# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

## TECHNICAL NOTE

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# EFFECT OF EXHAUST PRESSURE ON KNOCK-LIMITED PERFORMANCE

## OF AN AIR-COOLED AIRCRAFT-ENGINE CYLINDER

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SUMMARY

An investigation was conducted to determine the effect of exhaust pressure on the knock-limited performance of an air-cooled aircraft-engine cylinder.

Curves are presented showing the relation between the ratio of exhaust pressure to inlet-manifold pressure, the inlet-manifold pressure, and the inlet mixture temperature at incipient knock. The corresponding values of indicated mean effective pressure and indicated specific fuel consumption are given.

The knock-limited inlet-manifold pressure and the mixture temperature corresponding to constant knock-limited inlet-manifold pressure were less sensitive to change in exhaust-to-inlet-manifold pressure ratio at a fuel-air ratio of 0.080 than at 0.066.

INTRODUCTION

Analytical studies of the performance of compound-engine systems consisting of a conventional internal-combustion engine linked with a steady-flow turbine lead to the following conclusions:

(a) The available exhaust power increases with the engine exhaust pressure (reference 1).

(b) The maximum brake horsepower of the compound engine occurs at an engine exhaust-to-inlet-manifold pressure ratio of approximately 0.8 for the engines investigated (references 2 and 3).

(c) The minimum brake specific fuel consumption of the compound engine occurs at an engine exhaust-to-inlet-manifold pressure ratio of approximately 1.1 for the engines investigated (references 2 and 3).

Permissible exhaust and inlet-manifold pressures and exhaust-to-inlet-manifold pressure ratios are limited by:

(a) The strength of the engine parts subject to the pressure
      loads

(b) The ability of the valve springs to close the inlet or
      exhaust valve against the difference between the exhaust
      and inlet-manifold pressures

(c) The incidence of engine knock

Several investigations have been conducted at the NACA Cleveland
laboratory on the effect of exhaust pressure on the performance of air-
cooled aircraft engines. The effect of exhaust-to-inlet-manifold pres-
sure ratio on brake horsepower, charge-air flow, and volumetric effi-
ciency of a multicylinder air-cooled aircraft engine is given in refer-
ence 4. The effect of changing valve overlap from 40° to 62° is also
shown.

A comparison of the relative knock-limited sensitivities of two
fuels to variable exhaust pressure in an air-cooled aircraft-engine
cylinder is given in reference 5. Data are presented only for a
fuel-air ratio of 0.078 and an inlet-air temperature of 200° F.

The effect of exhaust pressure on the knock-limited performance
of two air-cooled aircraft-engine cylinders is discussed in refer-
ence 6. Curves of knock-limited manifold pressure, indicated specific
fuel consumption, and indicated mean effective pressure are presented
for a range of fuel-air ratios from 0.055 to 0.100 and exhaust-manifold
pressures from 5 to 55 inches of mercury absolute. The data show that
the knock-limited inlet-manifold pressure and indicated mean effective
pressure decrease very rapidly with increasing exhaust pressure when
the exhaust pressure is approximately equal to the inlet-manifold
pressure. This effect was most pronounced at lean fuel-air ratios.

The investigation reported herein was made to obtain the effect
of exhaust pressure on knock-limited performance over a more extensive
range of mixture temperatures than had been covered in previous investi-
gations for use in the analysis of compound-engine systems. The data
were obtained on an air-cooled single-cylinder engine that differed
from those used in reference 6. Curves are presented showing the
relation of the ratio of exhaust-to-inlet-manifold pressure and the
inlet-manifold pressure at incipient knock for various inlet mixture
temperatures. The corresponding values of indicated mean effective
pressure and indicated specific fuel consumption are given.

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## APPARATUS

The present investigations were made on a cylinder from a radial engine with a displacement of 2800 cubic inches mounted on a CUE crankcase. The auxiliary apparatus was similar to that described in reference 5.

The cooling-air supply was controlled by an automatic regulating valve,which was governed by a thermocouple in the cylinder wall located approximately in the knocking zone. The knocking zone was assumed to coincide with the exhaust end zone, which was about 25° (due to swirl) from the exhaust valve toward the rear of the cylinder. The regulator maintained the temperature of the wall next to the end zone at 400° F.

The inlet mixture temperature was measured by a thermocouple installed in the inlet duct and shielded from radiation from the valve port by a bend in the passage.

After completion of the back-pressure runs, the intake system was modified as shown in figure 1 in order to measure the quantity of unvaporized fuel that had been entering the cylinder. A commercial type of centrifugal separator was used to remove droplets of entrained fluid. The volume rate of separated fluid was measured with a burette and a stop watch.

## PROCEDURE

A range of ratios of exhaust pressure to inlet-manifold pressure $p_e/p_m$ from 0.2 to 1.6 were studied. During any single series of runs, all conditions except inlet-manifold pressure, exhaust pressure, and charge flow were held constant. For each setting of the exhaust throttling valve, the manifold pressure was increased until incipient knock was shown on an oscilloscope screen. In the course of the investigation, the effects of varying engine speed, valve overlap, fuel, fuel-air ratio, and mixture temperature were studied. The two fuels used were 28-R and 33-R. The fuel-air ratios investigated were 0.066, 0.080, and 0.100. The effect of changing valve overlap from 40° to 62° was also studied. The mixture temperatures used were 85°, 155°, 200°, 250°, 275°, and 300° F.

The entire experimental investigation consisted of four series of runs at the following conditions:

| Run series | Fuel | Engine speed (rpm) | Valve overlap (deg) |
|---|---|---|---|
| I | 28-R | 2200 | 40 |
| II | 28-R | 2600 | 40 |
| III | 33-R | 2200 | 40 |
| IV | 28-R | 2200 | 62 |

For each of these series, knock-limited data were obtained at the fuel-air ratios and mixture temperatures previously mentioned. The following conditions were held constant for the entire investigation:

Compression ratio . . . . . . . . . . . . . . . . . . . . . 6.74
Spark advance, both plugs, deg B.T.C. . . . . . . . . . . . 25/25
Inlet-oil temperature, $^\circ F$ . . . . . . . . . . . . . . . . . 180
End-zone cylinder temperature, $^\circ F$ . . . . . . . . . . . . . . 400

## RESULTS AND DISCUSSION

The curves in figures 2 to 4 show the relation between the inlet-manifold pressure $p_m$ and the ratio of exhaust-to-inlet-manifold pressure $p_e/p_m$ at the condition of incipient knock. Data at several mixture temperatures and fuel-air ratios are shown. Values for the curve shown by the broken line were found by extrapolating experimental data.

From figure 2 it is seen that at a fuel-air ratio of 0.066 the knock-limited manifold pressure generally decreased with increasing $p_e/p_m$. Comparison of figures 2(a) and 2(b) shows that engine speed had little effect on the knock-limited manifold pressure. Comparison of figures 2(a) and 2(c) shows that 33-R fuel gives consistently higher knock-limited performance than 28-R. Comparison of figures 2(a) and 2(d) shows that increasing the valve overlap increased the sensitivity of the knock-limited inlet-manifold pressure to exhaust-to-inlet-manifold pressure ratio. The higher valve overlap raised the knock-limited inlet-manifold pressure for the range of $p_e/p_m$ covered. Visual extrapolation of the two sets of curves indicates that at a $p_e/p_m$ somewhat higher than 1.6 the knock-limited manifold pressure curves would cross. At a 62° valve

overlap, a fuel-air ratio of 0.066, and a mixture temperature of 85° F, the curve peaked at a $p_e/p_m$ of approximately 0.5 (fig. 2(d)). From subsequent figures it will be seen that the range of operation in which the knock-limited manifold pressure increases with increasing $p_e/p_m$ is larger at higher fuel-air ratios. The arrangement of the plots for observation of fuel, speed, and valve-overlap effects is the same in all subsequent figures.

At a fuel-air ratio of 0.080 (fig. 3), the knock-limited manifold pressure was less sensitive to change in $p_e/p_m$ than at a fuel-air ratio of 0.066. The effect of increased engine speed was small. A 62° valve overlap and 33-R fuel again gave higher performance than a 40° valve overlap and 28-R fuel, respectively.

At a fuel-air ratio of 0.100 (fig. 4), there are regions at high inlet-manifold pressure where the lines of knock-limited manifold pressure cross. The significance of this behavior is indicated later in this report.

The results of an investigation of the relation of knock-limited inlet-manifold pressure with exhaust pressure performed under engine conditions approximating those covered in this report are given in reference 6. These data were taken with engine cylinders of model engines that are different from the one used in the present investigation. The curves in reference 6 show that in the region where the exhaust pressure is approximately equal to the inlet-manifold pressure the knock-limited inlet-manifold pressure decreases rapidly with increased exhaust pressure. No such critical region appears in the data obtained in this investigation.

The test equipment and operating conditions of the investigations covered in reference 6 and in this report were studied in an attempt to isolate the factors in engine design and/or operating conditions responsible for these large changes in knock sensitivity. The factors that may have caused this marked difference are not apparent. However, the following differences in operating conditions might have affected the knock sensitivity to exhaust pressure:

(a) The valve overlap in reference 6 was 60° and in the present investigation 62°. It is not known whether the shape of the running valve diagrams in each of the investigations was the same.

(b) In reference 6, the cylinder temperature was held constant at 450° F at the rear spark-plug bushing; whereas in the present investigation the combustion end-zone temperature was held at 400° F. In the present investigation, however, the rear spark-plug temperature remained nominally constant for each inlet-air temperature.

Figures 5 to 7 consist of cross plots of the curves of figures 2 to 4 and show the variation of mixture temperature with the ratio of exhaust-to-inlet-manifold pressure at constant knock-limited inlet-manifold pressures.

At a fuel-air ratio of 0.066 (fig. 5), the mixture temperature for constant knock-limited inlet-manifold pressure $p_m$ consistently decreased with increasing $p_e/p_m$. The sensitivity of the mixture temperature to exhaust-to-inlet-manifold pressure ratio was affected very little by engine speed, but was substantially increased by increasing valve overlap.

The mixture temperature was less sensitive to exhaust-to-inlet-manifold pressure ratio at a fuel-air ratio of 0.080 than at 0.066 (fig. 6). A 62° valve overlap and 33-R fuel gave higher performance than a 40° valve overlap and 28-R fuel, respectively.

The curves in figure 7 are for a fuel-air ratio of 0.100. At each of the four engine conditions, there is an area at low mixture temperature, high inlet-manifold pressure $p_m$ and, in general, low $p_e/p_m$ where at constant exhaust pressure there is an upper and lower mixture temperature at which each inlet-manifold pressure is knock-limited. In portions of this area, incomplete fuel vaporization was subsequently found. Runs made with the fluid-separating device have shown that at mixture temperatures below 125° F and at rich fuel-air mixtures a measurable part of the fuel is unvaporized in the inlet manifold.

The results of an investigation to determine the effect of fuel vaporization on the knock-limited performance of a single-cylinder engine are presented in reference 7. It is shown that at a fuel-air ratio of 0.100, incomplete fuel vaporization raises the knock-limited inlet-manifold pressure at inlet-air temperatures below 235° F and lowers the knock limit at inlet-air temperatures above 235° F.

Curves of indicated mean effective pressure against $p_e/p_m$ at incipient knock are shown in figures 8 to 10. At a fuel-air ratio of 0.066 (fig. 8), an increase in engine speed from 2200 to 2600 rpm had little effect on the knock-limited indicated mean effective pressure. Consistently higher performance was obtained with 33-R fuel than with 28-R fuel. Increasing the valve overlap from 40° to 62° substantially raised the knock-limited indicated mean effective pressure at low exhaust-to-inlet-manifold pressure ratios. The higher knock-limited performance at a 62° valve overlap tended to disappear as $p_e/p_m$ approached 1.6 (fig. 8(d)).

At a fuel-air ratio of 0.080 (fig. 9), the knock-limited indicated mean effective pressure was less sensitive to change in exhaust-to-inlet-manifold pressure ratio than at a fuel-air ratio of 0.066.

The curves in figure 10 are for a fuel-air ratio of 0.100. Increasing the engine speed from 2200 to 2600 rpm had little effect on the knock-limited mean effective pressure. Consistently higher performance was obtained with 33-R fuel than with 28-R fuel and increasing the valve overlap from 40° to 62° lowered the knock-limited indicated mean effective pressure at low mixture temperatures and raised it at high mixture temperatures.

Figures 11 to 13 consist of cross plots of the curves of figures 8 to 10 and show the variation of mixture temperature with the ratio of exhaust-to-inlet-manifold pressure at constant knock-limited indicated mean effective pressures. It is seen that this relation for the four engine conditions and the three fuel-air ratios is similar to the plots of mixture temperature against $p_e/p_m$ at constant manifold pressure (figs. 5 to 7). At a fuel-air ratio of 0.100 (fig. 13), a lower knock limit of the mixture temperature did not appear as in the curves of mixture temperature at constant manifold pressure and a fuel-air ratio of 0.100 (fig. 7).

The effect of exhaust-to-inlet-manifold pressure ratio on indicated specific fuel consumption is shown in figure 14. The indicated specific fuel consumption consistently decreased with increasing exhaust-to-inlet-manifold pressure ratio. Mixture temperature had no noticeable effect on the indicated specific fuel consumption.

## SUMMARY OF RESULTS

From an investigation to determine the effect of exhaust pressure on the knock-limited performance of a single-cylinder air-cooled engine, the following results were obtained:

1. At fuel-air ratios of 0.066 and 0.080 and mixture temperatures above 155° F, the knock-limited inlet-manifold pressure decreased with increasing exhaust-to-inlet-manifold pressure ratio.

2. The knock-limited inlet-manifold pressure and the mixture temperature corresponding to constant knock-limited inlet-manifold pressure were less sensitive to change in exhaust to-inlet-manifold pressure ratio at a fuel-air ratio of 0.080 than at 0.066.

3. At a fuel-air ratio of 0.100, there was an area at low mixture temperature, high inlet-manifold pressure, and, in general, low exhaust-to-inlet-manifold pressure ratio where at constant exhaust pressure there was an upper and lower mixture temperature at which each inlet-manifold pressure was knock-limited.

4. For the range of exhaust pressures covered, 33-R fuel gave higher knock-limited performance than 28-R fuel.

5. Indicated specific fuel consumption decreased with increasing exhaust-to-inlet-manifold pressure ratio.

6. An increase in valve overlap increased knock-limited inlet-manifold pressure and the sensitivity of knock-limited inlet-manifold pressure to change in exhaust pressure.


Flight Propulsion Research Laboratory,
    National Advisory Committee for Aeronautics,
        Cleveland, Ohio, February 13, 1948.


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    TN No. 1232, 1947.

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    and Mixture Temperature on the Knocking Characteristics of an
    Allison Single-Cylinder Test Engine.  NACA MR No. E5D24, 1945.

Fuel nozzle

Surge
tank

Vaporization
tank

Sight
tube

Separator

Burette
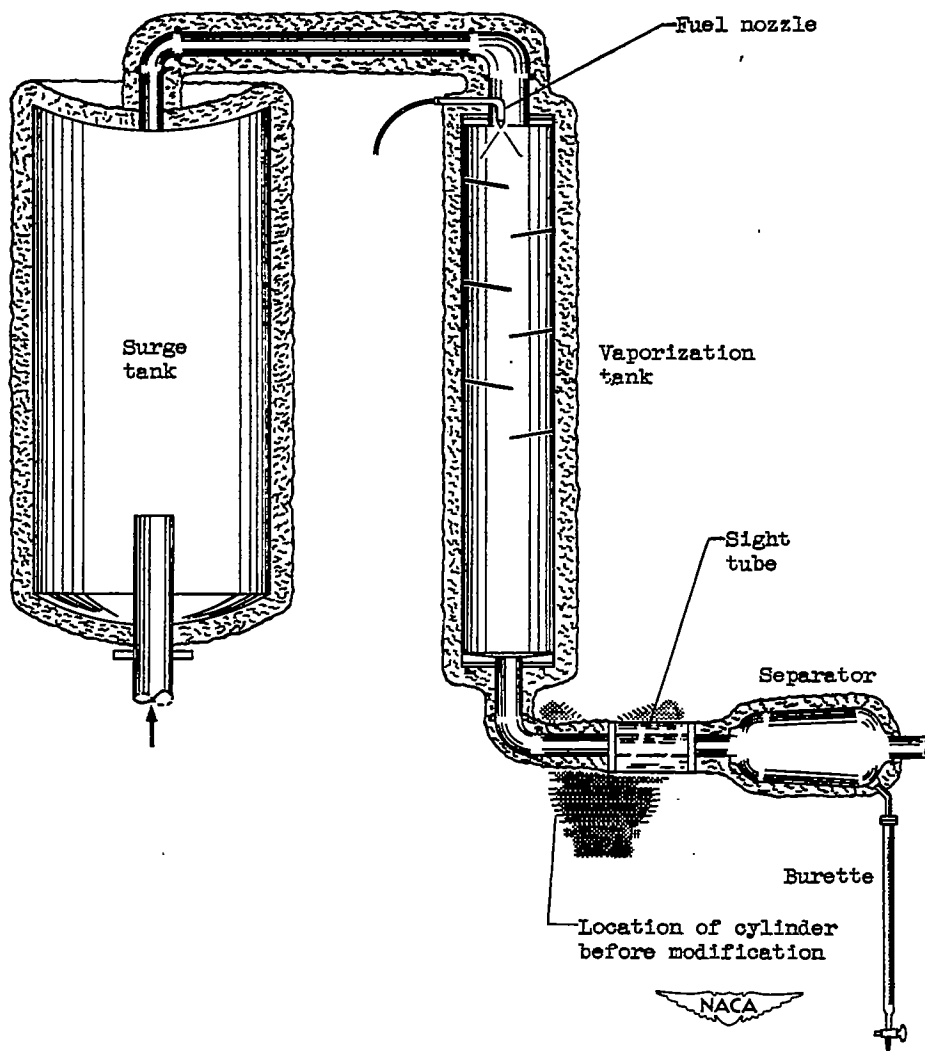
Location of cylinder
before modification

NACA

Figure 1. - Modification of intake system for determining percentage of unvaporized fuel
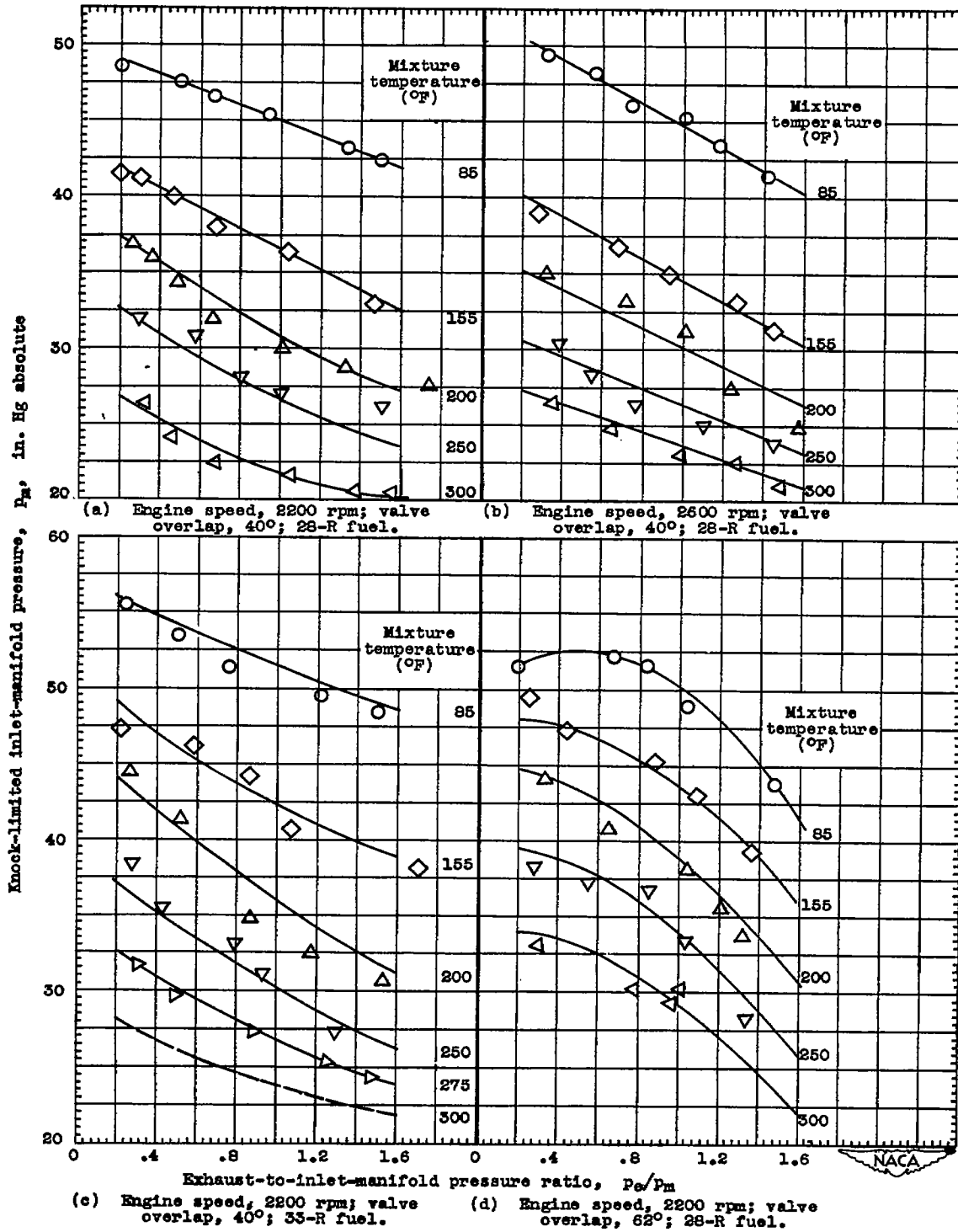at inlet manifold.

Figure 2. - Effect of exhaust-to-inlet-manifold pressure ratio on knock-limited inlet-manifold pressure at fuel-air ratio of 0.066 for various mixture temperatures.
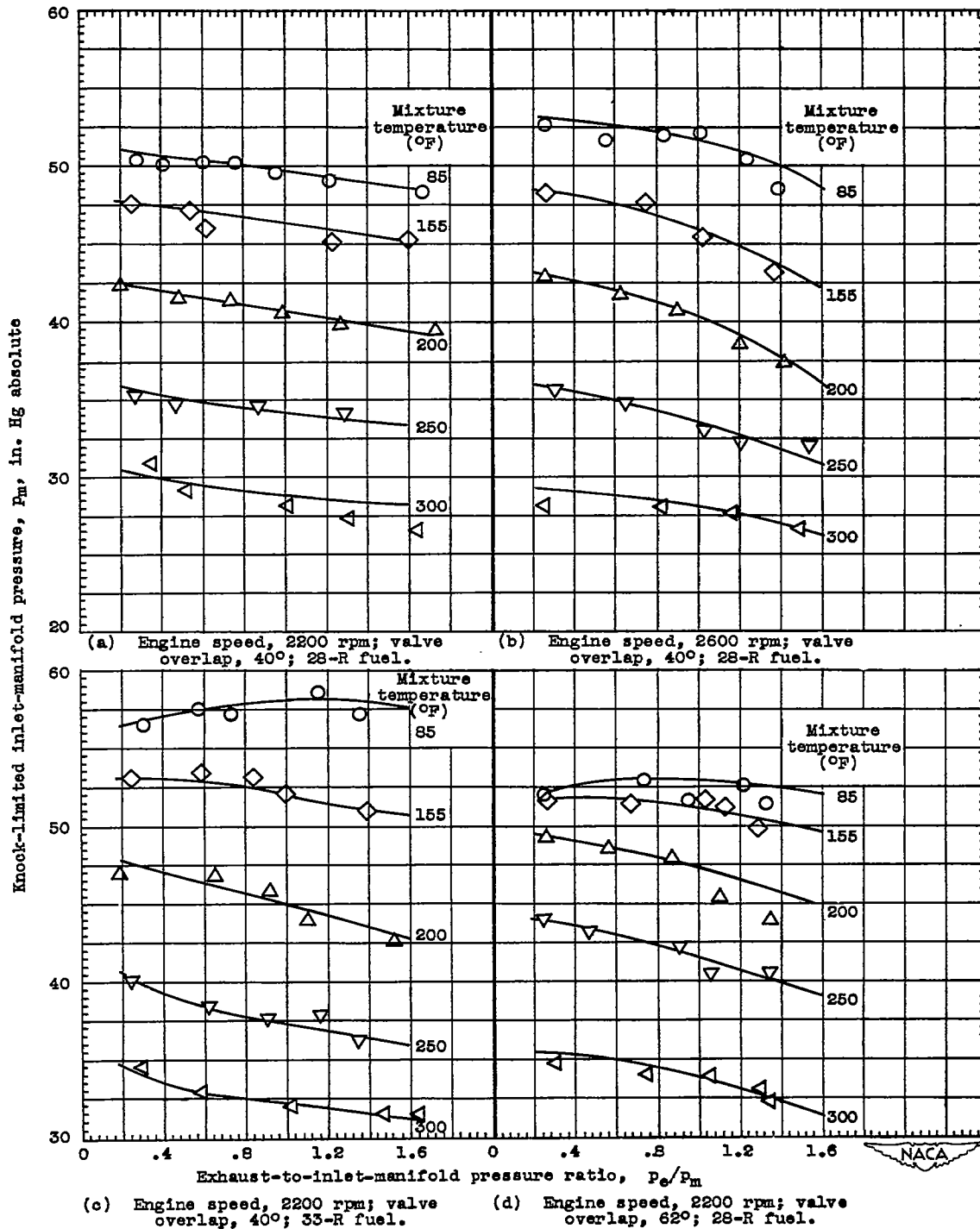
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Figure 3. - Effect of exhaust-to-inlet-manifold pressure ratio on knock-limited inlet-manifold pressure at fuel-air ratio of 0.080 for various mixture temperatures.

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(a) Engine speed, 2200 rpm; valve
    overlap, 40°; 28-R fuel.

(b) Engine speed, 2600 rpm; valve
    overlap, 40°; 28-R fuel.

(c) Engine speed, 2200 rpm; valve
    overlap, 40°; 33-R fuel.

(d) Engine speed, 2200 rpm; valve
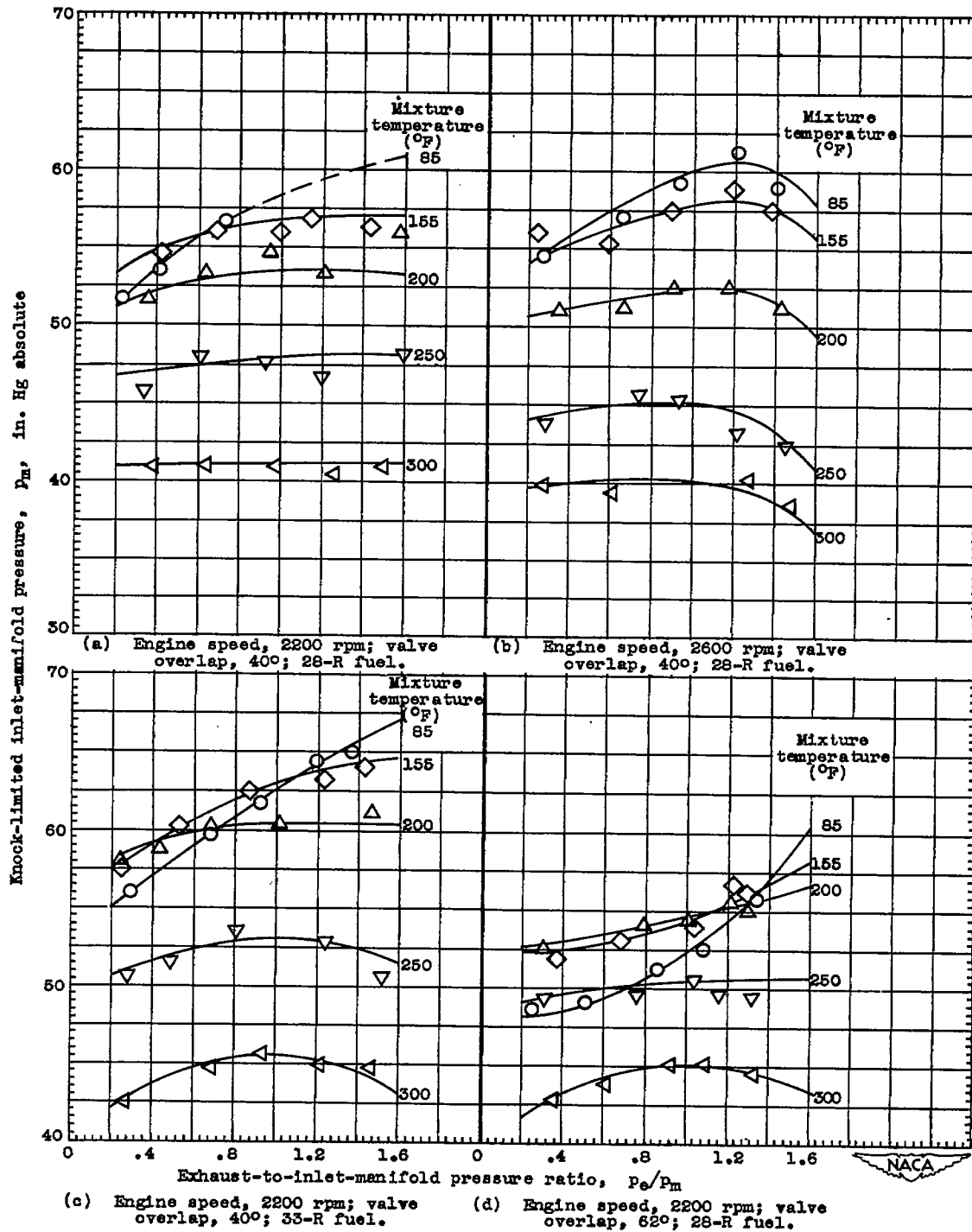    overlap, 62°; 28-R fuel.

Figure 4. - Effect of exhaust-to-inlet-manifold pressure ratio on knock-limited inlet-manifold
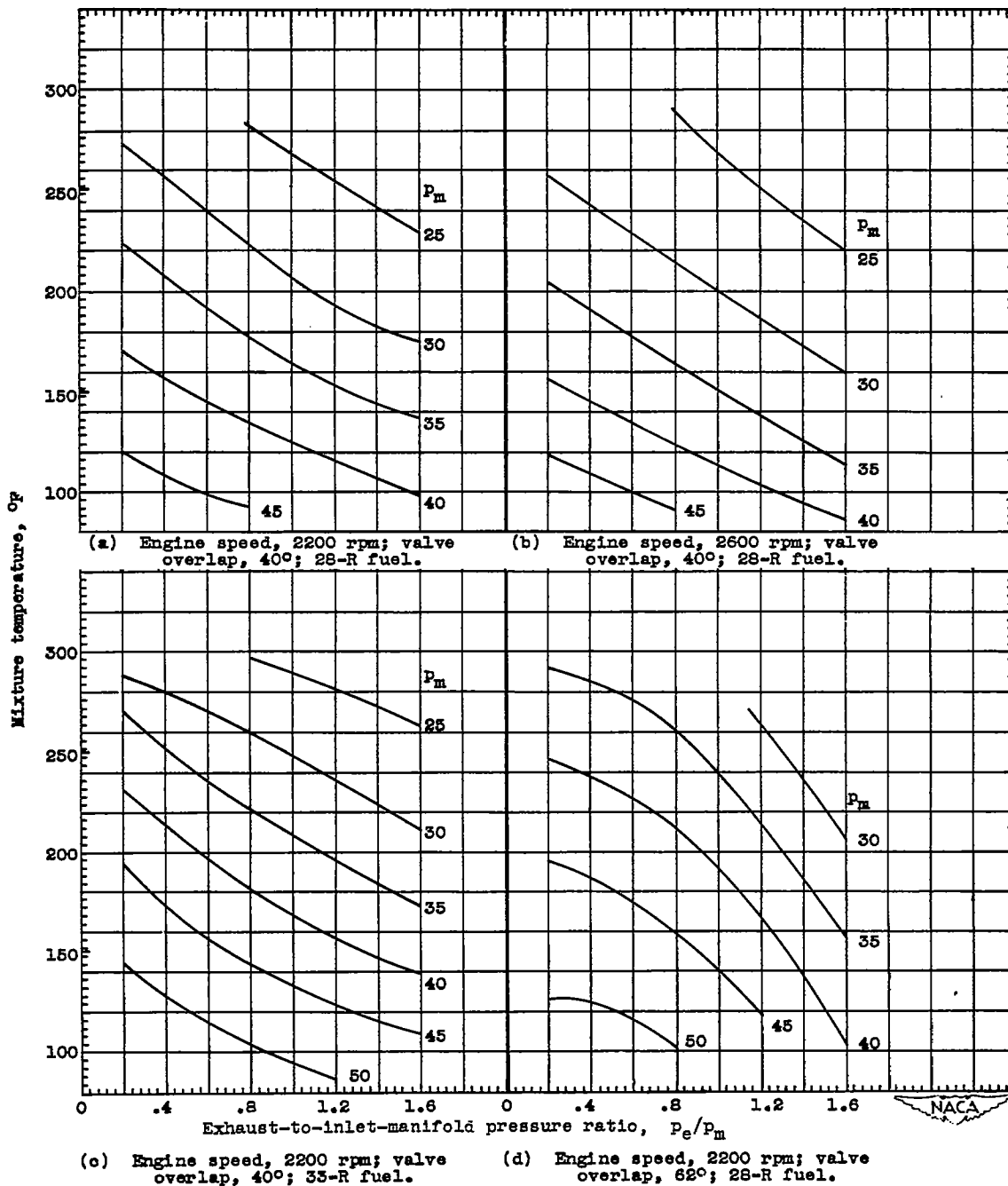pressure at fuel-air ratio of 0.100 for various mixture temperatures.

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(a)  Engine speed, 2200 rpm; valve
     overlap, 40°; 28-R fuel.

(b)  Engine speed, 2600 rpm; valve
     overlap, 40°; 28-R fuel.

(c)  Engine speed, 2200 rpm; valve
     overlap, 40°; 33-R fuel.

(d)  Engine speed, 2200 rpm; valve
     overlap, 62°; 28-R fuel.

Figure 5. - Effect of exhaust-to-inlet-manifold pressure ratio on mixture temperature at fuel-
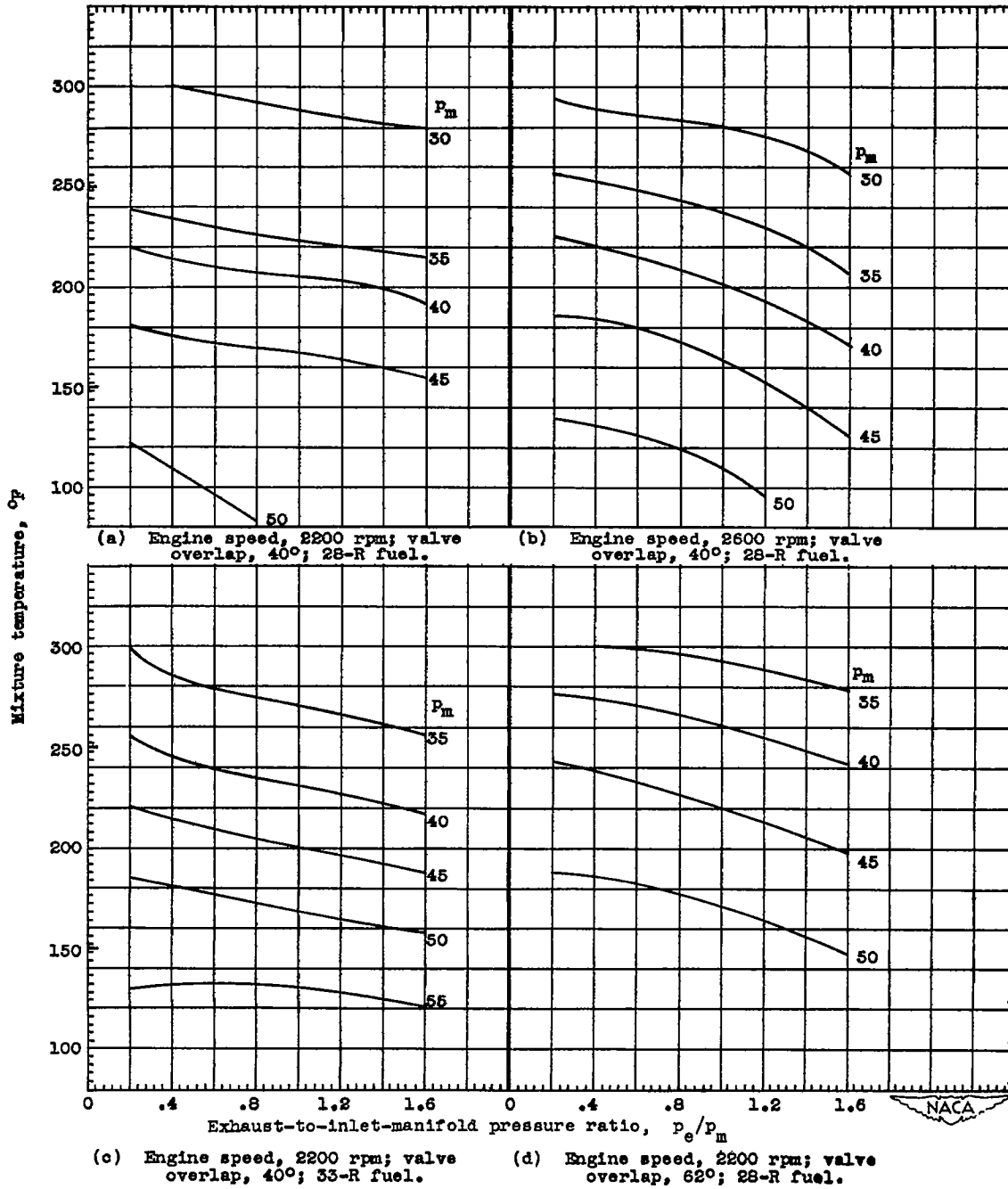air ratio of 0.066 for various knock-limited manifold pressures.

(a) Engine speed, 2200 rpm; valve overlap, 40°; 28-R fuel.

(b) Engine speed, 2600 rpm; valve overlap, 40°; 28-R fuel.

(c) Engine speed, 2200 rpm; valve overlap, 40°; 33-R fuel.

(d) Engine speed, 2200 rpm; valve overlap, 62°; 28-R fuel.

Figure 6. - Effect of exhaust-to-inlet-manifold pressure ratio on mixture temperature at fuel-air ratio of 0.080 for various knock-limited manifold pressures.
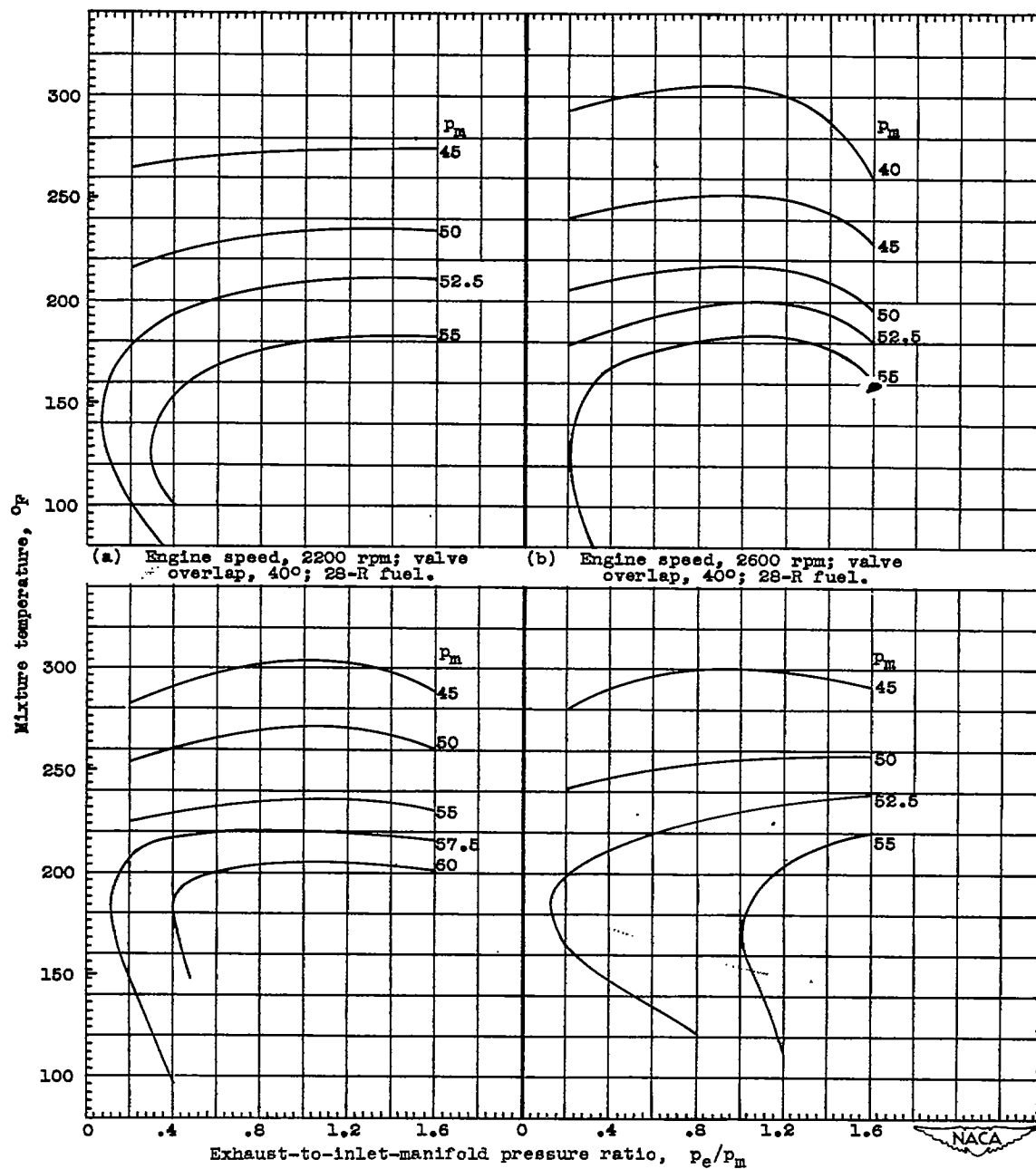
(a) Engine speed, 2200 rpm; valve overlap, 40°; 28-R fuel.

(b) Engine speed, 2600 rpm; valve overlap, 40°; 28-R fuel.

(c) Engine speed, 2200 rpm; valve overlap, 40°; 33-R fuel.

(d) Engine speed, 2200 rpm; valve overlap, 62°; 28-R fuel.

Figure 7. - Effect of exhaust-to-inlet-manifold pressure ratio on mixture temperature at fuel-air ratio of 0.100 for various knock-limited manifold pressures.

(a) Engine speed, 2200 rpm; valve overlap, 40°; 28-R fuel.

(b) Engine speed, 2600 rpm; valve overlap, 40°; 28-R fuel.

(c) Engine speed, 2200 rpm; valve overlap, 40°; 33-R fuel.

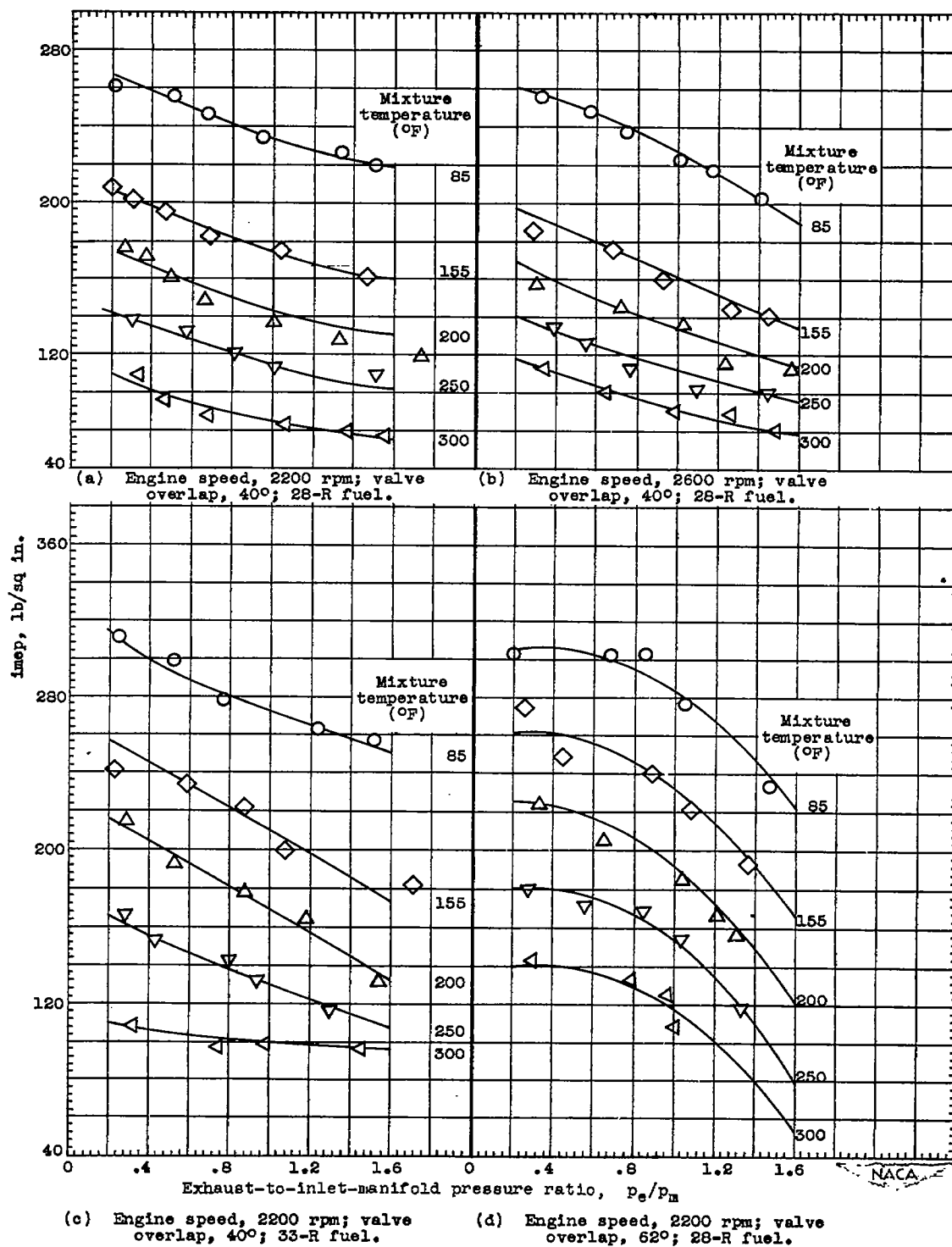(d) Engine speed, 2200 rpm; valve overlap, 62°; 28-R fuel.

Figure 8. - Effect of exhaust-to-inlet-manifold pressure ratio on knock-limited indicated mean effective pressure at fuel-air ratio of 0.066 for various mixture temperatures.
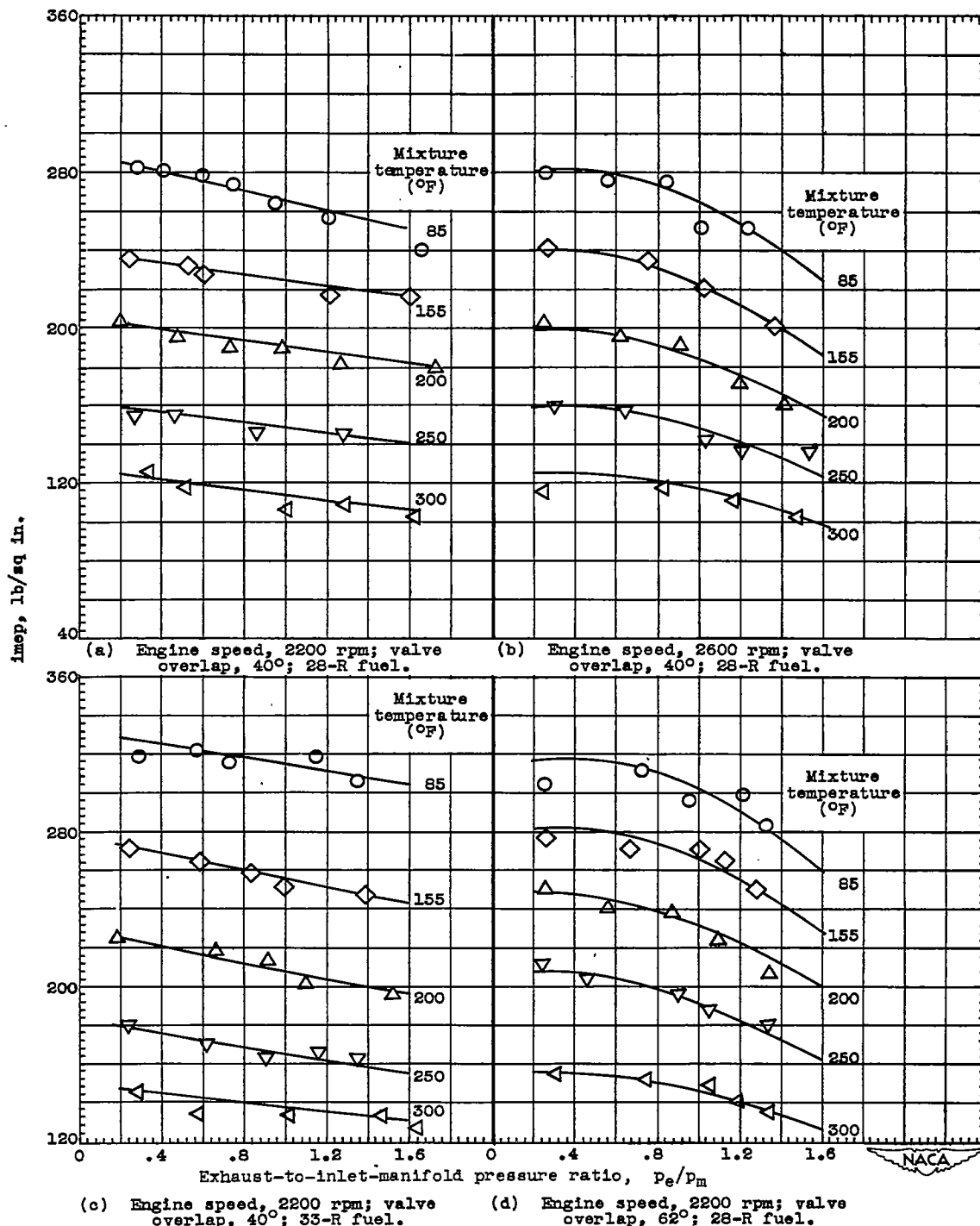
(a) Engine speed, 2200 rpm; valve overlap, 40°; 28-R fuel.

(b) Engine speed, 2600 rpm; valve overlap, 40°; 28-R fuel.

(c) Engine speed, 2200 rpm; valve overlap, 40°; 33-R fuel.

(d) Engine speed, 2200 rpm; valve overlap, 62°; 28-R fuel.

Figure 9. - Effect of exhaust-to-inlet-manifold pressure ratio on knock-limited indicated mean effective pressure at fuel-air ratio of 0.080 for various mixture temperatures.
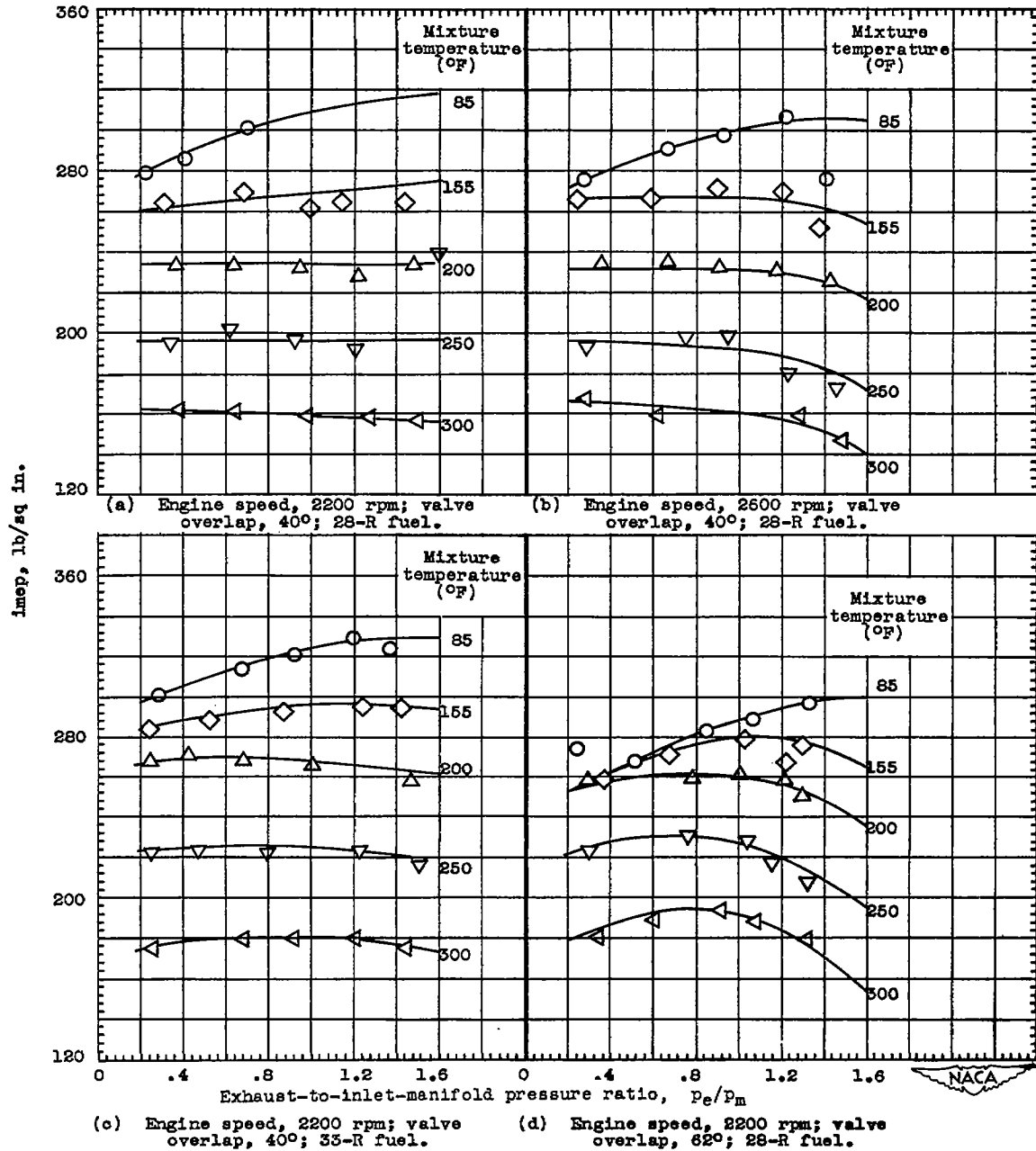
Figure 10. – Effect of exhaust-to-inlet-manifold pressure ratio on knock-limited indicated mean effective pressure at fuel-air ratio of 0.100 for various mixture temperatures.
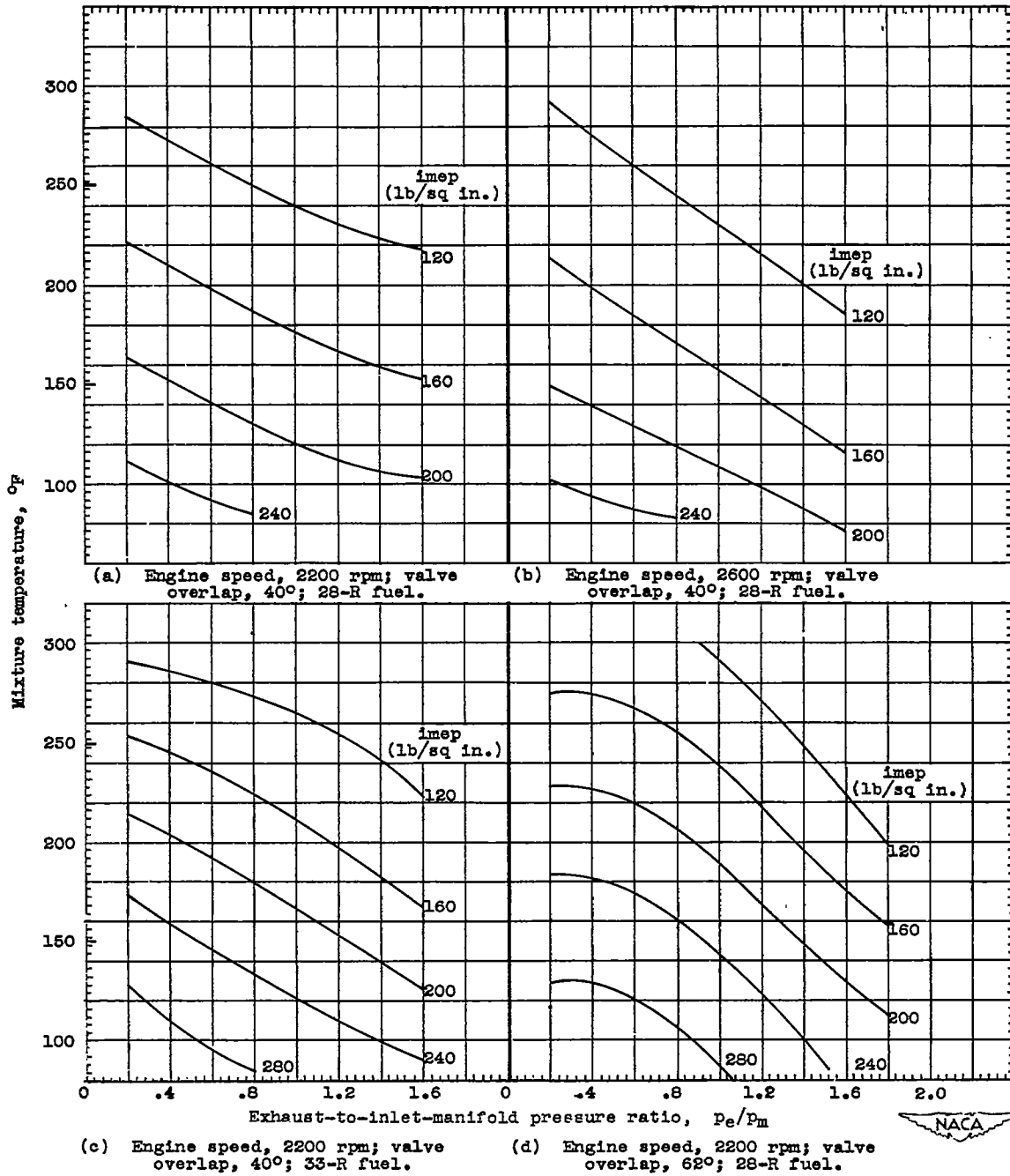
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(a)  Engine speed, 2200 rpm; valve
     overlap, 40°; 28-R fuel.

(b)  Engine speed, 2600 rpm; valve
     overlap, 40°; 28-R fuel.

(c)  Engine speed, 2200 rpm; valve
     overlap, 40°; 33-R fuel.

(d)  Engine speed, 2200 rpm; valve
     overlap, 62°; 28-R fuel.

Figure 11. - Effect of exhaust-to-inlet-manifold pressure ratio on mixture temperature at
fuel-air ratio of 0.066 for various knock-limited indicated mean effective pressures.
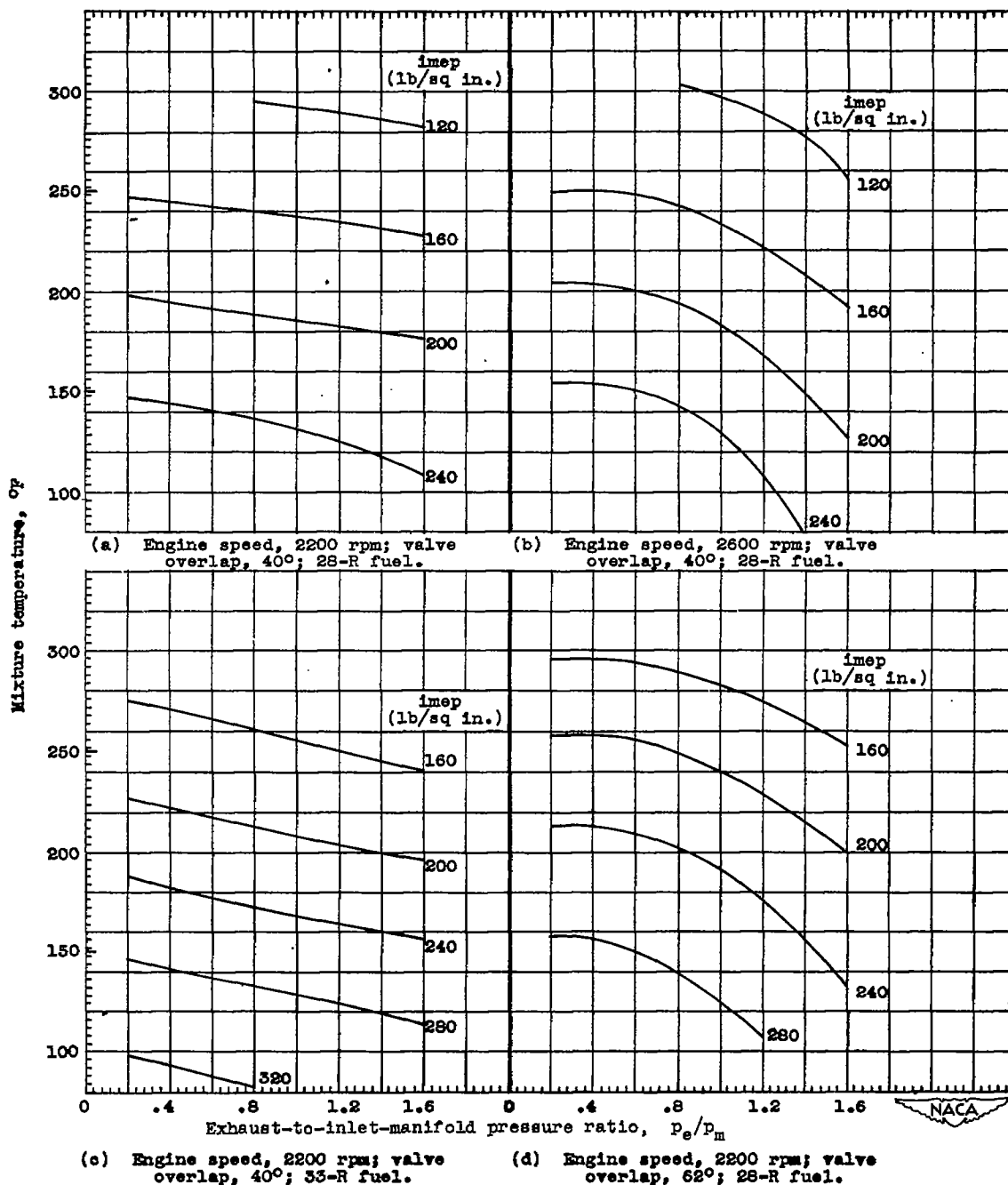
Figure 12. - Effect of exhaust-to-inlet-manifold pressure ratio on mixture temperature at fuel-air ratio of 0.080 for various knock-limited indicated mean effective pressures.
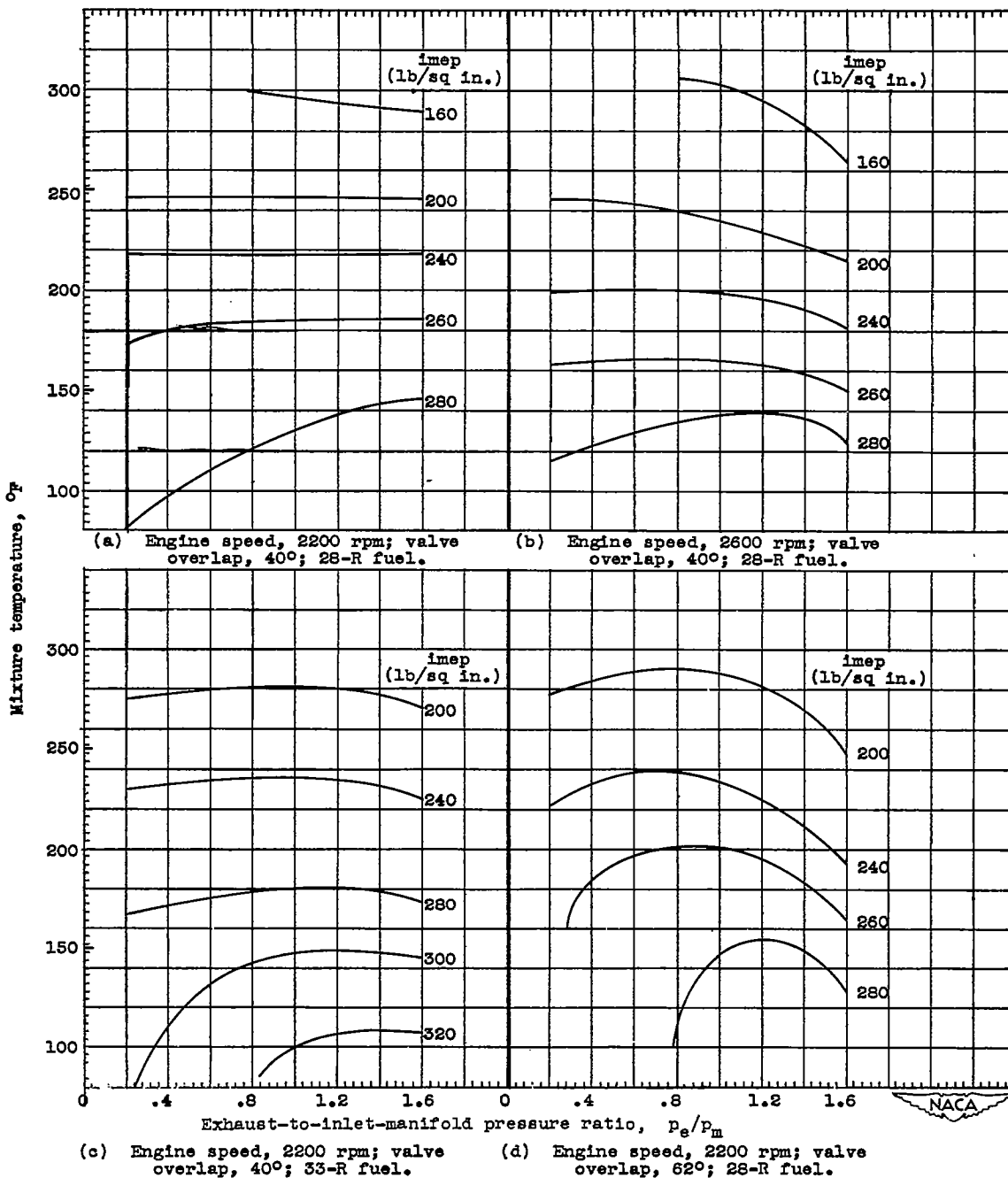
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Figure 13. - Effect of exhaust-to-inlet-manifold pressure ratio on mixture temperature at fuel-air ratio of 0.100 for various knock-limited indicated mean effective pressures.

(a)   Engine speed, 2200 rpm; valve overlap, 40°; 28-R fuel.

(b)   Engine speed, 2600 rpm; valve overlap, 40°; 28-R fuel.

(c)   Engine speed, 2200 rpm; valve overlap, 40°; 33-R fuel.

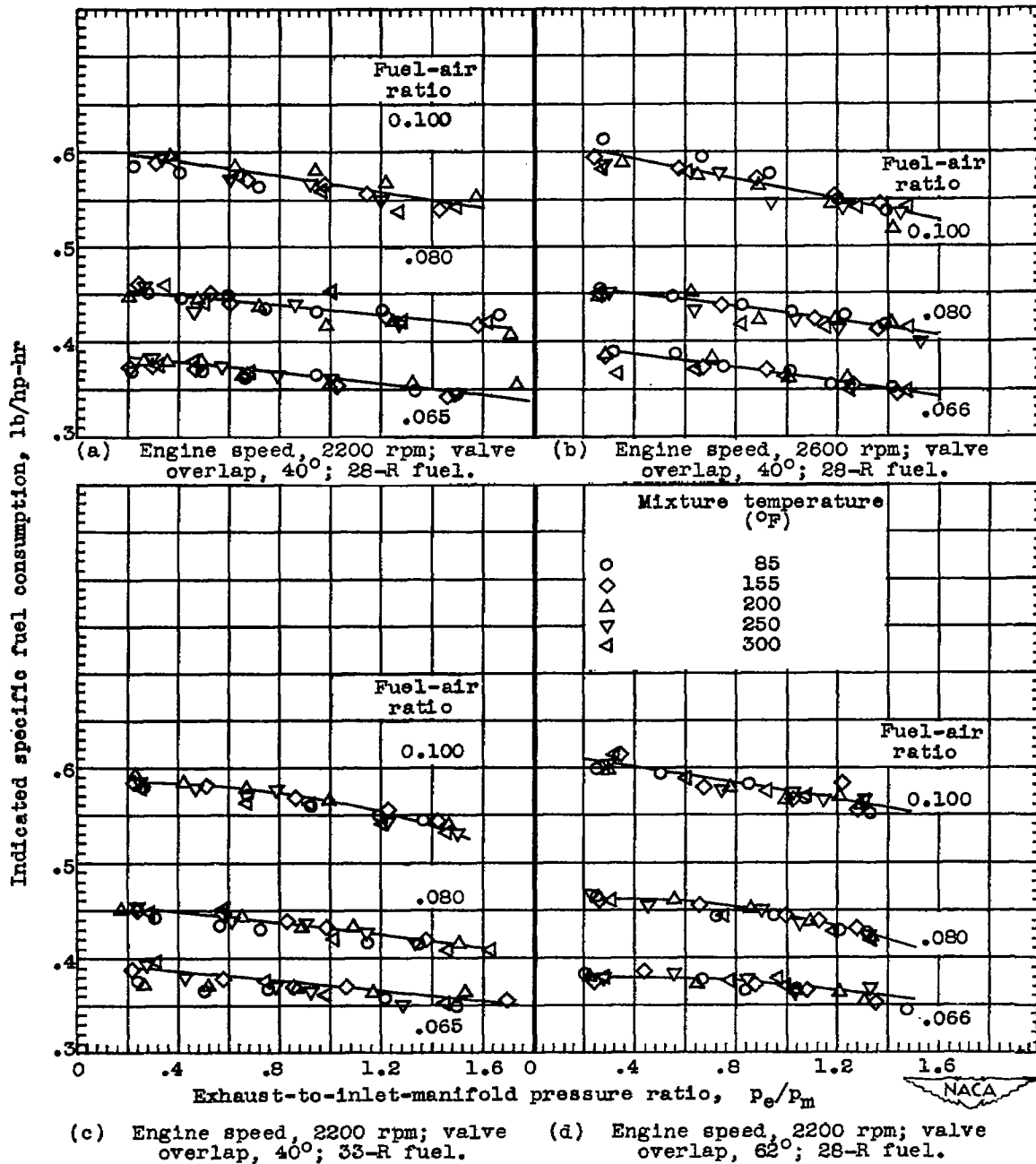(d)   Engine speed, 2200 rpm; valve overlap, 62°; 28-R fuel.

Figure 14. - Effect of exhaust-to-inlet-manifold pressure ratio on indicated specific fuel consumption.