NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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KNOCK-LIMITED PERFORMANCE OF SEVERAL BRANCHED PARAFFINS AND OLEFINS

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SUMMARY

The knock-limited performance of 2,2,3,3-tetramethylpentane, 2,4-dimethyl-3-ethylpentane, 2,3-dimethylpentane, and 2,3-dimethyl-2-pentene, individually blended in several base fuels was determined in F-3, F-4, and supercharged 17.6 engines. Temperature sensitivity of the fuels is shown by compression temperature-density curves computed from knock data at five compression ratios on a modified F-4 engine; these curves are also presented for blends of 2,3,4-trimethyl-2-pentene and 3,4,4-trimethyl-2-pentene, whose knock-limited performance was previously reported.

The engine conditions of this investigation are roughly classified as to degree of severity and this concept is used in comparing these compounds with other selected hydrocarbons.

Of a group of high-performance paraffins, the 2,2,3,3-tetramethylpentane blend was the best for high knock-limit at conditions of mild or moderate engine severity, but at more severe conditions it was the poorest of the group; at severe conditions (F-3), the triptane blend was the best; at very severe conditions, more severe than F-3, the relatively insensitive fuels such as isooctane were thought to be as good as or better than any of the others. For high antiknock performance in blends over a fairly wide range of engine severity, triptane may still be considered the best liquid paraffinic hydrocarbon known.

INTRODUCTION

An investigation to determine the antiknock effectiveness of selected compounds as blending agents for aviation fuels is being conducted at the NACA Cleveland laboratory. As part of this study, the NBS (National Bureau of Standards) Hydrocarbon Fuel Research Laboratory has prepared and submitted to the NACA for investigation in engines 13 paraffinic and 5 olefinic hydrocarbons of high purity.

Knock-limited-performance data on most of these hydrocarbons are presented in references 1 and 2.

New knock data on six NBS hydrocarbons are presented herein and ratings of all the NBS hydrocarbons submitted are compared. Blends of each hydrocarbon with reference base fuels were investigated on four small laboratory engines; information was thus provided on the following knock-limited-performance factors: F-3 and F-4 ratings, mixture response in the F-4 and 17.6 engines, lead susceptibility and inlet-air-temperature sensitivity in the 17.6 engine, and compression-air-temperature sensitivity in a modified F-4 engine as shown by compression temperature-density curves.

FUELS, APPARATUS, AND METHODS

Fuels. - The National Bureau of Standards provided 7 to 10 gallons of each of the following fuels:

2,2,3,3-tetramethylpentane
2,4-dimethyl-3-ethylpentane
2,3-dimethylpentane
2,3-dimethyl-2-pentene
2,3,4-trimethyl-2-pentene
3,4,4-trimethyl-2-pentene

The three paraffins and 2,3-dimethyl-2-pentene were individually blended in a concentration of 20 percent by volume with S reference fuel with and without 4 ml TEL per gallon. All six of the hydrocarbons were individually blended in a concentration of 25 percent by volume with a base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane plus 4 ml TEL per gallon in the final blend.

The two trimethylpentenes were run only in the modified F-4 engine; F-3, F-4, and 17.6-engine data for these two compounds are reported in reference 2.

Apparatus. - A description of the F-3, F-4, and 17.6 engines may be found in reference 3. The modified F-4 engine is equipped with a four-hole cylinder, dual ignition, and a shrouded intake valve. A pressurized-water coolant system was used with the jacket-outlet temperature maintained at 250° F.

Methods. - The following table presents an outline of engines (except F-3), engine variables, and fuel composition:

Engine	Engine variables				Fuel composition		
	Compression ratio	Coolant temperature (°F)	Inlet-air temperature (°F)	Spark advance (deg B.T.C.)	Base fuel	Hydrocarbon in blend (percent by volume)	TEL in blend (ml/gal)
17.6	7.0	212	100	30	S	0, 20	0
			250		S	0, 20	0
			100		S	0, 20	4
			250		S	0, 20	4
			250		87.5 percent S + 12.5 percent n-heptane	0, 25	4
F-4	7.0	375	225	45	87.5 percent S + 12.5 percent n-heptane	0, 25	4
Modified F-4	5.0 6.0 7.3 8.7 10.0	250	250	20	87.5 percent S + 12.5 percent n-heptane	0, 25	4

The engines were run at a speed of 1800 rpm. All blends were tested with an F-3 engine conforming to Army specification AN-VV-F-746, Amendment-1.

Operation of the F-4 engine conformed to Army specification AN-VV-F-748a, Amendment-1, except for the use of two independent fuel systems and the detection of incipient knock by a magnetostriction internal pickup and a cathode-ray oscilloscope.

RESULTS

F-4 mixture-response curves for the hydrocarbon blends are presented in figure 1; F-3 ratings and rich (fuel-air ratio F/A of 0.11) F-4 ratings are given in table I. The F-4 ratings in terms of percentage S plus 4 ml TEL in n-heptane plus 4 ml TEL were obtained from reciprocal imep plots and converted to Army-Navy performance numbers as described in reference 4.

A summary of F-3 and rich F-4 ratings for all the NBS hydrocarbons submitted, arranged to facilitate comparison on the basis of molecular structure, is presented in table II in terms of the ratio of performance number of blend to performance number of base fuel. This ratio was used to put all the F-3 data on a more comparable basis inasmuch as several base fuels with slightly different composition and performance were used; for simplicity, the F-4 data were put on the same basis. Data for isooctane blended with the base fuel consisting of 85 percent S plus 4 ml TEL in M plus 4 ml TEL are also included in table II; the F-3 value was estimated by linear interpolation between the performance numbers for the base fuel and for 100-percent S plus 4 ml TEL (25 percent isooctane in the base fuel is essentially the same as 88.75 percent S plus 4 ml TEL in M plus 4 ml TEL).

The 17.6-engine mixture-response curves for the hydrocarbons blended in two base fuels with and without lead and at two inlet-air temperatures are presented in figures 2 and 3. Indicated mean effective pressures at five fuel-air ratios and imep ratios of blends relative to base fuel in the 17.6 and F-4 engines are given in table III. From the data in table III, relative inlet-air-temperature sensitivity and relative lead susceptibility in the 17.6 engine were computed and are shown in tables IV and V, respectively.

The data for the modified F-4 engine are presented in figures 4 and 5 as curves of knock-limited air flow against fuel-air ratio. From this data, compression-air densities and temperatures at five fuel-air ratios were computed and the resulting faired curves are shown in figure 6. The 2,4-dimethyl-3-ethylpentane blend was not run in the modified F-4 engine because of the limited quantity of this fuel. Table VI presents average compression-air-temperature sensitivities of blends and of blends relative to base fuel in terms of the ratio of knock-limited compression-air densities at compression temperatures of 1400° and 1700° R.

DISCUSSION

Methods of comparing fuels. - Because fuels may rate in a different order when tested under different conditions, comparing the knock-limited performance of different fuels and generalizing therefrom is difficult. From a consideration of chemical kinetics, it is believed that the knock-limited power of a given fuel-air mixture is a function of the temperature history of the unburned gas in the cylinder from the initial conditions up to the time of knock and that the effect on the knock-limited power of changing any engine condition is primarily the effect of the corresponding change in this temperature history. Unfortunately, the rapidly changing gas temperatures in the cylinder cannot yet be accurately measured. Another difficulty to be overcome before the comparison of fuels can be put on an exact basis that will take account of any engine conditions is that the temperature history associated with given operating conditions is to some extent also a function of the fuel.

Two approximate methods of correlating the effects of at least a few engine variables upon knock limit will be used in this report in making general comparisons of the fuels. The conventional method compares the knock-limited power of the fuels at several sets of conditions that are presumed to cover the ordinary range of engine severity. An exact definition of engine severity, according to the preceding discussion, would have to be in terms of temperature history (perhaps for several reference fuels); in other words, engine severity is a multidimensional concept, a function of several independent variables. However, as the term is commonly used (and as it will be used in the rest of this report), the degree of engine severity is designated by words such as "mild" or "severe" that correspond to rough units on a one-dimensional scale. The combining of several independent variables into a single entity in this way can, of course, result only in an approximation. The reason that this approximation is of any use at all is thought to be that in the range of engine conditions ordinarily used most of the variation in engine severity is probably caused by one variable, namely, temperature.

A further approximation may be made by assuming that the effect of fuel-air ratio is primarily a temperature effect and thus including it in the engine-severity factor. In the following sections, the combined effects of the different engines, operating conditions, and fuel-air ratios have been roughly classified as to degree of severity, and this concept has been used to simplify the comparison of the fuels.

The other method of making over-all comparisons of fuels uses plots of compression-air density against compression-air temperature; these plots are suggested in reference 5 in place of the more fundamental end-gas density and temperature. References 5 and 6 show the usefulness of such a plot in correlating the effects of compression ratio and inlet-air temperature on knock limit. The following formulas are used in computing the coordinates for such a plot (reference 5 or 6):

$$\rho = \frac{A}{nv_c} = \frac{A(r-1)}{nv_d}$$

and

$$T = T_o r^{\gamma-1}$$

where

ρ compression-air density, pounds per cubic inch

A intake-air flow, pounds per minute

n intake cycles per minute

v_c engine clearance volume, cubic inches

r compression ratio

v_d engine displacement volume, cubic inches

T compression-air temperature, °R

T_o inlet-air temperature, °R

γ ratio of specific heat of charge air at constant pressure to that at constant volume (A ratio of 1.4 was used.)

Classification of engine conditions. - Empirically, one engine condition is said to be more severe than another when at the "more severe" condition many fuels rate lower relative to a fuel like isooctane whose knock-limited power is known to be comparatively insensitive to changes in conditions. In other words, the relative severity of different engine conditions might be determined by knock-testing a group of fuels having widely differing sensitivities and then comparing the orders of ratings under the different conditions.

In order to classify the engine conditions used in this report, table VII was compiled, which lists for each condition the order of the ratings of blends of 11 fuels from this report, references 1 and 2, and unpublished data. The use of F-3 ratings in this compilation might be questioned because they are not true knock ratings, but in view of the approximate nature of this discussion they were included.

The double line in table VII emphasizes the fact that the data for the 25-percent blends in the mixed base fuel cannot be directly compared with the data for the 20-percent blends in S reference fuel.

Because the 25-percent blends were not run with an inlet-air temperature of 100° F in the 17.6 engine, data for the 20-percent blends in S reference fuel are given to show the change in the order of rating that is obtained in passing from an inlet-air temperature of 250° to 100° F.

With some exceptions, the order of rating of a relatively insensitive fuel like isooctane goes down in passing from the left-hand columns to the right-hand columns (table VII), whereas the order of rating of a relatively sensitive fuel like 2,2,3,3-tetramethylpentane (shown to be sensitive in fig. 6 and table II) goes up from left to right. The conditions are therefore thought to be roughly in order of engine severity, and the F-3 (and lean F-4) conditions may be considered, relatively, to be severe; the rich F-4 (and the lean 17.6-engine condition with 250° F inlet air, which gives nearly the same order of knock ratings) may be considered moderate; and the rich 17.6-engine condition with 100° F inlet air may be considered mild. The rich condition at 250° F and the lean condition at 100° F in the 17.6 engine give an order of ratings intermediate between the mild and moderate degrees of severity, but, for simplicity, comparison will be made mainly at the three degrees of severity. The terms "very severe" and "very mild" will be used to designate conditions more severe than F-3 and more mild than the rich condition at 100° F in the 17.6 engine, respectively.

Comparison of fuels at various levels of engine severity. - Table II, which compares all the NBS hydrocarbons submitted, shows that the 2,2,3,3-tetramethylpentane blend gave the highest F-4 rich rating and the lowest F-3 rating of the entire group of 14 high-performance paraffins; it was also the best at all the 17.6-engine conditions (table III). In other words, the 2,2,3,3-tetramethylpentane blend gives excellent knock-limited power at moderate or mild engine conditions but is relatively poor at severe conditions. The triptane blend was the best under the severe (F-3) conditions.

At least a half dozen aromatics (references 4 and 7) are better in blend performance than 2,2,3,3-tetramethylpentane at both F-3 and rich F-4 conditions but no aromatics are known to have F-3 blend performance quite as good as triptane and a few other paraffins. However, methyl tert-butyl ether is better in blend performance than any of the paraffins at the severe F-3 conditions as well as at milder conditions (unpublished data).

Of the 14 blended paraffins, those least sensitive to changes in engine severity as shown by the relative changes in ratings in going from the more severe to the less severe conditions in tables II and VII (the fuels in table VII are roughly in order of sensitivity) were isopentane, neohexane, 2,3-dimethylpentane, isooctane, and 2,2,4,4-tetramethylpentane; those most sensitive to changes in engine severity were 2,2,3,3-tetramethylpentane, 2,3,3,4-tetramethylpentane, and 2,2,3,4-tetramethylpentane. Over the range from F-3 to 17.6-engine conditions, the triptane blend was intermediate in engine-severity sensitivity. Reference 6 shows, however, that at very severe conditions straight triptane becomes highly sensitive to engine severity and gives lower knock-limited power than S reference fuel.

From the data of reference 6 and from the trend shown in table VII, it seems likely that at sufficiently severe conditions blends with relatively insensitive fuels like isooctane would have a knock limit equal to or higher than that for blends with triptane and other relatively sensitive hydrocarbons.

Some of the blended olefins, such as 3,4,4-trimethyl-2-pentene, seem to be in general less sensitive to engine severity than some paraffins, such as 2,2,3,3-trimethylpentane. However, all five blended olefins were more sensitive than the insensitive paraffins, such as isooctane. At very mild conditions, blends with the most sensitive olefins are probably as good as if not better in knock-limited power than blends with any of the paraffins, and especially if the blends are unleaded. Thus, the unleaded 20 percent 2,3-dimethyl-2-pentene blend was better in knock-limited power than the corresponding 2,2,3,3-tetramethylpentane blend at fuel-air ratios above 0.115 in the 17.6 engine with an inlet-air temperature of 100° F (fig. 2(a)). The blend performance of 2,4,4-trimethyl-1-pentene is probably better than that of 2,2,3,3-tetramethylpentane at mild conditions by an even greater margin inasmuch as it is thought to be more sensitive than 2,3-dimethyl-2-pentene (table II) and inasmuch as under moderate (F-4 rich) conditions it was far better in knock-limited power than 2,3-dimethyl-2-pentene and equal to the corresponding triptane blend (table II).

When the data in table II are examined for possible relations between molecular structure and knock limit of the blends, only one such relation seems to be general, namely, the well-known rule that lengthening any chain in a paraffin lowers knock limit. (Even this rule is merely an approximation whether applied to any chain or to the longest chain in a compound; several exceptions have appeared in unpublished American Petroleum Institute data.) Thus, the blend with 2,4-dimethyl-3-ethylpentane has poorer F-3 and F-4 values than the blend with 2,3,4-trimethylpentane, from which it may be considered to differ by addition of a carbon group to the center side chain; similarly, 2,3-dimethylpentane is poorer than diisopropyl, and 2,2,3- and 2,3,3-trimethylpentanes are poorer than triptane. Other generalizations concerning structure and knock limit of paraffins that have sometimes been used in the past, such as the effect of adding a carbon to form a new side chain, of centralization, and of compactness, show some exceptions when they are tried on the data of this report. The 2,3-dimethyl-2-pentene blend has a poorer F-3 rating than the 2,3-dimethylpentane blend and the same trend may be seen in the case of the F-3 ratings of the blends of the other olefins as compared to the paraffins from which they differ in structure only by the double bond. This rule does not, however, apply at the less severe engine conditions.

Compression temperature-density curves. - The ordinates in figure 6, the compression-air densities, may be regarded as proportional to the imep values that would have been obtained if the data had been run at variable inlet-air temperature and constant compression ratio. Variable compression ratio was used only because the engine severity could be more quickly changed in this way; the same temperature-density curve would presumably be obtained either way (reference 5).

The severity of the conditions of the modified F-4 engine was estimated by noting the compression temperatures at which the relative order of the compression-air densities of the six fuels in figure 6 was about the same as the relative order of ratings for the same six fuels in table VII. The degrees of engine severity that have been designated mild, moderate, and severe for this report were thus estimated to correspond roughly to compression temperatures of 1300°, 1450°, and 1600° R, respectively, at lean fuel-air ratios (0.065 or 0.070), or 1450°, 1600°, and 1750° R, respectively, at rich fuel-air ratios (0.10 or 0.11) in the modified F-4 engine. The agreement between the relative order of ratings and the order of compression densities was far from perfect (as expected because of the crudity of the entire analysis), but nevertheless these temperature values were chosen to illustrate more concretely the effect of engine severity on knock limit. If these values are assumed correct, then conditions corresponding to the rich modified F-4 compression-air temperature at the left-hand side of the plots (about 1300° R) might be designated as very mild, and conditions corresponding to the lean modified F-4 compression-air temperature at the right-hand side of the plots (about 1700° or 1800° R) might be designated as very severe.

The compression temperature-density curves for the five hydrocarbon blends and the mixed base fuel show the same general trends previously discussed. The 2,2,3,3-tetramethylpentane blend is the best in knock-limited power at mild conditions but eventually becomes one of the worst at very severe conditions; in general it has the steepest curve, which means that it is the most temperature-sensitive. The base fuel is the worst in knock-limited power at very mild conditions but becomes the best at severe conditions; in general it has the least slope, which means that it is the least temperature-sensitive.

When the entire range of engine severity is considered, the three olefins fall in between these two extremes both with regard to knock-limited power and temperature sensitivity. However, when only that part of the plot is considered which corresponds roughly to the range between F-3 engine conditions and the conditions in the 17.6 engine at an inlet-air temperature of 100° F, the curvature of some of the olefin curves is such as to place them at or near the bottom of the group.

Inlet-air-temperature sensitivity in 17.6 engine. - The relative temperature sensitivity in the 17.6 engine is presented as in previous reports to provide a measure of the percentage change in knock-limited power with change in inlet-air temperature from 100° to 250° F, computed as a ratio for blend relative to base fuel. The data in table IV show the 2,2,3,3-tetramethylpentane blend to be relatively insensitive, which seems to contradict the results obtained from the modified F-4 temperature-density curves, whose slope at any point is a measure of the absolute temperature sensitivity at that particular condition of engine severity. These two measures of temperature sensitivity are on an entirely different basis but even when put on a similar basis, as by comparing tables IV and VI, a discrepancy still remains. The following factors are all thought to contribute to this discrepancy: difference in base fuel and percentage composition; difference in range of severity covered; differences in rich-peak fuel-air ratio for the 17.6-engine mixture-response curves with inlet-air at 100° and 250° F; and experimental error and the approximate nature of the analysis, which permits only rough general comparison at best.

Lead susceptibility in 17.6 engine. - Lead susceptibilities for the 20-percent blends in S reference fuel of the four hydrocarbons investigated in the 17.6 engine (table V) were roughly about the same as for S reference fuel.

CONCLUSIONS

The following conclusions were drawn from a comparison of laboratory-engine data for a group of high-performance paraffins and olefins in blends with base fuels:

1. At conditions of mild or moderate engine severity, a blend containing 2,2,3,3-tetramethylpentane has a higher knock limit than corresponding blends of all other paraffins investigated, but, at more severe conditions, it is the poorest of the group.

2. At severe conditions like those corresponding to F-3 ratings, the triptane blend has the highest knock limit of the group. For high antiknock performance in blends over a fairly wide range of engine

severity, triptane may still be considered the best liquid paraffinic hydrocarbon known.

3. At very severe conditions, more severe than F-3, the relatively insensitive fuels such as isooctane are thought to be as good as or better than any of the others in antiknock performance.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 4, 1948.

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TABLE I - F-4 AND F-3 RATINGS OF HYDROCARBON BLENDS

Compound	Blend composition (percent by volume)			Tetraethyl lead (ml/gal)	F-4 ratings (F/A = 0.11)		F-3 ratings	
	Hydrocarbon	S reference fuel	87.5 percent S + 12.5 percent n-heptane		S + 4 ml TEL/gal in n-heptane + 4 ml TEL/gal (percent)	Performance number	S + ml TEL/gal	Performance number
87.5 percent S + 12.5 percent n-heptane	0	0	100	4	87.5	111	0.65	119
2,2,3,3-Tetramethylpentane	25	0	75	4	>100	[a]156	0.20	107
2,4-Dimethyl-3-ethylpentane					92	127	.45	115
2,3-Dimethylpentane					88	113	.60	118
2,3-Dimethyl-2-pentene					89	115	0	100
2,2,3,3-Tetramethylpentane	20	80	0	4	———	———	1.14	128
2,4-Dimethyl-3-ethylpentane					———	———	2.30	140
2,3-Dimethylpentane					———	———	2.75	145
2,3-Dimethyl-2-pentene					———	———	.22	108
2,2,3,3-Tetramethylpentane	20	80	0	0	———	———	[b]94.6	84
2,4-Dimethyl-3-ethylpentane					———	———	[b]95.6	86
2,3-Dimethylpentane					———	———	[b]96.2	88
2,3-Dimethyl-2-pentene					———	———	[b]92.0	78

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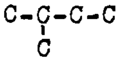
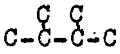
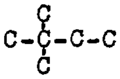
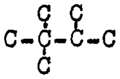
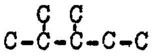
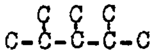
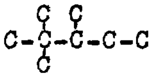
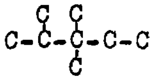
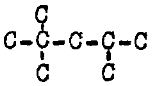
[a] Estimated performance number = $\frac{\text{imep of blend}}{\text{imep of S + 4 ml TEL/gal}}$ × performance number of S + 4 ml TEL/gal.

[b] Octane number.

TABLE II - COMPARISON OF F-3 AND F-4 DATA FOR 14 PARAFFINS

[The values in this table are computed from values in an
references 1 and 2 un-

Structure	Compound	Performance-number ratio relative to base fuel[a]	
		F-3	F-4(F/A=0.11)
 $C-\underset{C}{C}-C-C$	Isopentane (2-methylbutane)	1.09	1.08
 $C-\overset{C}{C}-\overset{C}{C}-C$	Diisopropyl (2,3-dimethylbutane)	1.09	1.16
 $C-\overset{C}{\underset{C}{C}}-C-C$	Neohexane (2,2-dimethylbutane)	1.09	1.09
 $C-\overset{C}{\underset{C}{C}}-\overset{C}{C}-C$	Triptane (2,2,3-trimethylbutane)	1.15	1.30
 $C-\overset{C}{C}-\overset{C}{C}-C-C$	2,3-Dimethylpentane	[b]0.99	[b]1.01
 $C-\overset{C}{C}-\overset{C}{C}-\overset{C}{C}-C$	2,3,4-Trimethylpentane	1.03	1.18
 $C-\overset{C}{\underset{C}{C}}-\overset{C}{C}-C-C$	2,2,3-Trimethylpentane	1.10	1.26
 $C-\overset{C}{C}-\overset{C}{\underset{C}{C}}-C-C$	2,3,3-Trimethylpentane	1.05	1.23
 $C-\overset{C}{\underset{C}{C}}-C-\underset{C}{C}-C$	Isooctane (2,2,4-trimethylpentane)	[c]1.09	1.10

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[a] The base fuels (85 percent S in M, and 87.5 percent S in n-heptane, both containing 4 ml TEL/gal) had approximately the same knock ratings.

[b] These values were computed from values in Table I.

[c] Estimated value.

AND 5 OLEFINS IN LEADED 25-PERCENT-BY-VOLUME BLENDS

unpublished National Bureau of Standards report and from
less otherwise noted]

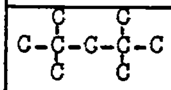
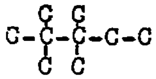
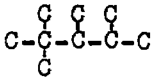
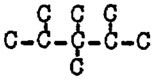
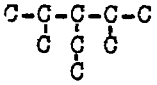
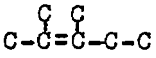
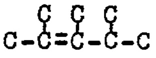
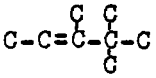
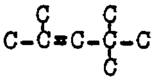
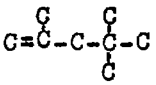
Structure	Compound	Performance-number ratio relative to base fuel[a]	
		F-3	F-4 (F/A=0.11)
 $C-\overset{C}{\underset{C}{C}}-C-\overset{C}{\underset{C}{C}}-C$	2,2,4,4-Tetramethylpentane	0.99	0.98
 $C-\overset{C}{\underset{C}{C}}-\overset{C}{\underset{C}{C}}-C-C$	2,2,3,3-Tetramethylpentane	[b].90	[b]1.39
 $C-\overset{C}{\underset{C}{C}}-\overset{C}{C}-\overset{C}{C}-C$	2,2,3,4-Tetramethylpentane	.99	1.25
 $C-\overset{C}{C}-\overset{C}{\underset{C}{C}}-\overset{C}{C}-C$	2,3,3,4-Tetramethylpentane	.92	1.28
 $C-\underset{C}{C}-\underset{\underset{C}{C}}{C}-\underset{C}{C}-C$	2,4-Dimethyl-3-ethylpentane	[b].96	[b]1.13
 $C-\overset{C}{C}=\overset{C}{C}-C-C$	2,3-Dimethyl-2-pentene	[b]0.84	[b]1.04
 $C-\overset{C}{C}=\overset{C}{C}-\overset{C}{C}-C$	2,3,4-Trimethyl-2-pentene	.85	.92
 $C-C=\overset{C}{C}-\overset{C}{\underset{C}{C}}-C$	3,4,4-Trimethyl-2-pentene	.89	.96
 $C-\overset{C}{C}=C-\overset{C}{\underset{C}{C}}-C$	2,4,4-Trimethyl-2-pentene	.90	1.06
 $C=\overset{C}{C}-C-\overset{C}{\underset{C}{C}}-C$	2,4,4-Trimethyl-1-pentene	.88	1.30

TABLE III - SUPERCHARGED 17.6 AND F-4

Compound	Blend composition (percent by volume)			Tetraethyl lead (ml/gal)	Inlet-air temperature (°F)
	Hydrocarbon	S reference fuel	87.5 percent S + 12.5 percent *n*-heptane		
17.6 engine					
2,2,3,3-Tetramethylpentane 2,4-Dimethyl-3-ethylpentane 2,3-Dimethylpentane 2,3-Dimethyl-2-pentene	20	80	0	0	250
2,2,3,3-Tetramethylpentane 2,4-Dimethyl-3-ethylpentane 2,3-Dimethylpentane 2,3-Dimethyl-2-pentene	20	80	0	0	100
2,2,3,3-Tetramethylpentane 2,4-Dimethyl-3-ethylpentane 2,3-Dimethylpentane 2,3-Dimethyl-2-pentene	20	80	0	4	250
2,2,3,3-Tetramethylpentane 2,4-Dimethyl-3-ethylpentane 2,3-Dimethylpentane 2,3-Dimethyl-2-pentene	20	80	0	4	100
2,2,3,3-Tetramethylpentane 2,4-Dimethyl-3-ethylpentane 2,3-Dimethylpentane 2,3-Dimethyl-2-pentene	25	0	75	4	250
F-4 engine					
2,2,3,3-Tetramethylpentane 2,4-Dimethyl-3-ethylpentane 2,3-Dimethylpentane 2,3-Dimethyl-2-pentene	25	0	75	4	225

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[a] imep ratio = $\frac{\text{imep of blend}}{\text{imep of base fuel}}$.

ENGINE DATA FOR HYDROCARBON BLENDS

imep	[a]imep ratio	imep	[a]imep ratio	imep	[a]imep ratio	imep	[a]imep ratio	imep	[a]imep ratio
Fuel-air ratio									
0.065		0.07		0.085		0.10		0.11	
17.6 engine									
184	1.12	183	1.14	201	1.20	234	1.32	234	1.31
162	.99	161	1.00	168	1.00	178	1.01	178	1.00
155	.95	154	.96	158	.94	166	.94	168	.94
162	.99	160	.99	170	1.01	193	1.09	205	1.15
244	1.23	236	1.22	239	1.27	244	1.27	247	1.27
204	1.03	197	1.02	192	1.02	189	.98	189	.97
185	.93	180	.93	179	.95	181	.94	182	.93
225	1.14	216	1.12	219	1.17	237	1.23	247	1.27
308	1.19	303	1.18	348	1.31	366	1.34	361	1.32
261	1.01	259	1.01	271	1.02	275	1.01	270	.99
249	.96	249	.97	261	.98	262	.96	258	.95
246	.95	244	.95	266	1.00	309	1.13	316	1.16
375	1.23	374	1.25	376	1.28	374	1.29	365	1.29
306	1.00	302	1.01	298	1.01	291	1.01	284	1.00
294	.96	290	.97	286	.97	277	.96	269	.95
347	1.14	342	1.14	350	1.19	358	1.24	347	1.23
226	1.26	226	1.26	255	1.35	270	1.39	265	1.37
187	1.04	190	1.06	204	1.08	209	1.08	206	1.07
185	1.03	185	1.03	198	1.05	201	1.04	197	1.02
185	1.03	192	1.07	211	1.12	225	1.16	232	1.20
F-4 engine									
112	0.83	125	0.83	187	1.06	242	1.31	254	1.39
132	1.05	143	1.05	174	1.07	193	1.09	196	1.10
130	.96	144	.96	174	.98	185	1.00	184	1.00
94	.75	108	.79	142	.88	168	.95	182	1.02

TABLE IV - INLET-AIR-TEMPERATURE SENSITIVITY OF HYDROCARBON BLENDS RELATIVE TO S REFERENCE FUEL

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

Compound	Blend composition (percent by volume)		Tetraethyl lead (ml/gal)	Relative temperature sensitivity (a)				
	Hydrocarbon	S reference fuel		Fuel-air ratio				
				0.065	0.07	0.085	0.10	0.11
2,2,3,3-Tetramethylpentane	20	80	0	1.10	1.07	1.06	0.97	0.96
2,4-Dimethyl-3-ethylpentane				1.04	1.02	1.02	.98	.97
2,3-Dimethylpentane				.99	.97	1.01	1.01	.99
2,3-Dimethyl-2-pentene				1.15	1.13	1.15	1.14	1.09
2,2,3,3-Tetramethylpentane	20	80	4	1.03	1.06	0.98	0.96	0.97
2,4-Dimethyl-3-ethylpentane				.99	1.00	1.00	1.00	1.00
2,3-Dimethylpentane				1.00	1.00	1.00	1.00	1.00
2,3-Dimethyl-2-pentene				1.20	1.20	1.20	1.09	1.06

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

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

TABLE V - LEAD SUSCEPTIBILITY OF HYDROCARBON BLENDS RELATIVE TO S REFERENCE FUEL

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

Compound	Inlet-air temperature (°F)	Blend composition (percent by volume)		Relative lead susceptibility[a]				
				Fuel-air ratio				
		Hydrocarbon	S reference fuel	0.065	0.07	0.085	0.10	0.11
2,2,3,3-Tetramethylpentane	250	20	80	1.07	1.04	1.09	1.02	1.01
2,4-Dimethyl-3-ethylpentane				1.03	1.01	1.02	1.00	.99
2,3-Dimethylpentane				1.02	1.02	1.04	1.03	1.00
2,3-Dimethyl-2-pentene				.97	.96	.99	1.04	1.01
2,2,3,3-Tetramethylpentane	100	20	80	1.00	1.02	1.00	1.02	1.02
2,4-Dimethyl-3-ethylpentane				.97	.99	.97	1.02	1.04
2,3-Dimethylpentane				1.03	1.04	1.03	1.01	1.02
2,3-Dimethyl-2-pentene				1.00	1.02	1.02	1.00	.97

[a] Relative lead susceptibility $= \dfrac{\dfrac{\text{imep of blend (with 4 ml TEL/gal)}}{\text{imep of blend (with 0 ml TEL/gal)}}}{\dfrac{\text{imep of S (with 4 ml TEL/gal)}}{\text{imep of S (with 0 ml TEL/gal)}}}$

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

TABLE VI - COMPRESSION-AIR-TEMPERATURE SENSITIVITY OF HYDROCARBON BLENDS IN A MODIFIED F-4 ENGINE

[Compression ratio, variable; engine speed, 1800 rpm; coolant temperature, 250° F; inlet-air temperature, 250° F; spark advance, 20° B.T.C.]

Compound	Average compression-air-temperature sensitivity over the range of 1400° to 1700° R									
	Blend[b]					Blend[c]/Base fuel				
	Fuel-air ratios									
(a)	0.065	0.07	0.085	0.10	0.11	0.065	0.07	0.085	0.10	0.11
87.5 percent S + 12.5 percent n-heptane	1.17	1.16	1.12	1.12	1.10	1.00	1.00	1.00	1.00	1.00
2,2,3,3-Tetramethylpentane	1.97	1.90	1.68	[d]1.41	[d]1.46	1.68	1.64	1.50	[d]1.26	[d]1.33
2,3-Dimethylpentane	1.24	1.24	1.26	[d]1.25	[d]1.24	1.06	1.07	1.13	[d]1.12	[d]1.13
2,3-Dimethyl-2-pentene	1.64	1.60	1.53	1.23	[d]1.29	1.40	1.38	1.37	1.10	[d]1.17
2,3,4-Dimethyl-2-pentene	1.60	1.63	1.56	1.44	1.36	1.37	1.41	1.39	1.29	1.24
3,4,4-Trimethyl-2-pentene	1.29	1.31	1.34	1.34	1.25	1.10	1.13	1.20	1.20	1.14

NACA

[a] All blends contain 25 percent compound plus 75 percent (87.5 percent S in n-heptane) plus 4 ml TEL per gallon.

[b] $$\text{Temperature sensitivity of blend} = \frac{\text{knock-limited compression-air density of blend at } 1400^\circ \text{ R}}{\text{knock-limited compression-air density of blend at } 1700^\circ \text{ R}}$$

[c] $$\begin{array}{l}\text{Temperature sensitivity of blend} \\ \quad\text{relative to base fuel}\end{array} = \frac{\dfrac{\text{knock-limited compression-air density of blend at } 1400^\circ \text{ R}}{\text{knock-limited compression-air density of blend at } 1700^\circ \text{ R}}}{\dfrac{\text{knock-limited compression-air density of base fuel at } 1400^\circ \text{ R}}{\text{knock-limited compression-air density of base fuel at } 1700^\circ \text{ R}}}$$

[d] Extrapolated value.

TABLE VII - ORDER OF KNOCK RATINGS OF 11 PURE-HYDROCARBON BLENDS

[For each fuel there are two rows of values: first row is imep ratio of blend relative to base fuel except in case of F-3 ratings, where it is performance-number ratio of blend relative to base fuel; second row is relative order of ratings of fuels under each set of conditions. (Best fuel is 1, worst fuel is 11.)]

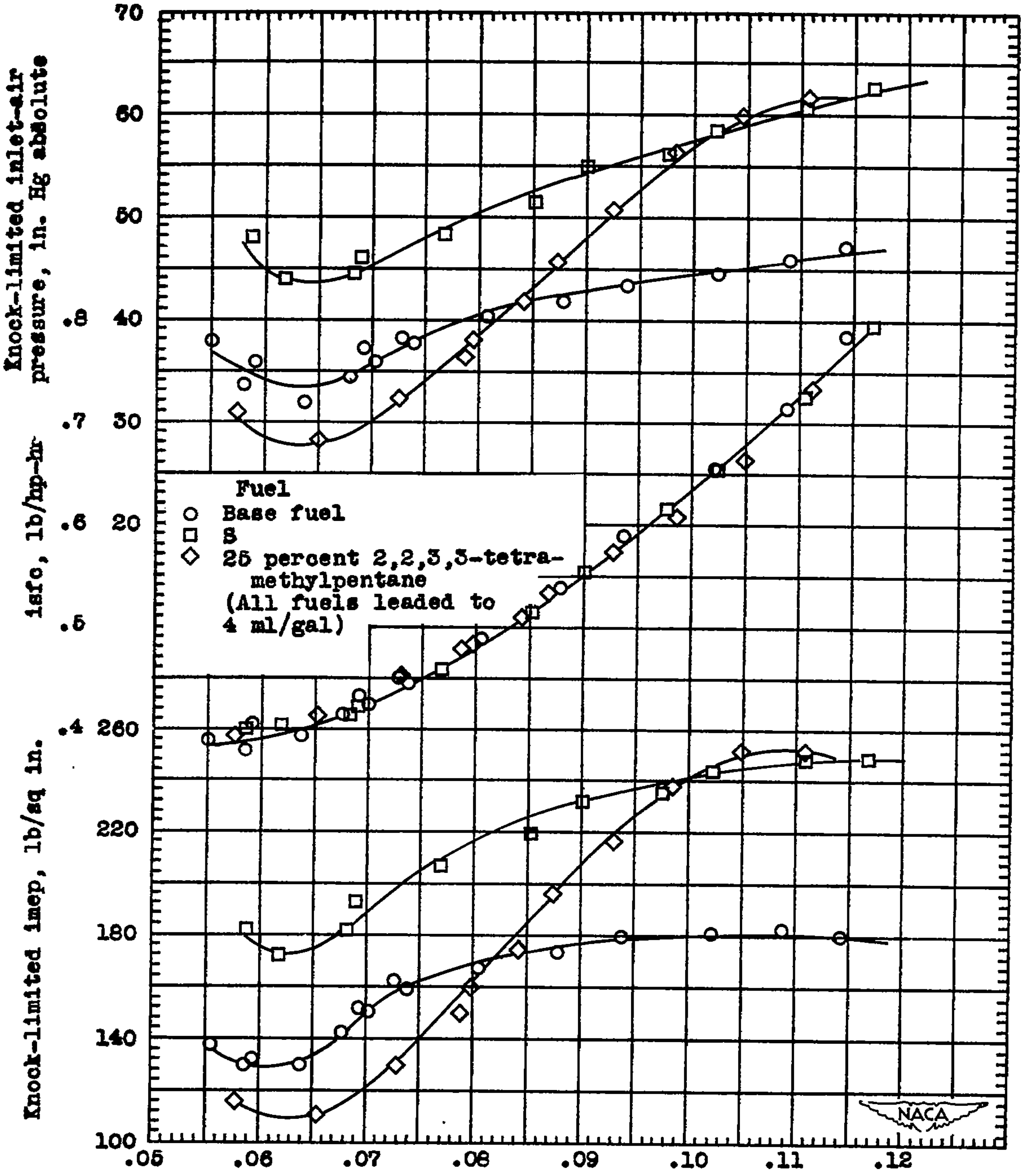
Compound (a)	Ratings								
	25-percent blend in mixed base fuel[b]					20-percent blend in S			
	F-3	F-4		17.6 engine (250° F air)		17.6 engine (250° F air)		17.6 engine (100° F air)	
		Fuel-air ratio				Fuel-air ratio			
		0.065	0.11	0.065	0.11	0.065	0.11	0.065	0.11
Mixed base fuel[b]	1.00	1.00	1.00	1.00	1.00	[c]0.95	[c]0.94	[c]0.93	[c]0.93
	3	4	9	9	11	9	10	11	11
Isooctane	[d]1.09	1.04	1.08	[c]1.05	[c]1.07	1.00	1.00	1.00	1.00
	2	3	6	5	7	6	7	7	8
2,3-Dimethylpentane	.99	.96	1.00	1.03	1.02	.96	.95	.96	.95
	4	5	8	8	10	7	9	10	10
2,4-Dimethyl-3-ethylpentane	.96	1.05	1.10	1.04	1.07	1.01	.99	1.00	1.00
	6	2	5	6	8	5	8	8	9
Triptane	1.15	1.13	1.28	1.24	1.28	1.13	1.24	1.20	1.19
	1	1	2	2	3	2	3	2	5
2,2,3,4-Tetramethylpentane	.99	.85	1.24	1.12	1.26	1.04	1.23	1.17	1.19
	5	7	4	4	4	4	4	4	4
2,3,3,4-Tetramethylpentane	.92	.87	1.28	1.13	1.30	1.10	1.27	1.17	1.19
	7	6	3	3	2	3	2	3	3
3,4,4-Trimethyl-2-pentene	.89	.75	.97	.99	1.13	.93	1.07	1.10	1.18
	9	10	10	10	6	10	6	6	6
2,3,4-Trimethyl-2-pentene	.85	.69	.93	.94	1.05	.81	.92	.99	1.09
	10	11	11	11	9	11	11	9	7
2,2,3,3-Tetramethylpentane	.90	.83	1.39	1.26	1.37	1.19	1.32	1.23	1.29
	8	8	1	1	1	1	1	1	1
2,3-Dimethyl-2-pentene	.84	.75	1.02	1.03	1.20	.95	1.16	1.14	1.23
	11	9	7	7	5	8	5	5	2

[a] All blends contain 4 ml TEL/gal.

[b] The mixed base fuels (85 percent S in M, and 87.5 percent S in n-heptane) were approximately equivalent in knock rating.

[c] Estimated from plot of reciprocal indicated mean effective pressure against percentage leaded S in n-heptane.

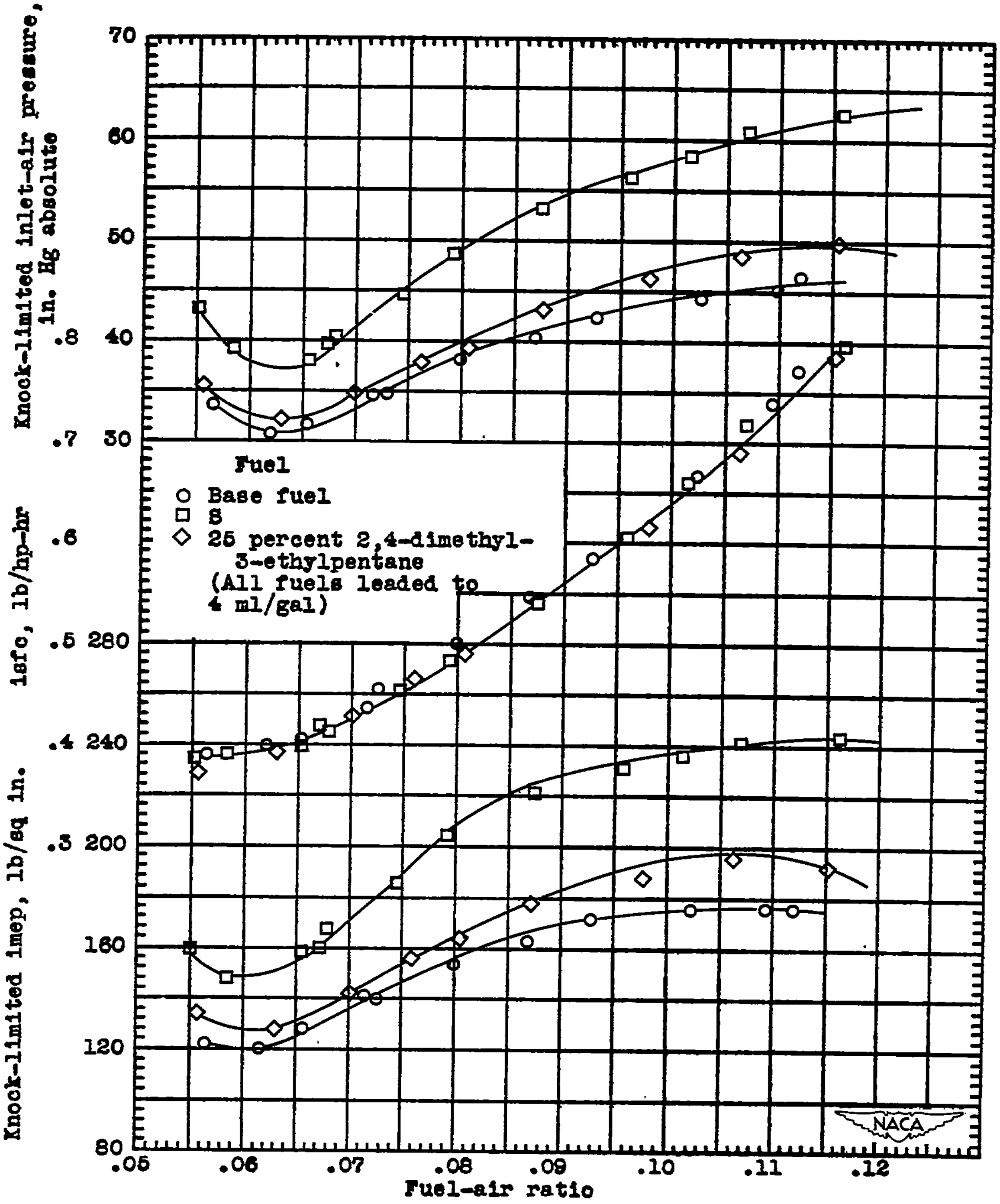
[d] Estimated from plot of performance number against percentage leaded S in M fuel.



(a) 2,2,3,3-Tetramethylpentane.

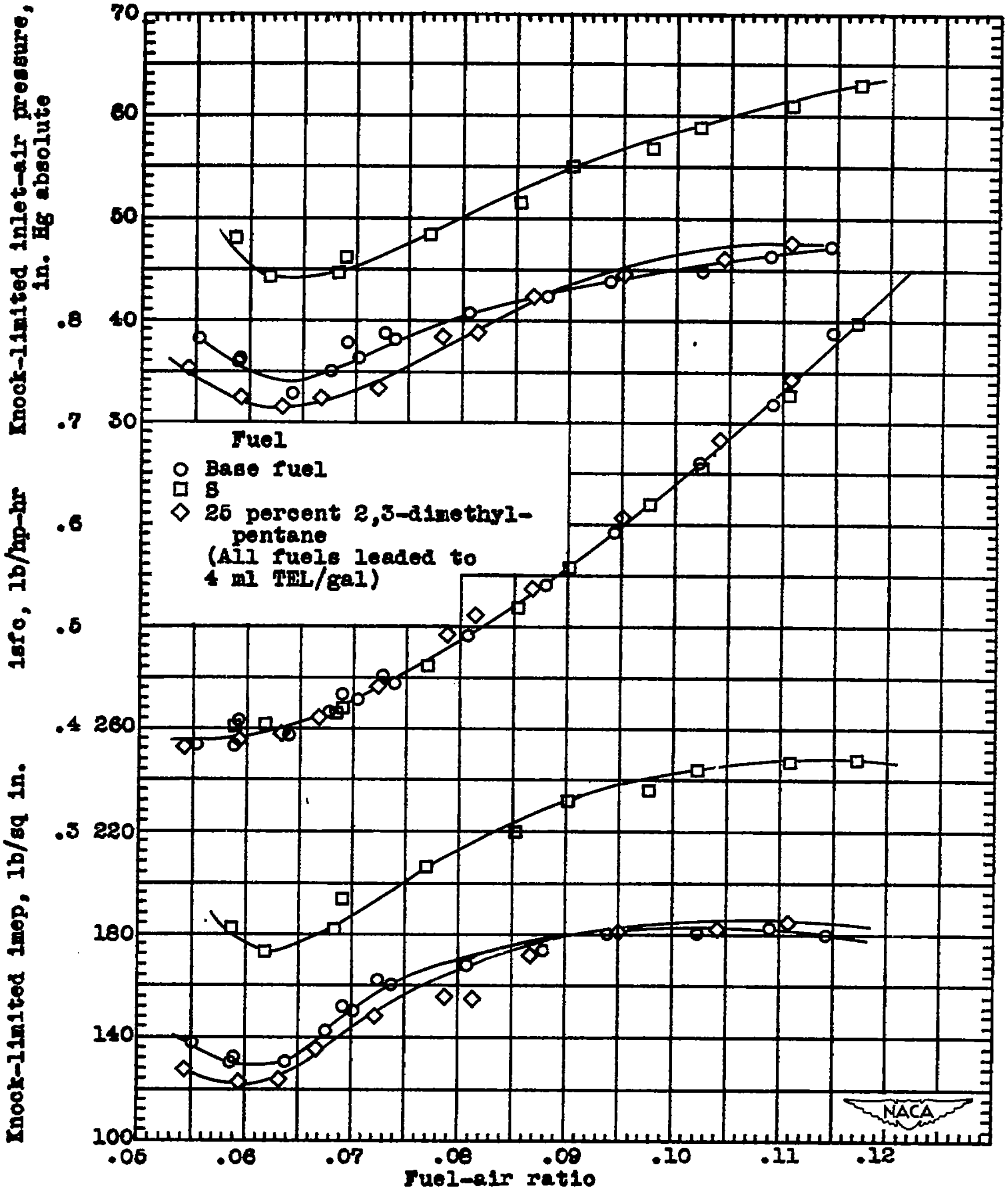
Figure 1. - Knock-limited mixture response of leaded 25-percent blends of hydrocarbons in base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane in F-4 engine.

934



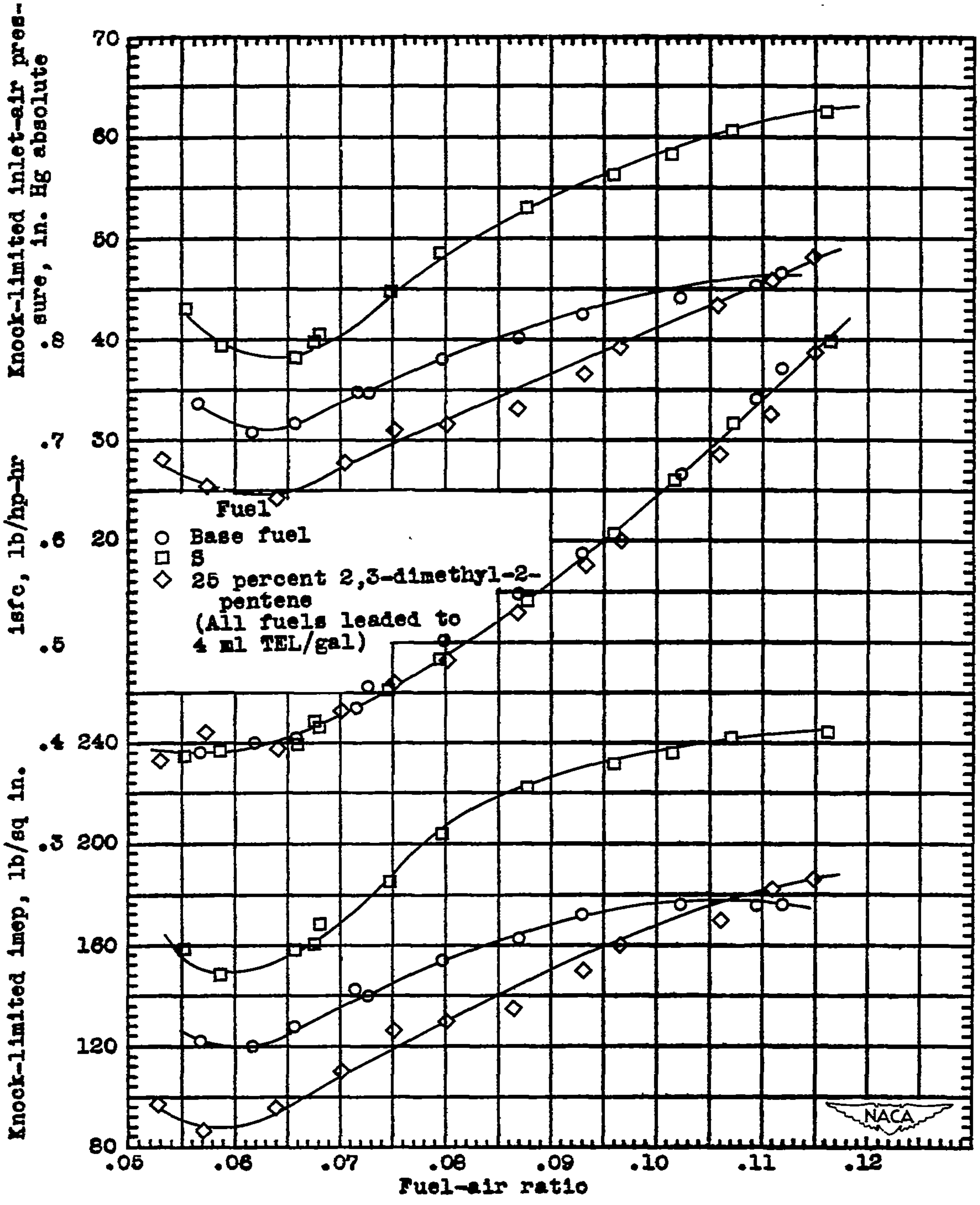
(b) 2,4-Dimethyl-3-ethylpentane.

Figure 1. - Continued. Knock-limited mixture response of leaded 25-percent blends of hydrocarbons in base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane in F-4 engine.



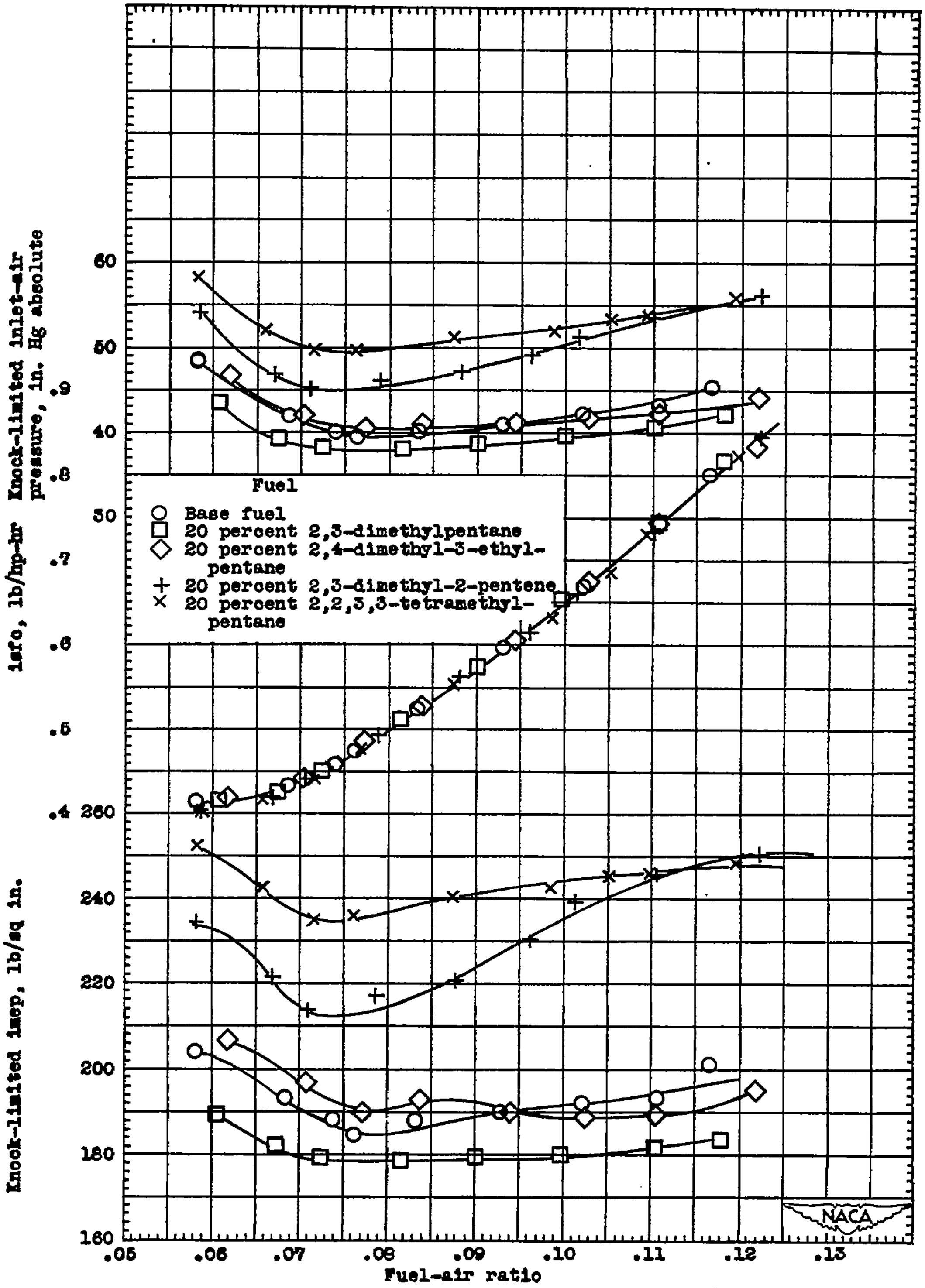
(c) 2,3-Dimethylpentane.

Figure 1. - Continued. Knock-limited mixture response of leaded 25-percent blends of hydrocarbons in base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane in F-4 engine.



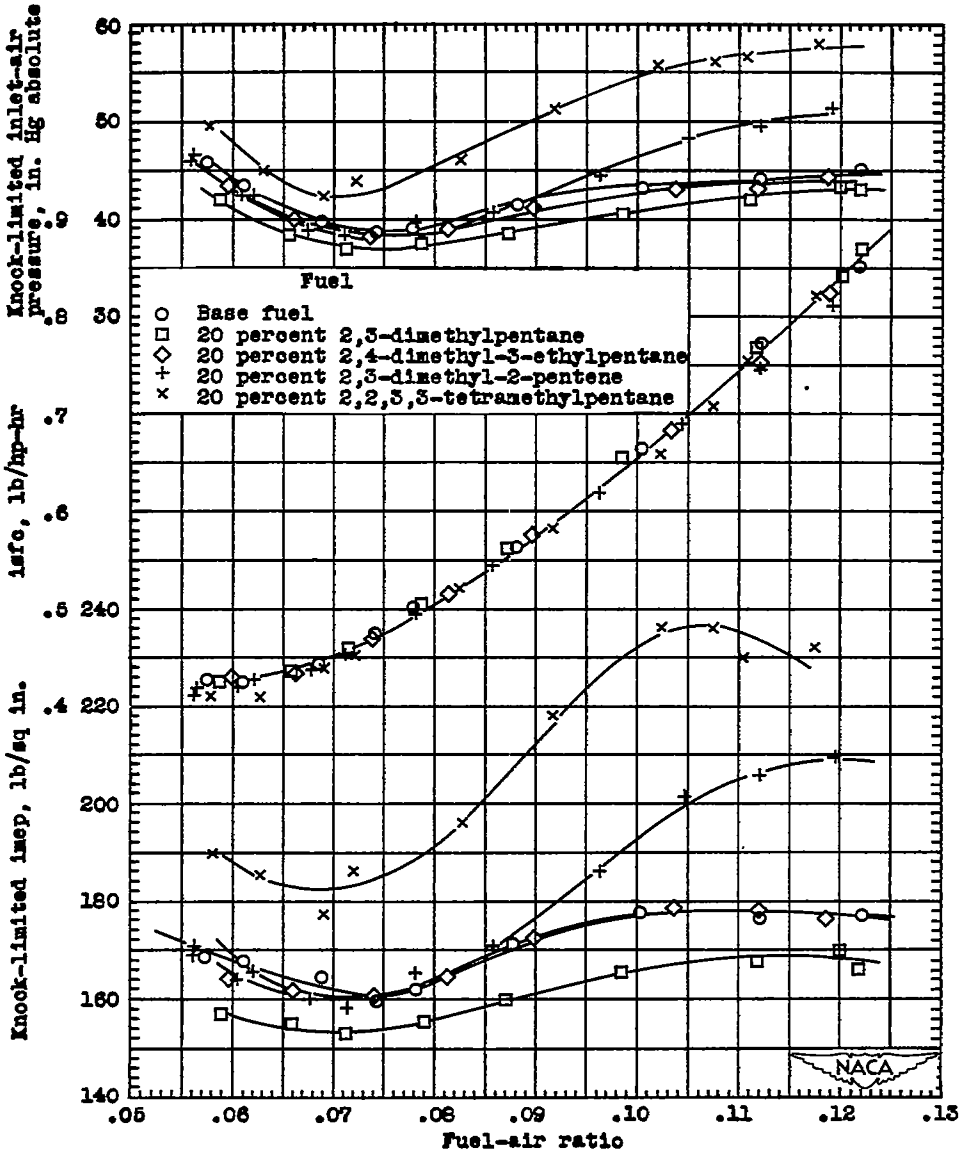
(d) 2,3-Dimethyl-2-pentene.

Figure 1. - Concluded. Knock-limited mixture response of leaded 25-percent blends of hydrocarbons in base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane in F-4 engine.



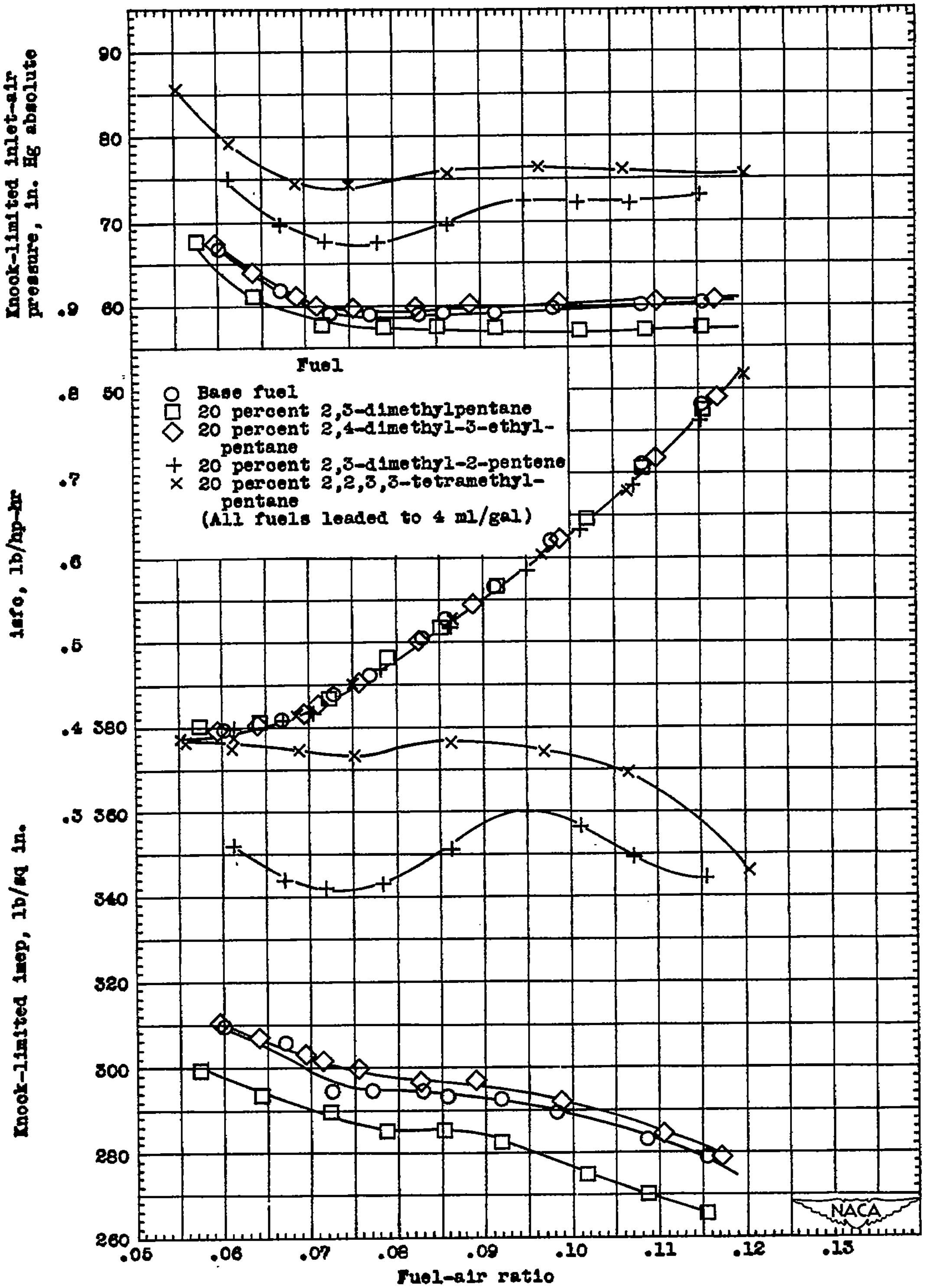
(a) Unleaded blends; inlet-air temperature, 100° F.

Figure 2. - Knock-limited performance of 20-percent blends of four pure hydrocarbons in S reference fuel in 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.



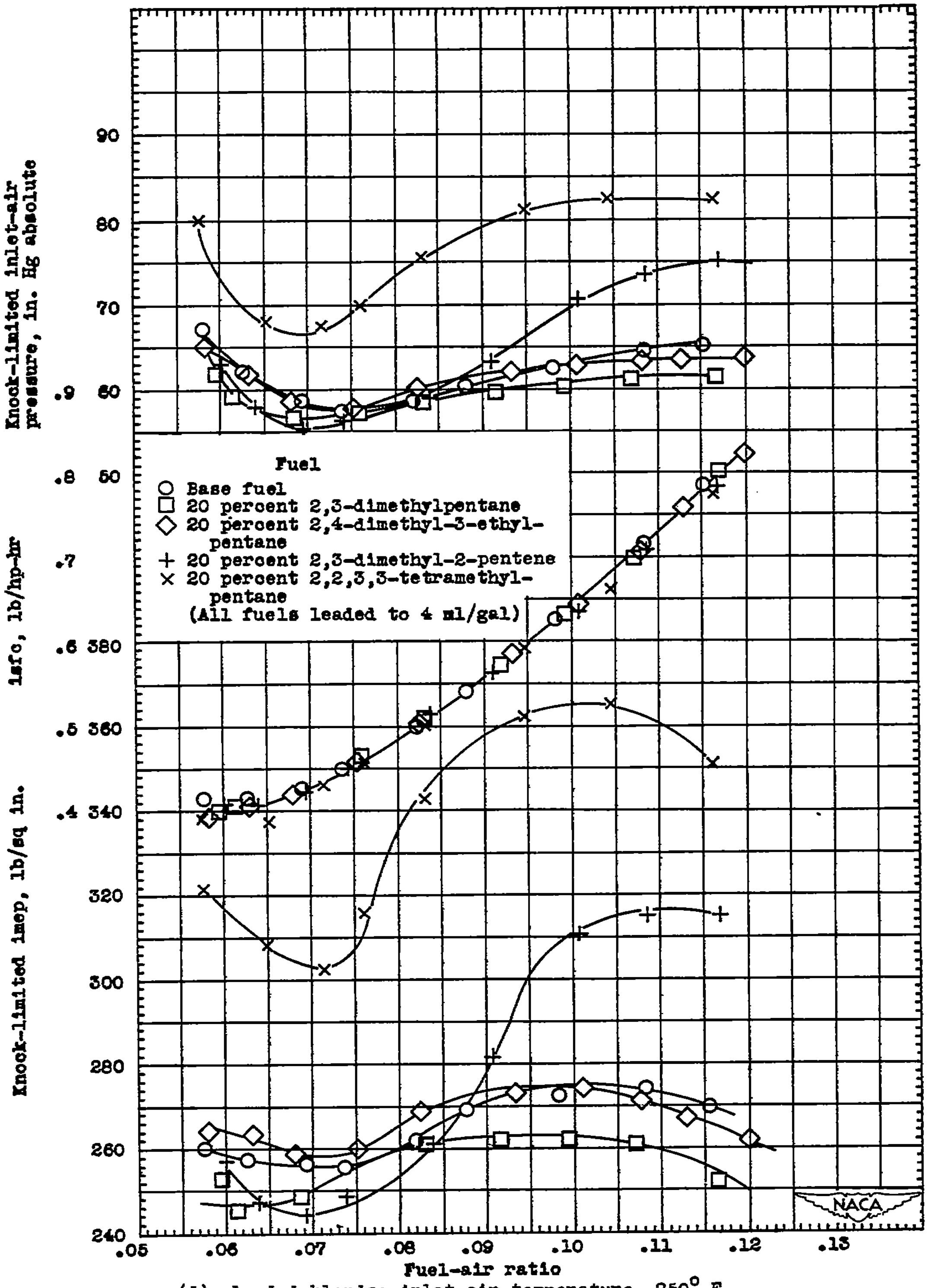
(b) Unleaded blends; inlet-air temperature 250° F.

Figure 2. - Continued. Knock-limited performance of 20-percent blends of four pure hydrocarbons in S reference fuel in 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.



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

Figure 2. - Continued. Knock-limited performance of 20-percent blends of four pure hydrocarbons in S reference fuel in 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.



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

Figure 2. - Concluded. Knock-limited performance of 20-percent blends of four pure hydrocarbons in S reference fuel in 17.6 engine. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.

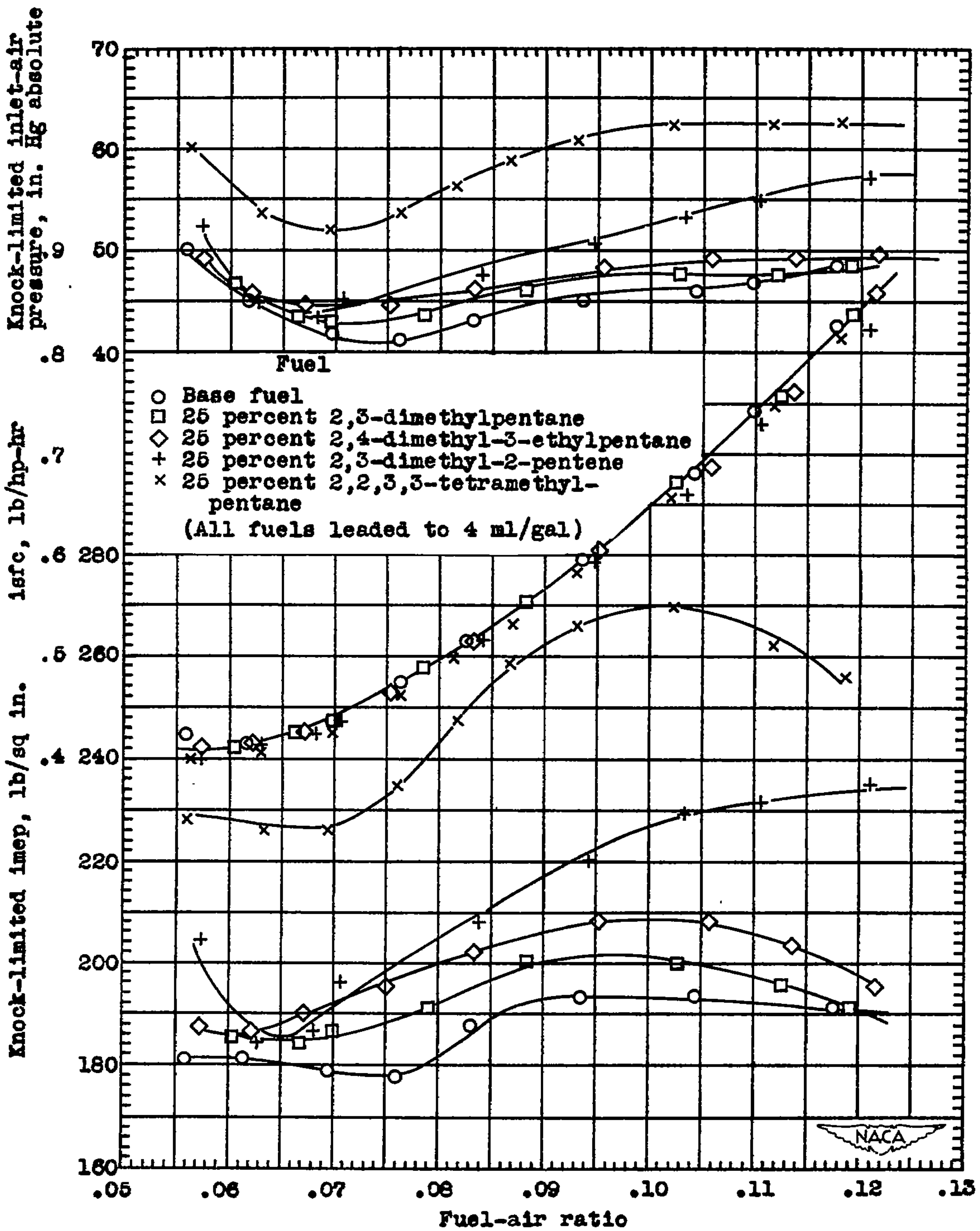


Figure 3. - Knock-limited performance of leaded 25-percent blends of four pure hydrocarbons in a base fuel consisting of 87.5 percent S reference fuel plus 12.5 percent n-heptane in 17.6 engine at inlet-air temperature of 250° F. Compression ratio, 7.0; engine speed, 1800 rpm; spark advance, 30° B.T.C.; coolant temperature, 212° F.

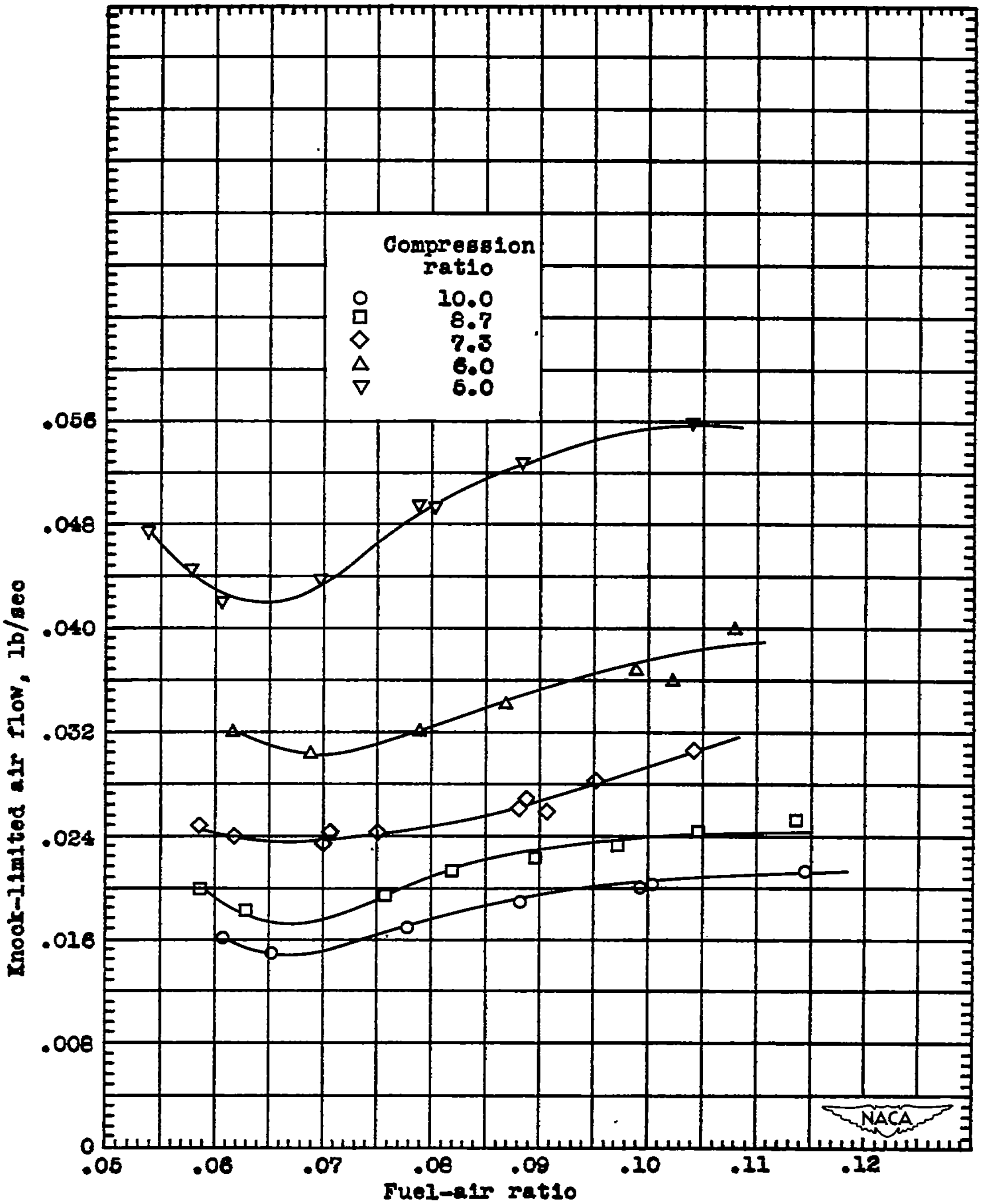
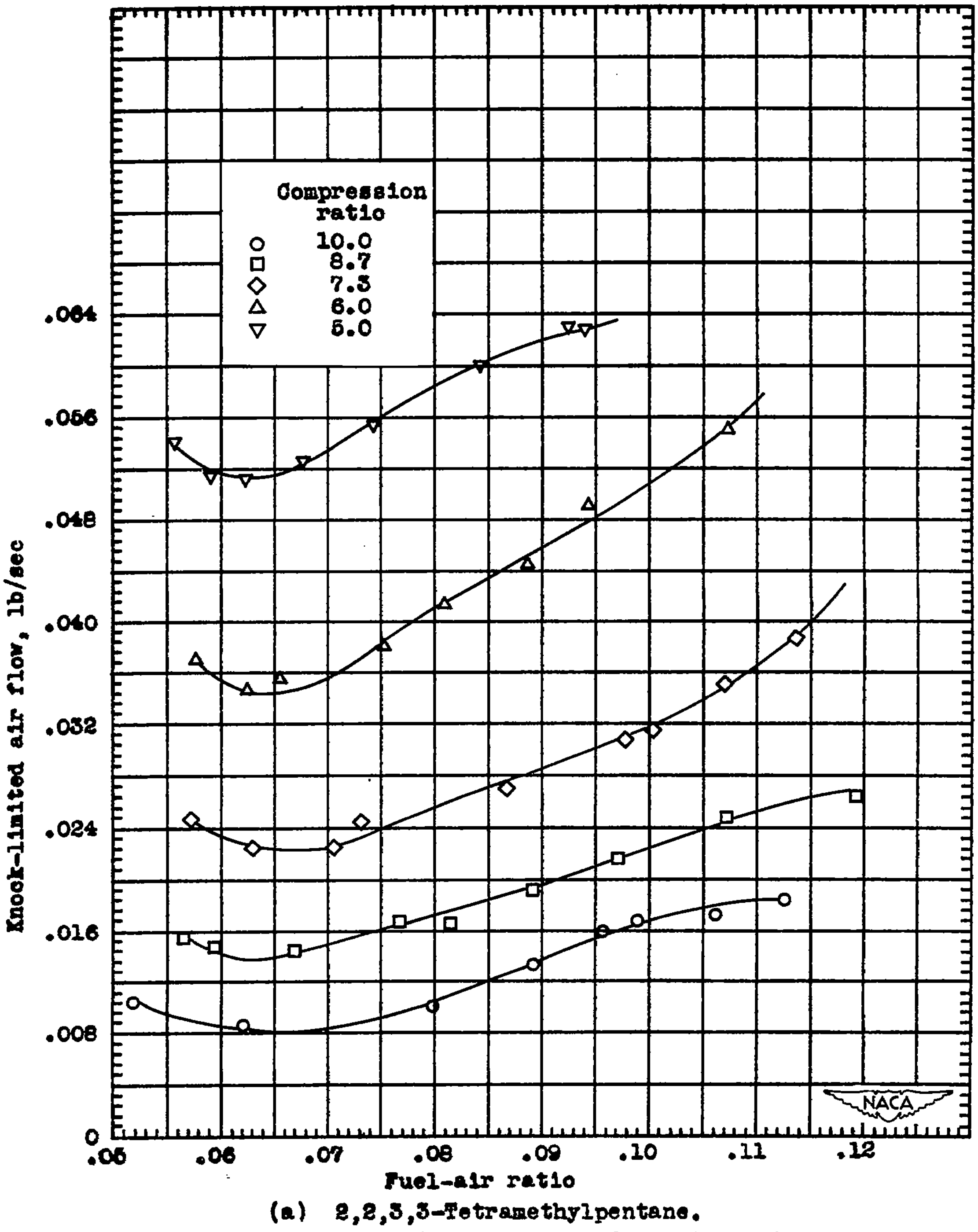
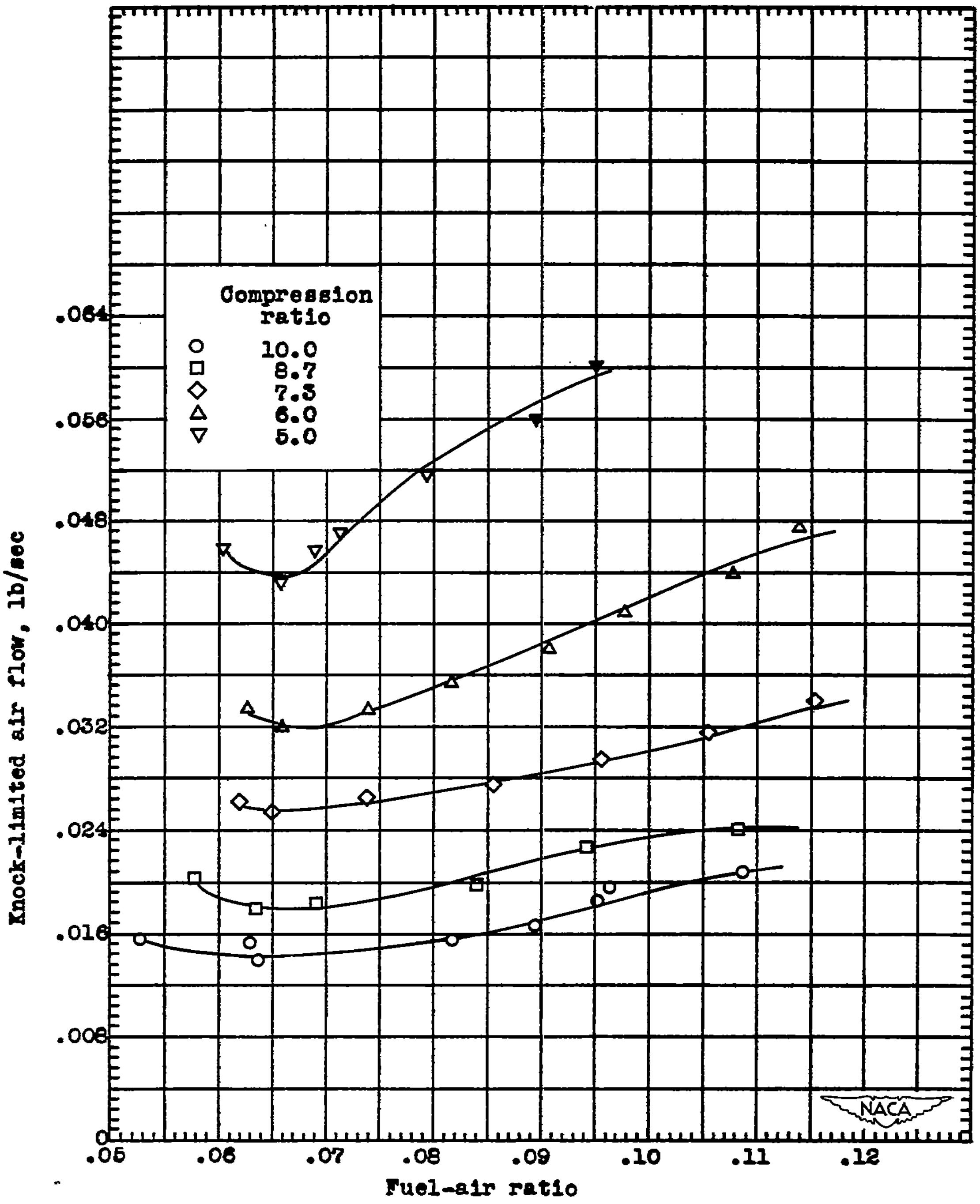


Figure 4. - Effect of compression ratio and fuel-air ratio on knock-limited air flow for base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane plus 4 ml TEL per gallon in modified F-4 engine. Inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 20° B.T.C.; coolant temperature, 250° F.



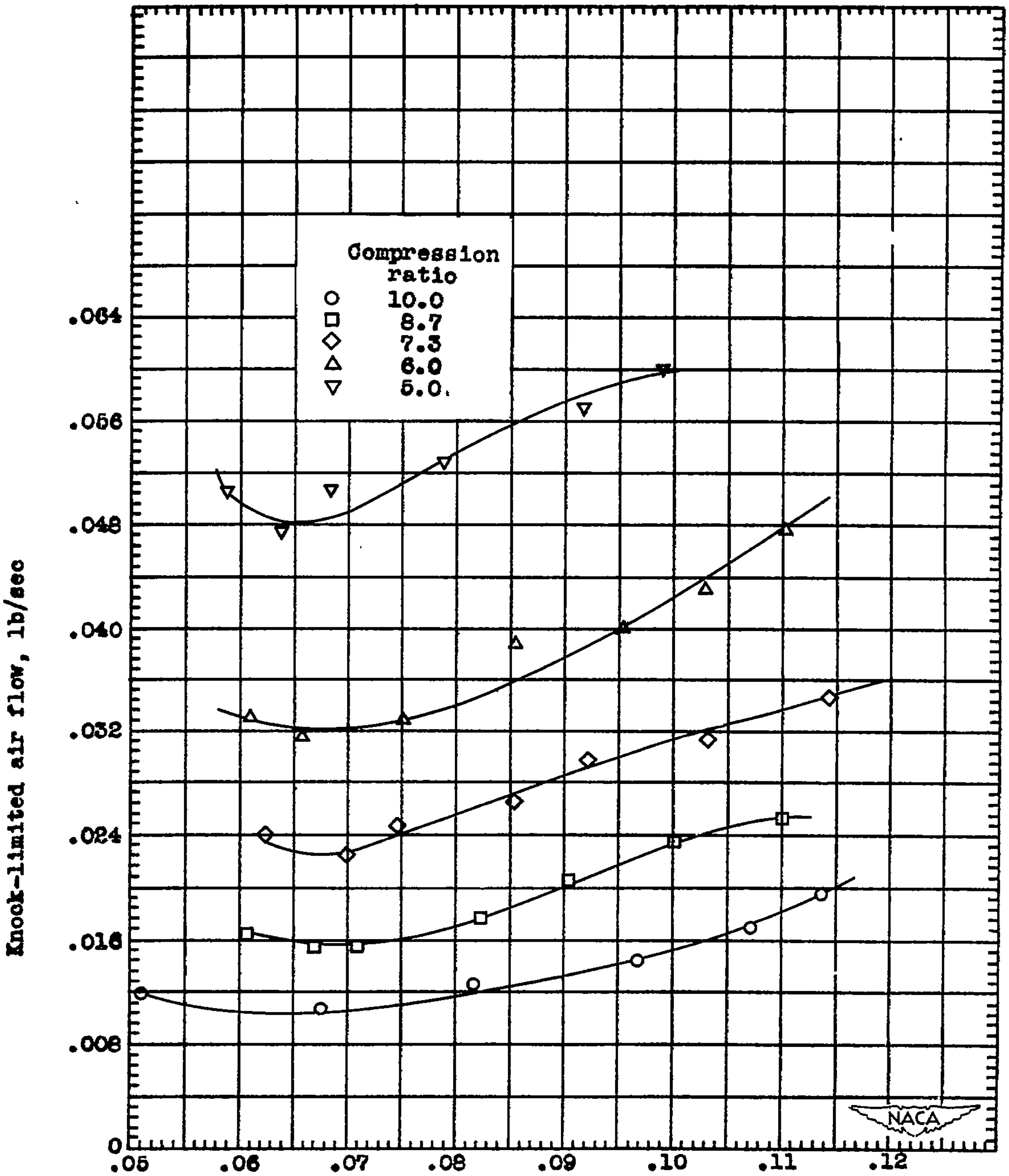
(a) 2,2,3,3-Tetramethylpentane.

Figure 5. - Effect of compression ratio and fuel-air ratio on knock-limited air flow for 25-percent blends of hydrocarbons in base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane plus 4 ml TEL per gallon in modified F-4 engine. Inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 20° B.T.C.; coolant temperature, 250° F.



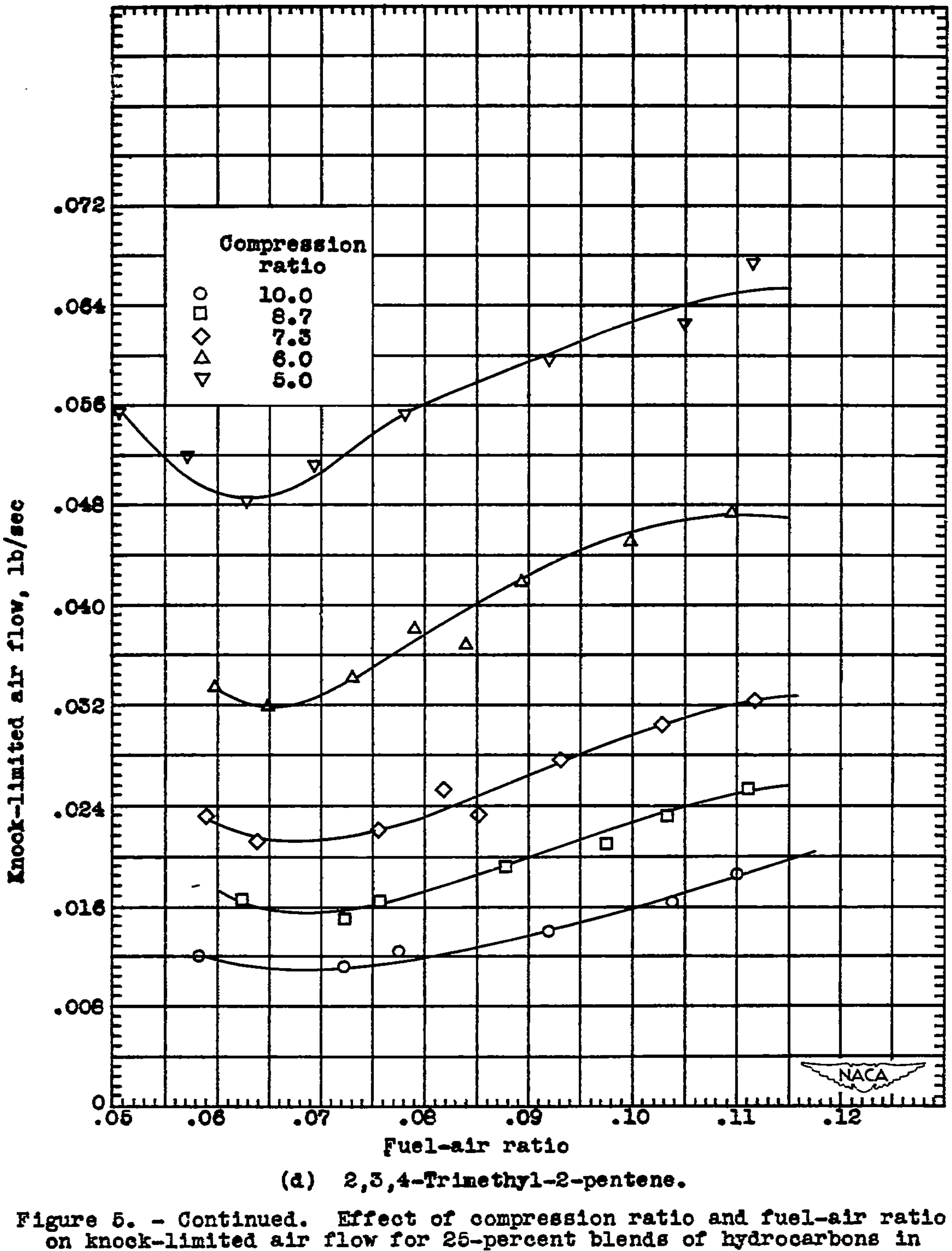
(b) 2,3-Dimethylpentane.

Figure 5. - Continued. Effect of compression ratio and fuel-air ratio on knock-limited air flow for 25-percent blends of hydrocarbons in base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane plus 4 ml TEL per gallon in modified F-4 engine. Inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 20° B.T.C.; coolant temperature, 250° F.



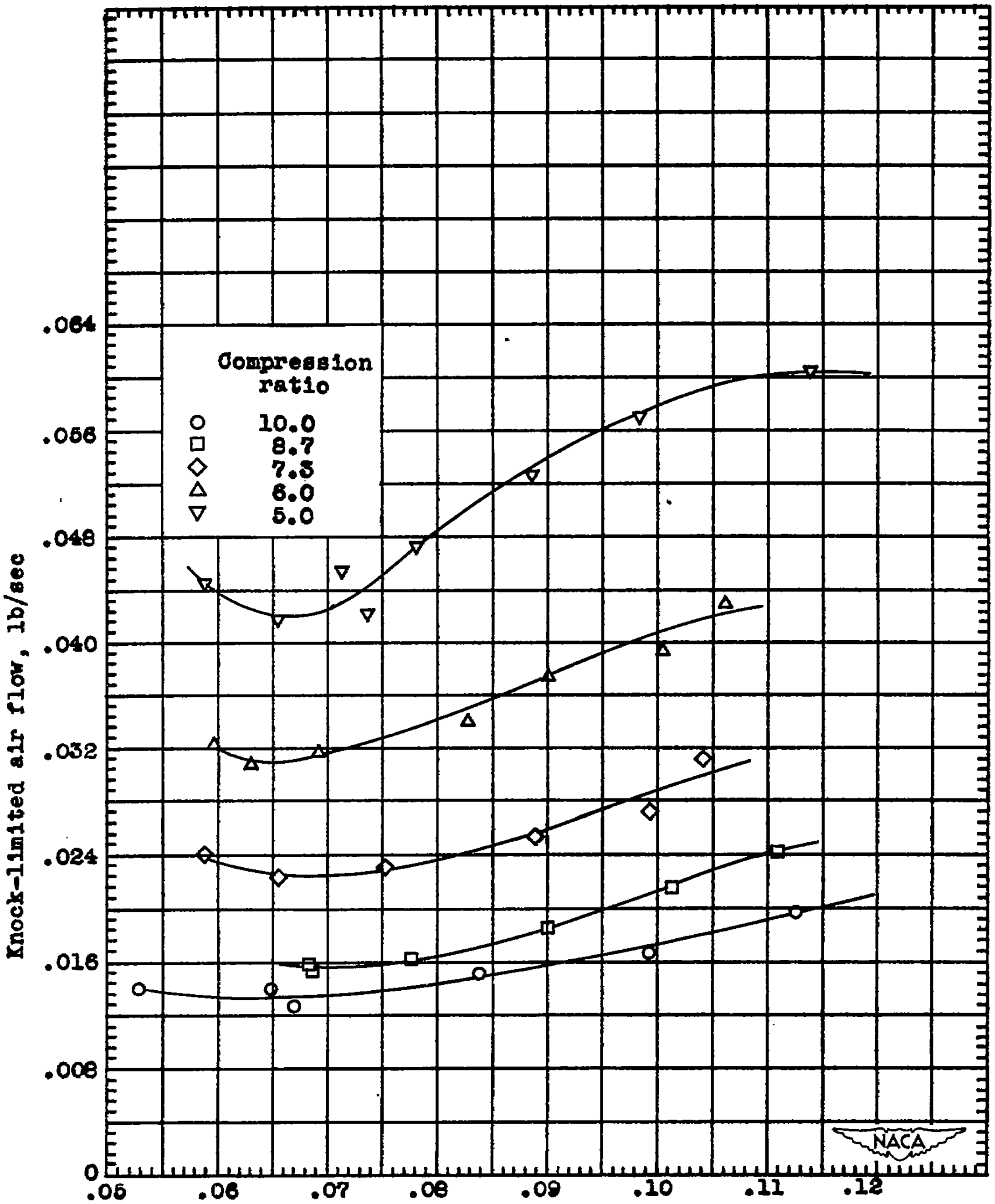
(c) 2,3-Dimethyl-2-pentene.

Figure 5. - Continued. Effect of compression ratio and fuel-air ratio on knock-limited air flow for 25-percent blends of hydrocarbons in base fuel consisting of 87.5 percent S plus 12.5 percent *n*-heptane plus 4 ml TEL per gallon in modified F-4 engine. Inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 20° B.T.C.; coolant temperature, 250° F.



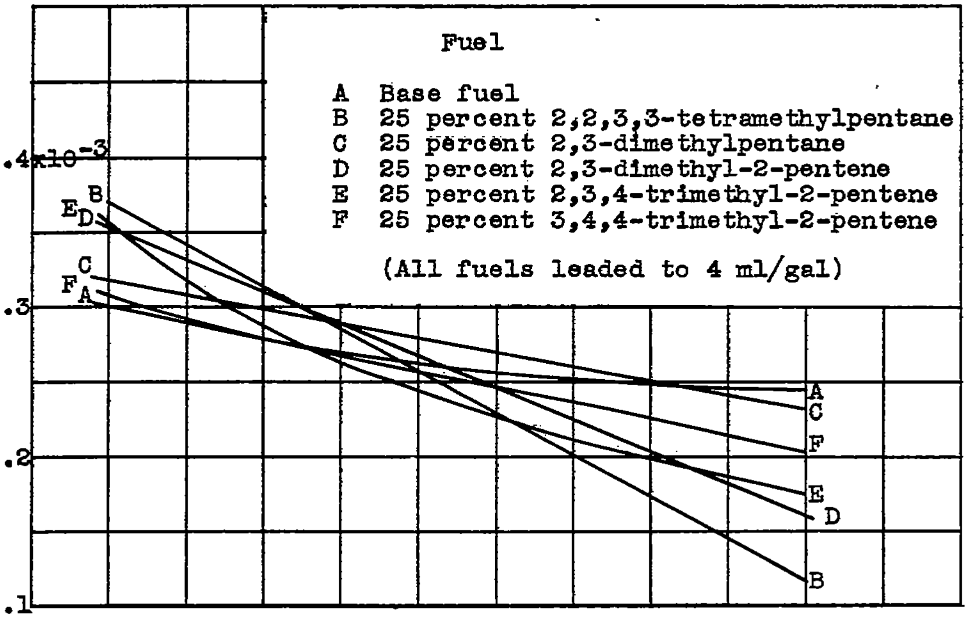
(d) 2,3,4-Trimethyl-2-pentene.

Figure 5. - Continued. Effect of compression ratio and fuel-air ratio on knock-limited air flow for 25-percent blends of hydrocarbons in base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane plus 4 ml TEL per gallon in modified F-4 engine. Inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 20° B.T.C.; coolant temperature, 250° F.

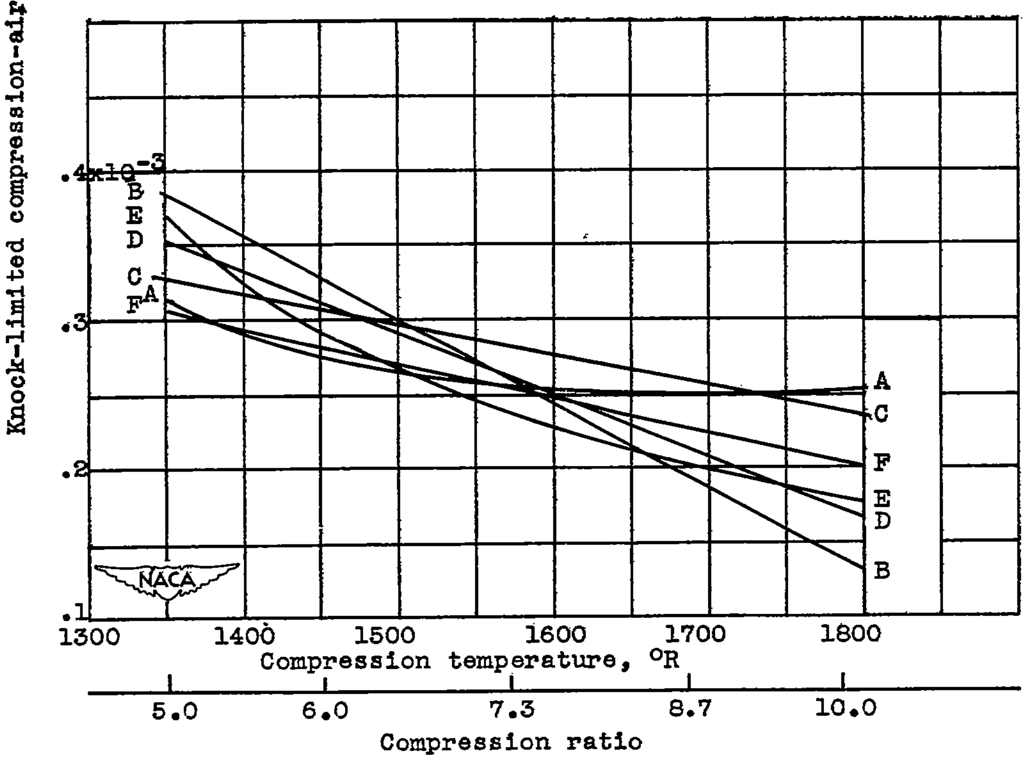


(e) 3,4,4-Trimethyl-2-pentene.

Figure 5. - Concluded. Effect of compression ratio and fuel-air ratio on knock-limited air flow for 25-percent blends of hydrocarbons in base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane plus 4 ml TEL per gallon in modified F-4 engine. Inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 20° B.T.C.; coolant temperature, 250° F.

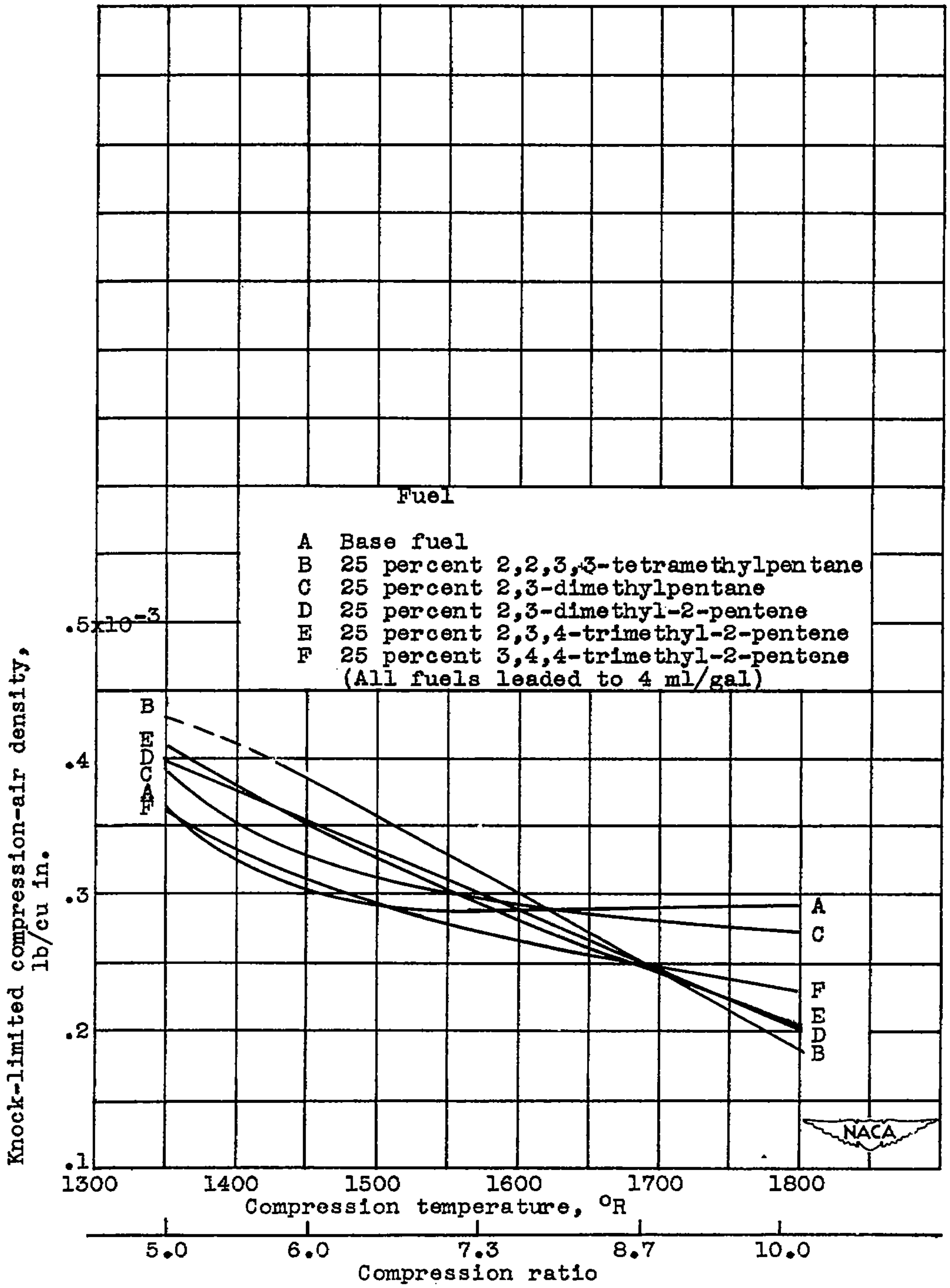


(a) Fuel-air ratio, 0.065.



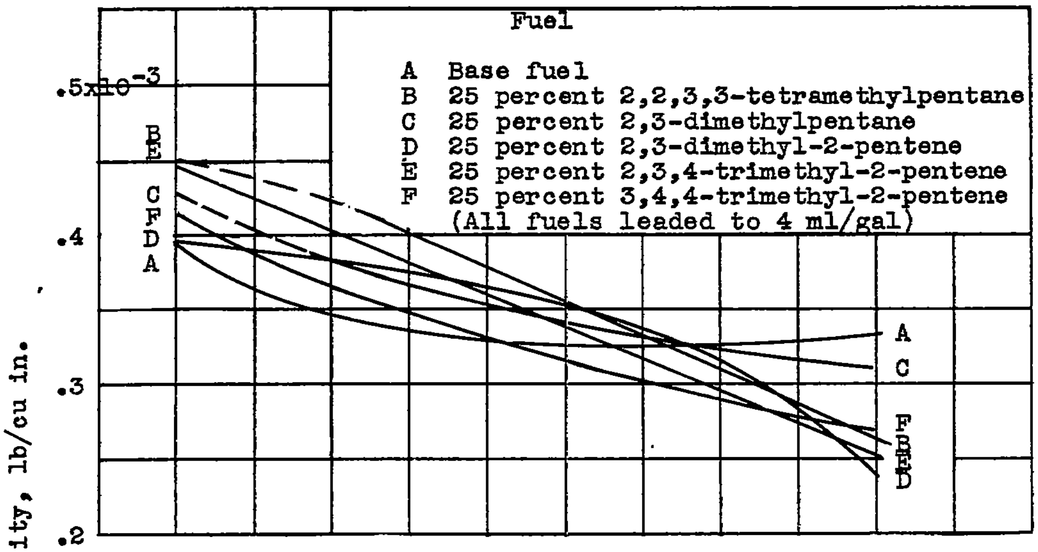
(b) Fuel-air ratio, 0.07.

Figure 6. - Effect of compression temperature on knock-limited compression-air density for leaded 25 percent hydrocarbon blends in a base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane in modified F-4 engine. Inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 20° B.T.C.; coolant temperature, 250° F.

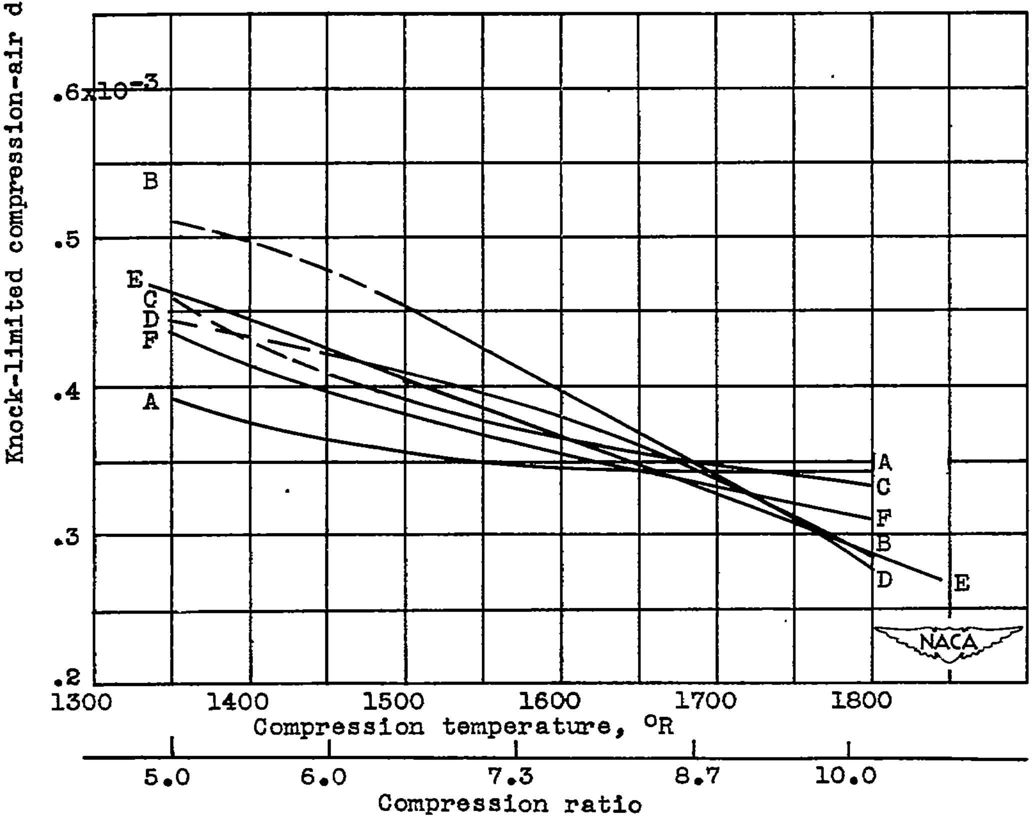


(c) Fuel-air ratio, 0.085.

Figure 6. - Continued. Effect of compression temperature on knock-limited compression-air density for leaded 25 percent hydrocarbon blends in a base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane in modified F-4 engine. Inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 20° B.T.C.; coolant temperature, 250° F.



(d) Fuel-air ratio, 0.10.



(e) Fuel-air ratio, 0.11.

Figure 6. - Concluded. Effect of compression temperature on knock-limited compression-air density for leaded 25 percent hydrocarbon blends in a base fuel consisting of 87.5 percent S plus 12.5 percent n-heptane in modified F-4 engine. Inlet-air temperature, 250° F; engine speed, 1800 rpm; spark advance, 20° B.T.C.; coolant temperature, 250° F.