | 1.20 | 1.20 | 1.10 | 1.15 | 1.15 | 1.10 | 1.05 | 1.05 |
| 1,4-Diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.15 | 1.15 | 1.10 | 1.05 | 1.05 | 1.05 | 1.10 | 1.10 | 1.05 | 1.05 |
| 1,3-Dimethyl-5-ethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.05 | 1.15 | 1.15 | 1.10 | 1.05 | 1.10 | 1.15 | 1.15 | 1.10 | 1.10 |
| 1-Methyl-3-tert-butylbenzene | $C_{11}H_{16}$ | ----- | ---- | ----- | ---- | ---- | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| 1-Methyl-4-tert-butylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.10 | 1.10 | 1.10 | 1.05 | 1.00 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| 1-Methyl-3,5-diethylbenzene | | ----- | ---- | ----- | ---- | ---- | 1.10 | 1.15 | 1.10 | 1.05 | 1.05 | 1.15 | 1.15 | 1.10 | 1.05 | 1.00 |
| 1,3,5-Triethylbenzene | $C_{12}H_{18}$ | ----- | ---- | ----- | ---- | ---- | 1.10 | 1.15 | 1.15 | 1.15 | 1.05 | 1.10 | 1.15 | 1.05 | 1.00 | 1.05 |

[a]Relative lead susceptibility = $\frac{\text{imep ratio of blend with 4 ml TEL/gal}}{\text{imep ratio of blend with 0 ml TEL/gal}}$

TABLE IX - 17.6 ENGINE LEAD SUSCEPTIBILITY OF BLENDS RELATIVE TO ISOOCTANE - Concluded

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

(c) Ethers.

| Ether | Formula | Relative lead susceptibility[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Inlet-air temperature, 250° F | | | | | | | | | | Inlet-air temperature, 100° F | | | | |
| | | Volume percent ether in blend with isooctane | | | | | | | | | | | | | | |
| | | 10 | | | | | 20 | | | | | 20 | | | | |
| | | Fuel-air ratio | | | | | | | | | | | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 1.10 | 1.05 | 1.10 | 1.05 | 1.05 | 1.10 | 1.10 | 1.10 | 1.05 | 1.05 | 1.15 | 1.10 | 1.10 | 1.05 | 1.10 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | 1.00 | 1.00 | .95 | .95 | .95 | 1.15 | 1.10 | 1.05 | 1.00 | .95 | 1.05 | 1.05 | 1.05 | 1.00 | .95 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.10 | 1.05 | 1.00 | 1.00 | 1.00 | 1.05 | 1.05 | 1.05 | 1.00 | 1.00 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.05 | 1.05 | 1.00 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | 1.00 | 1.00 | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | 1.10 | 1.05 | 1.05 | 1.05 | 1.05 | 1.10 | 1.00 | 1.00 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | 1.00 | 1.05 | 1.05 | 1.05 | 1.05 | .95 | 1.05 | 1.05 | 1.05 | 1.05 | 1.10 | 1.10 | 1.05 | 1.00 | 1.05 |

[a]Relative lead susceptibility = $\frac{\text{imep ratio of blend with 4 ml TEL/gal}}{\text{imep ratio of blend with 0 ml TEL/gal}}$

TABLE X - FULL-SCALE SINGLE-CYLINDER ENGINE KNOCK-LIMITED INDICATED MEAN EFFECTIVE PRESSURE RATIOS OF ETHER BLENDS WITH MIXED BASE FUEL CONSISTING OF 87.5-PERCENT (BY VOLUME) ISOOCTANE AND 12.5-PERCENT n-HEPTANE + 4 ML TEL PER GALLON

[Full-scale cruise conditions; compression ratio, 7.3; engine speed, 1800 rpm; inlet-air temperature, 210° F; spark advance, 20° B.T.C.; cooling-air flow such that rear-spark-plug-bushing temperature equals 365° F at 140 bmep and 0.10 fuel-air ratio]

| Ether | Formula | Imep ratio[a] | | | | |
|---|---|---|---|---|---|---|
| | | 10 volume percent ether in blend with mixed base fuel | | | | |
| | | Fuel-air ratio | | | | |
| | | 0.065 | 0.07 | 0.085 | 0.10 | 0.11 |
| Methyl tert-butyl ether | $C_5H_{12}O$ | 1.27 | 1.21 | 1.24 | 1.25 | 1.19 |
| Ethyl tert-butyl ether | $C_6H_{14}O$ | 1.19 | 1.16 | 1.19 | 1.16 | 1.11 |
| Isopropyl tert-butyl ether | $C_7H_{16}O$ | 1.17 | 1.16 | 1.15 | 1.15 | 1.14 |
| Methyl phenyl ether (anisole) | $C_7H_8O$ | 1.11 | 1.08 | 1.08 | 1.11 | 1.11 |
| Ethyl phenyl ether (phenetole) | $C_8H_{10}O$ | 1.13 | 1.11 | 1.11 | 1.15 | 1.12 |
| Methyl p-tolyl ether (p-methylanisole) | $C_8H_{10}O$ | 1.20 | 1.16 | 1.15 | 1.17 | 1.19 |

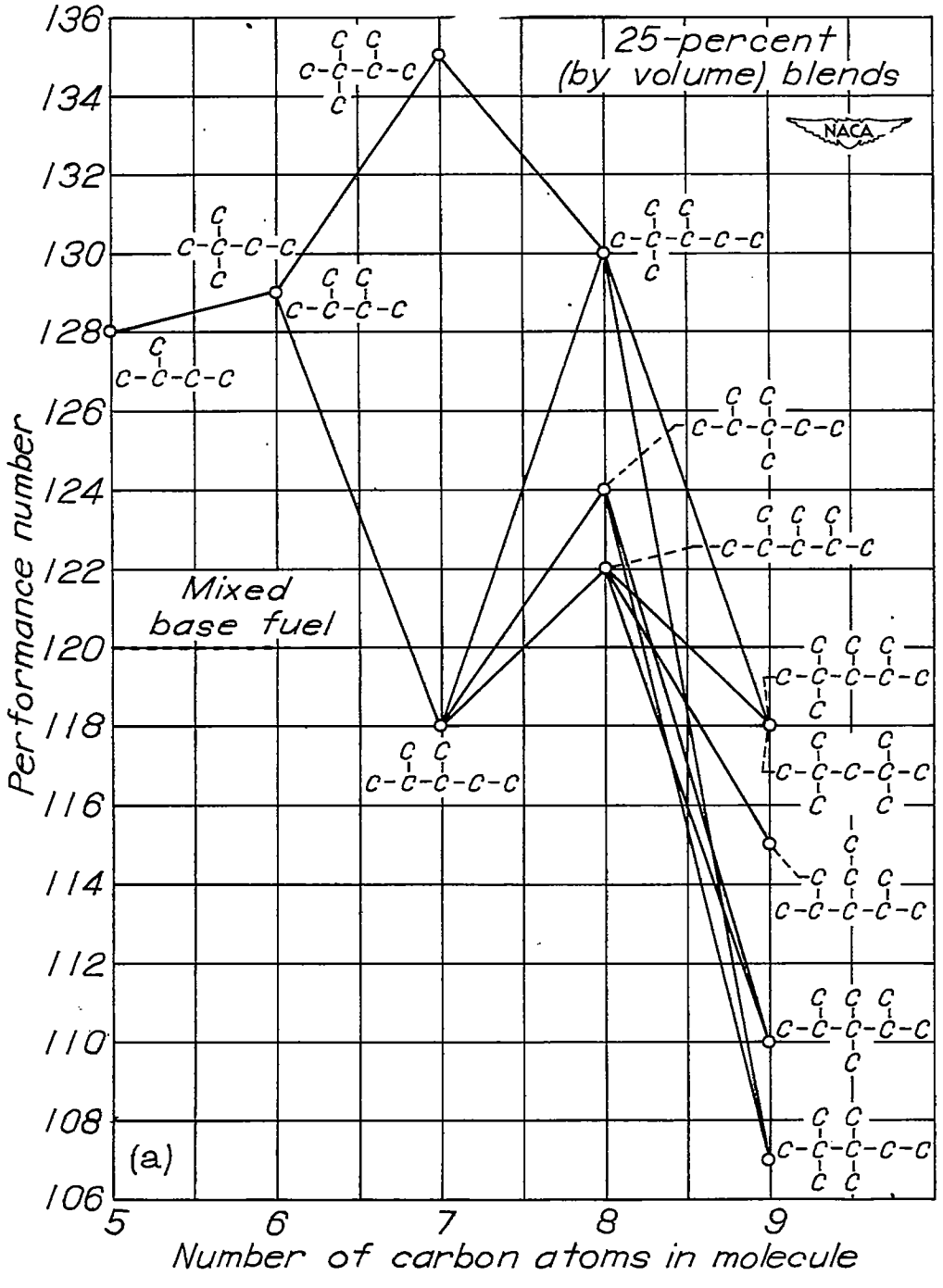
[a]Imep ratio = $\frac{\text{knock-limited imep of blend with 4 ml TEL/gal}}{\text{knock-limited imep of mixed base fuel with 4 ml TEL/gal}}$

NACA

TABLE XI - DEGREE OF SEVERITY OF VARIOUS OPERATING CONDITIONS

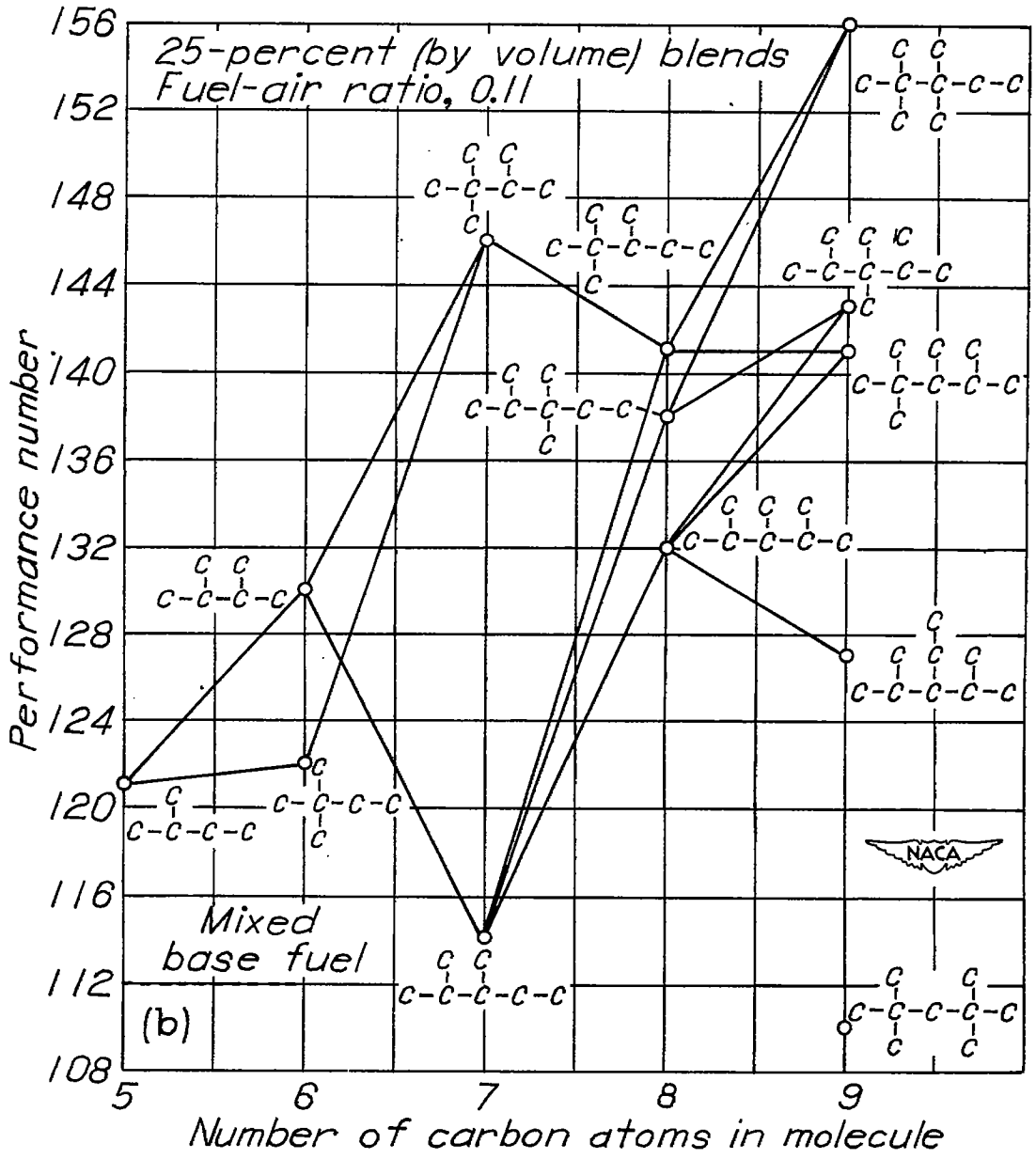
| Engine | Mixture condition | Degree of severity |
|---|---|---|
| A.S.T.M. Aviation | Lean | Severe |
| Full-scale take-off | Lean | Moderate to severe |
| A.S.T.M. Supercharge | Rich | Moderate |
| Full-scale take-off | Rich | Moderate |
| Full-scale cruise | Lean | Moderate |
| 17.6 (inlet-air temperature, 250° F) | Lean | Moderate |
| Full-scale cruise | Rich | Moderate to mild |
| 17.6 (inlet-air temperature, 250° F) | Rich | Moderate to mild |
| 17.6 (inlet-air temperature, 100° F) | Lean | Moderate to mild |
| 17.6 (inlet-air temperature, 100° F) | Rich | Mild |

NACA




(a) Engine, A.S.T.M. Aviation.

Figure 1. - Knock-limited performance of paraffins in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(b) Engine, A.S.T.M. Supercharge.

Figure 1. - Concluded. Knock-limited performance of paraffins in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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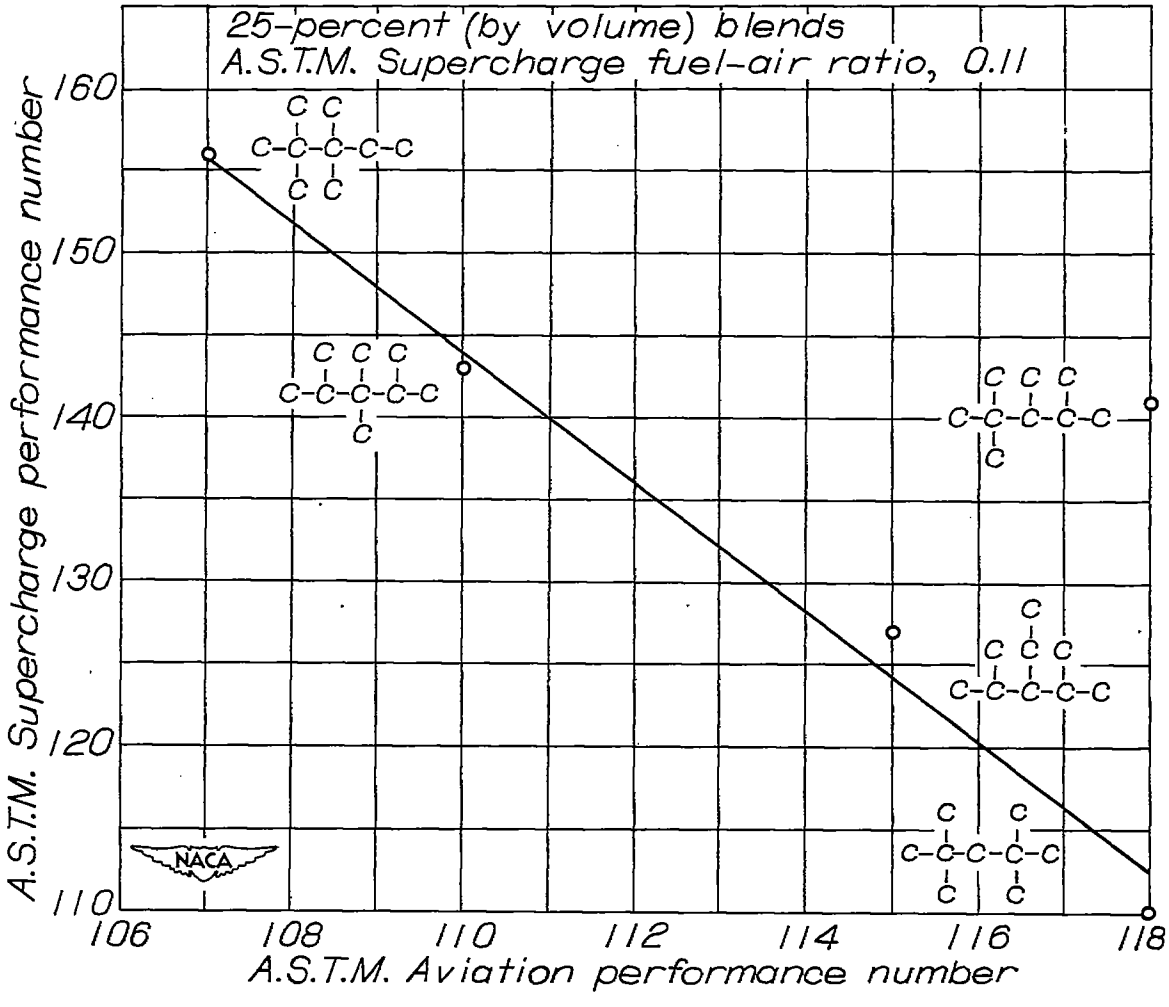
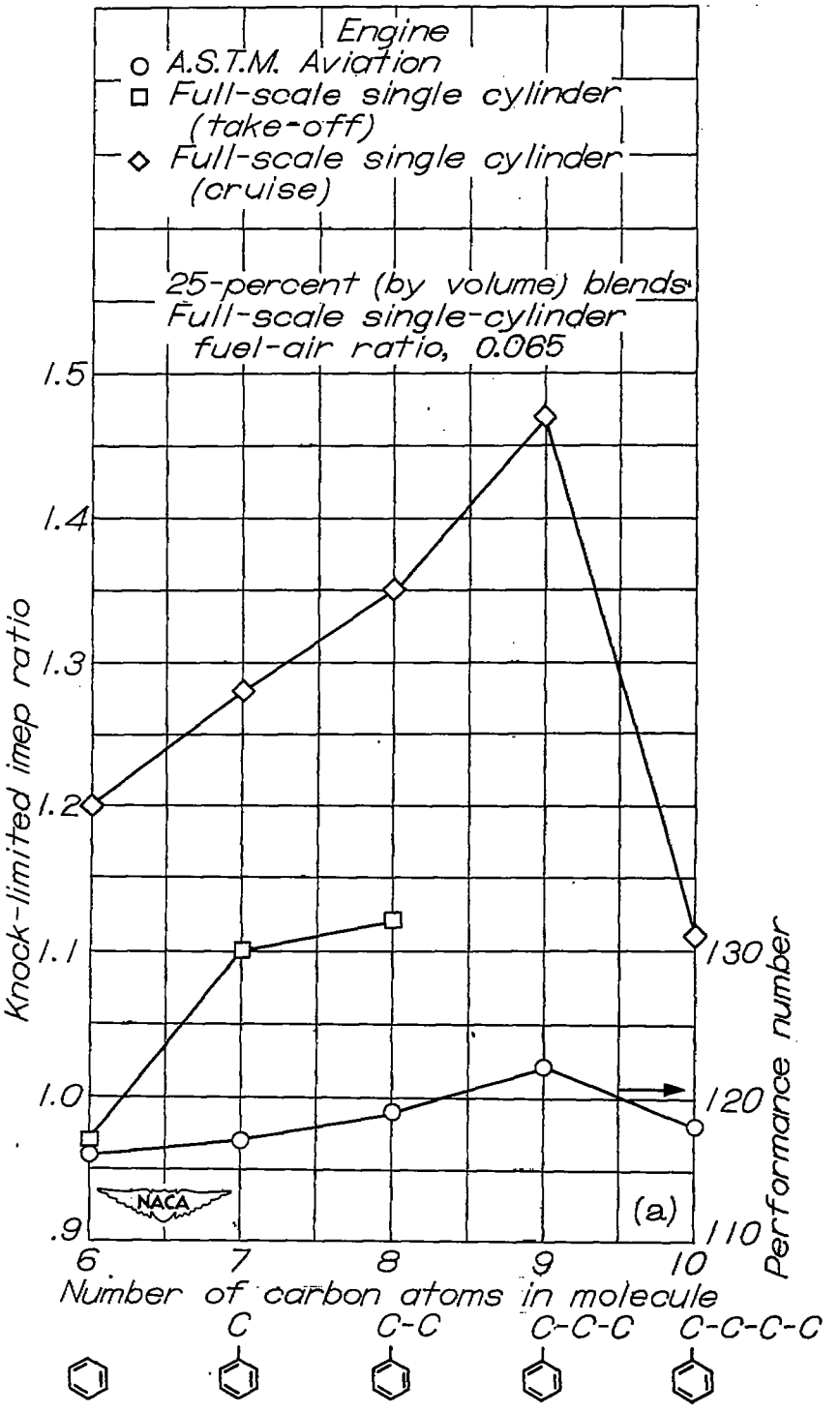



Figure 2. - Relation between A.S.T.M. Supercharge and A.S.T.M. Aviation performance numbers of nonanes in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(a) n-Alkylbenzenes; lean conditions.

Figure 3. - Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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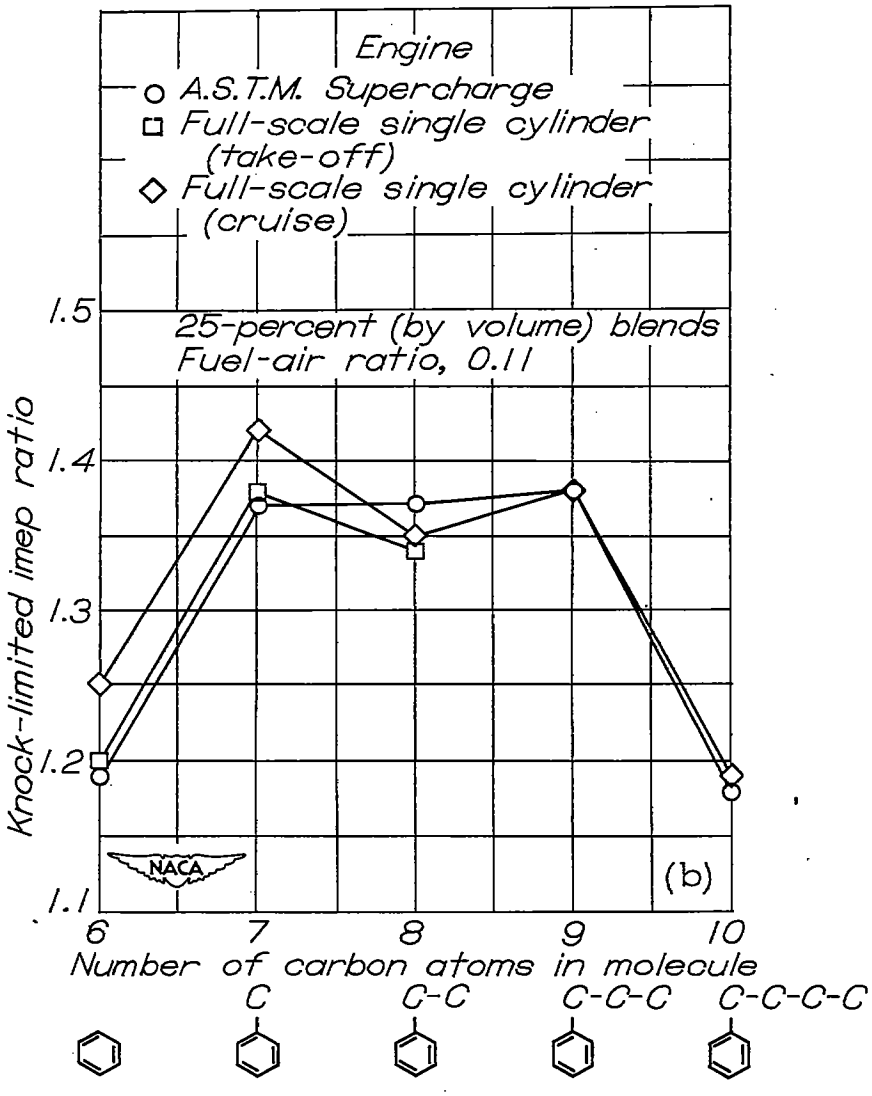
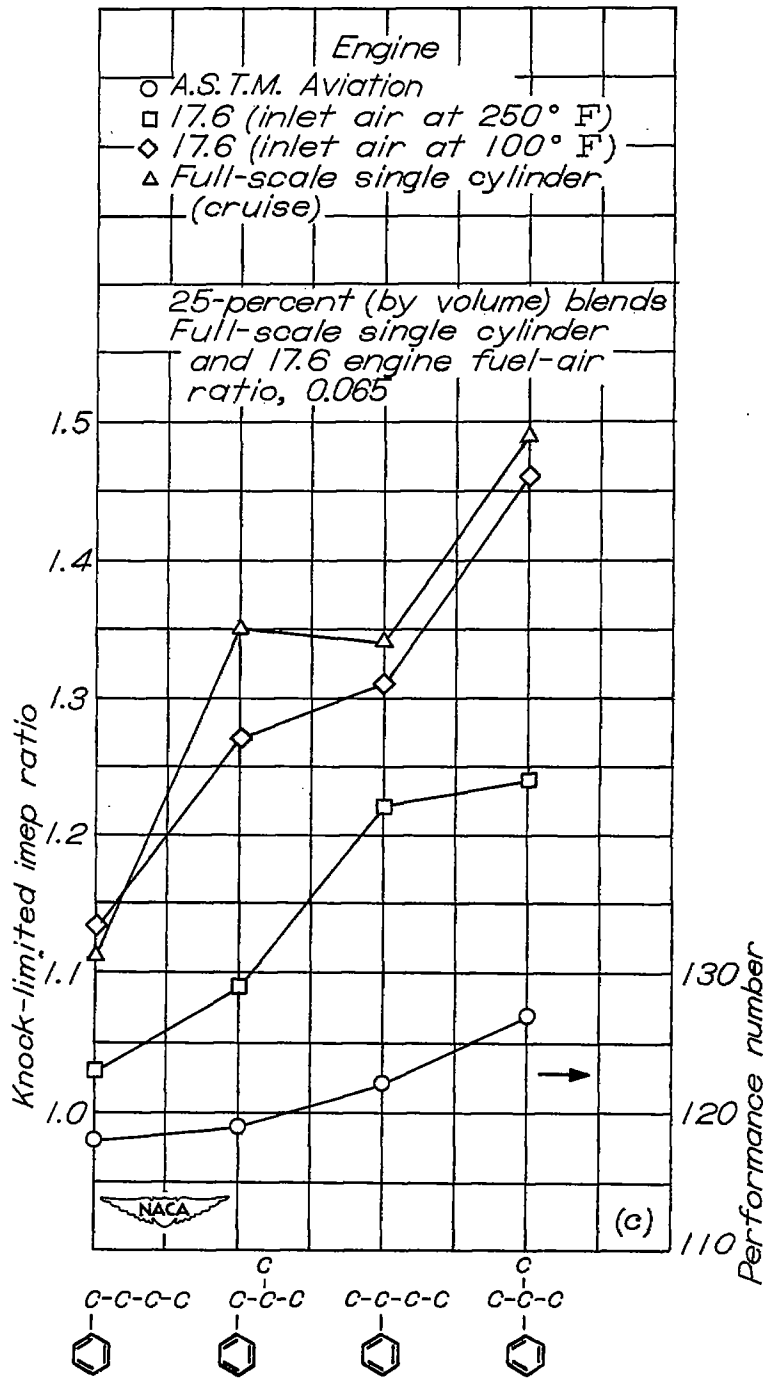



(b) n-Alkylbenzenes; rich conditions.

Figure 3. - Continued. Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(c) Butylbenzenes; lean conditions.

Figure 3. - Continued. Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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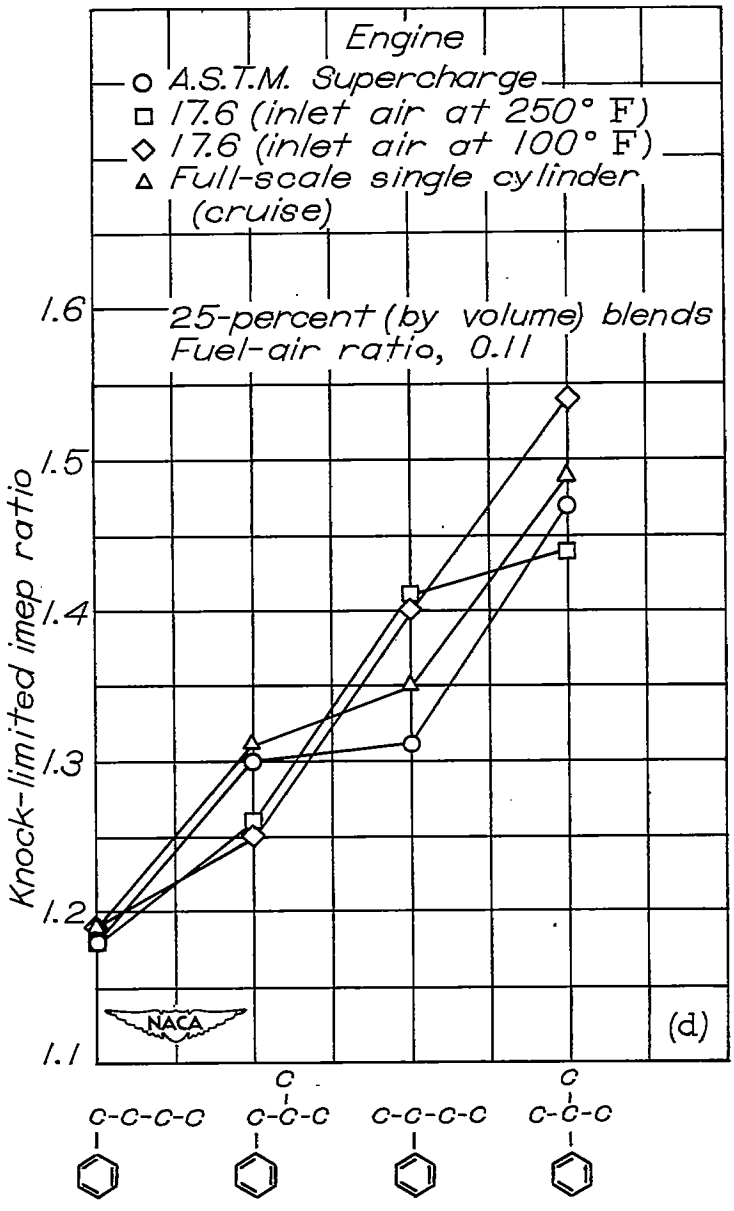
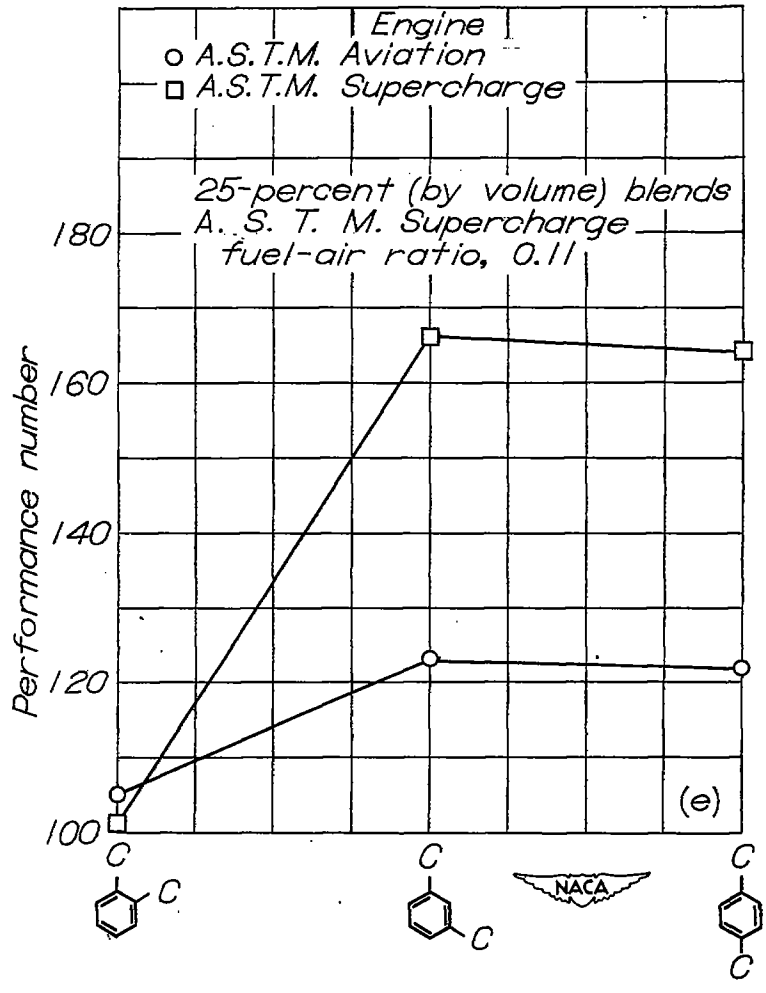



(d) Butylbenzenes; rich conditions.

Figure 3. - Continued. Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(e) Dimethylbenzenes.

Figure 3. - Continued. Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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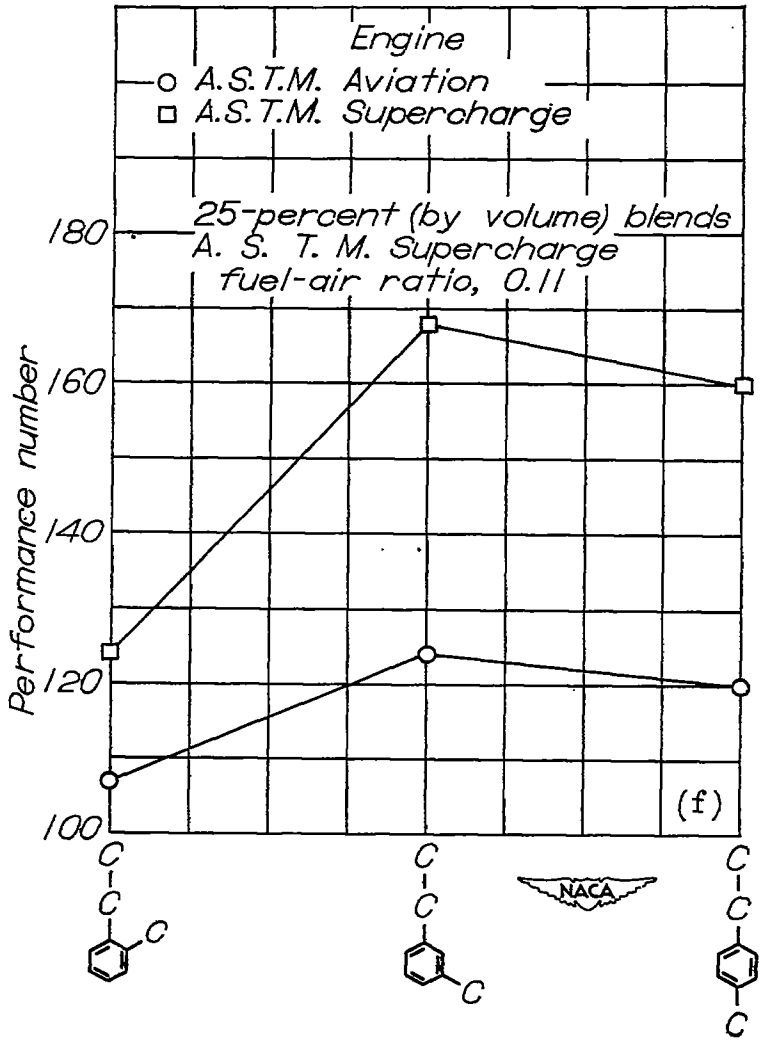
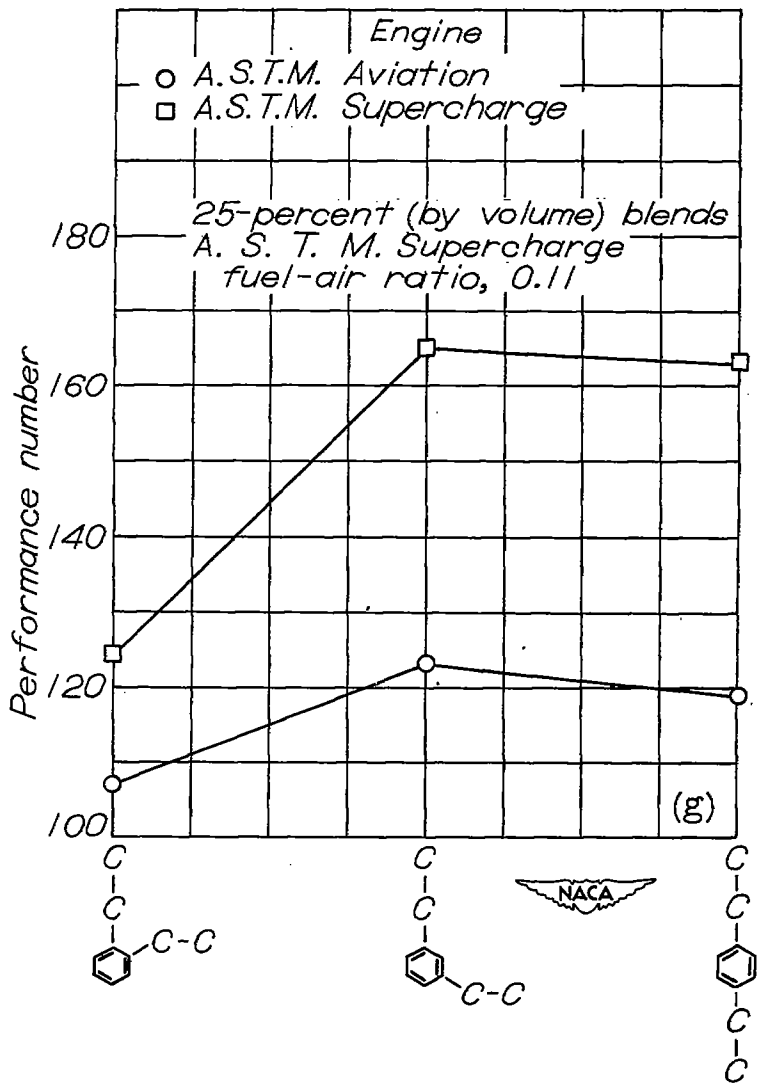



(f) Methylethylbenzenes.

Figure 3. - Continued. Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(g) Diethylbenzenes.

Figure 3. - Continued. Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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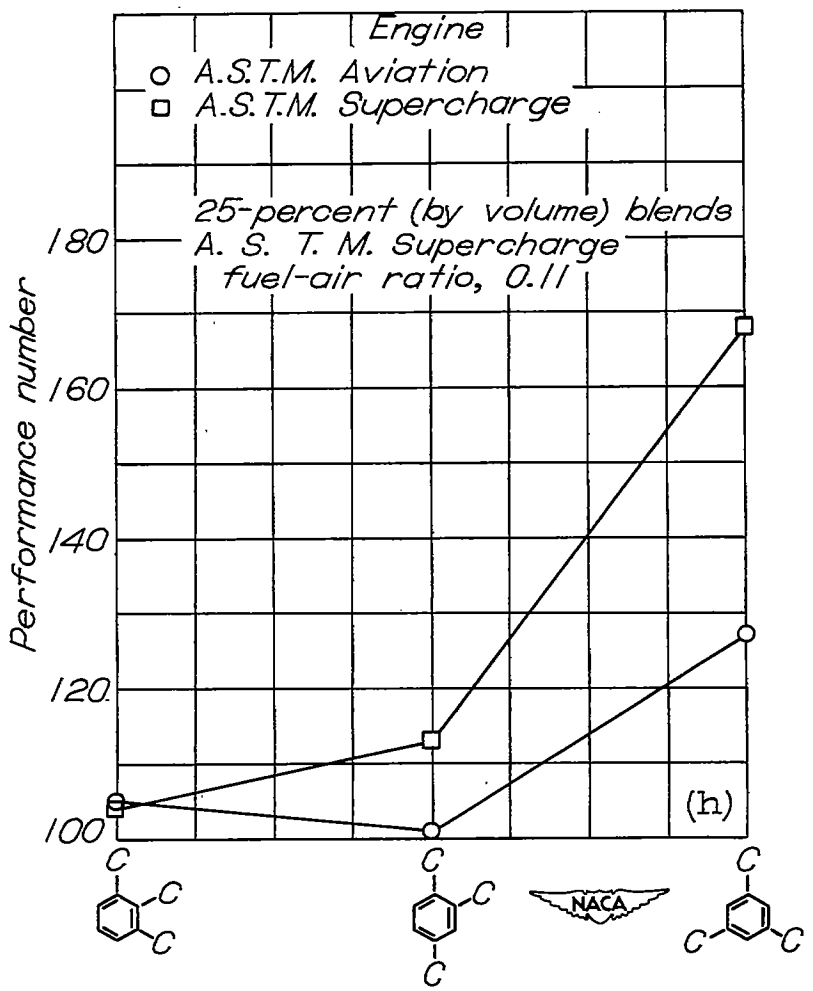
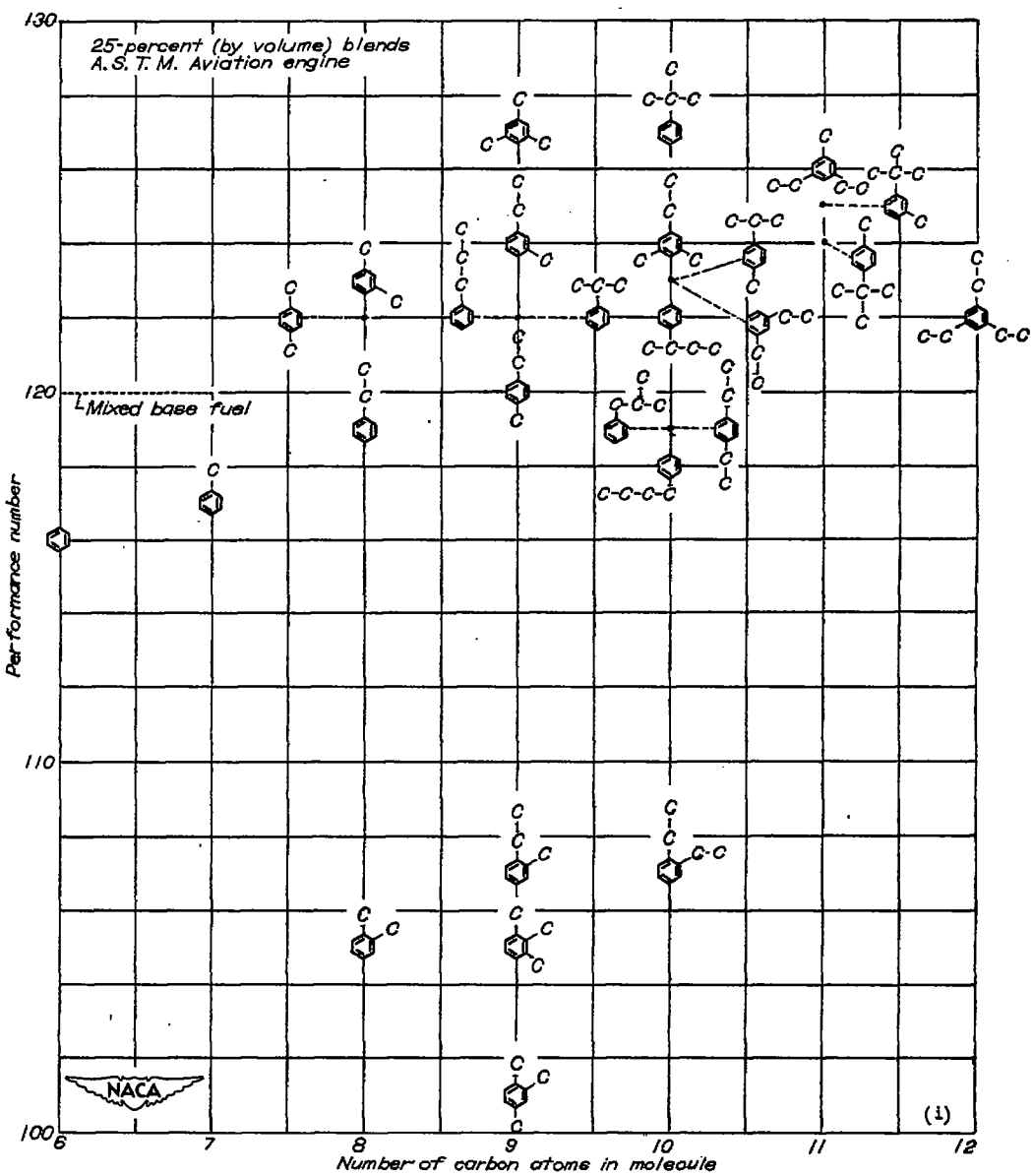



(h) Trimethylbenzenes.

Figure 3. - Continued. Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(i) Aromatics; lean conditions.

Figure 3. - Continued. Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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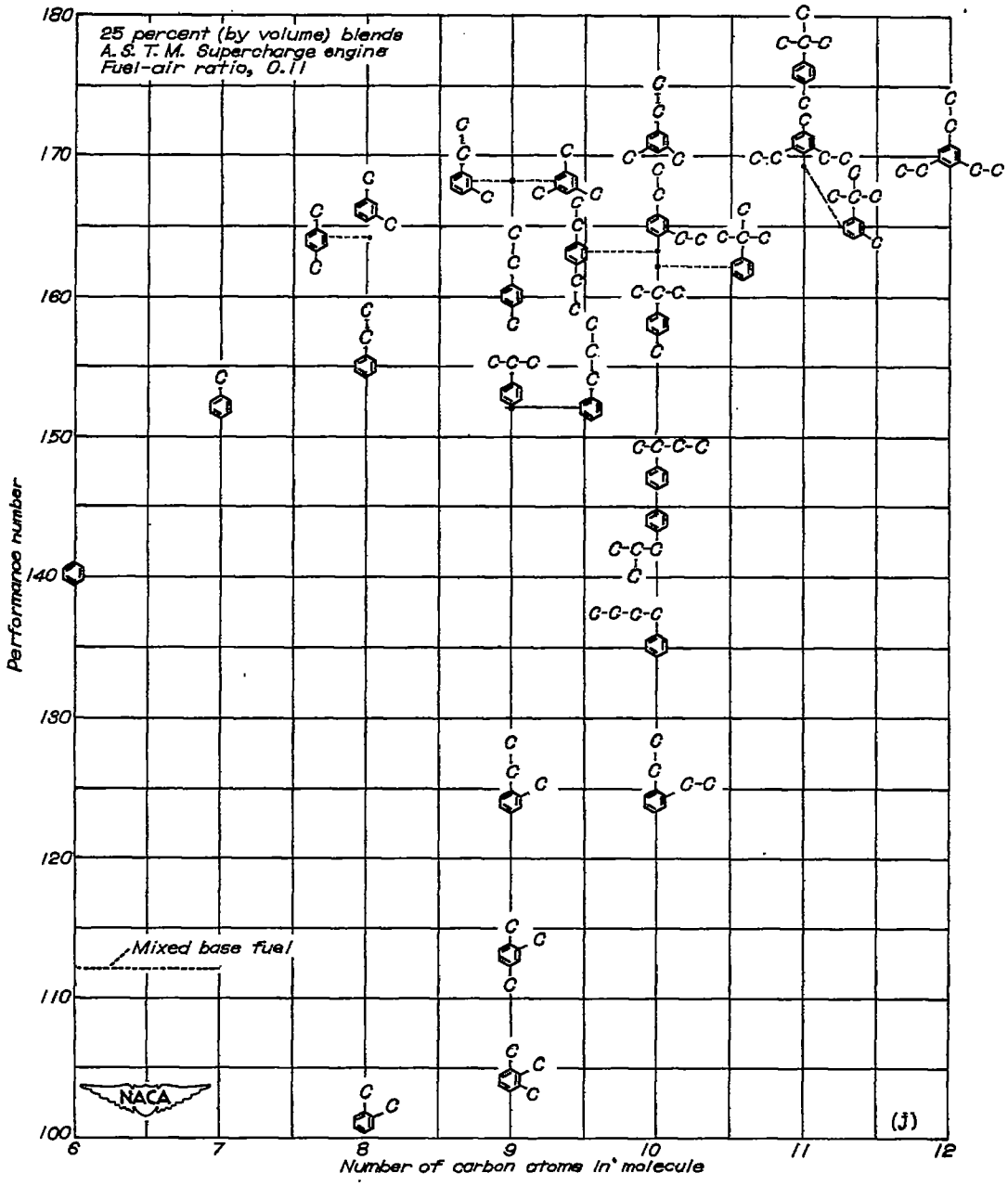
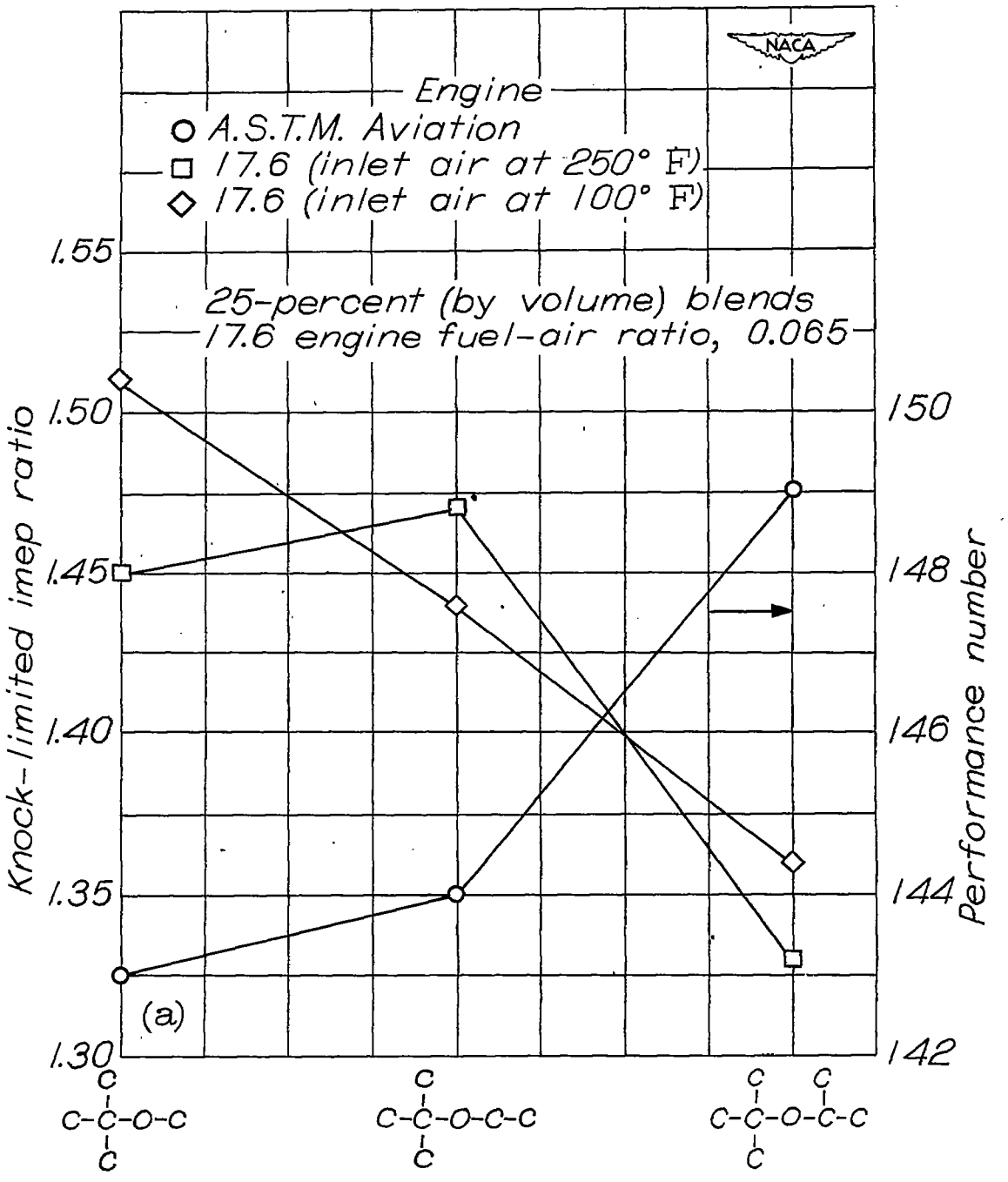



(j) Aromatics; rich conditions.

Figure 3. - Concluded. Knock-limited performance of aromatics in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(a) tert-Butyl alkyl ethers; lean conditions.

Figure 4. - Knock-limited performance of ethers in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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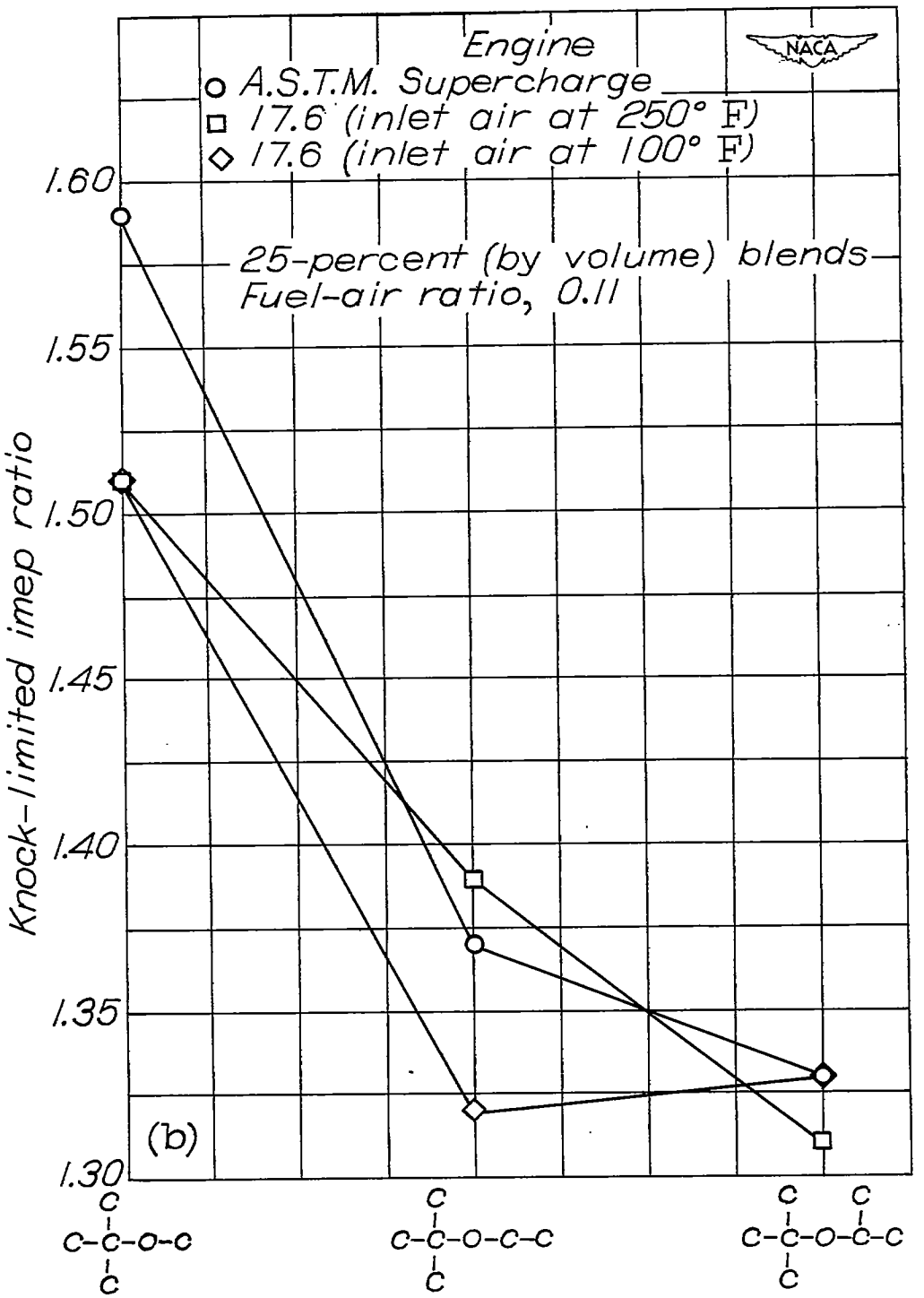
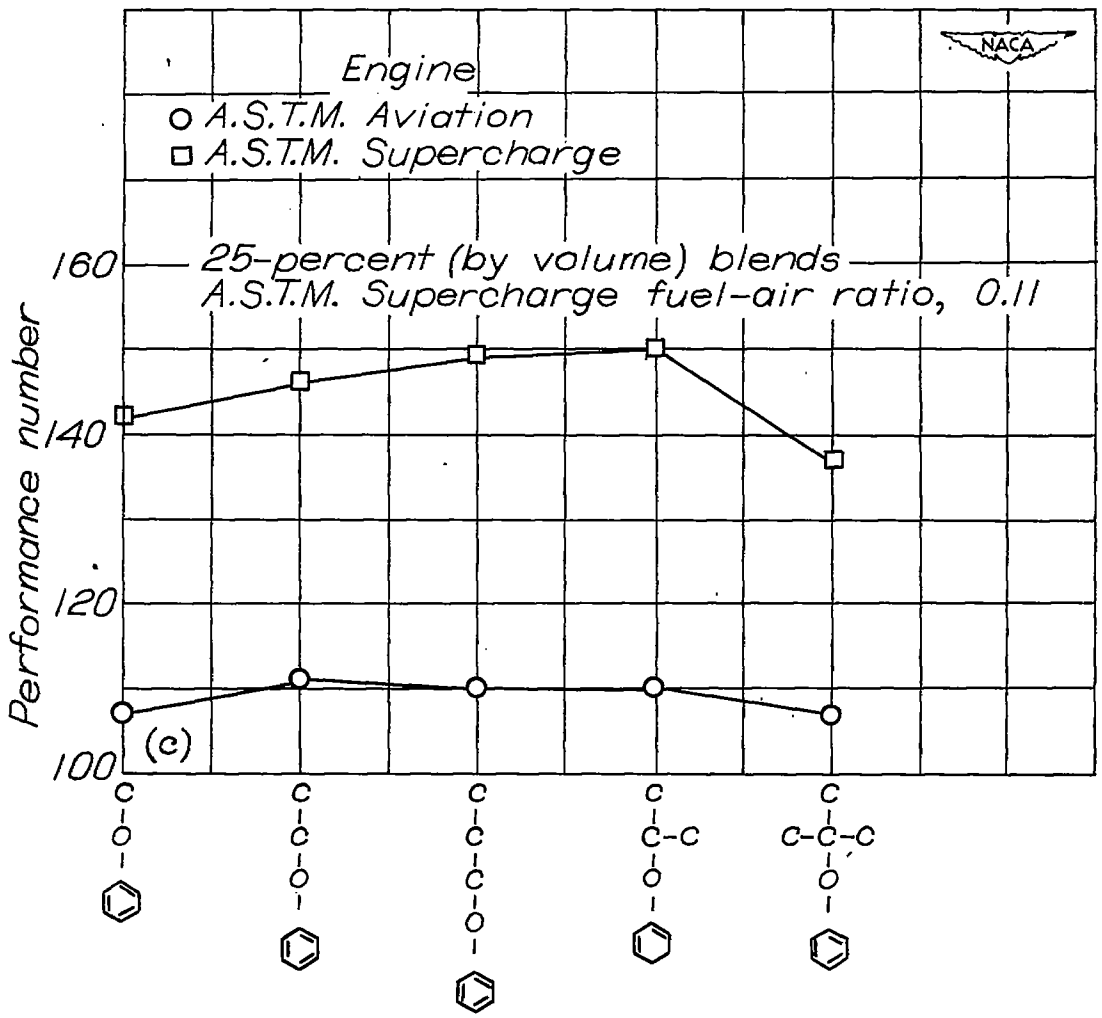



(b) tert-Butyl alkyl ethers; rich conditions.

Figure 4. - Continued. Knock-limited performance of ethers in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(c) Phenyl alkyl ethers.

Figure 4. - Continued. Knock-limited performance of ethers in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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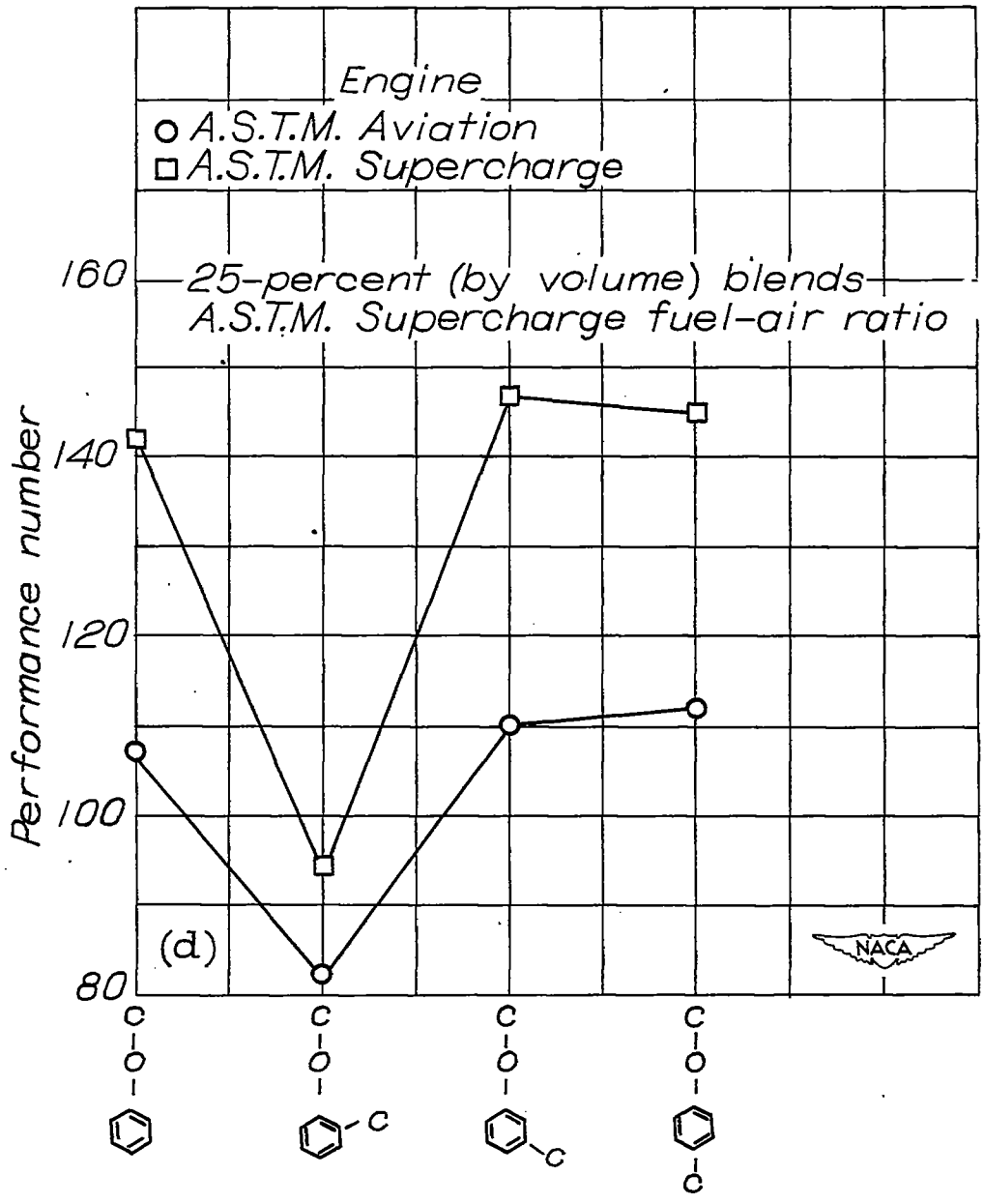
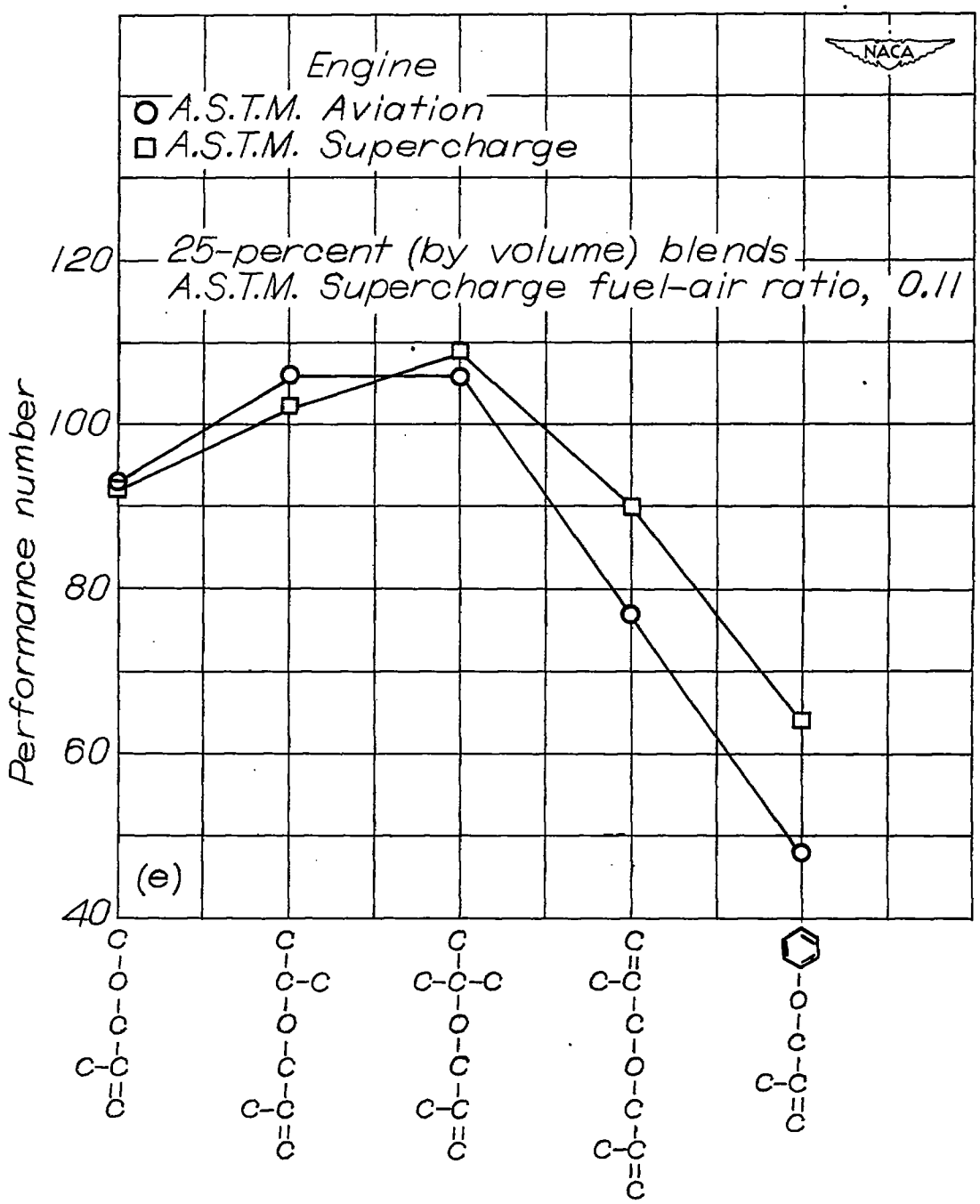



(d) Anisoles.

Figure 4. - Continued. Knock-limited performance of ethers in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(e) Methallyl ethers.

Figure 4. - Continued. Knock-limited performance of ethers in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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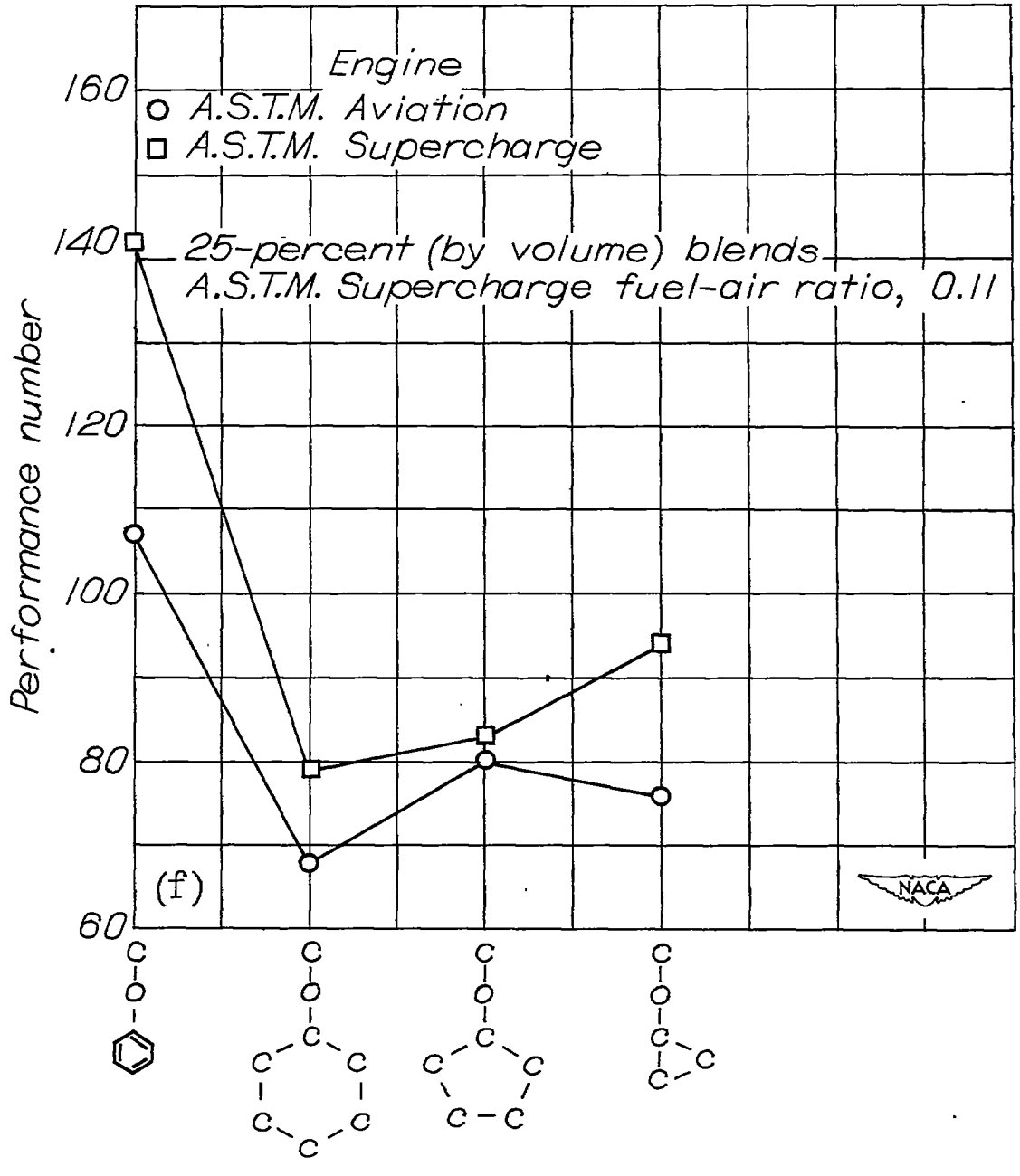
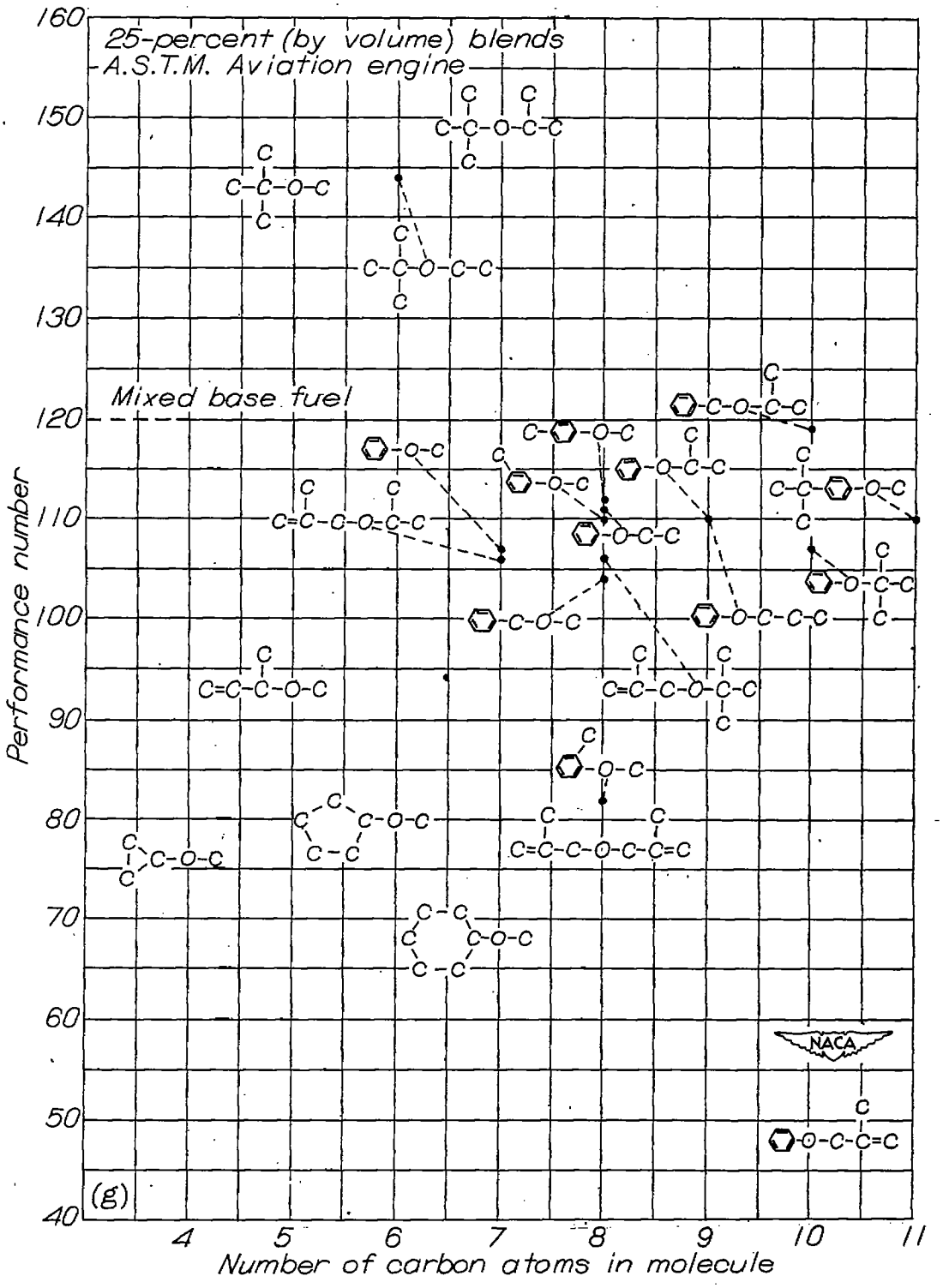



(f) Anisole and three methyl cycloalkyl ethers.

Figure 4. - Continued. Knock-limited performance of ethers in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(g) Ethers; leaf conditions.

Figure 4. - Continued. Knock-limited performance of ethers in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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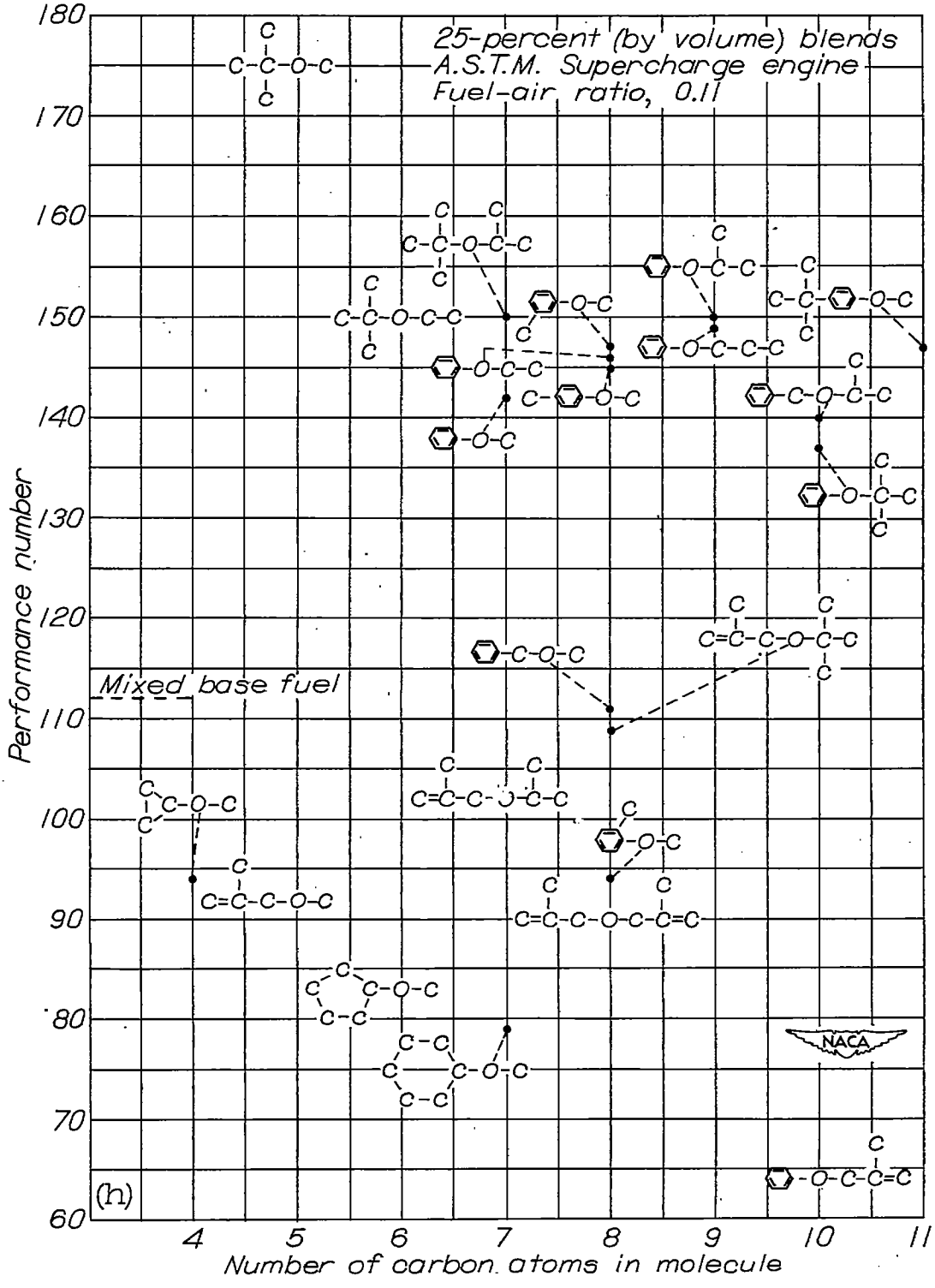
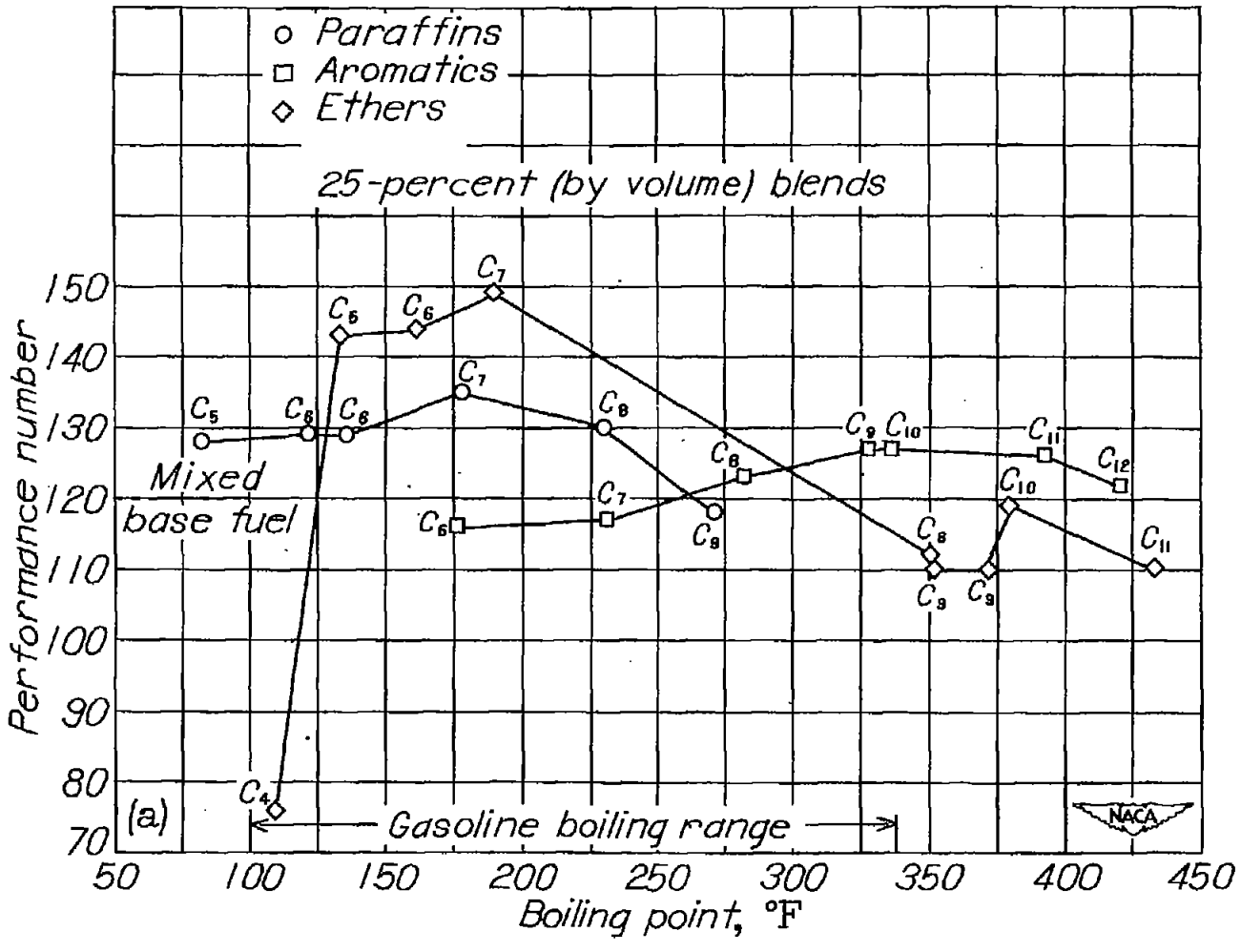


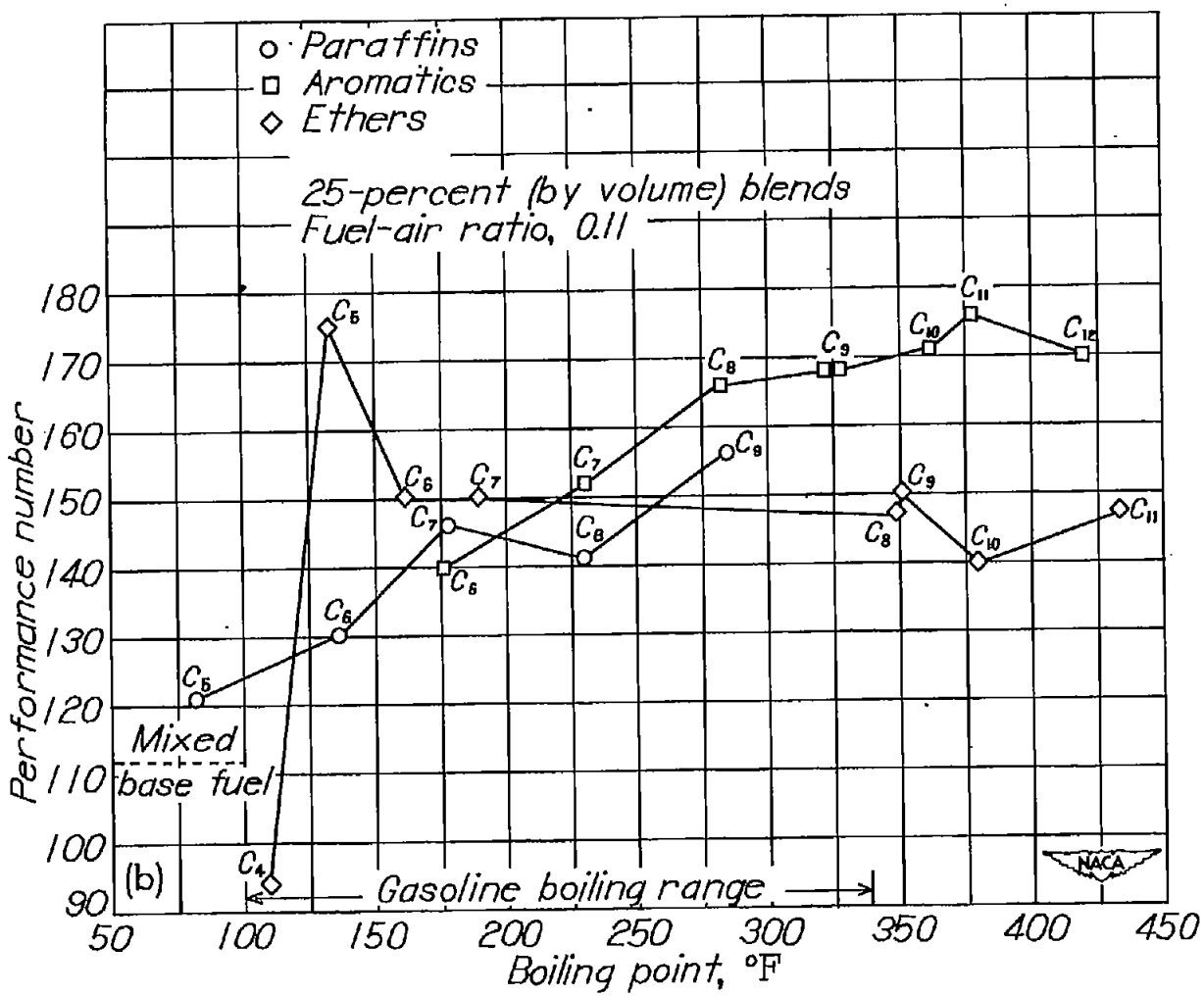

(h) Ethers; rich conditions.

Figure 4. - Concluded. Knock-limited performance of ethers in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.



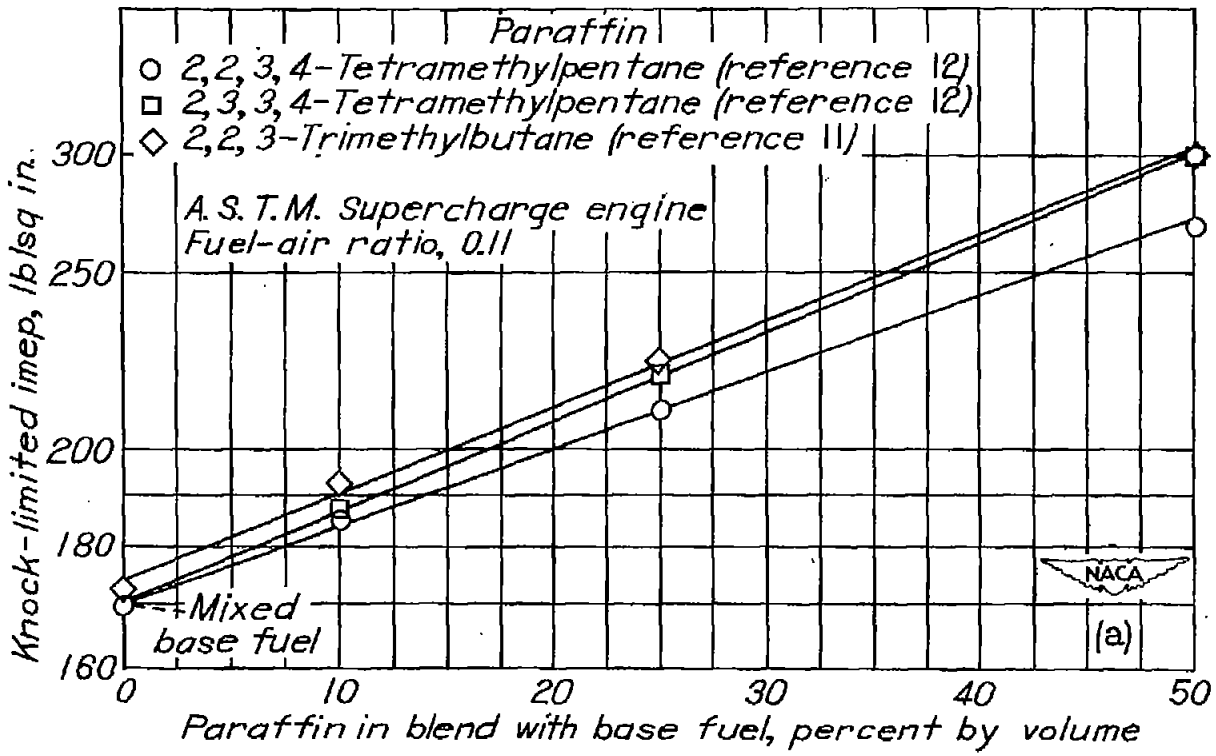

(a) Engine, A.S.T.M. Aviation.

Figure 5. - Comparison of isomers having highest antiknock values in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.



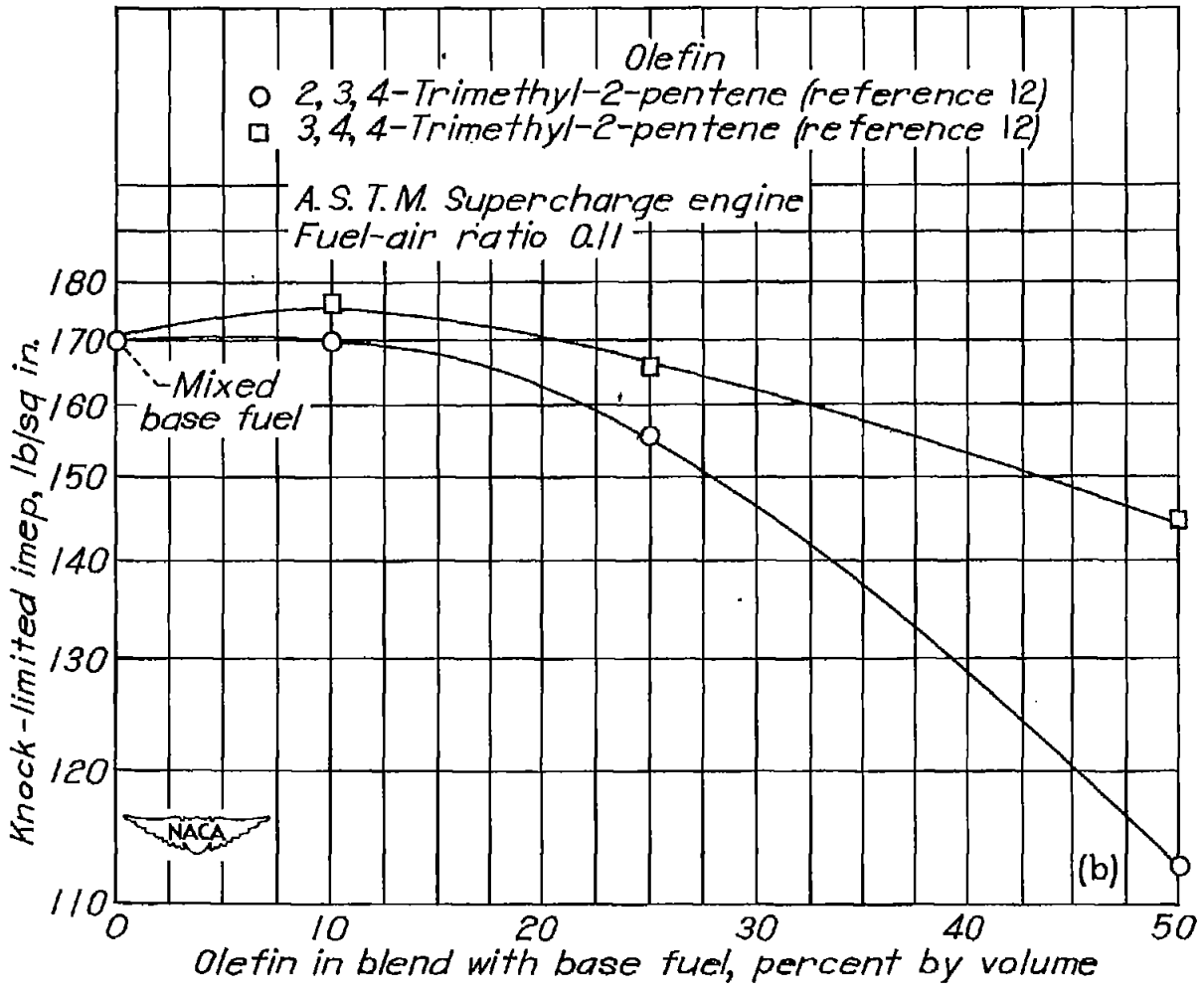

(b) Engine, A.S.T.M. Supercharge.

Figure 5. - Concluded. Comparison of isomers having highest antiknock values in blend with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.



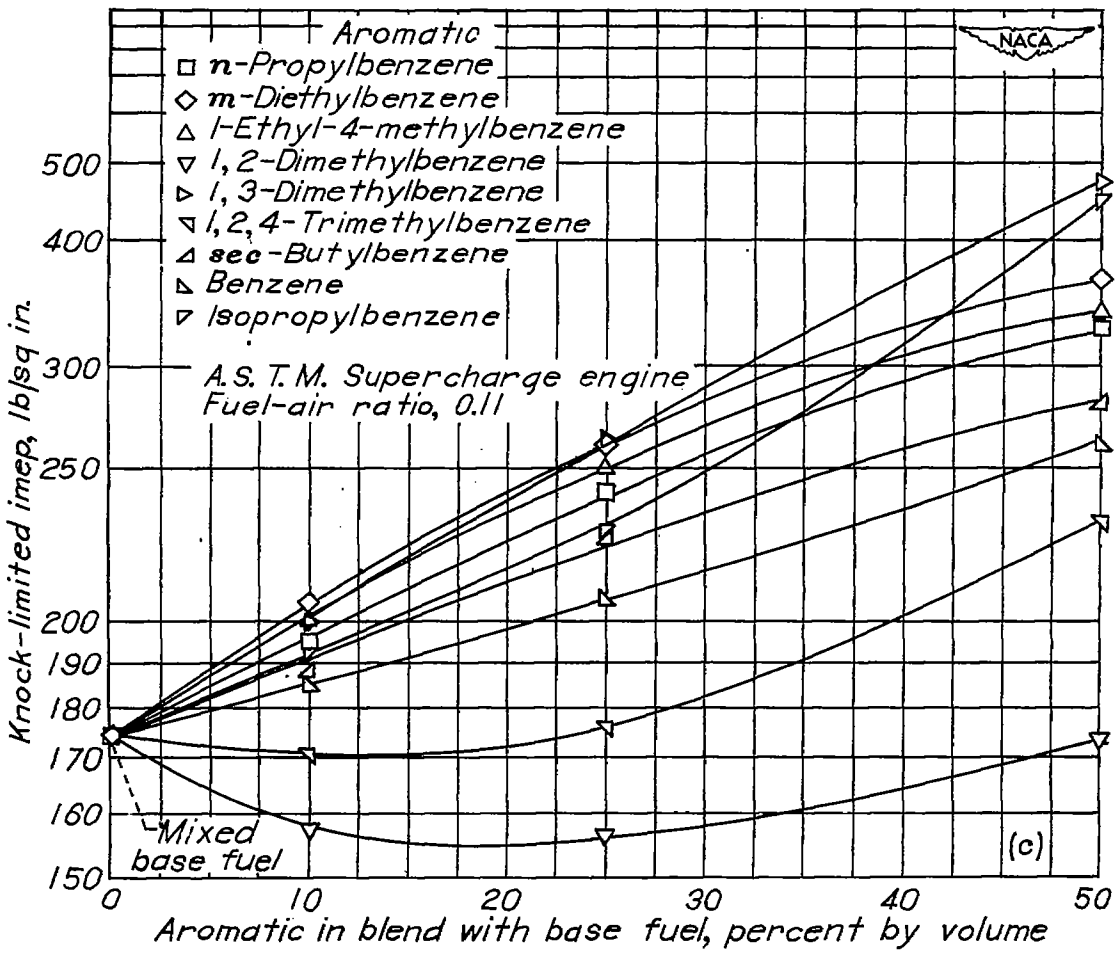

(a) Paraffins.

Figure 6. - Knock-limited performance of blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(b) Olefins.

Figure 6. - Continued. Knock-limited performance of blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(c) Aromatics.

Figure 6. - Concluded. Knock-limited performance of blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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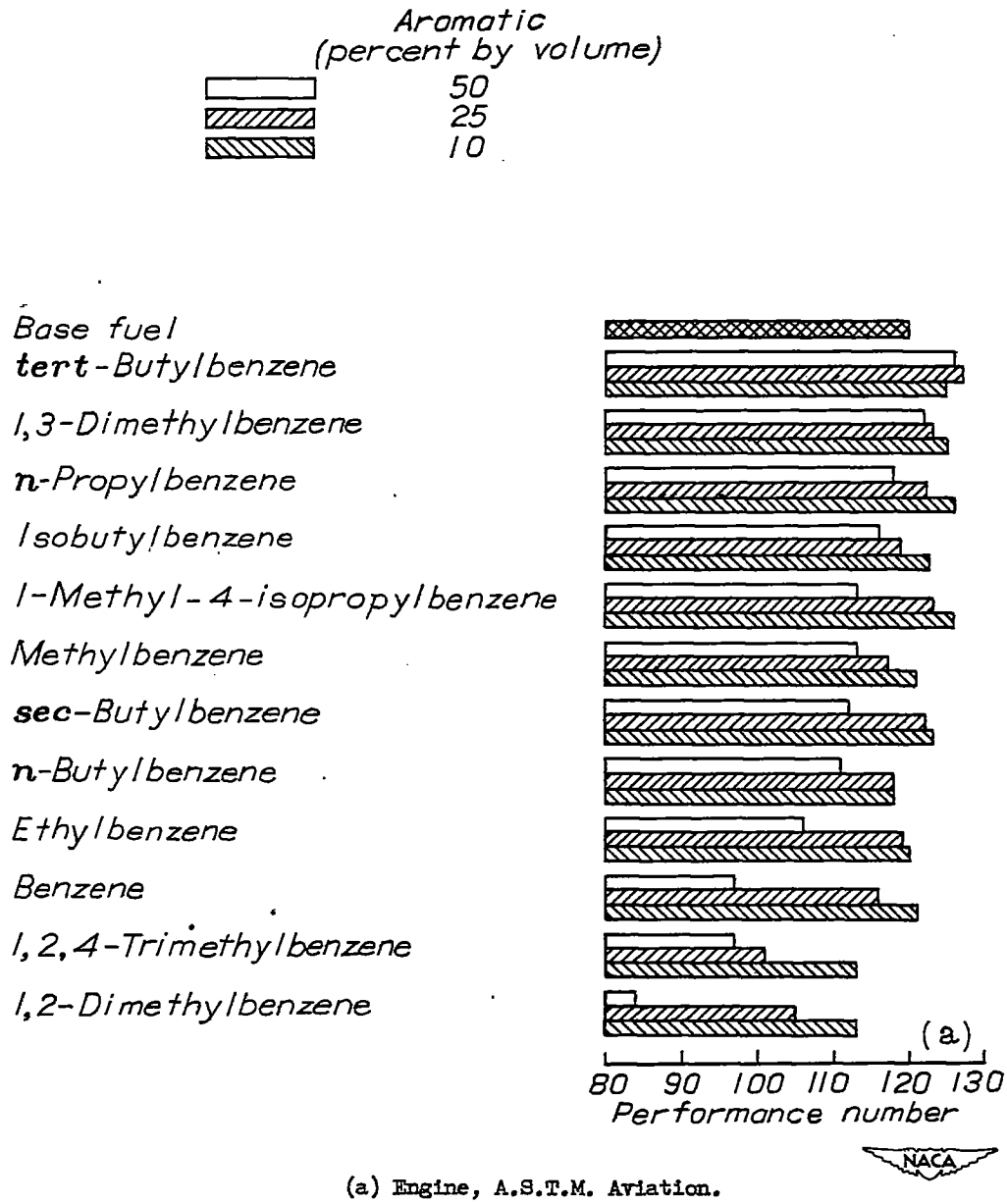
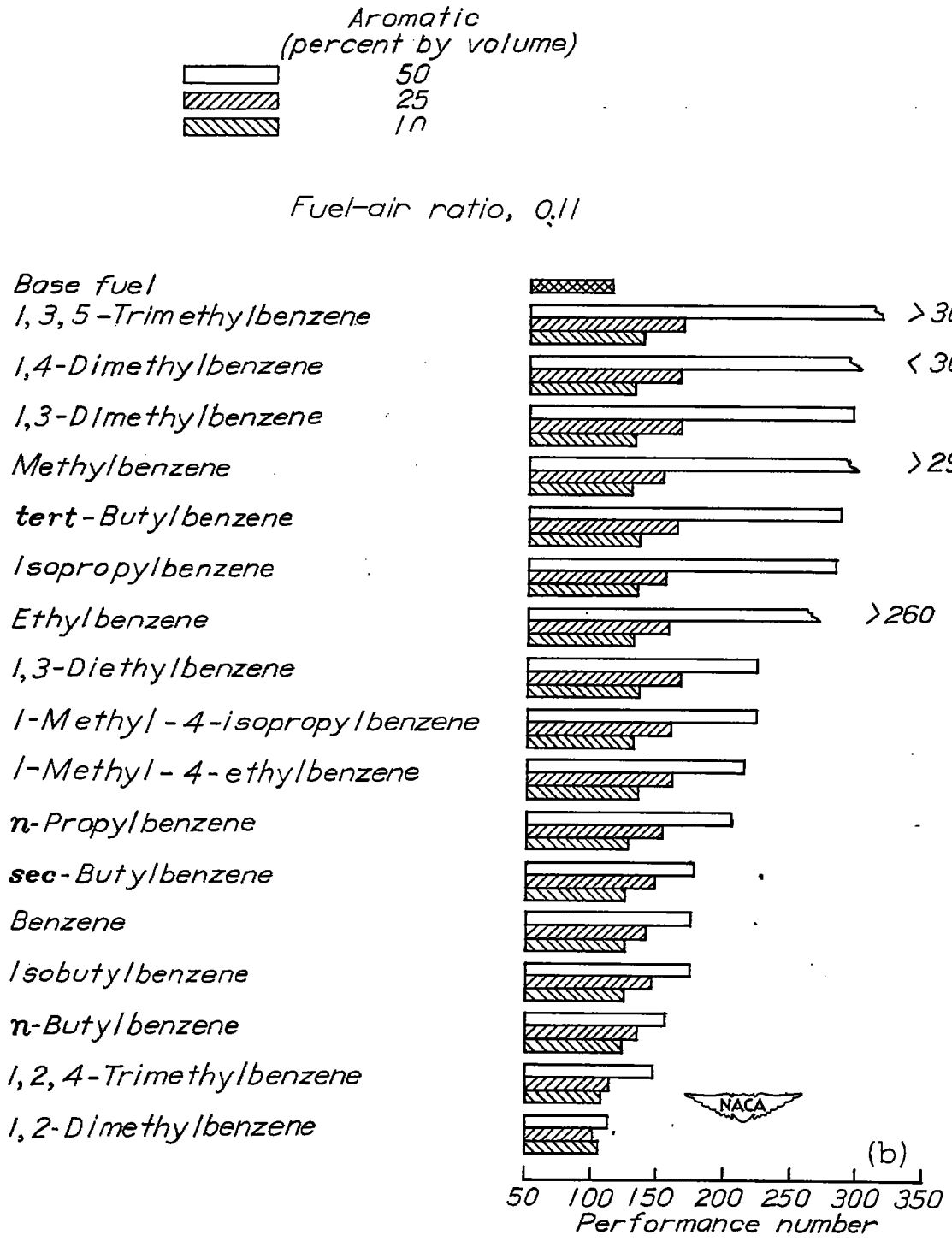



(a) Engine, A.S.T.M. Aviation.

Figure 7. - Comparison of knock-limited performance of aromatic blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.




(b) Engine, A.S.T.M. Supercharge.

Figure 7. - Concluded. Comparison of knock-limited performance of aromatic blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.

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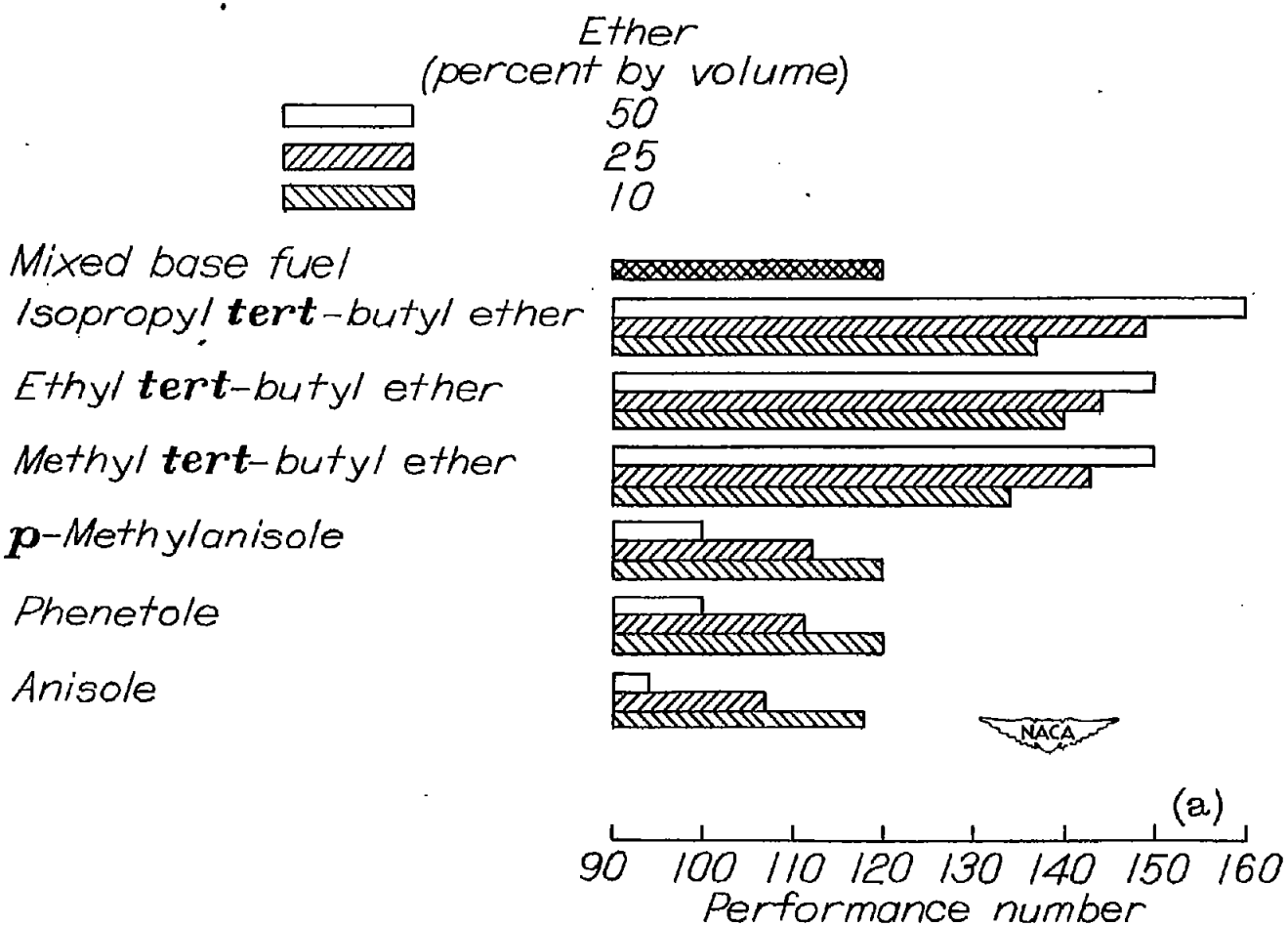
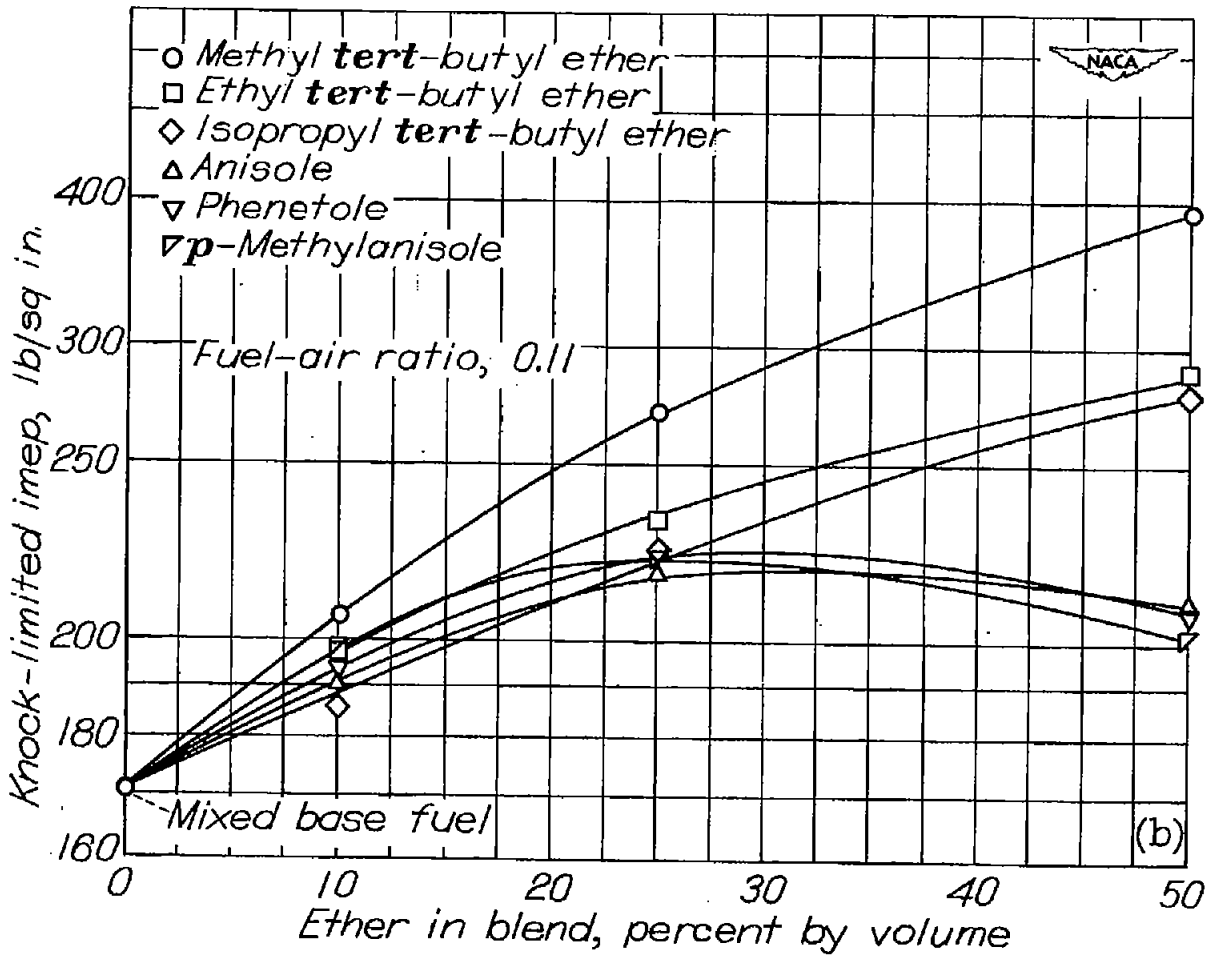


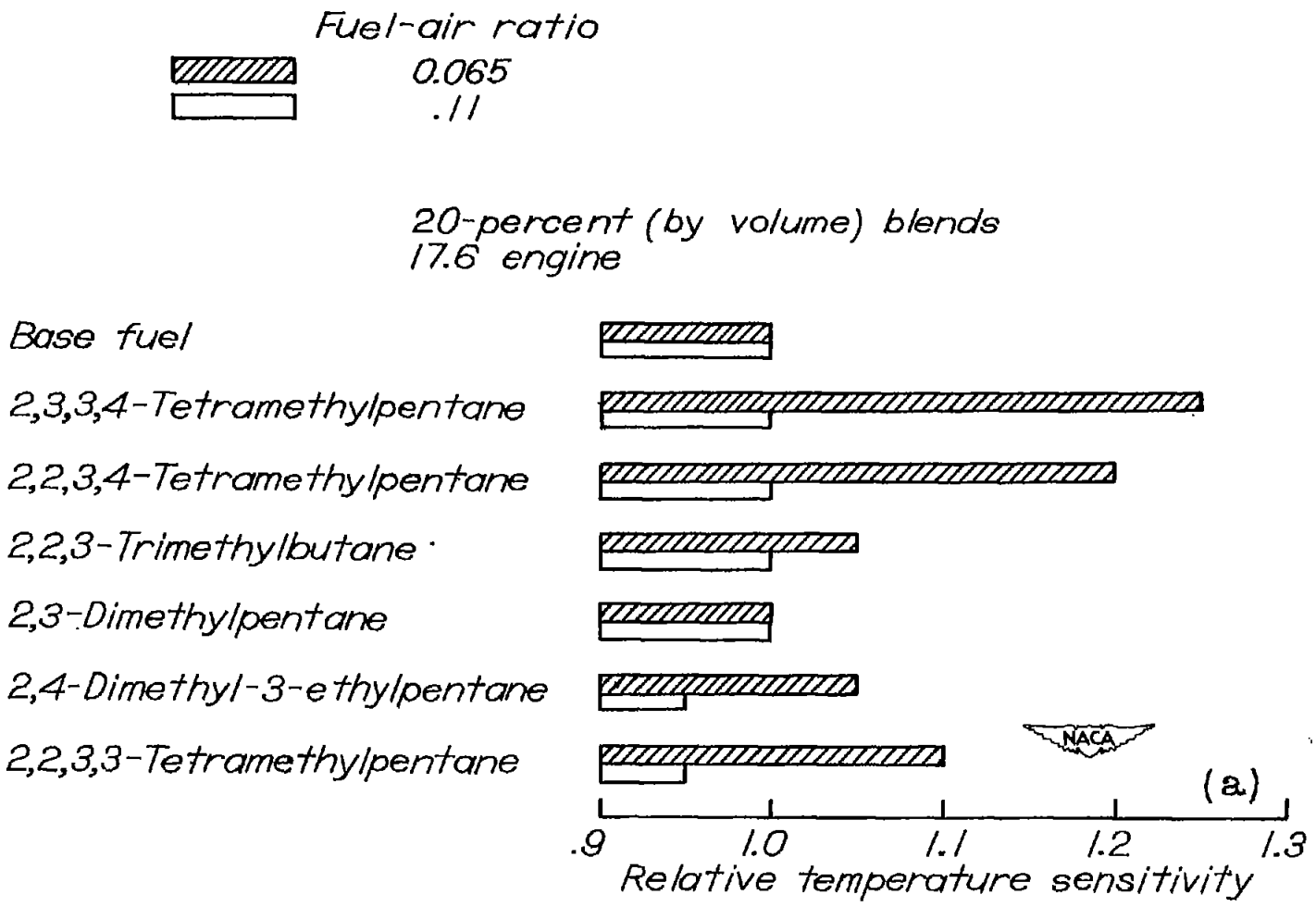

(a) Engine, A.S.T.M. Aviation.

Figure 8. - Comparison of knock-limited performance of ether blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.



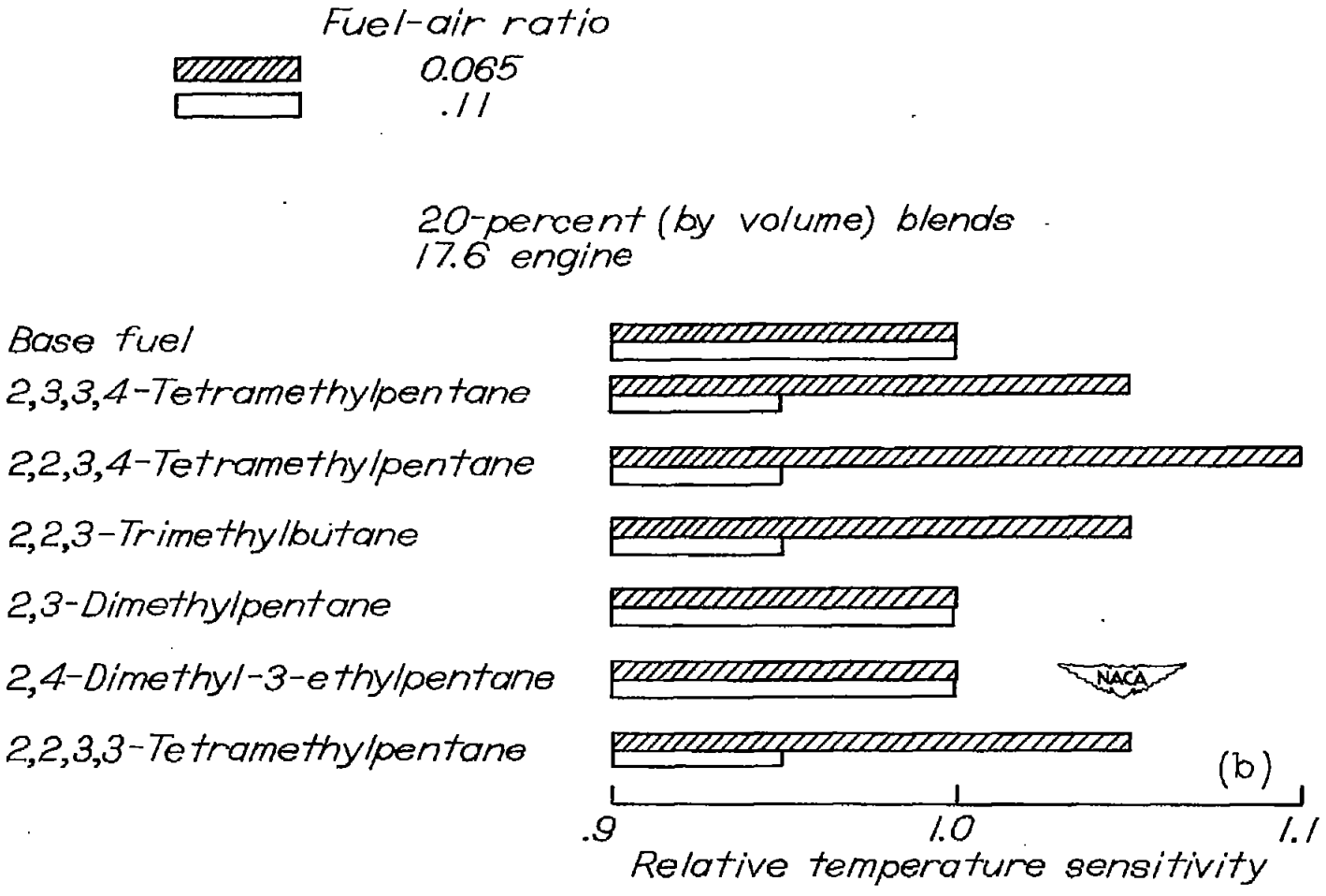

(b) Engine, A.S.T.M. Supercharge.

Figure 8. - Concluded. Comparison of knock-limited performance of ether blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon.



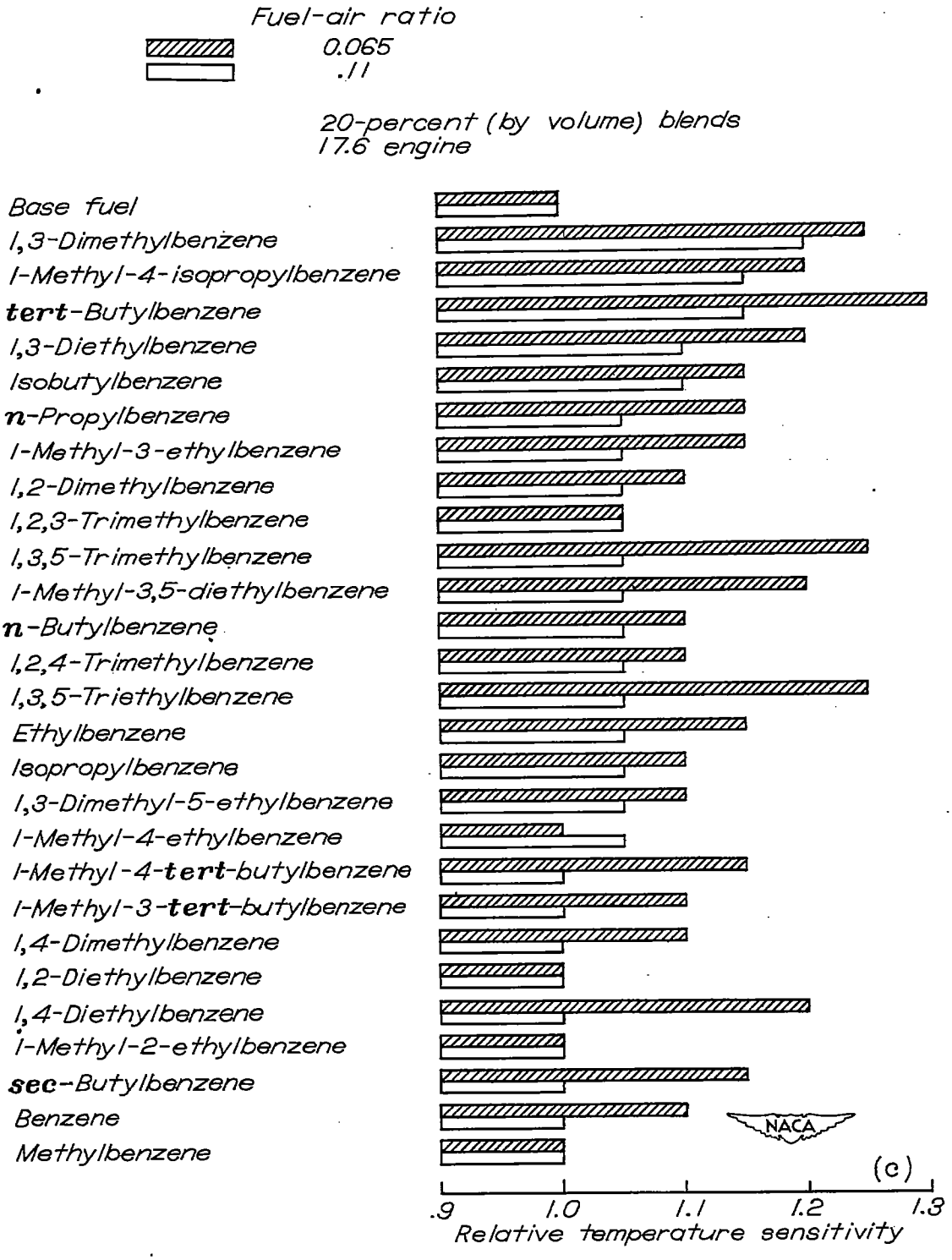

(a) Paraffins; unleaded.

Figure 9. - Temperature sensitivity of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.



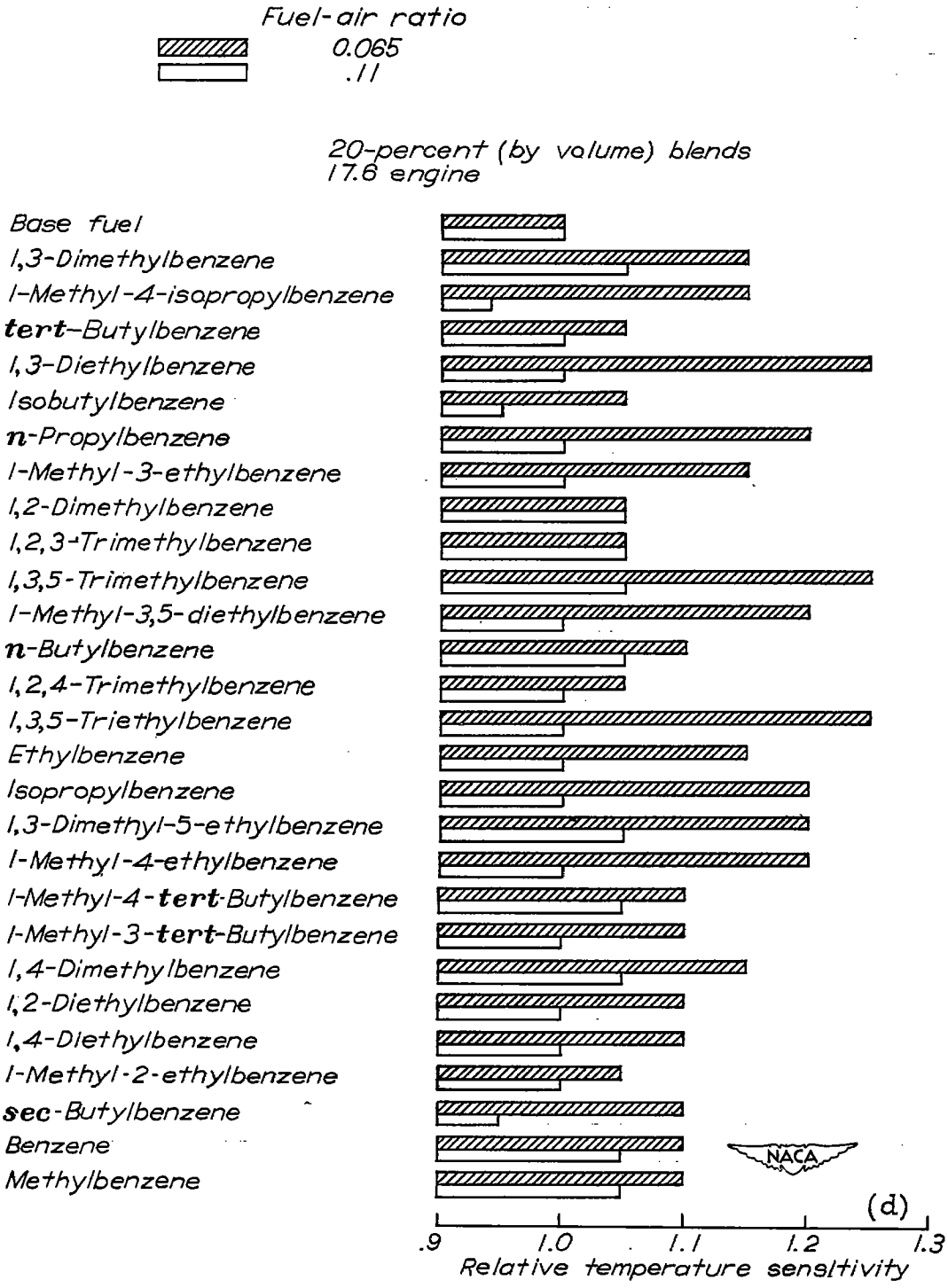

(b) Paraffins; leaded to 4 ml TEL per gallon.

Figure 9. - Continued. Temperature sensitivity of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.



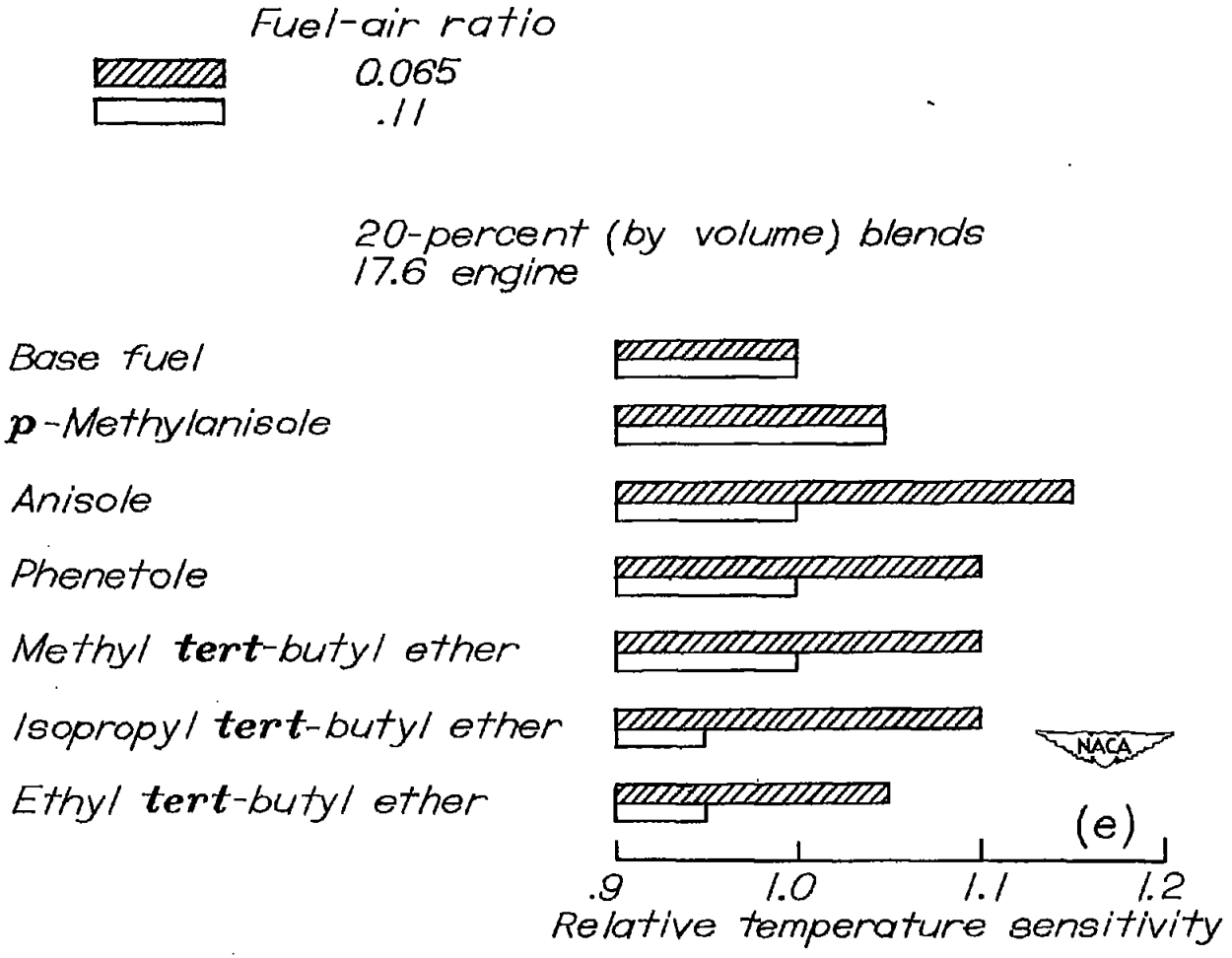

(c) Aromatics; unleaded.

Figure 9. - Continued. Temperature sensitivity of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 36° B.T.C.; coolant temperature, 212° F.



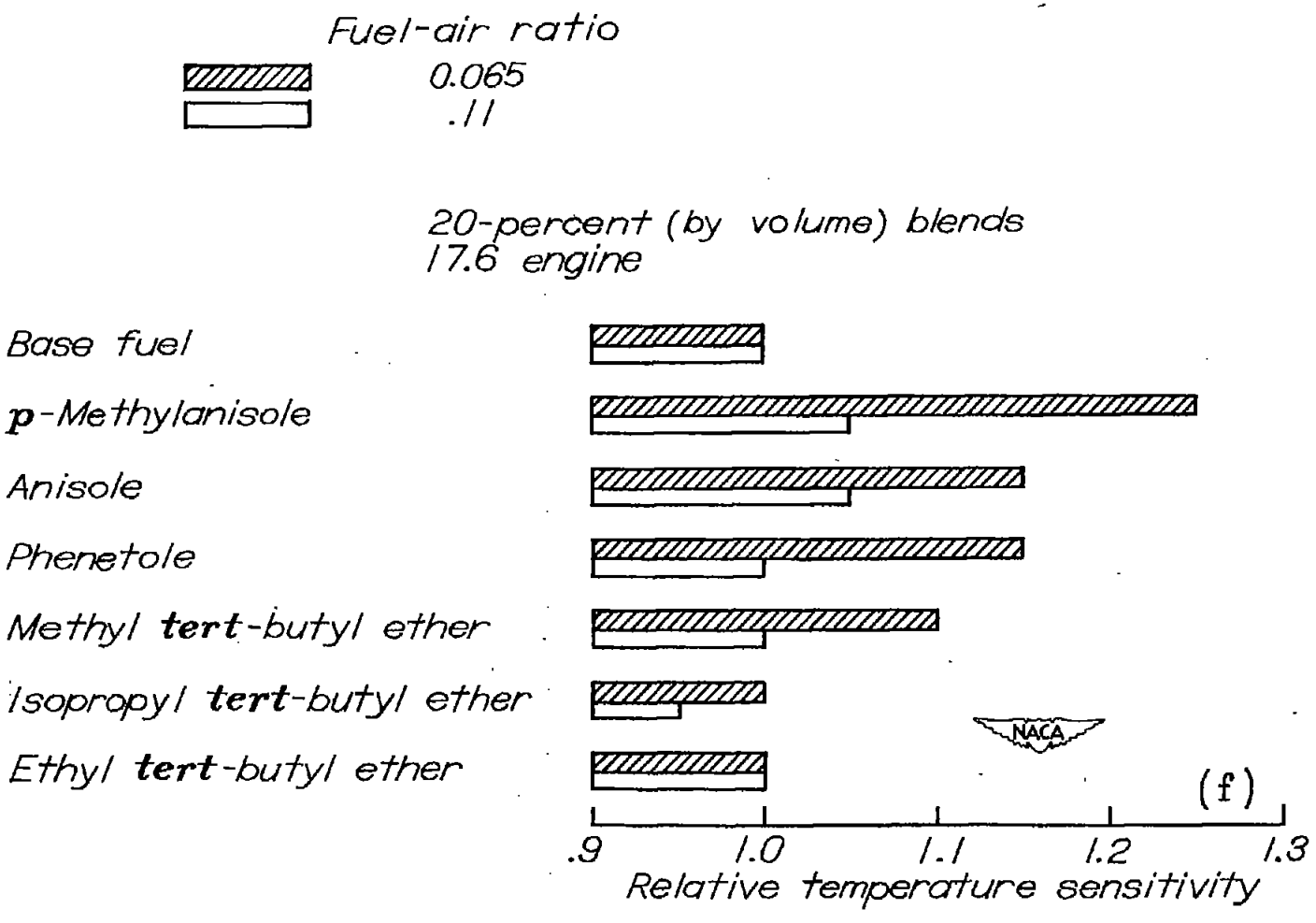

(d) Aromatics; leaded to 4 ml TEL per gallon.

Figure 9. - Continued. Temperature sensitivity of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.




(e) Ethers; unleaded.

Figure 9. - Continued. Temperature sensitivity of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.




(f) Ethers; leaded to 4 ml TEL per gallon.

Figure 9. - Concluded. Temperature sensitivity of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.

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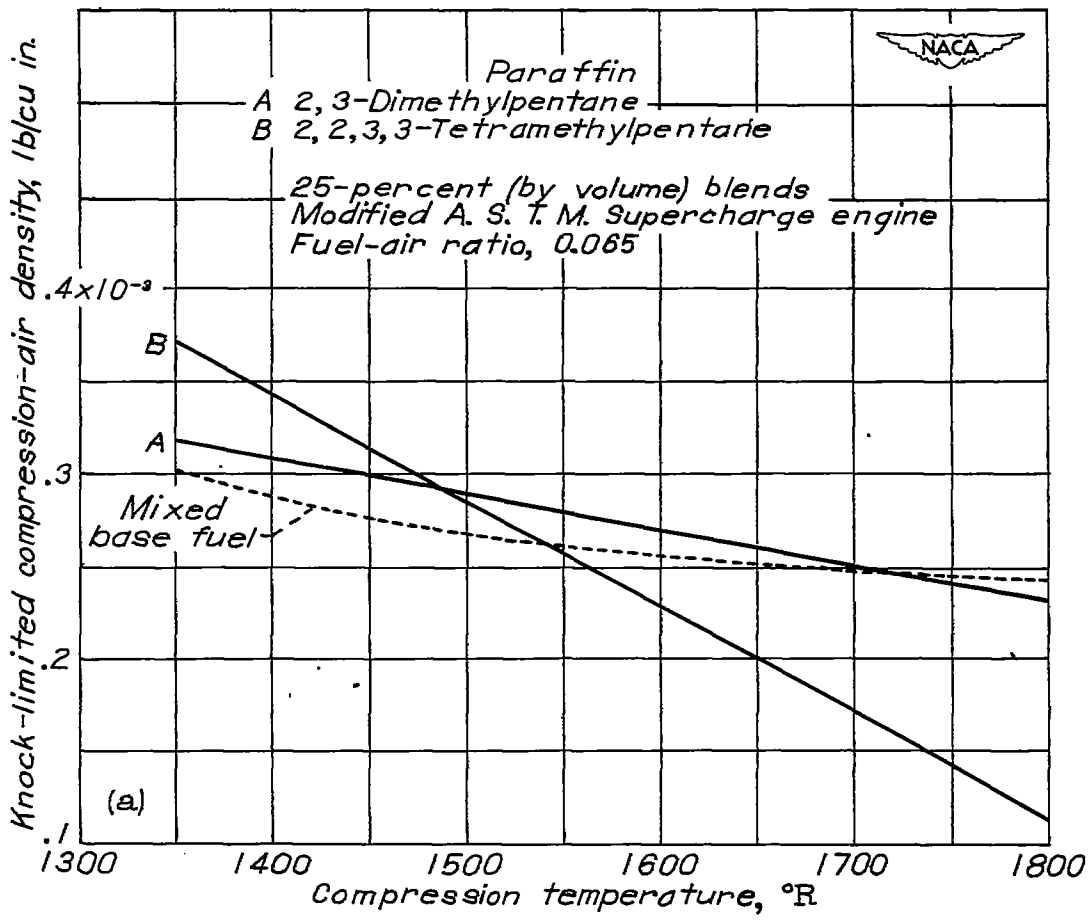
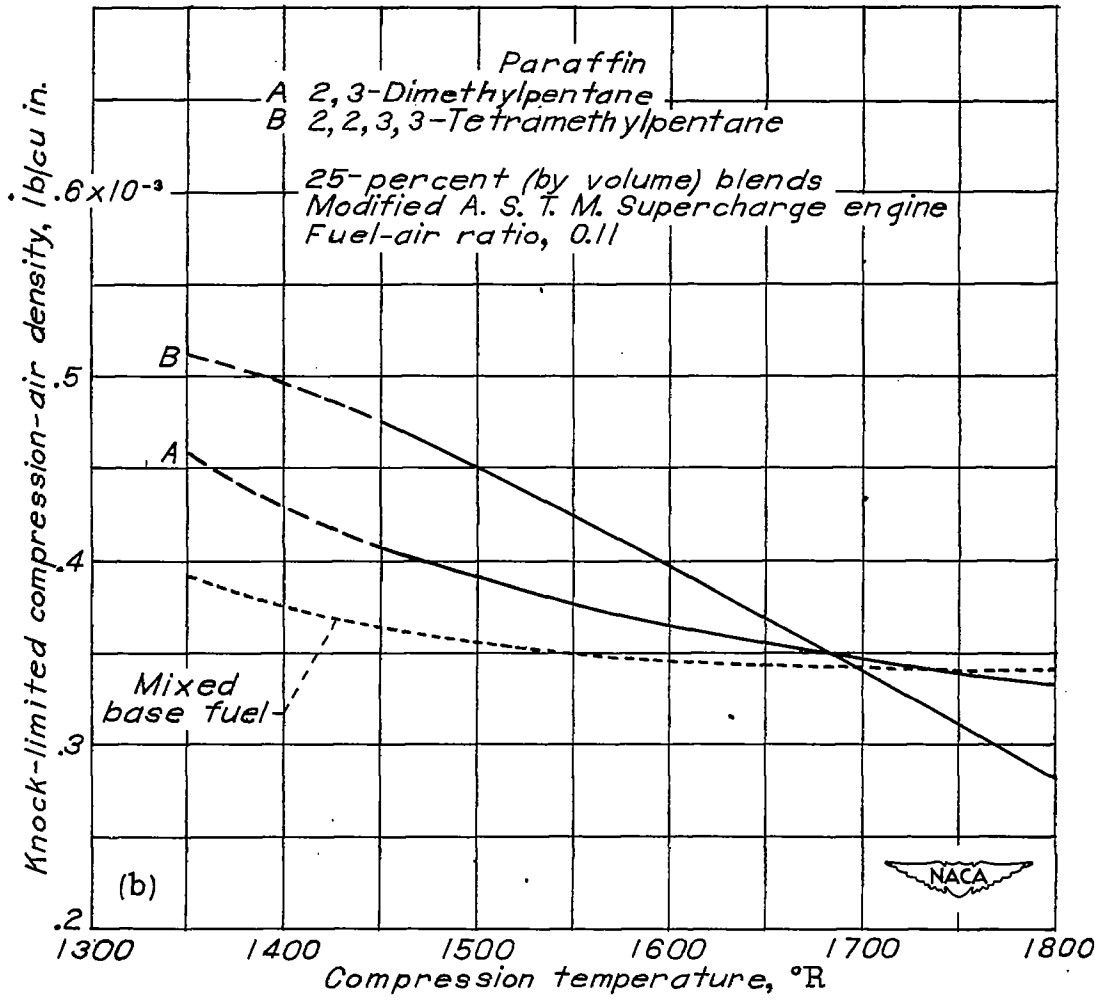



(a) Paraffins; lean conditions.

Figure 10. - Effect of compression temperature on compression-air density for blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon. Compression ratio, variable; inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 250° F.




(b) Paraffins; rich conditions.

Figure 10. - Continued. Effect of compression temperature on compression-air density for blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon. Compression ratio, variable; inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 250° F.

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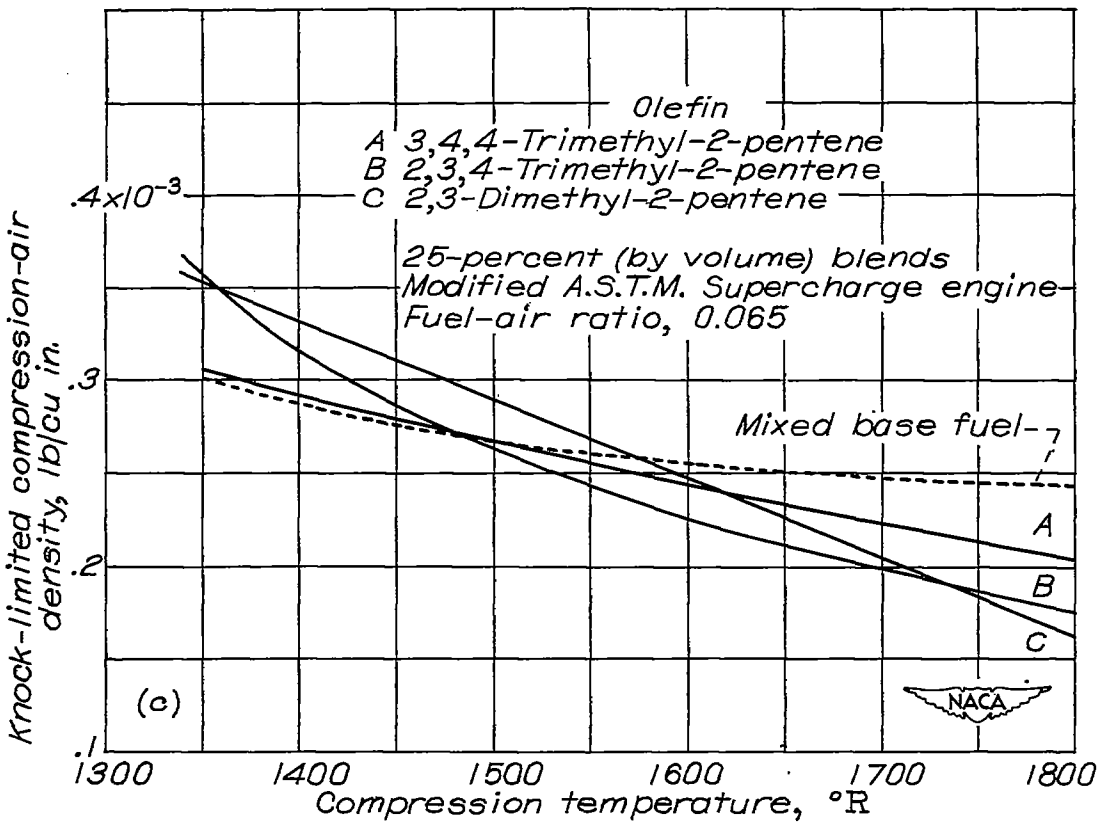
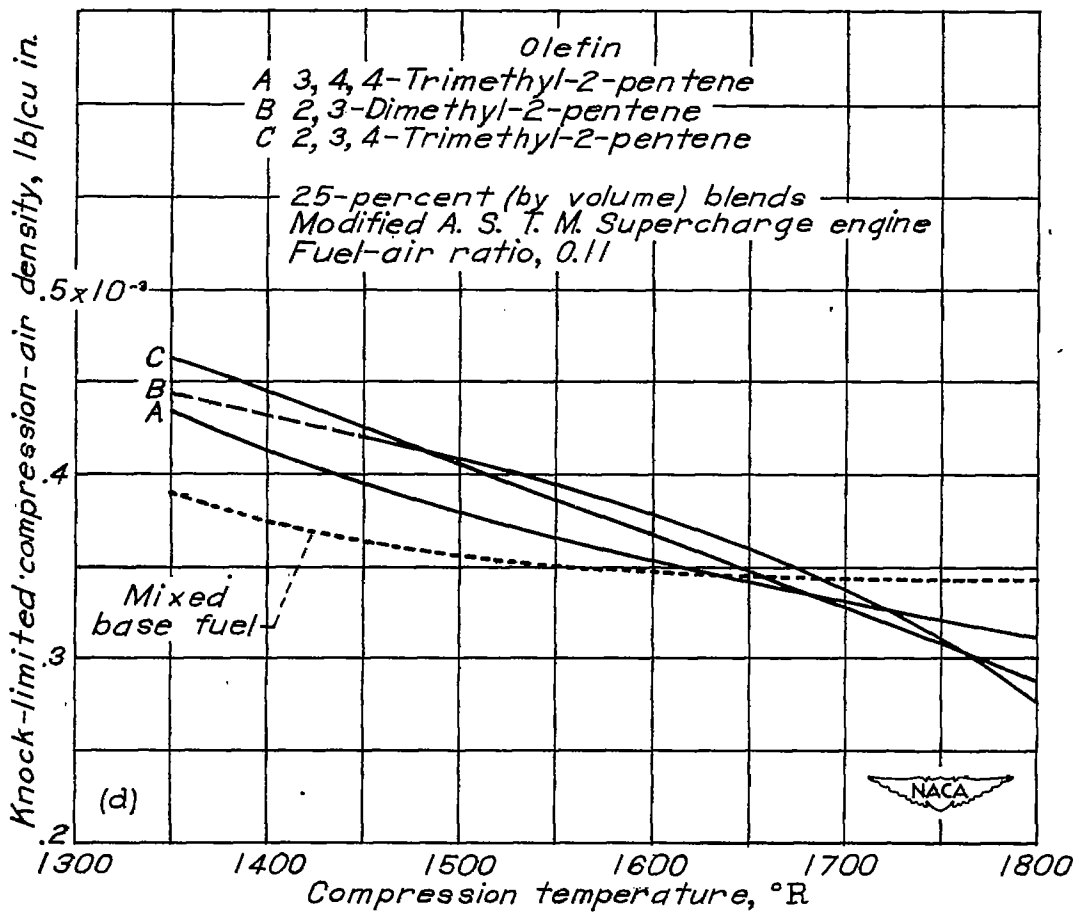



(c) Olefins; lean conditions.

Figure 10. - Continued. Effect of compression temperature on compression-air density for blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon. Compression ratio, variable; inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 250° F.




(d) Olefins; rich conditions.

Figure 10. - Continued. Effect of compression temperature on compression-air density for blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon. Compression ratio, variable; inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 250° F.

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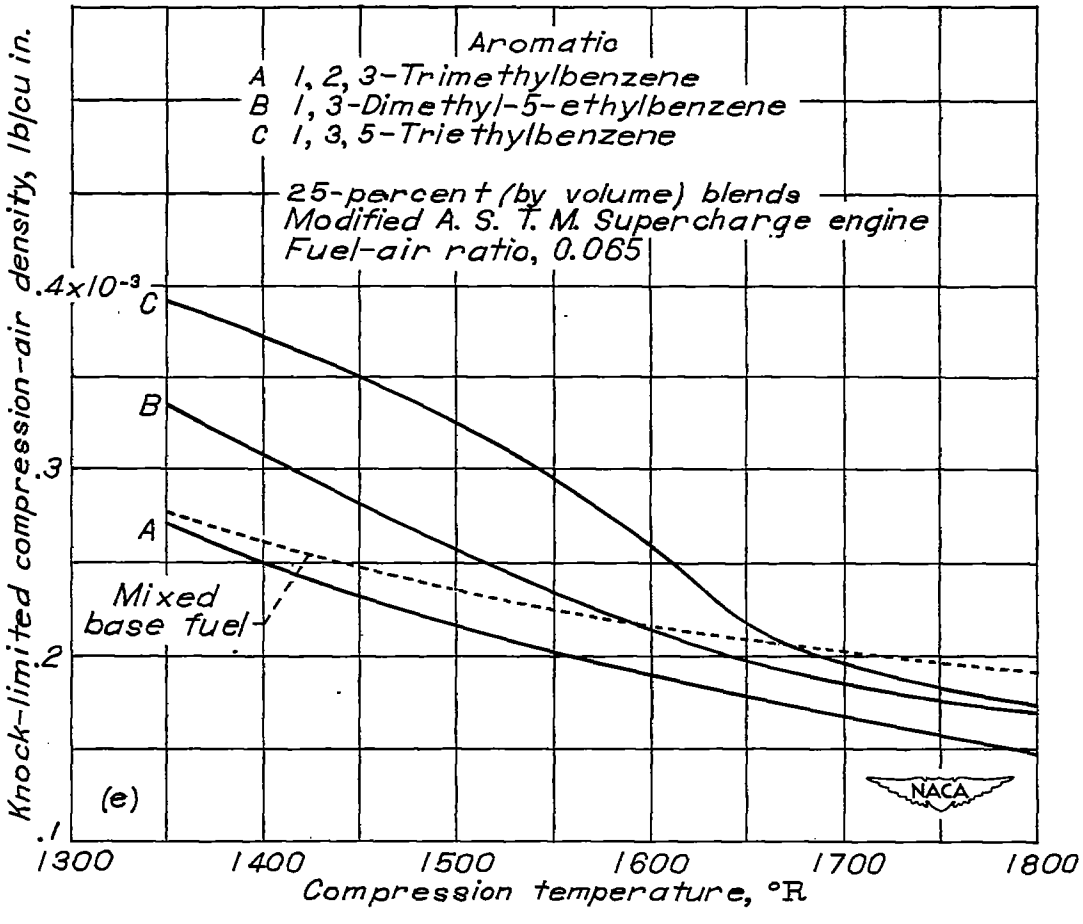
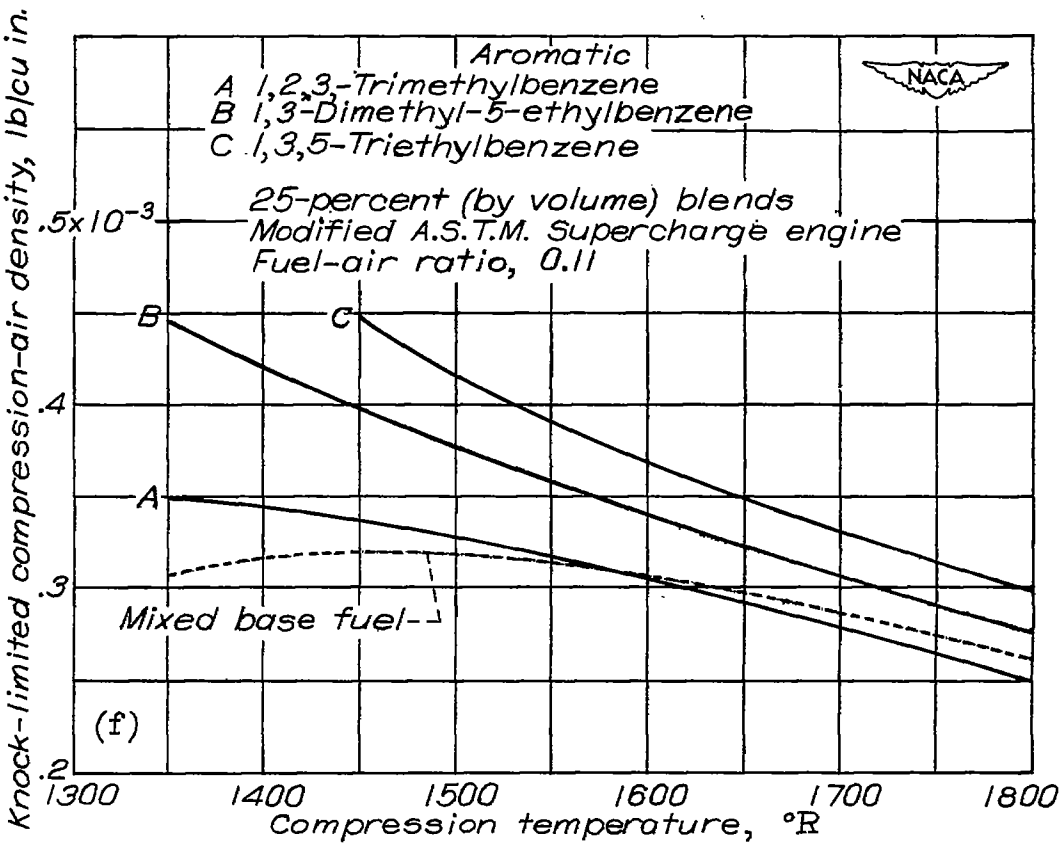



(e) Aromatics; lean conditions.

Figure 10. - Continued. Effect of compression temperature on compression-air density for blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon. Compression ratio, variable; inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 250° F.




(f) Aromatics; rich conditions.

Figure 10. - Concluded. Effect of compression temperature on compression-air density for blends with mixed base fuel consisting of 87.5-percent isooctane and 12.5-percent n-heptane + 4 ml TEL per gallon. Compression ratio, variable; inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 250° F.

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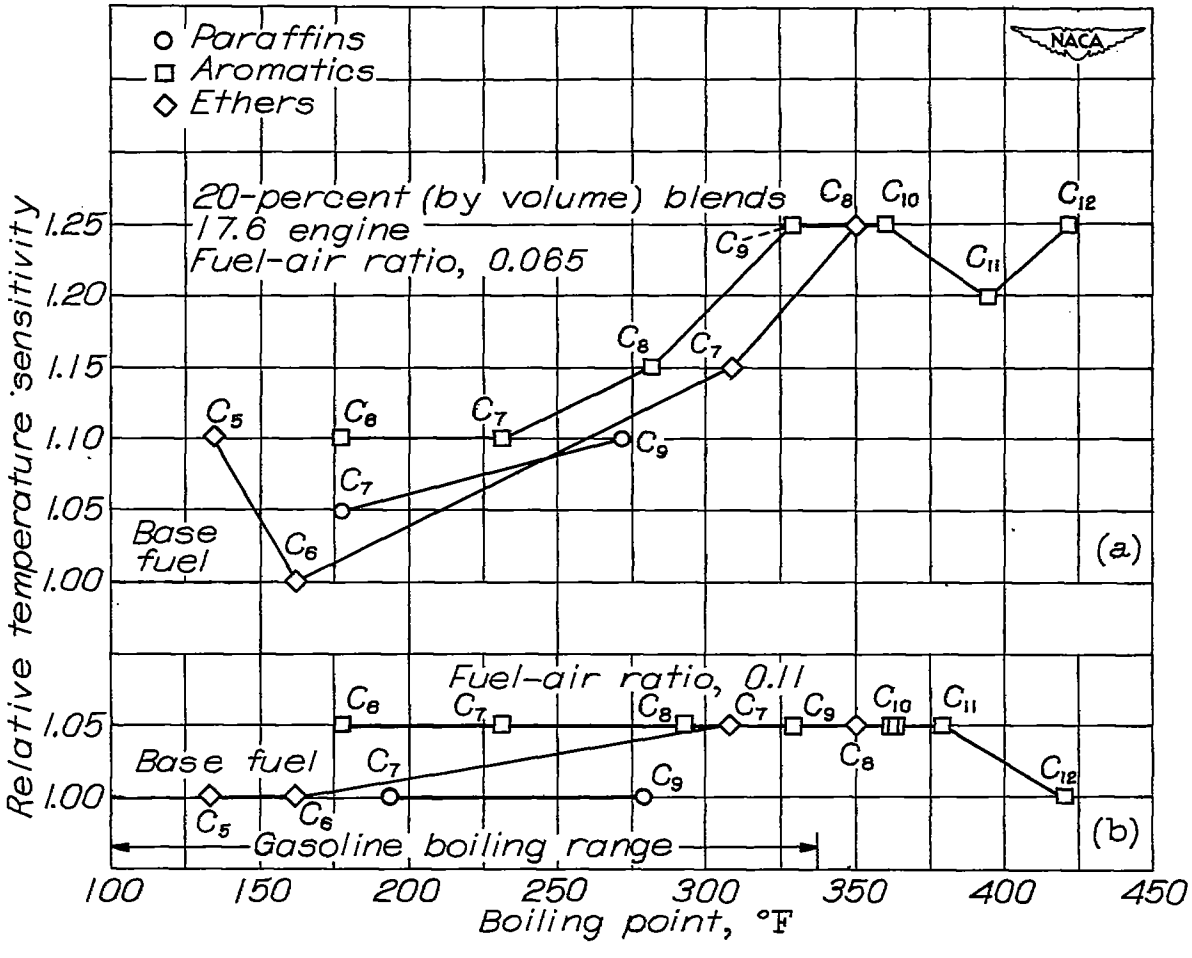
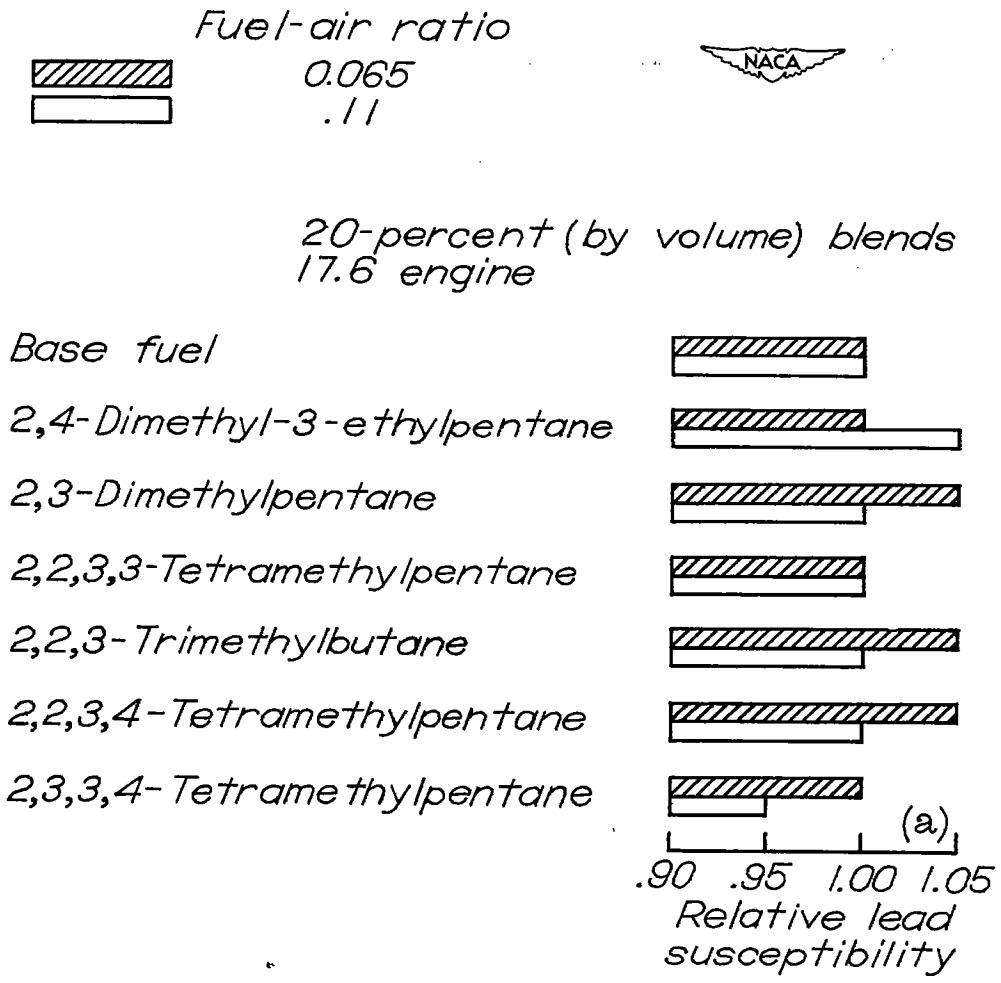


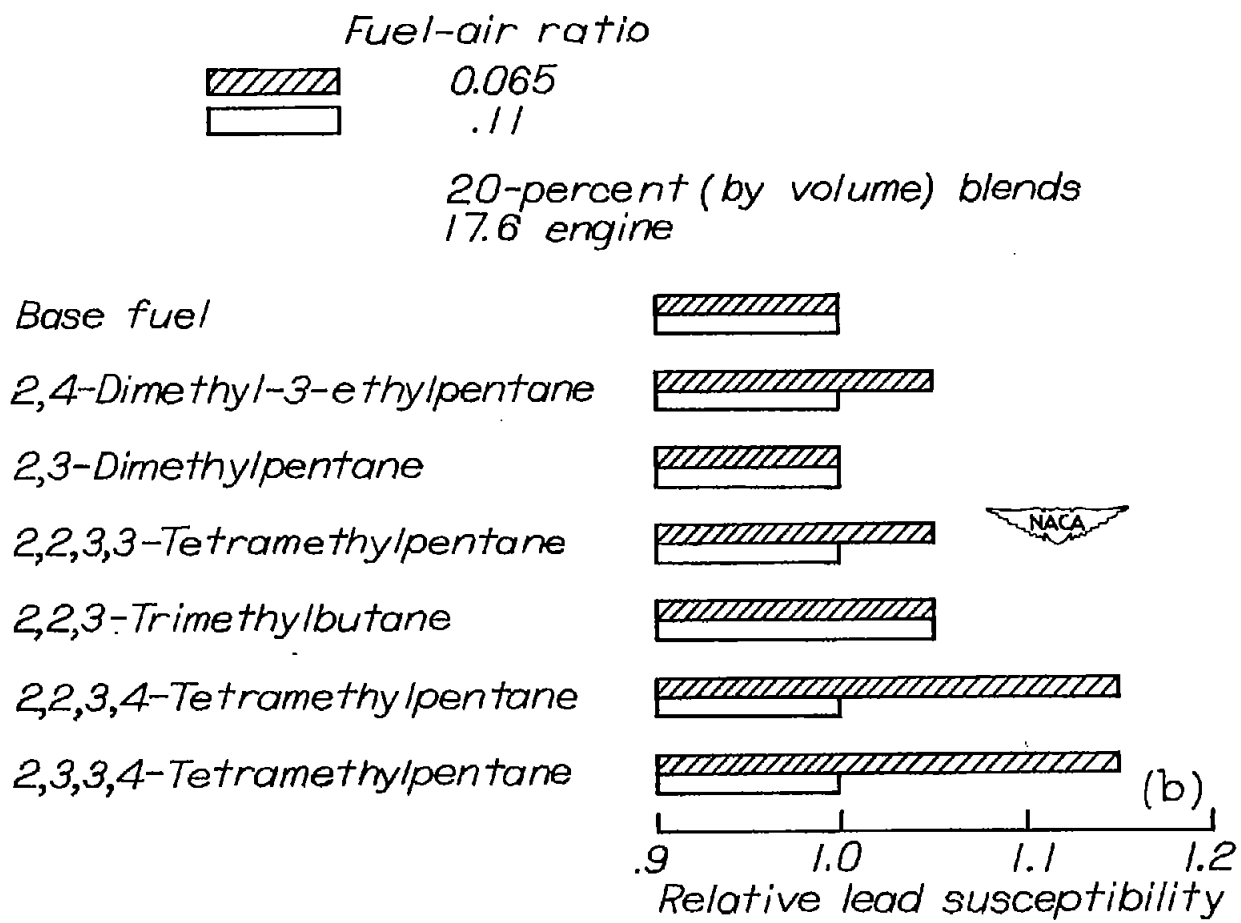

(a) Lean conditions.
(b) Rich conditions.

Figure 11. - Comparison of isomers having highest temperature sensitivities in blend with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.



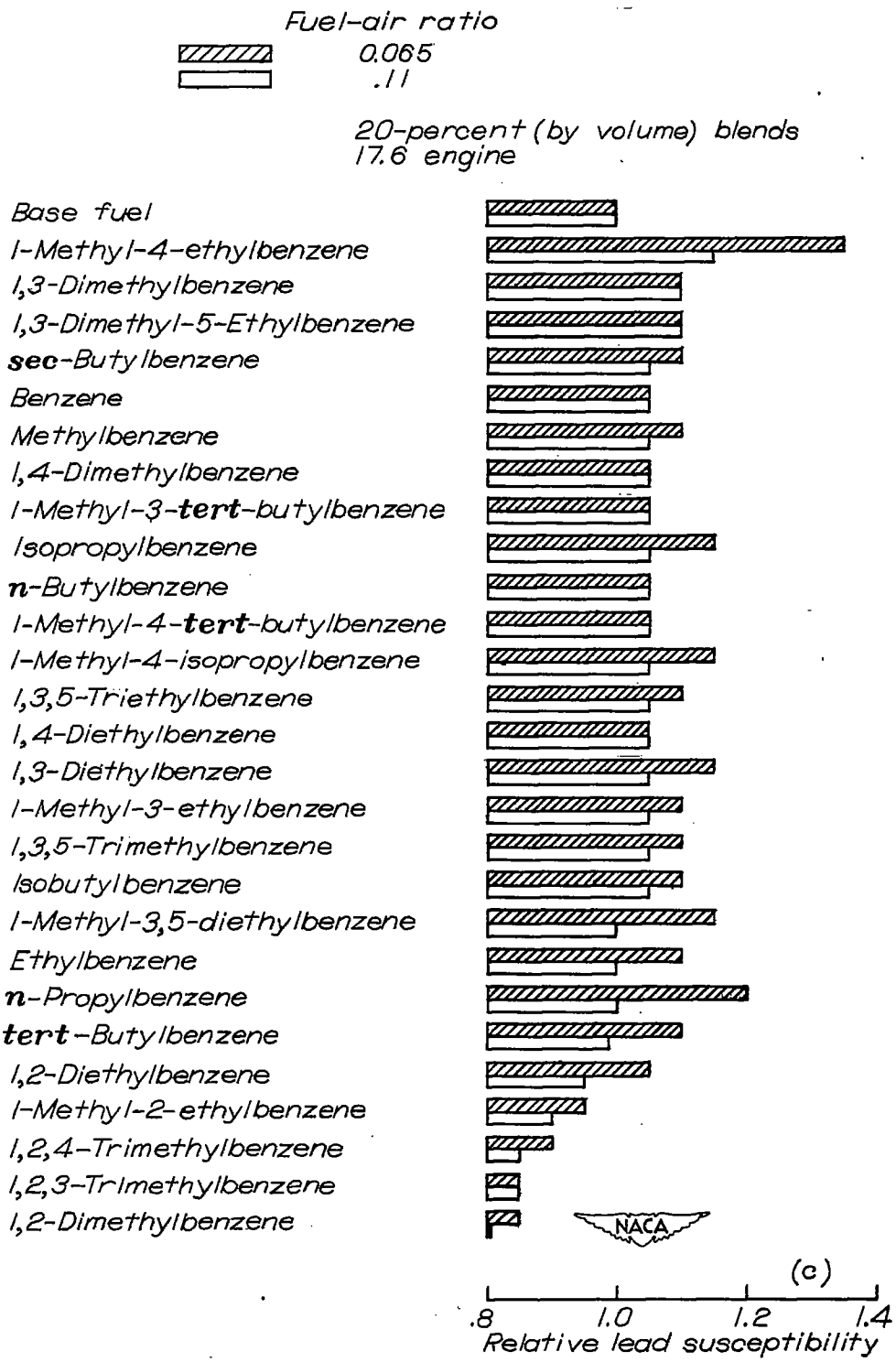

(a) Paraffins; inlet-air temperature, 100° F.

Figure 12. - Lead susceptibility (4 ml TEL/gal) of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.




(b) Paraffins; inlet-air temperature, 250° F.

Figure 12. - Continued. Lead susceptibility (4 ml TEL/gal) of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.




(c) Aromatics; inlet-air temperature, 100° F.

Figure 12. - Continued. Lead susceptibility (4 ml TEL/gal) of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.

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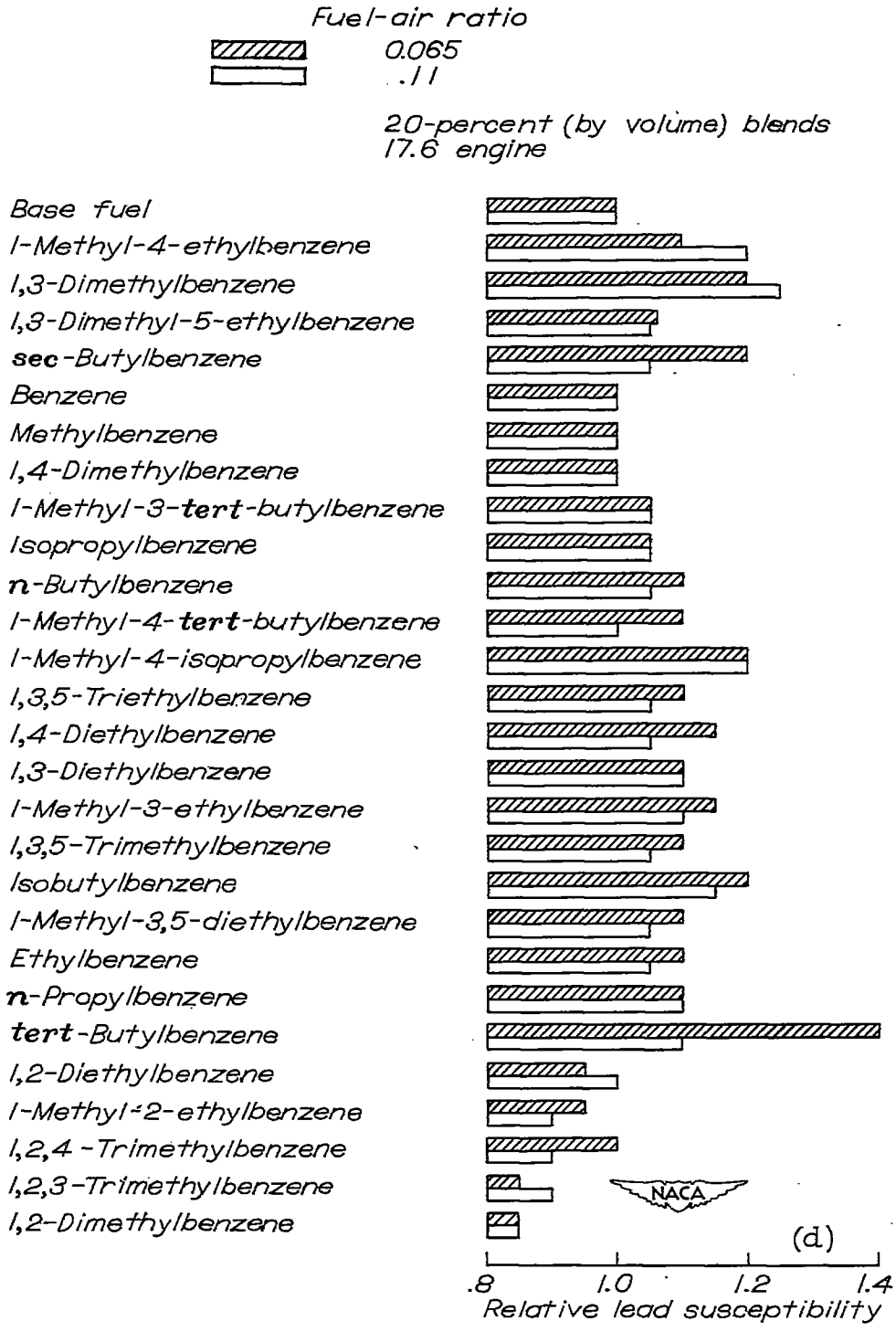
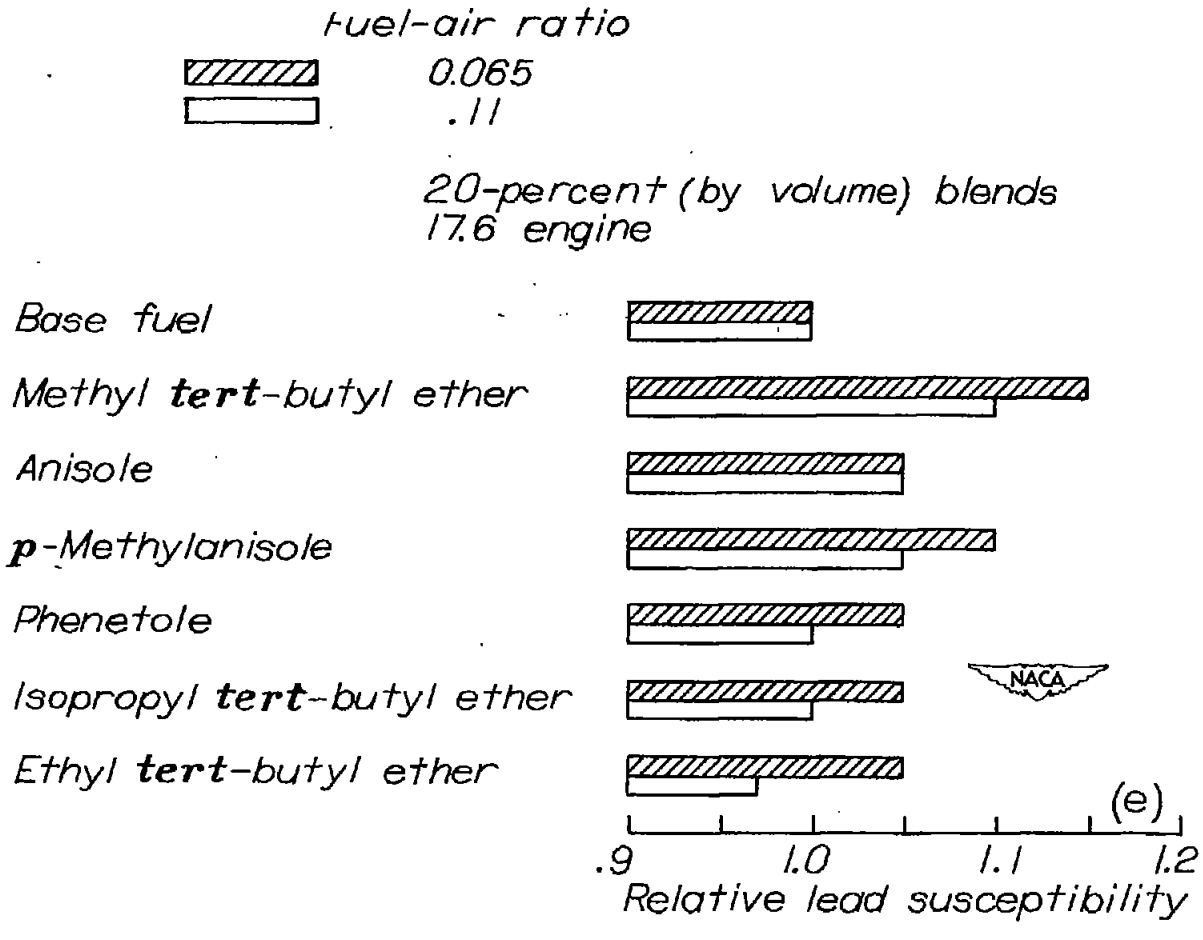


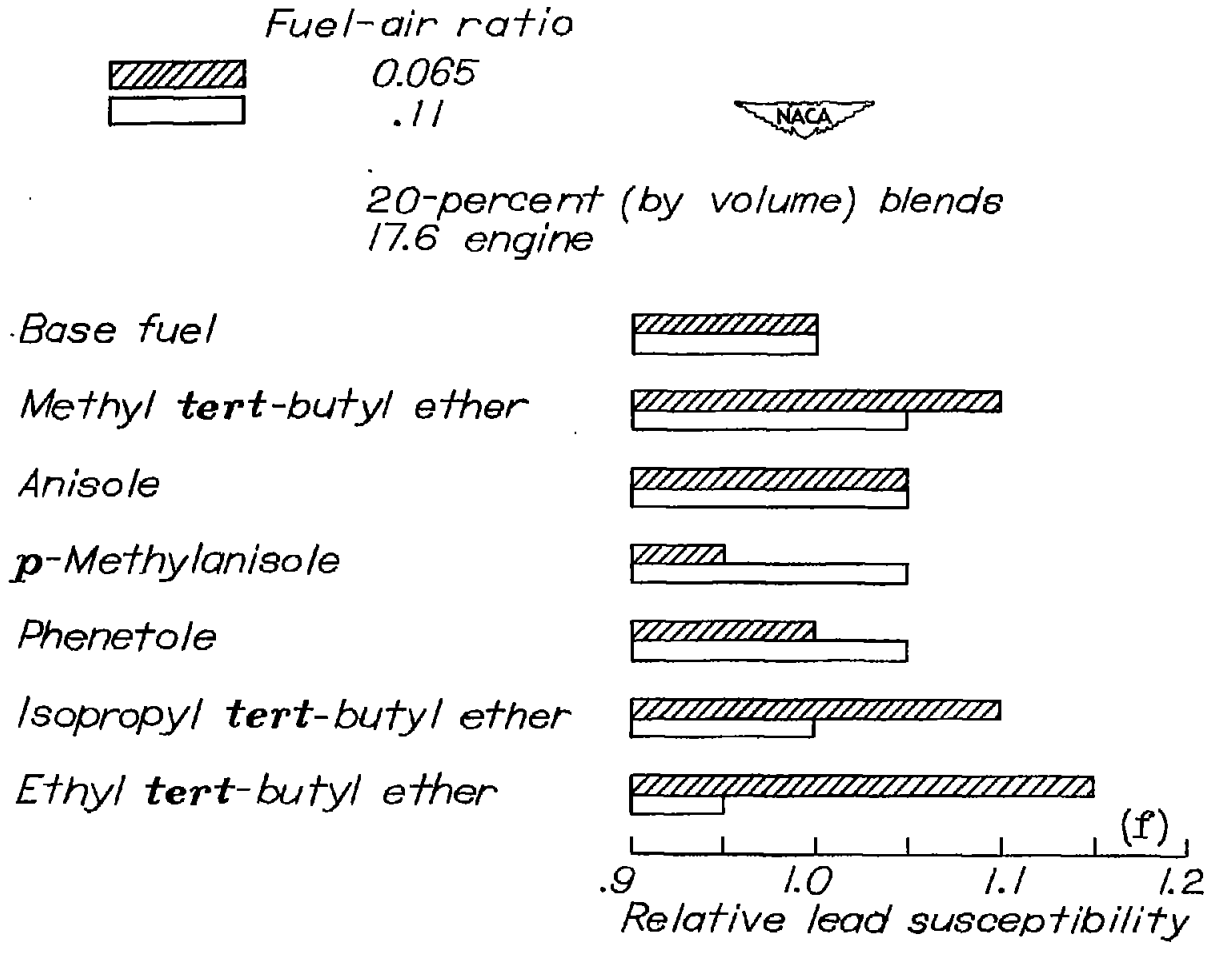

(d) Aromatics; inlet-air temperature, 250° F.

Figure 12. - Continued. Lead susceptibility (4 ml TEL/gal) of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.



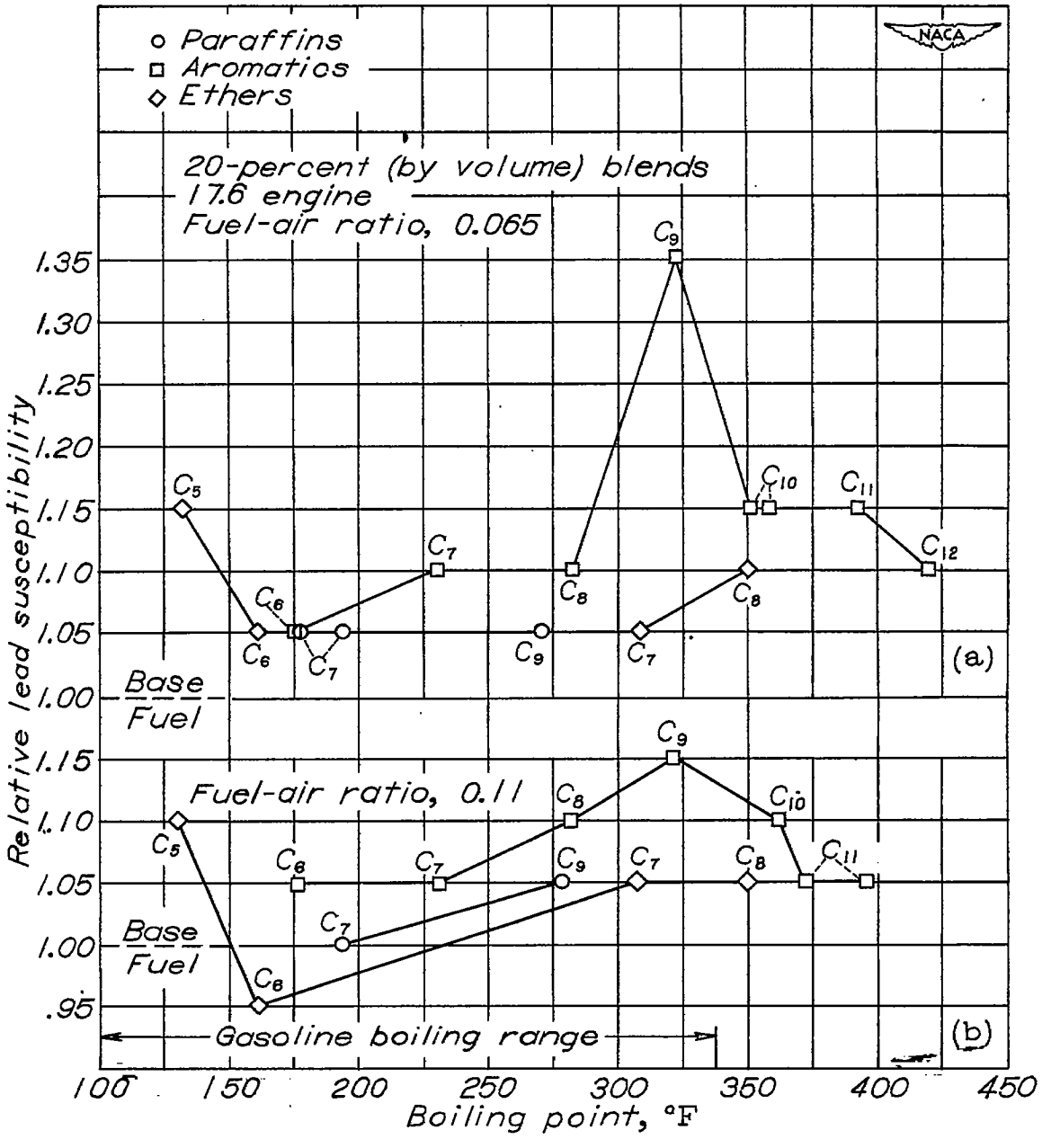

(e) Ethers; inlet-air temperature, 100° F.

Figure 12. - Continued. Lead susceptibility (4 ml TEL/gal) of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.




(f) Ethers; inlet-air temperature, 250° F.

Figure 12. - Concluded. Lead susceptibility (4 ml TEL/gal) of blends with isooctane. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.




(a) Lean conditions.
(b) Rich conditions.

Figure 13. - Comparison of isomers having highest lead susceptibility in blends with isooctane. Compression ratio, 7.0; inlet-air temperature, 100° F; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.