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EXPERIMENTAL STUDIES OF THE KNOCK-LIMITED BLENDING CHARACTERISTICS OF AVIATION FUELS

I - PRELIMINARY TESTS IN AN AIR-COOLED CYLINDER

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ADVANCE RESTRICTED REPORT

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SUMMARY

Object. - To investigate the relation between the knock limit and the blend composition of aviation fuels when tested under supercharged conditions in an air-cooled aircraft-engine cylinder.

Scope. - The relation between blend concentration and knock limit for two-component blends was investigated for pairs of the following fuels: two commercial gasolines - 130-grade aviation fuel and 62-octane fuel; four paraffins - aviation alkylate, S-3 reference fuel, M-4 reference fuel, and 62-octane fuel; one olefin - diisobutylene; one naphthene - cyclopentane; and two aromatics - toluene and benzene. Tetraethyl lead and xylidines were added to the components of some of the blends. All tests were conducted with a Pratt & Whitney R-2800 cylinder at an engine speed of 2000 rpm and an inlet-air temperature of 200° F. The blending relationships previously investigated for the small-scale supercharged engines were applied to results from the full-scale aircraft engine cylinder and extended to include blends of benzene, aviation alkylate, and 62-octane fuels.

Summary of results. - No general conclusions are drawn from the limited number of tests, but the following results were observed: The reciprocal of the knock-limited indicated mean effective pressure of the binary fuel blends was a linear function of blend composition for paraffinic fuels when tested at a fuel-air ratio of 0.10. This result was also true for blends of paraffinic fuels containing benzene, tetraethyl lead, or xylidines for a constant concentration of one or more of these three materials in the blends. Data taken at fuel-air ratios of 0.07 or 0.075 did not correlate well with the derived reciprocal relation except in three cases. Binary blends of diisobutylene, cyclopentane, toluene, or benzene with paraffinic fuels did not follow the reciprocal relation at either rich or lean mixtures.

Test data for trinary blends of benzene, alkylate, and 62-octane fuel at a fuel-air ratio of 0.10 agreed well with an extended equation relating the knock limit of fuel blends to the blend composition.

INTRODUCTION

An investigation of the knock-limited blending characteristics of aviation-fuel components that are in current use or are contemplated for future use is being conducted at the NACA Aircraft Engine Research Laboratory. The approach to the problem of blending characteristics of fuels being followed is to examine the fundamental relationships and the experimental data involved and from these factors to formulate blending equations that will apply to the experimental data and at the same time will have certain physical justification.

The first analysis of the problem as presented in reference 1 gave the following result: When the knock limit of a fuel blend is determined in a supercharged test engine, the knock limit of the blend at constant fuel-air ratio is related to the knock limits of the components at the same fuel-air ratio by the following equation:

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

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 the blend

The data presented in reference 1, although admittedly meager, indicated that this relationship did apply to blends of S-2 and M-3 in the CFR engine. Heron and Beatty (reference 2) had previously obtained the same results in tests on a CFR engine. A theoretical explanation of the equation based on certain assumptions that have not been proved is also presented in reference 1.

The purpose of the present report is to present data obtained during January 1944 in the investigation of the knock-limited blending relation of aviation-fuel components when tested in a full-scale aircraft-engine cylinder and to determine the extent to which equation (1) or modifications of this equation are applicable.

The Petroleum Administration for War has published (reference 3) a method of estimating the knock ratings of aviation-gasoline blends. In this method the ratings of the fuels and the blends are converted to index numbers; the index number for the blend is found by making a weighted average of the index numbers of the components. The index number is then converted back into a rating for the blend. No details regarding the relation between the index numbers and the knock-limited indicated mean effective pressures are given but a letter from the authors of that report states that the index numbers are linearly related to the reciprocal of the indicated mean effective pressures except for values corresponding to fuels having ratings less than 90 octane number.

APPARATUS AND TEST CONDITIONS

Tests were conducted with a Pratt & Whitney R-2800 cylinder mounted on a CUE crankcase. Standard engine baffles were fitted to the cylinder. Flight conditions in regard to temperature distribution over the cylinder were simulated by placing special directing vanes in the cooling-air stream in front of the cylinder.

Thermocouples were placed in the cylinder walls and the cylinder head in such a way that a fairly complete temperature survey was obtained. The thermocouple used as a reference in controlling the cylinder temperature was embedded in the rear spark-plug boss.

Figure 1 is a diagram of the combustion-air and the fuel-supply systems. The combustion air is metered through a control valve located between the engine and the air supply. An orifice installation, immediately behind the pressure-regulating valve, permits the measurement of the quantity of air flowing. After leaving the orifice the air passes through the air-heater unit in which the temperature is controlled by bypassing part of the air past the heater. The heated air passes through a surge tank with a volume of 15 cubic feet and then into the vaporization tank. Fuel is injected at the top of the vaporization tank. The volume of the vaporization tank is approximately 30 times the cylinder volume. Baffle plates are placed in the vaporization tank to assist the mixing of the fuel and air. Vaporization tests conducted previous to the work covered in this report indicated that, under the engine operating conditions used in these tests, the fuel was completely vaporized before it left the vaporization tank. The intake pipe between the vaporization tank and the cylinder has an inside diameter of $2\frac{5}{16}$ inches and is approximately 24 inches long. The inlet-mixture temperature is measured by a thermocouple located in the intake pipe approximately 15 inches from the intake port.

The fuels are supplied through two different fuel systems. Each operates independently of the other. By means of the two fuel systems, binary fuel blends were tested without prior mixing of the fuel. A check was made in which two components were mixed in a drum and supplied to the engine through one of the injection systems. For equal blends, the knock limit was the same with premixing of fuel as when the two components were injected separately into the vaporization tank by means of the two injection systems.

Fuel is drawn from constant-head supply tanks and fuel flow is measured by calibrated rotameters. Each fuel system has two rotameters of different ranges of flow connected in parallel. The rotameters are so selected that a continuous fuel-flow range from 2 to 150 pounds per hour can be measured. Surge eliminators of the Sylphon bellows type are located between the rotameters and the engine to prevent any surging caused by the injection pumps from affecting the rotameter reading. Fuel is metered by a four-cylinder Bosch injection pump, which supplies the fuel to a spring-loaded injection nozzle in the top of the vaporization tank.

The fixed engine-operating conditions were:

Compression ratio	6.7
Engine speed, rpm	2000
Inlet-mixture temperature, °F	200
Spark advance, both plugs, degrees B.T.C.	20
Cooling-air temperature, °F	50-80
Oil pressure, pounds per square inch	60
Oil-in temperature, °F	185
Rear spark-plug-boss temperature, °F	400
Valve timing:	
Intake opens, degrees B.T.C.	21
Intake closes, degrees A.B.C.	72
Exhaust opens, degrees B.B.C.	75
Exhaust closes, degrees A.T.C.	17

Knock was detected with a magnetostriction pickup unit used with a cathode-ray oscilloscope.

FUELS

Fuels from different hydrocarbon classes were selected for testing in order that the different blending characteristics of these types of fuel could be determined. This report covers tests of the following blends:

Commercial gasolines:
130 grade fuel (AN-F-28, Amendment-2) and
62-octane fuel (AN-F-22) plus 4 ml tetraethyl lead

Paraffins:
S-3 reference fuel plus 6 ml tetraethyl lead and
M-4 reference fuel plus 6 ml tetraethyl lead
Aviation alkylate and 62-octane fuel
Aviation alkylate plus tetraethyl lead and 62-octane fuel plus tetraethyl lead

Olefin:
Diisobutylene and 62-octane fuel

Naphthene:
Cyclopentane and 62-octane fuel

Aromatics:
Toluene and 62-octane fuel
Benzene (95 - 98 percent benzene) and 62-octane fuel
Benzene and aviation alkylate

Additive:
Aviation alkylate plus 4.5 ml tetraethyl lead and 62-octane fuel plus 4.5 ml tetraethyl lead
Aviation alkylate plus tetraethyl lead plus xylidines and 62-octane fuel plus tetraethyl lead plus xylidines

TEST METHODS

The fuel components were tested in pairs as listed. Mixture-response curves were obtained where possible for each of the two components of any given pair. During the determination of each mixture-response curve the data were plotted on an engine control chart similar to the one shown in figure 2. An explanation of the chart is given in the appendix. The control chart facilitated the selection of test-point spacing and also made possible the detection of errors in data that otherwise would not have been found until the data were computed. In some cases, limited fuel supplies prevented the determination of complete mixture-response curves.

After the mixture-response curve for each component was determined, various blends of the two components were tested at constant fuel-air ratio. Blend composition was adjusted by proportioning the flow rates in the two independent fuel systems that supplied two blend components. Selection of fuel flows was accomplished with the aid of a composition control chart illustrated in figure 3 wherein the reading of the rotameter in one fuel system is plotted against the reading of the rotameter in the other system.

Advantage was taken of the fact that, for knock-limited conditions at constant fuel-air ratio with fuels to which equation (1) is applicable, the fuel flow in one system is a linear function of the fuel flow in the other system, as shown in figure 3. The rotameter reading at the knock limit for the higher antiknock component at the selected fuel-air ratio was read from the engine control chart and plotted on the abscissa of the composition control chart. Similarly, the rotameter reading for the lower-grade component was read from the engine control chart and plotted on the ordinate of the composition control chart. The points on the ordinate and the abscissa were joined by a straight line. When it was desired to test a 40-percent blend, the two desired rotameter readings were read at the intersection of the straight line previously drawn and the radial line representing blends containing 40 percent of one component. Fuel flows were adjusted to give the desired rotameter readings and the inlet-air pressure was increased until the knock limit was reached. The fuel-air ratio was then determined from the total fuel flow with the aid of the engine control chart. In the case of fuel blends that followed the reciprocal blending relation, the observed fuel-air ratio equaled the desired fuel-air ratio.

For blends that did not follow the reciprocal blending relation, the fuel flows were adjusted by trial and error until the correct fuel-air ratio at the knock limit was observed.

For aromatic fuels this procedure was modified because the knock limits of the pure aromatics were too high to be determined within the limitations of the equipment.

The cooling-air flow in all tests was so adjusted that the temperature of the rear spark-plug boss was maintained at a constant value of 400° F.

Generally, the mixture-response knock curves for any pair of fuel components and for various blends of these components were obtained during the same day. This procedure was followed to eliminate the effect of any day-to-day changes in engine operating conditions.

PRECISION OF DATA

The greatest single source of error is in the measurements of fuel flow. Inasmuch as two separate systems were used, the accidental errors in readings would be expected to be larger than the errors encountered with one fuel system. When the two components were blended, the rotameter readings were smaller than the readings ordinarily encountered, especially when only a small amount of one component was entering into the blend.

Another source of error peculiar to these tests is the difficulty of determining from the oscilloscope trace whether the knocking is of the same intensity when operating over a range of widely varying power levels. The power-level range covered in a series of blending tests on two components may be much greater than that encountered in the ordinary mixture-response knock test.

When a datum point did not fall near the desired fuel-air ratio, it was necessary to fair a curve through it to the desired fuel-air ratio. In some cases where there was a considerable increase in power in going from the lower-grade component to the higher and where the two mixture-response curves were not of the same shape, the fairing of these interpolated-curve segments introduced an appreciable error.

RESULTS

The results of the tests are shown in figures 4 to 16. Part (a) of each figure gives the knock-limited indicated mean effective pressure and the indicated specific fuel consumption for the fuel components and the blends plotted against the fuel-air ratio. Part (b) of each figure is a cross plot of the percentage by weight of the higher-grade component in the blend, against the knock-limited indicated mean effective pressure for the data presented in part (a) at a fuel-air ratio of 0.10 and a fuel-air ratio of 0.07 or 0.075. The vertical scale is an inverted reciprocal scale. When plotted in this manner, the data should fall on a straight line if the results are represented by equation (1). The values in part (b) of each figure are not actual test points but are picked from the intersection of the mixture-response-curve segments and the desired fuel-air-ratio line.

<u>Blending characteristics of two gasolines.</u> - Figure 4 shows the data obtained by blending a 130-grade fuel with a 62-octane fuel to which had been added tetraethyl lead in the same concentration as that in the 130-grade fuel. The data for both fuel-air ratios lie on straight lines in figure 4(b), which shows that blending equation (1) is applicable to blends of those fuels under the test conditions.

<u>Blending characteristics of paraffinic fuels.</u> - The results of tests in which S-3 reference fuel plus 6.0 ml tetraethyl lead was blended with 50 percent M-4 reference fuel plus 50 percent S-3 reference fuel plus 6.0 ml tetraethyl lead are shown in figure 5. At a fuel-air ratio of 0.10, a straight line represents the results. At a fuel-air ratio of 0.075, there is a consistent deviation of the test data from the straight-line relationship predicted by equation (1).

Figure 6 shows the test results of blends of aviation alkylate and 62-octane fuel, both highly paraffinic fuels. Figures 7 and 8 present the test results of blends of the same two fuels, each plus 3.0 and 6.0 ml tetraethyl lead, respectively. In all three cases, equation (1) applies to tests at a fuel-air ratio of 0.10. Deviations from the values predicted by the equation occur at a fuel-air ratio of 0.075.

Blending characteristics of an olefinic fuel. - The results of tests with blends of diisobutylene and 62-octane fuel are presented in figure 9. The fuels were blended only at a fuel-air ratio of approximately 0.10 because the mixture-response curves showed that there was little difference in the knock-limited power levels of the two fuels when tested under lean-mixture conditions. From figure 9(b) it is apparent that the test data deviate considerably from the values predicted by the reciprocal relationship.

Blending characteristics of a naphthenic fuel. - Figure 10 gives the results of blending tests using cyclopentane and 62-octane fuel. The mixture-response curve for cyclopentane is similar to that for diisobutylene in that the knock-limited performance with lean mixtures is little better than that for 62-octane fuel; consequently, blends were tested only at a fuel-air ratio of approximately 0.10. The blending characteristics of cyclopentane are similar to those of diisobutylene.

Blending characteristics of aromatic fuels. - Results of blending tests using toluene and 62-octane fuel are shown in figure 11. When toluene or other aromatic fuels were blended, it was impossible to obtain knock-limited performance data for aromatic concentrations higher than about 80 percent because of the occurrence of preignition before knock. The data for neither of the fuel-air ratios tested check the reciprocal blending relation (equation (1)). The curvature of the lines in figure 11(b) is opposite to that for the curves in figures 9(b) and 10(b).

Figures 12 and 13 show the blending characteristics of benzene when blended with 62-octane fuel and when blended with aviation alkylate, respectively. The data for both series of tests are similar to those obtained by blending toluene and 62-octane fuel (fig. 11).

Figure 14 gives the results of blending a mixture of 66 percent benzene in 34 percent aviation alkylate with a mixture of 66 percent benzene and 34 percent 62-octane fuel. The dashed line in figure 14(b) will be referred to later.

Blending characteristics when xylidines are present in the fuel components. - Figure 15 presents the results of blending aviation alkylate plus 4.5 ml tetraethyl lead per gallon with 62-octane fuel plus 4.5 ml tetraethyl lead without xylidines and figure 16 presents results with 3 percent xylidines added to each of the same two fuels. The results are similar to those previously presented for blends of aviation alkylate plus tetraethyl lead and 62-octane fuel plus tetraethyl lead. The knock-limited indicated mean effective pressure observed agreed within 5 pounds per square inch with the values given by blending equation (1).

Blending characteristics of fuel components containing unequal concentrations of tetraethyl lead. - In order to illustrate the blending characteristics of fuel components with unequal tetraethyl-lead concentrations, 130-grade fuel was blended with 62-octane fuel containing no tetraethyl lead (fig. 17). As was expected, there is a large variation from the reciprocal blending relation.

Figure 18 shows the data obtained by blending S-3 reference fuel plus 6.0 ml tetraethyl lead per gallon and blending S-3 reference fuel plus 2.0 ml tetraethyl lead per gallon with S-3 reference fuel. These blends were tested in order to determine any irregularities in the lead-susceptibility curve for S-3 reference fuel. The results plotted in figure 18(b) show that a distinct irregularity in the susceptibility curve exists in the region from 0.8 to 1.4 ml tetraethyl lead per gallon.

DISCUSSION OF RESULTS

Applicability of reciprocal blending relationship. - All tests with paraffinic fuels and 130-grade aviation fuel showed that the reciprocal blending relationship, as expressed by equation (1), was applicable at a fuel-air ratio of 0.10 under the conditions tested. Only a few of the tests at fuel-air ratios of 0.07 and 0.075 agreed with equation (1), although unpublished results of tests conducted on a standard F-4 liquid-cooled engine at this laboratory have shown that the reciprocal blending relationship is applicable to paraffinic fuels at lean mixtures in this engine. The difference between the test results with an air-cooled cylinder and with a liquid-cooled cylinder may be caused by the differences in the temperature-distribution patterns in the cylinders.

The reciprocal blending relationship was applicable to blends containing benzene when the blends were tested at a fuel-air ratio of 0.10 and when the concentration of the benzene was the same for all blends tested, as is illustrated in figure 14. Similarly, figure 16 shows that the reciprocal blending relationship was applicable to blends containing xylidines when the concentration of xylidines was the same for all blends.

The blends mentioned in the preceding paragraphs with the addition of tetraethyl lead follow equation (1) provided that the concentration of tetraethyl lead is the same for all blends. A tentative conclusion is drawn as follows: If the reciprocal blending relationship applies to the knock limits of blends of two fuels, the addition of a third fuel or additive in equal concentrations in the fuels will not affect the nature of the blending relationship, even though the third component has a quantitative effect upon the knock limits of the blends.

Temperature effects in fuel blending. - The blending equation applicable to supercharged-engine knock tests was derived using the assumption that the cyclic and the end-gas temperatures remain constant for all blends tested. If this assumption were not applicable, but instead the temperatures varied for different blends, equation (1) would not hold; that is, a straight line would not be obtained when the indicated mean effective pressures for different blends are plotted against the percentage composition on reciprocal graph paper. Any heat transfer to or from the charge before the completion of combustion will affect the end-gas temperature. If the heat transfer varies for different blends (that is, for different power levels), the results would not be expected to check with equation (1).

Another assumption made in the derivation of the blending equation was that all blends are tested at stoichiometric fuel-air ratio or with a constant percentage of excess fuel or air. Knock data for blends of two fuels such as isooctane and benzene when tested at constant fuel-air ratio would not be expected to follow the reciprocal blending relation because the stoichiometric fuel-air ratio for isooctane is 0.0655 as compared with 0.0744 for benzene.

In the absence of any method of determining the end-gas temperature and controlling it within definite limits, it was decided in the present tests to control the inlet-mixture temperature and the cylinder-head temperature by so adjusting the cooling-air flow that the temperature of some reference point on the cylinder would remain constant. The thermocouple installed in the rear spark-plug boss was selected as the temperature-reference point. The data obtained in this manner might be expected to follow the blending equation (1) closely if the reference temperature were closely related to the end-gas temperature. If the reference point were not a good indication of the effect of cylinder-wall temperature upon temperature conditions within the cylinder, the data would not be expected to follow the blending relation. If another point were selected, however, to be used as a constant-temperature reference in controlling the cooling-air flow, it would perhaps be possible to change the test conditions in such a manner that all data would be taken under the same temperature conditions within the cylinder and consequently permit a check on the blending equation and the assumptions on which it is based.

Another fact which indicates that temperature variation may have caused deviations from the reciprocal blending relation is the failure of blends of benzene, diisobutylene, and cyclopentane (which are temperature-sensitive fuels) to follow the reciprocal blending relation. It is noted, however, that the blends of benzene depart from the reciprocal blending relation in the opposite direction from the departures observed for blends containing diisobutylene or cyclopentane. These opposite effects are not readily explainable on the basis of temperature sensitivity and it is probable that other considerations such as differences in stoichiometric fuel-air ratios enter into the blending relationship.

Lead susceptibility of S-3 reference fuel. - It was mentioned earlier in the report that irregularities occur in the lead-susceptibility curve of S reference fuel. These irregularities are not a desirable feature in reference-fuel systems because they necessitate testing a large number of tetraethyl-lead concentrations in order to rate accurately fuels lying in this range. It is also questionable whether this characteristic would be found under all test conditions and, if it should, whether the irregularity would always appear at the same tetraethyl-lead concentration and would be of the same magnitude.

The discontinuity between the present rating scales for fuels below 100-octane rating and for those above 100-octane rating is another undesirable feature of the present fuel-rating framework.

A method of fuel rating which would eliminate these two objections to the present reference-fuel systems and which has been proposed by other research workers would be to use S reference fuel plus 6.0 ml tetraethyl lead per gallon and M reference fuel plus 6.0 ml tetraethyl lead per gallon; the ratings would be given in percentage S plus 6.0 ml tetraethyl lead per gallon in M plus 6.0 ml tetraethyl lead per gallon. With these two reference fuels, there would be no discontinuity or irregularity in fuel-rating systems in the region of greatest present interest. Figure 19 is a graph for the conversion of ratings given as tetraethyl lead in S-3 reference fuel to ratings given as percentage S-3 plus 6.0 ml tetraethyl lead in M-4 plus 6.0 ml tetraethyl lead as determined in the present tests. Reference fuels containing as much as 6.0 ml tetraethyl lead per gallon have not proved to be entirely satisfactory from the consideration of reproducibility of calibration.

The Coordinating Research Council is considering and the British Air Ministry has suggested the use of leaded S and M reference fuels containing toluene in order to give reference-fuel characteristics more nearly similar to commonly used aviation fuels.

Effectiveness of xylidines. - The effectiveness of xylidines in blends of paraffinic fuels can be found by comparing figures 15(b) and 16(b). The lines in figures 15(b) and 16(b) representing the knock-limits of the blends at 0.10 fuel-air ratio have been redrawn in figure 20. The fact that extensions of both lines intersect the infinite knock-limit line at the same point shows that the percentage increase in power resulting from the addition of xylidines was the same for all blends regardless of their knock limits.

BLENDING RELATIONS APPLICABLE TO BENZENE BLENDS

Extension of blending formula. - A previous section of this report stated that variation of end-gas temperature resulting from variation of cylinder-wall temperatures with the knock limit may account for some of the disagreements between the test data and equation (1). It was therefore decided to apply some modification of equation (6) in reference 1 to supercharged engine knock-test data. One modification of the equation is:

$$P_b = \frac{P_1N_1B_1 + P_2N_2B_2 + P_3N_3B_3 + \ldots}{N_1B_1 + N_2B_2 + N_3B_3 + \ldots} \tag{2}$$

where

B_1, B_2, B_3, . . . blending constants for components 1, 2, 3, . . . , respectively

The derivation given in reference 1 for equation (6) is not unique. Various forms can be derived; the choice of the form given was based upon convenience in application. Another form of equation (2) whose relation to equation (1) can be seen by inspection is

$$\frac{N_1\beta_1 + N_2\beta_2 + N_3\beta_3 + \ldots}{P_b} = \frac{N_1\beta_1}{P_1} + \frac{N_2\beta_2}{P_2} + \frac{N_3\beta_3}{P_3} + \ldots \tag{3}$$

where

β_1, β_2, β_3, . . . blending constants related to the constants B_1, B_2, B_3, . . . by the following equations:

$$\beta_1 = P_1B_1$$

$$\beta_2 = P_2B_2$$

$$\beta_3 = P_3B_3 \text{, etc.}$$

Applications of both equations will give identical results. Equation (2) reverts to equation (1) when $P_1B_1 = P_2B_2 = P_3B_3$ and equation (3) reverts to equation (1) when $\beta_1 = \beta_2 = \beta_3$. Equation (3) will be used in the succeeding analysis because the value of β is the same for all fuels whose blends follow the reciprocal relation.

It was stated in reference 1 that the blending constant β for any fuel component is a constant for that component regardless of what other fuels are in the blend. In the determination of the blending constants for a series of fuels, it is advantageous to let the constant for one of the fuels equal 1.00 and evaluate the constants for the other fuels relative to that for the base fuel. In the present analysis the value of β for S-3 reference fuel is chosen as 1.00.

In order to check equation (3), the data for the binary and the ternary blends of benzene, alkylate, and 62-octane fuel at a fuel-air ratio of 0.10 are considered. Figure 21 gives the knock limits of blends of benzene in 62-octane fuel, benzene in alkylate, and alkylate in 62-octane fuel. The data were replotted from figures 6, 12, and 13.

The first step in the analysis was to find the values of β and P for alkylate and 62-octane fuel. The assumption was made that blends of alkylate or 62-octane fuel with S-3 reference fuel follow the reciprocal relationship because these fuels are paraffinic. The value of β is therefore 1.00 for each of these fuels. The knock-limited indicated mean effective pressures of S-3, alkylate, and 62-octane fuel are 218, 209, and 104 (average of 100 and 108 found in figs. 6 and 12, respectively) pounds per square inch.

The second step was to plot the knock-limited data for blends of 62-octane fuel and benzene, as is shown in figure 21. A hyperbola was fitted to the data by using the knock limits for 62-octane fuel and two blends. Data, as picked from the hyperbola, were selected to be used in estimating the value of β for benzene, which will be explained in the third step. The knock limits of two pure components and one blend can usually be experimentally determined but no knock limit for pure benzene could be found.

The third step was to find the values of P and β for benzene by applying the data for 62-octane fuel and two blends to equation (3). The solution of equation (3) gave values of 7200 pounds per square inch for P and 0.33 for β. Actually a slight variation in the data used for calculating the value of P for benzene will markedly vary the value of P but, where P is used for calculating the knock limits of practicable blends of benzene, the errors in the results will be of the same magnitude as the error in the basic data.

It was then possible to predict the knock-limit curve for blends of benzene and aviation alkylate if equation (3) is valid. The values of P used for aviation alkylate and 62-octane fuel were 209 and 104 pounds per square inch, respectively. The values of P and β for benzene were 7200 and 0.33, respectively. The curve respresenting blends of benzene and aviation alkylate was plotted in figure 21 from equation (3) and test data were also plotted. The predicted curve agreed excellently with the observed data. It is concluded, therefore, that equation (3) applied to blends of benzene, aviation alkylate, and 62-octane fuel.

An analysis identical to the one described in the preceding paragraphs was applied without success to knock-test data at a fuel-air ratio of 0.075 for blends of benzene, aviation alkylate, and 62-octane fuel. Reasons for failure of the blending equation are not known at the present.

The values of β as determined in this investigation apply only to the engine and the test conditions employed in the investigation. It would be unsafe to draw conclusions regarding the generality of equation (3) based upon results of tests with one trio of fuels.

Representation of three-component blends with trilinear graph. - The knock-limited indicated mean effective pressure of three-component blends for which the binary blends are shown in figure 21 can be represented by a trilinear graph, as illustrated in figure 22. All points with the same indicated mean effective pressure lie on a straight line and all lines of constant indicated mean effective pressure pass through a common pole. The validity of the preceding statement will be checked by analogy between figures 22 and 23.

Figure 23 is a modification of figure 1 of reference 1. The abscissa is the blending constant. Lines of constant knock-limited indicated mean effective pressure pass through the origin and the slopes of the lines are inversely proportional to the indicated mean effective pressures. The points representing S-3 reference fuel, aviation alkylate, 62-octane fuel, and benzene have been plotted. Points representing any blend of two of the components lie on a straight line joining the points representing the components, and the blends divide the line in proportion to the composition of the blends. A composition triangle for benzene, aviation alkylate, and 62-octane fuel is shown in the figure.

The pole of the indicated mean effective pressure lines in figure 22 corresponds to the origin of figure 23 and the equilateral triangle in figure 22 corresponds to the composition triangle in figure 23. Figure 22 is, in fact, simply a distortion of figure 23.

An experimental check of figure 22 can be made with the data given in figure 14(b). The dashed line in figure 14(b) represents the knock limits predicted from figure 22 for blends of alkylate and 62-octane fuel, each containing 66 percent benzene. The experimental data agree with the predicted values within an indicated mean effective pressure of 4 pounds per square inch.

For blends of three fuels where the reciprocal relation applies for all blends, the lines of constant indicated mean effective pressure, in a figure similar to figure 22, will be parallel.

APPLICATION OF RESULTS TO FUEL RATINGS

It is usually desired to deal with the knock ratings of fuels expressed in terms of equivalent reference-fuel blends rather than direct application of knock-limited indicated mean effective pressures. If equation (1) applies to the knock limits of the reference-fuel blends, the following modifications of equations (1) and (3), respectively, may be used:

$$S_b = S_1N_1 + S_2N_2 + S_3N_3 + \ldots \qquad (4)$$

or

$$S_b = \frac{S_1N_1\beta_1 + S_2N_2\beta_2 + S_3N_3\beta_3 + \ldots}{N_1\beta_1 + N_2\beta_2 + N_3\beta_3 + \ldots} \qquad (5)$$

where

S_b knock rating of blend expressed as percentage of high antiknock fuel in corresponding reference-fuel blend

$S_1, S_2, S_3, \ldots$ knock ratings of components 1, 2, 3, . . . , respectively, expressed as percentage of high antiknock fuel in corresponding reference-fuel blend

In blends to which equation (4) applies, the ratings are a linear function of blend composition. For blends to which equation (5) applies, the relation is hyperbolic.

All the analysis given in the preceding section of this report can be repeated in terms of fuel ratings (using equations (4) and (5)) instead of knock-limited indicated mean effective pressures. As an illustration, all data from figures 21 and 22 have been replotted in figures 24 and 25 in terms of percentage of S-3 plus 6.0 ml tetraethyl lead in corresponding blends of S-3 plus 6.0 ml tetraethyl lead per gallon and M-4 plus 6.0 ml tetraethyl lead per gallon. The figures, as shown, have ordinates in excess of 100 percent of S-3 plus 6 ml tetraethyl lead. This concept is used as a convenience in estimating the knock ratings.

Figure 24 permits evaluation of the concept of "blending octane numbers." The blending octane number is usually found by obtaining a knock rating on a blend consisting of 20 percent of the fuel in question and 80 percent of a selected base fuel whose rating is known. A linear extrapolation to 100 percent of the test fuel gives the blending octane number of the fuel. The blending octane number is sometimes used for estimating the ratings of blends containing 20 percent of the test fuel in another base fuel whose rating is known. A check on this method will be made by applying the data for blends of benzene with 62-octane fuel and aviation alkylate (fig. 24).

The rating of pure benzene found by linear extrapolation from the ratings of 62-octane fuel and a blend of 20 percent benzene in 62-octane fuel is 62.0 percent of S plus 6 ml tetraethyl lead in M plus 6 ml tetraethyl lead. The rating of pure aviation alkylate is 76.5 and the estimated rating of 20 percent of benzene in aviation alkylate by linear interpolation between 76.5 and 62.0 is 73.5. The method predicts a rating of 73.5 when 20 percent of benzene is added to aviation alkylate as compared with an observed increase to 81.0. It is therefore concluded that the use of blending octane numbers to estimate the ratings of fuel blends is not generally applicable.

SUMMARY OF RESULTS

In a series of tests conducted to investigate the relation between the knock limit and the blend composition of aviation fuels when tested under supercharged conditions in an air-cooled aircraft-engine cylinder, the following results were obtained:

The reciprocal of the knock-limited indicated mean effective pressure of the binary fuel blends was a linear function of blend composition for paraffinic fuels when tested at a fuel-air ratio of 0.10. This result was also true for blends of paraffinic fuels containing benzene, tetraethyl lead, or xylidines for a constant concentration of one or more of these two materials in the blends. Data taken at fuel-air ratios of 0.07 or 0.075 did not correlate well with the derived reciprocal relation except in three cases. Binary blends of diisobutylene, cyclopentane, toluene, or benzene with paraffinic fuels did not follow the reciprocal relation at either rich or lean mixtures.

Test data for trinary blends of benzene, aviation alkylate, and 62-octane fuel at a fuel-air ratio of 0.10 agreed well with an extended equation relating the knock limit of fuel blends to the blend composition.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

APPENDIX

ENGINE CONTROL CHART

An engine control chart, similar to the one shown in figure 2, was used during the determination of the mixture-response curves for each pair of fuel components and while obtaining data for blends of the two components.

The abscissas of the engine control chart are values of the fuel flow in pounds per hour. These values were obtained from the rotameter readings and the rotameter calibrations determined by direct weighing. For blended fuels the fuel flow is the sum of the flows in the two systems supplying the two fuel components.

The ordinate $\sqrt{p_1 \Delta p}$, where p_1 is the upstream pressure at the inlet-air orifice in inches of mercury absolute and Δp is the orifice differential pressure in inches of water, is proportional to the air flow at a constant orifice-air temperature. The orifice-air temperature is sufficiently near a constant value that no perceptible error is introduced when the data points are plotted in this manner on the control chart. For the 1.5-inch orifice used in this test setup, the compressibility factor and the coefficient of discharge were constant within 0.5 percent over the range of Reynolds numbers and orifice differential pressures for the air flow supplied to the Pratt & Whitney R-2800 cylinder during operation. Therefore,

$$Q = K \sqrt{\frac{p_1 \Delta p}{T}}$$

where

Q air flow, lb/hr

T orifice-air temperature, °F absolute

K constant

or

$$Q = K_1 \sqrt{p_1 \Delta p}$$

for a constant orifice-air temperature. For the Pratt & Whitney R-2800 single-cylinder setup

$$Q = 24.21 \sqrt{p_1 \Delta p}$$

when

$$T = 80^{\circ} \text{ F}$$

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1. Sanders, Newell D.: A Method of Estimating the Knock Rating of Hydrocarbon Fuel Blends. NACA ARR No. 3H21, 1943.

2. Heron, S. D., and Beatty, Harold A.: Aircraft Fuels. Jour. Aero. Sci., vol. 5, no. 12, Oct. 1938, pp. 463-479.

3. Anon.: Methods for Estimating Properties of Aviation Gasoline Blends. Subcommittee on Blending Octane Numbers, Aviation Gasoline Advisory Committee, Rep. No. 3 for PAW, Aug. 2, 1943.

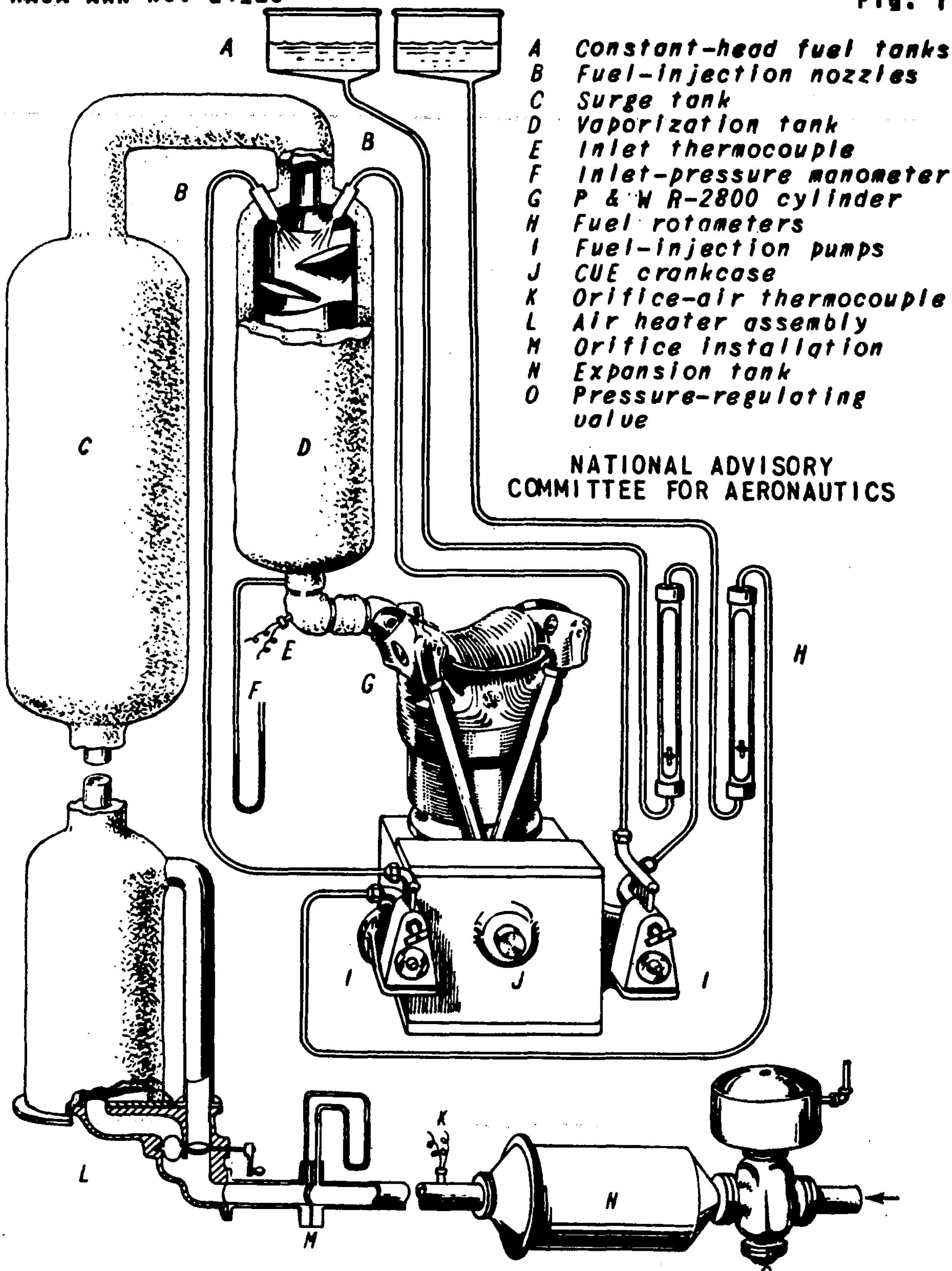


Figure 1. - Combustion-air and fuel systems.

NACA ARR No. E4I28

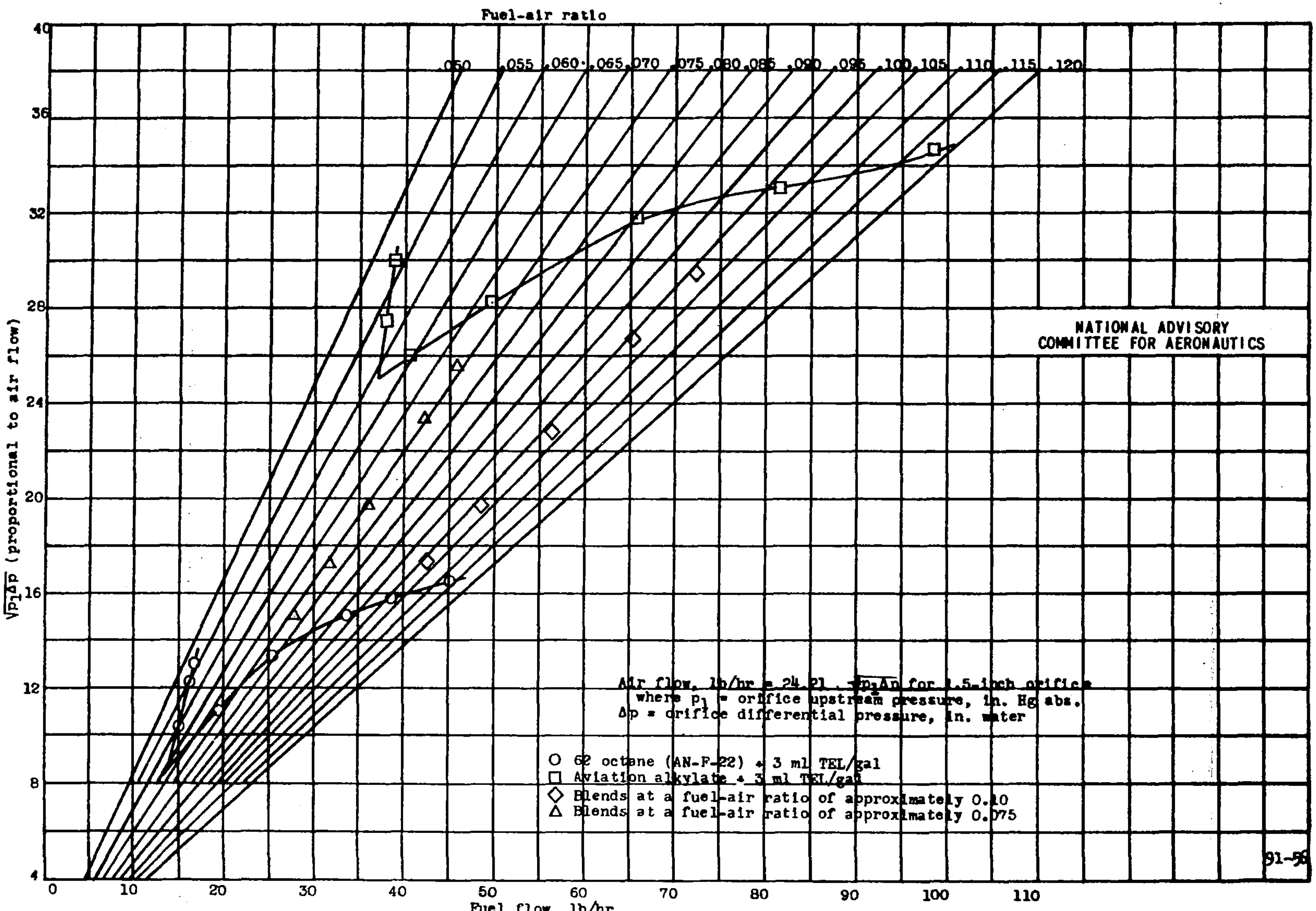


Figure 2. - Engine control chart.

Fig. 2

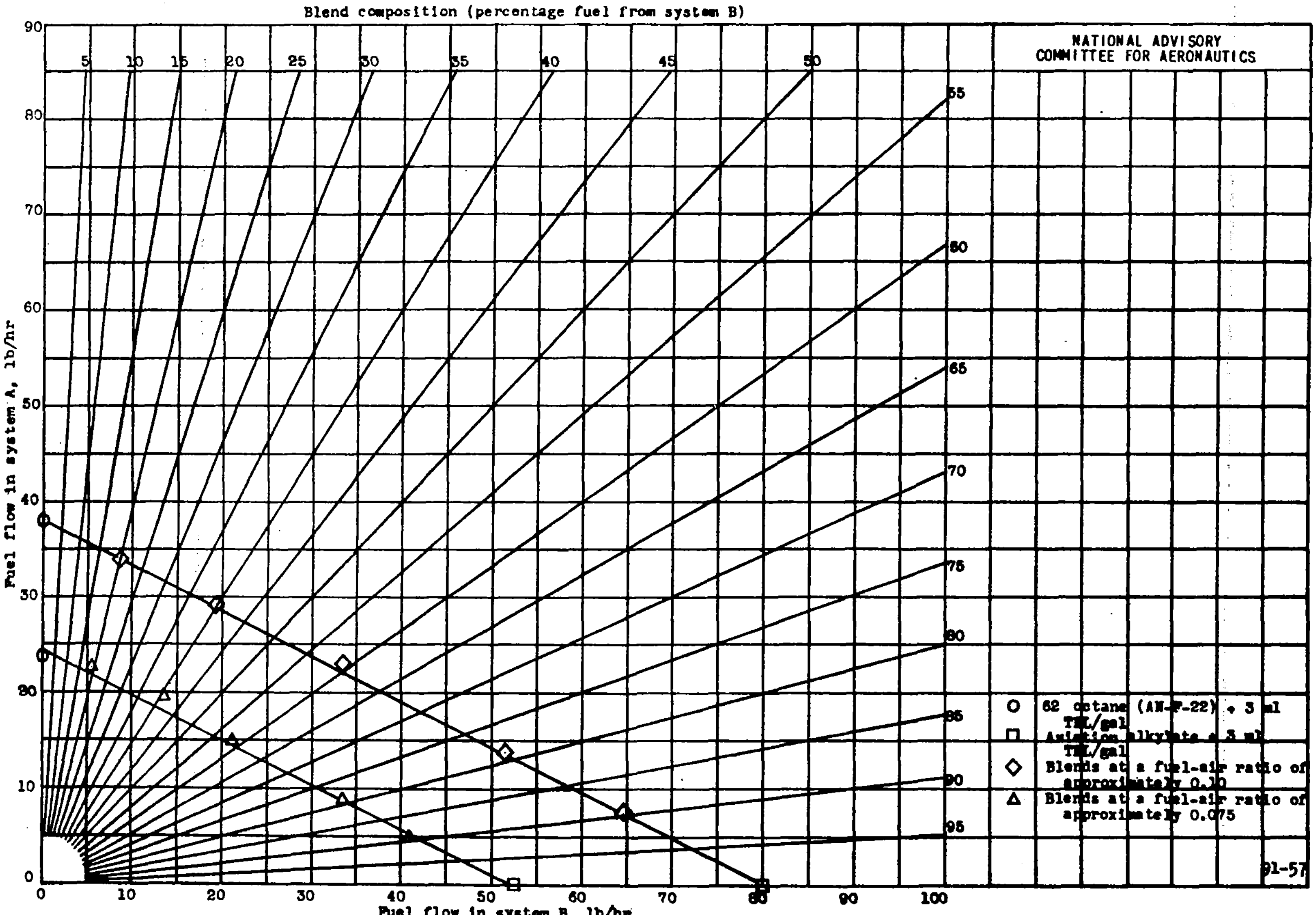
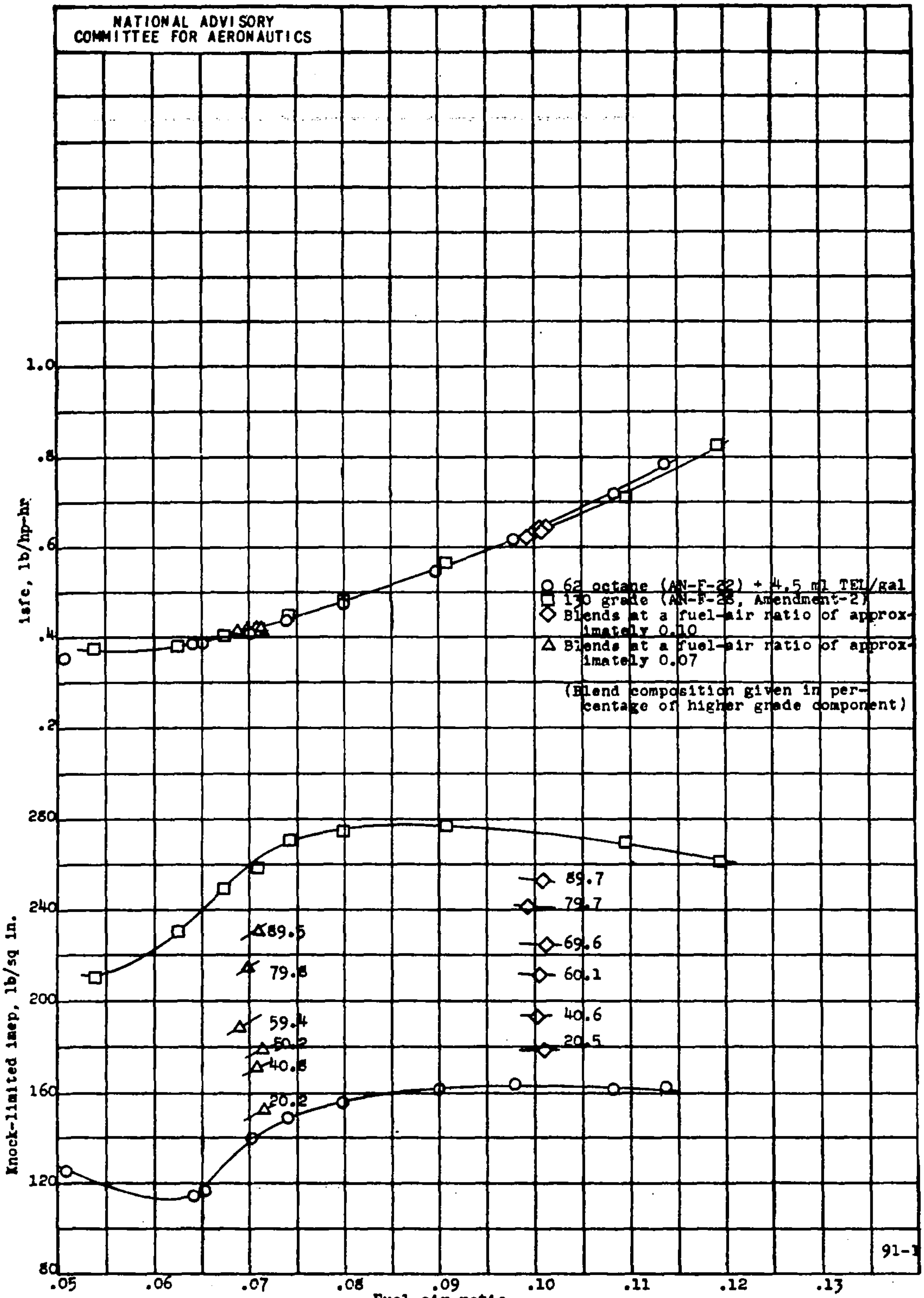
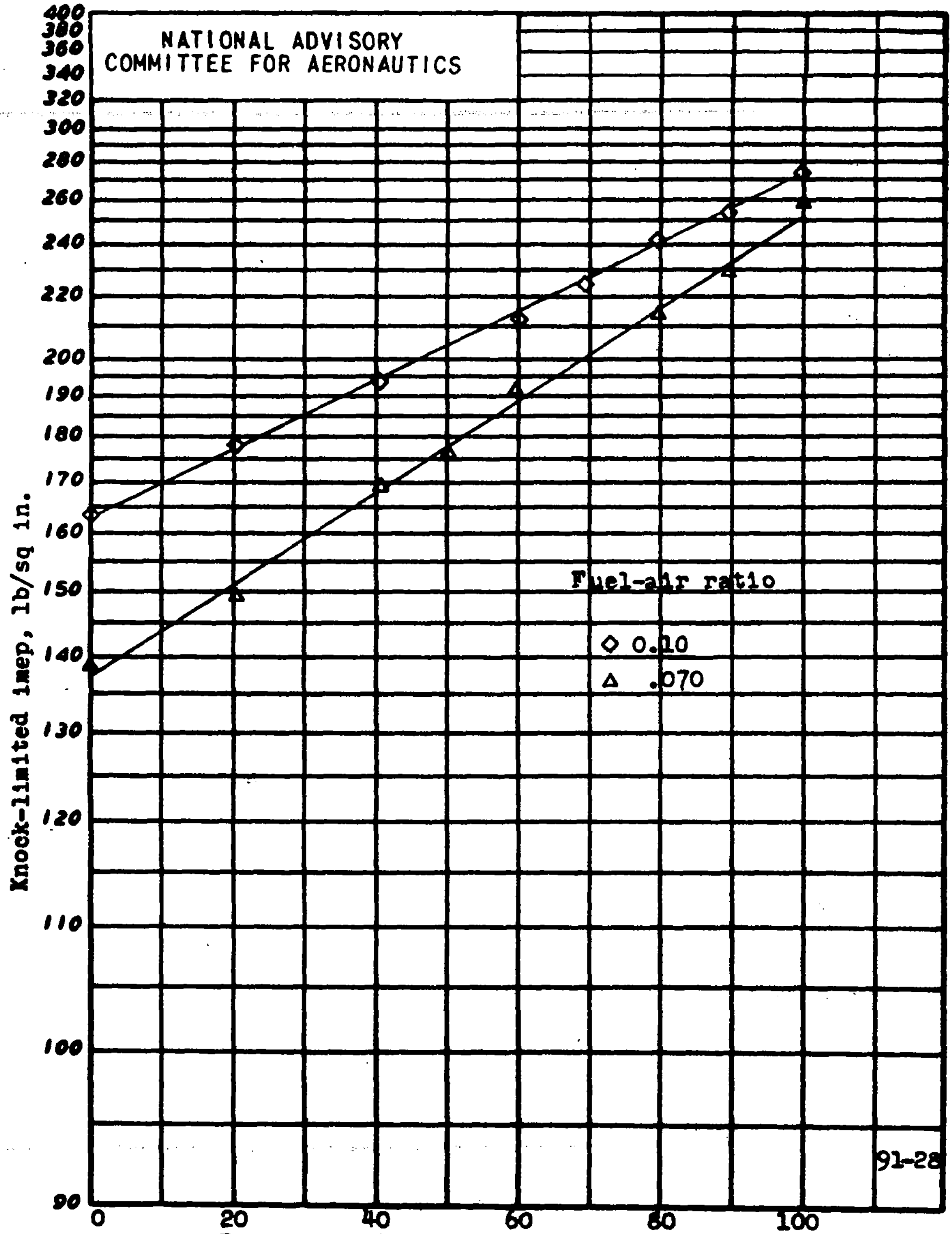


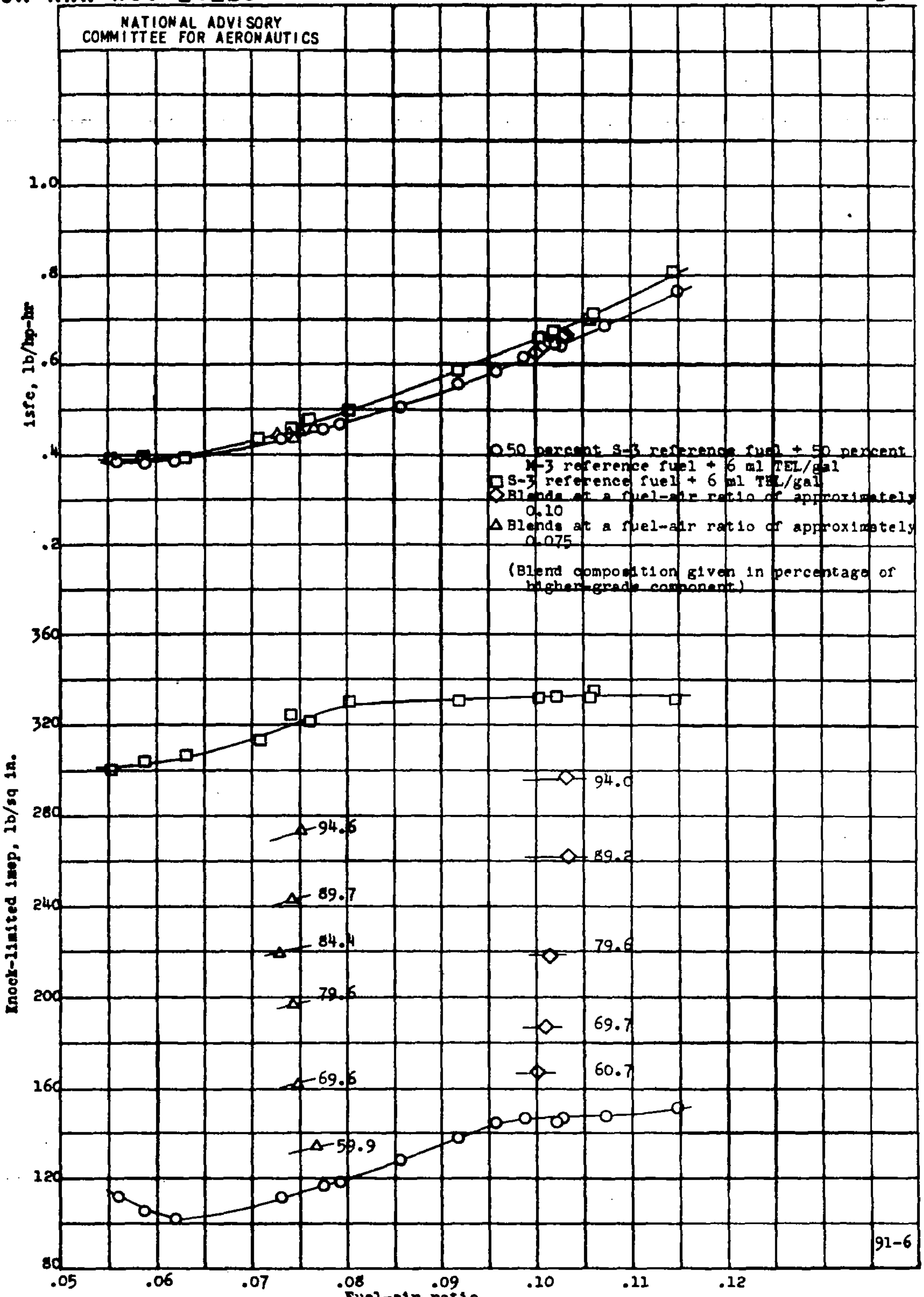
Figure 3. - Fuel-composition control chart.



(a) Mixture-response curves.
Figure 4. - The knock-limited performance of blends of 130-grade fuel and 62-octane fuel plus 4.5 ml tetraethyl lead per gallon. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

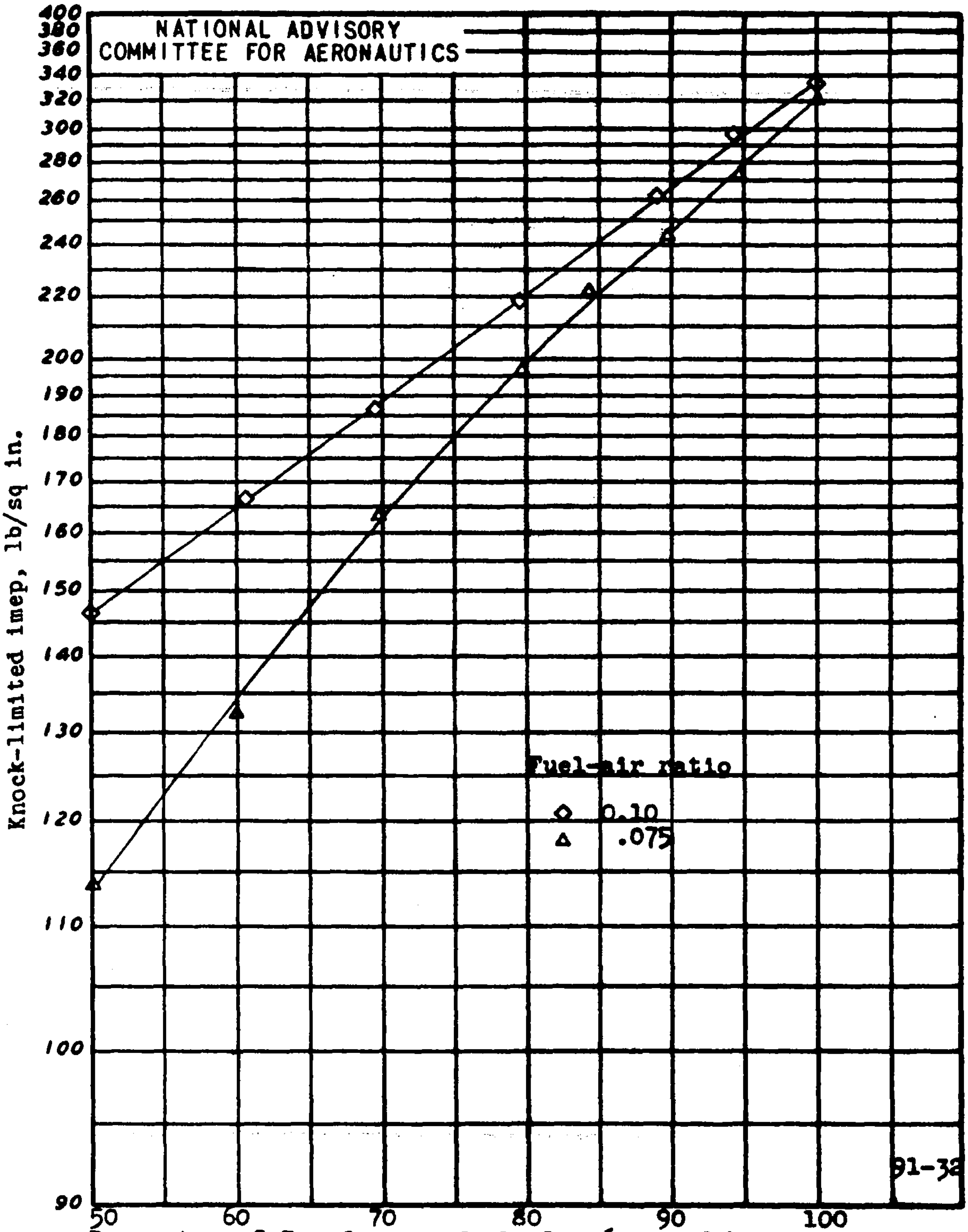


(b) Relationship of knock limit to fuel composition.
Figure 4. - Concluded.

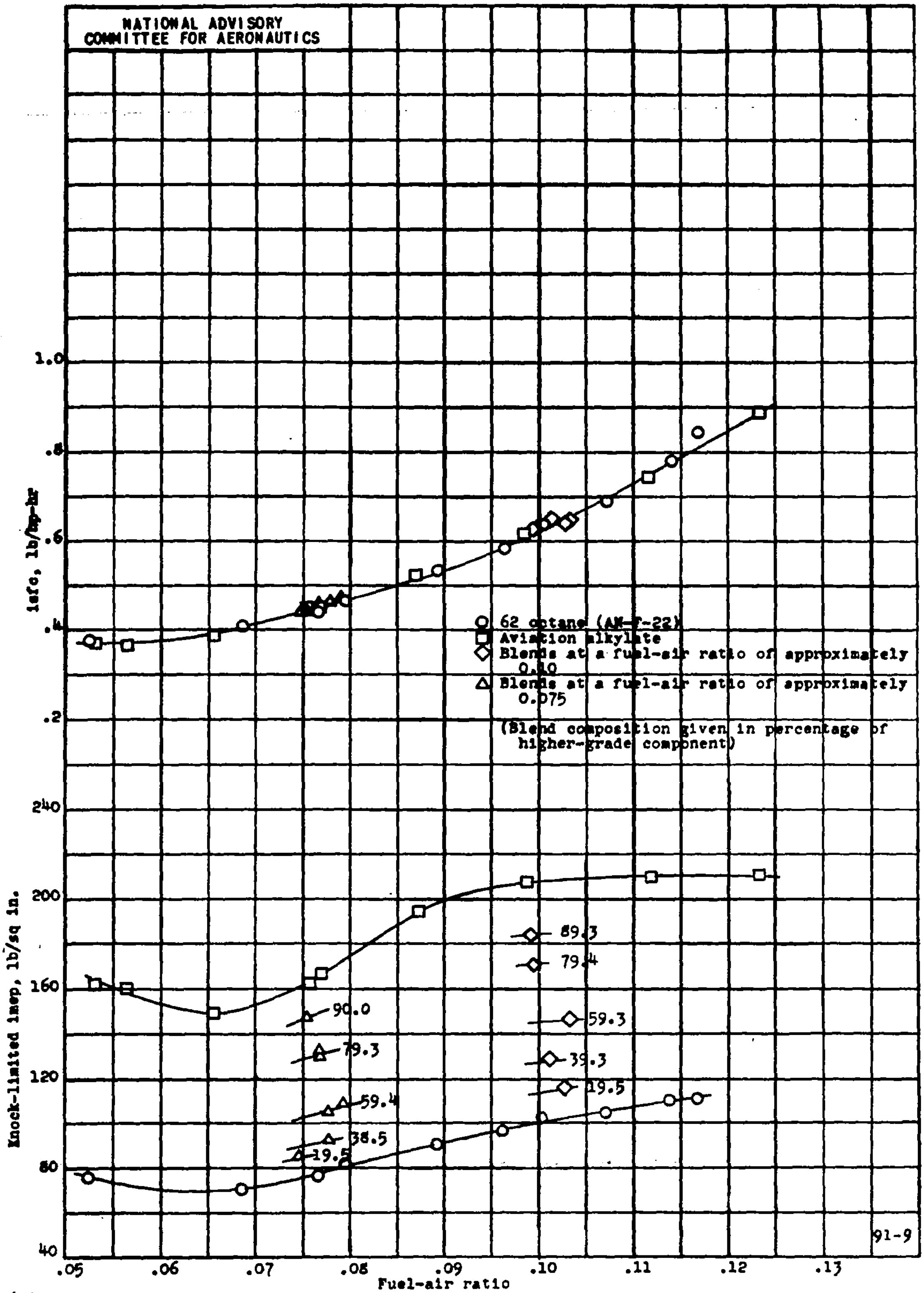


(a) Mixture-response curves.

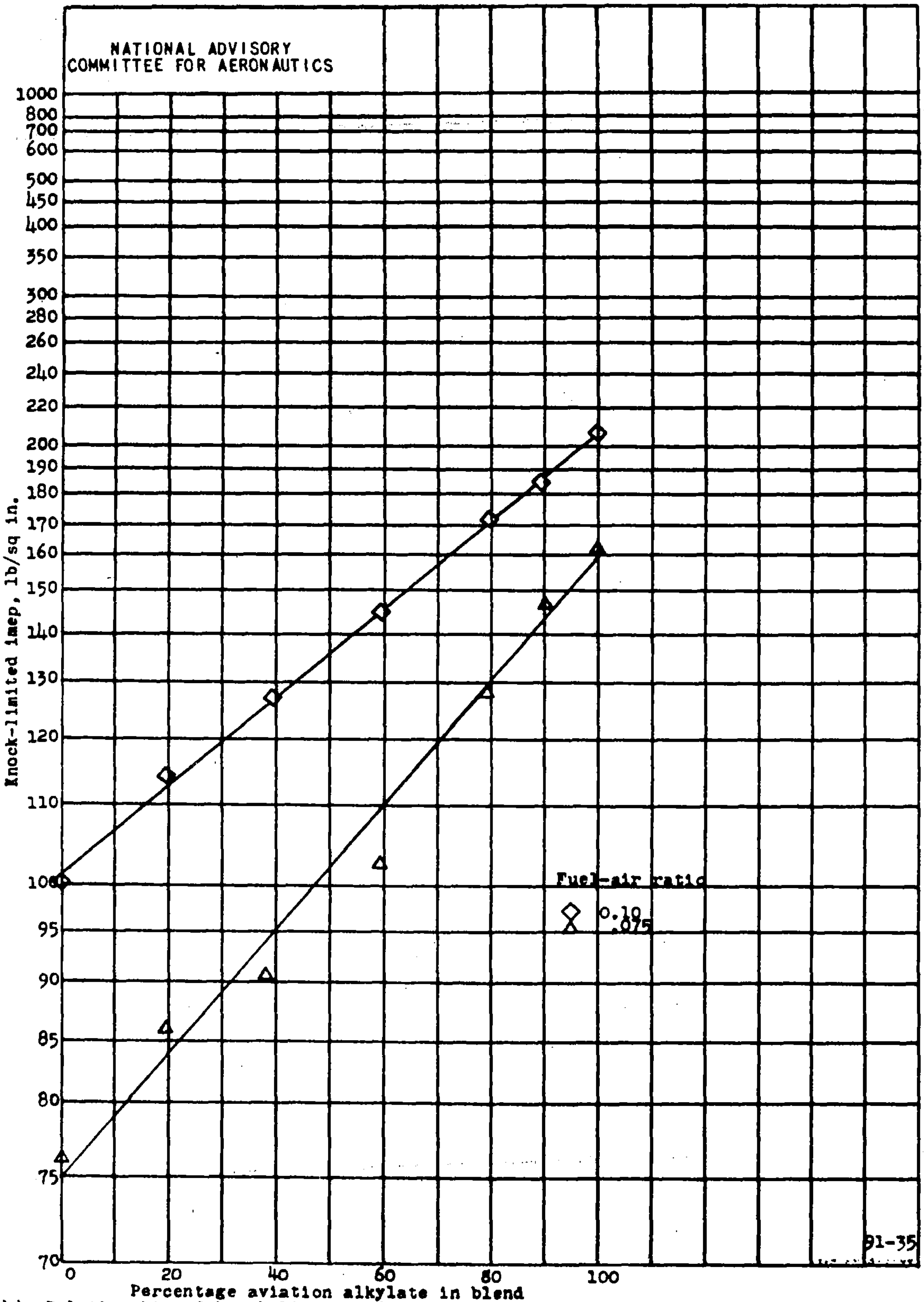
Figure 5. - The knock-limited performance of blends of S-3 reference fuel plus 6 ml tetraethyl lead per gallon and M-4 reference fuel plus 6 ml tetraethyl lead per gallon. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.



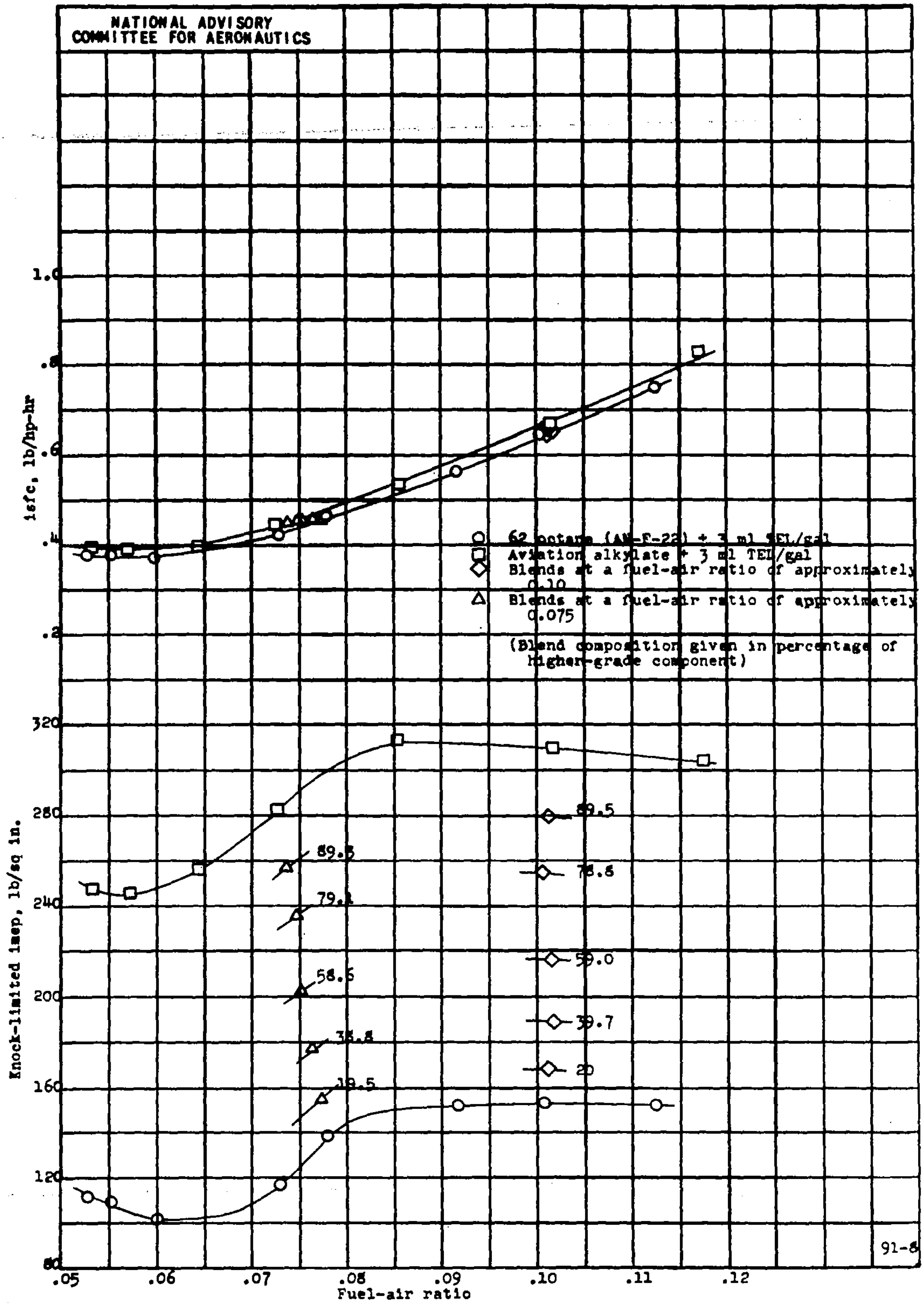
(b) Relationship of knock limit to fuel composition.
Figure 5. - Concluded.



(a) Mixture-response curves.
Figure 6. - The knock-limited performance of blends of aviation alkylate and 62-octane fuel. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

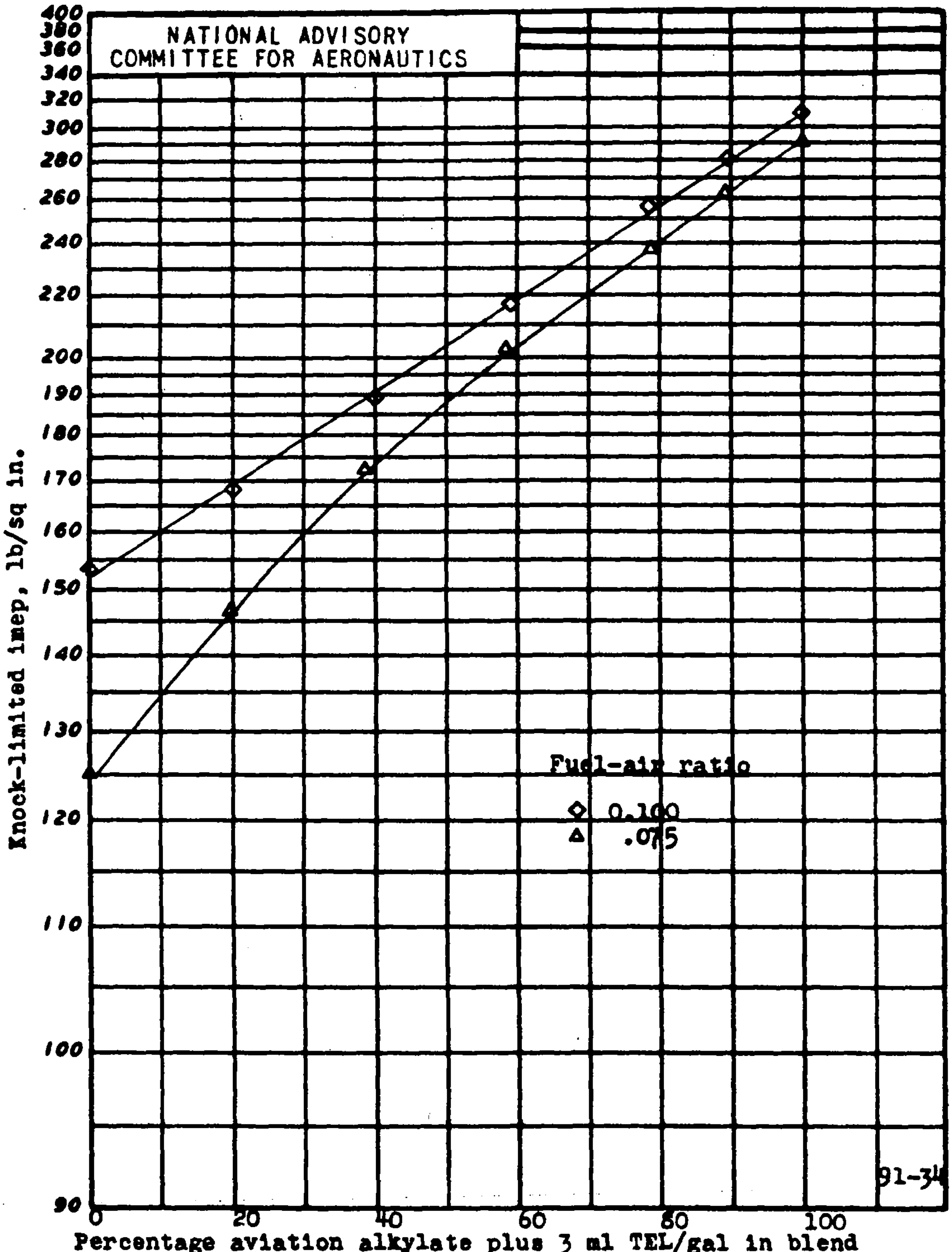


(b) Relationship of knock limit to fuel composition.
Figure 6. - Concluded.



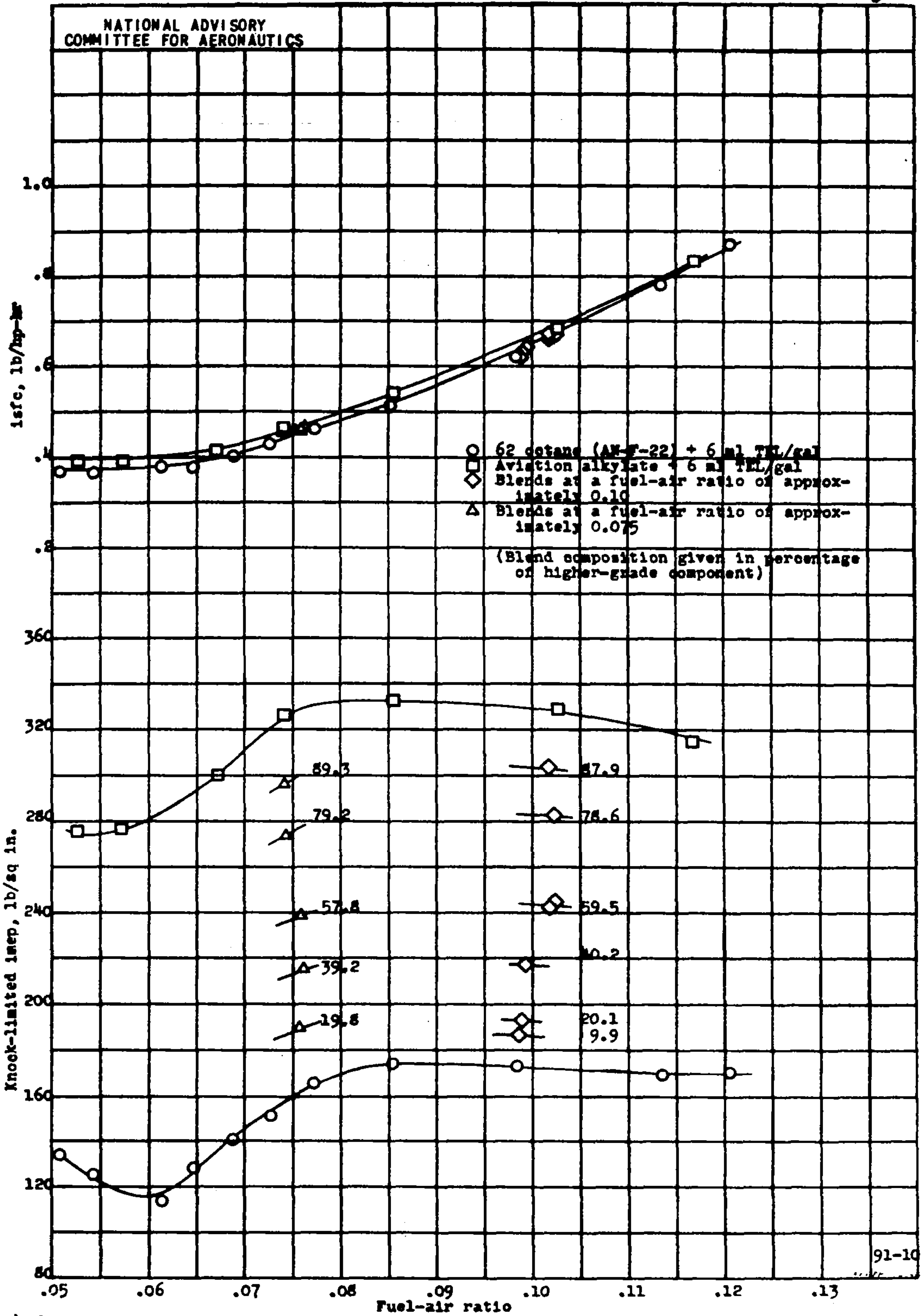
(a) Mixture-response curves.

Figure 7. - The knock-limited performance of blends of aviation alkylate plus 3 ml tetraethyl lead per gallon and 62-octane fuel plus 3 ml tetraethyl lead per gallon. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.



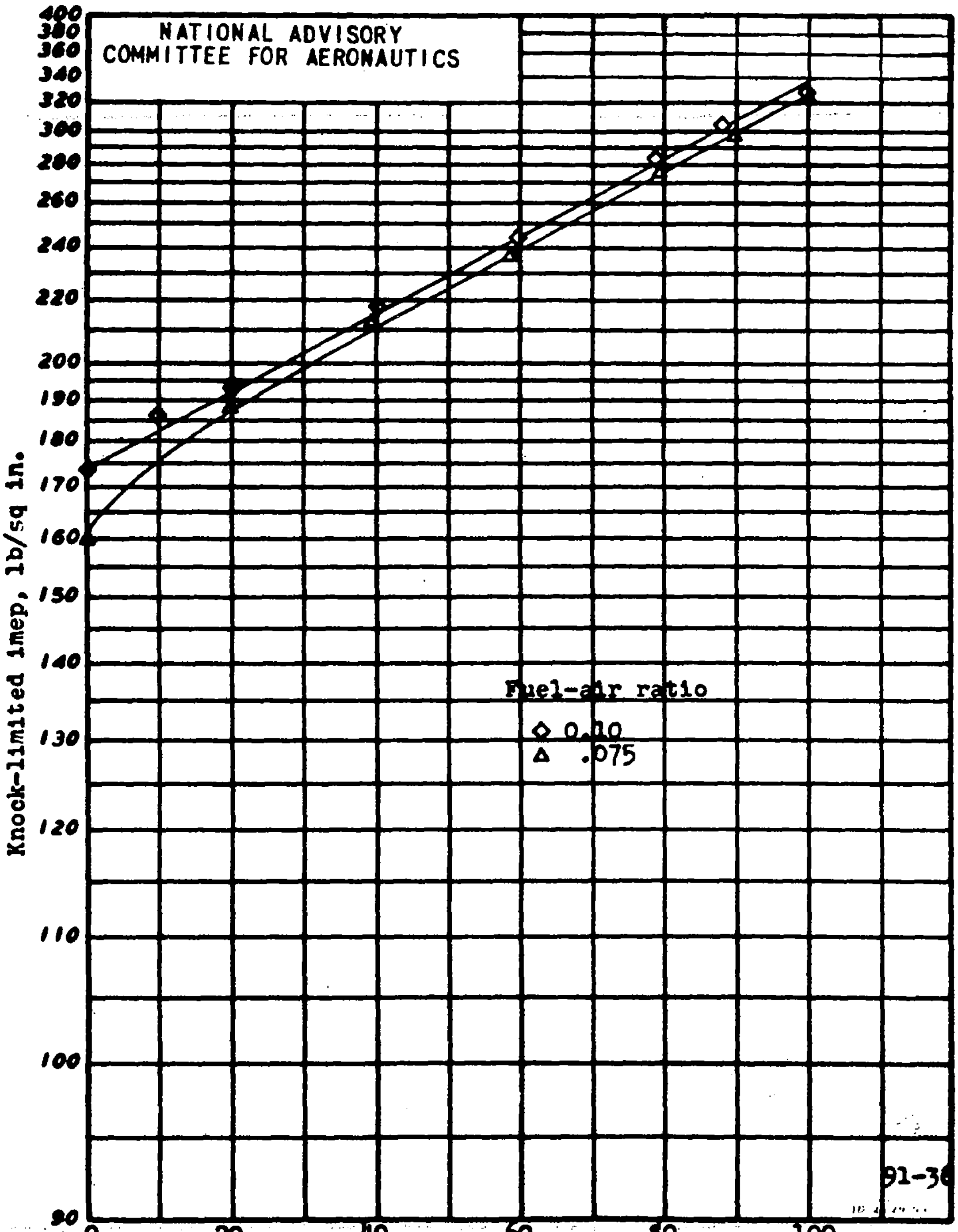
(b) Relationship of knock limit to fuel composition.

Figure 7. - Concluded.



(a) Mixture-response curves.

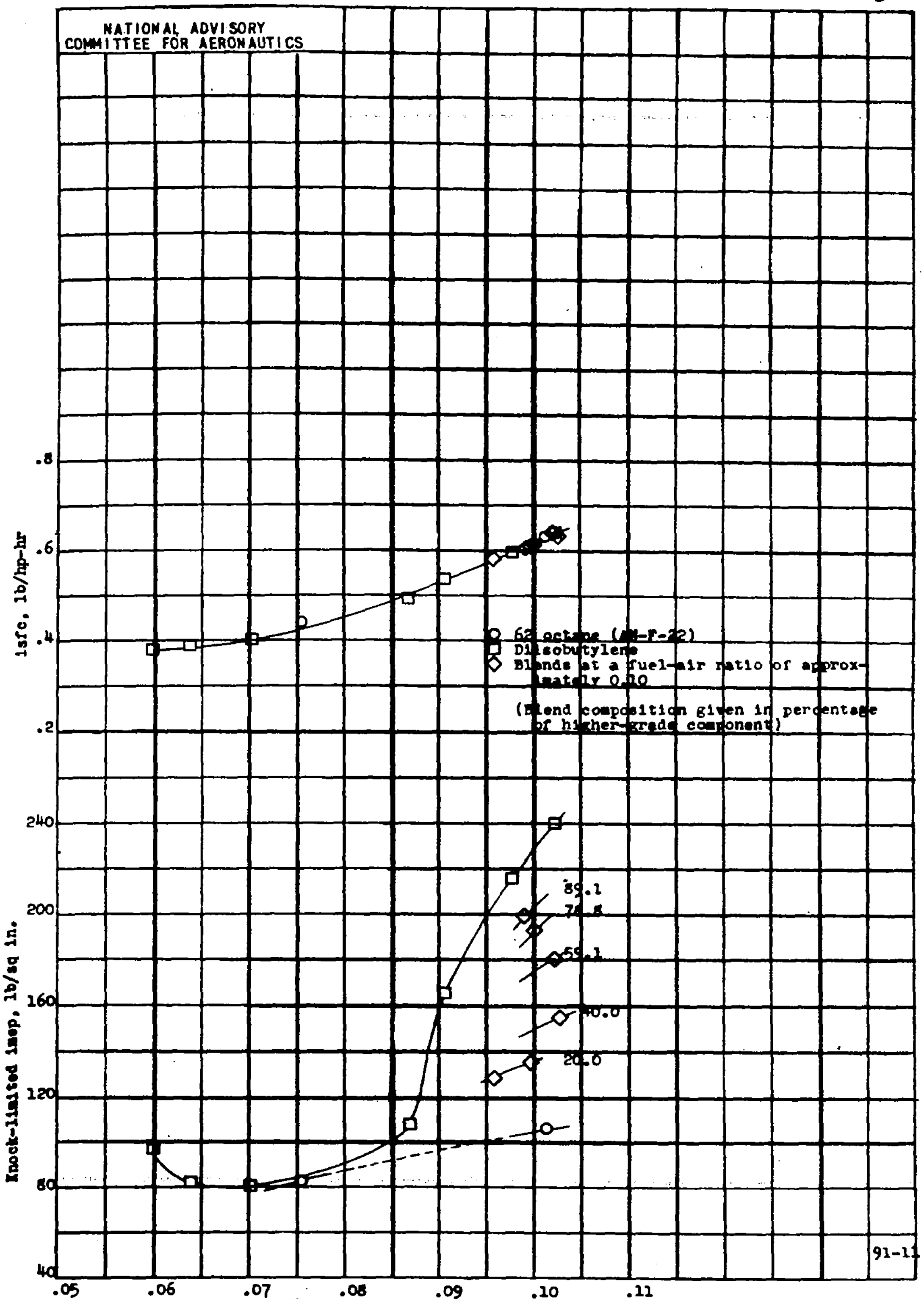
Figure 8. - The knock-limited performance of blends of aviation alkylate plus 6 ml tetraethyl lead per gallon and 62-octane fuel plus 6 ml tetraethyl lead per gallon. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.



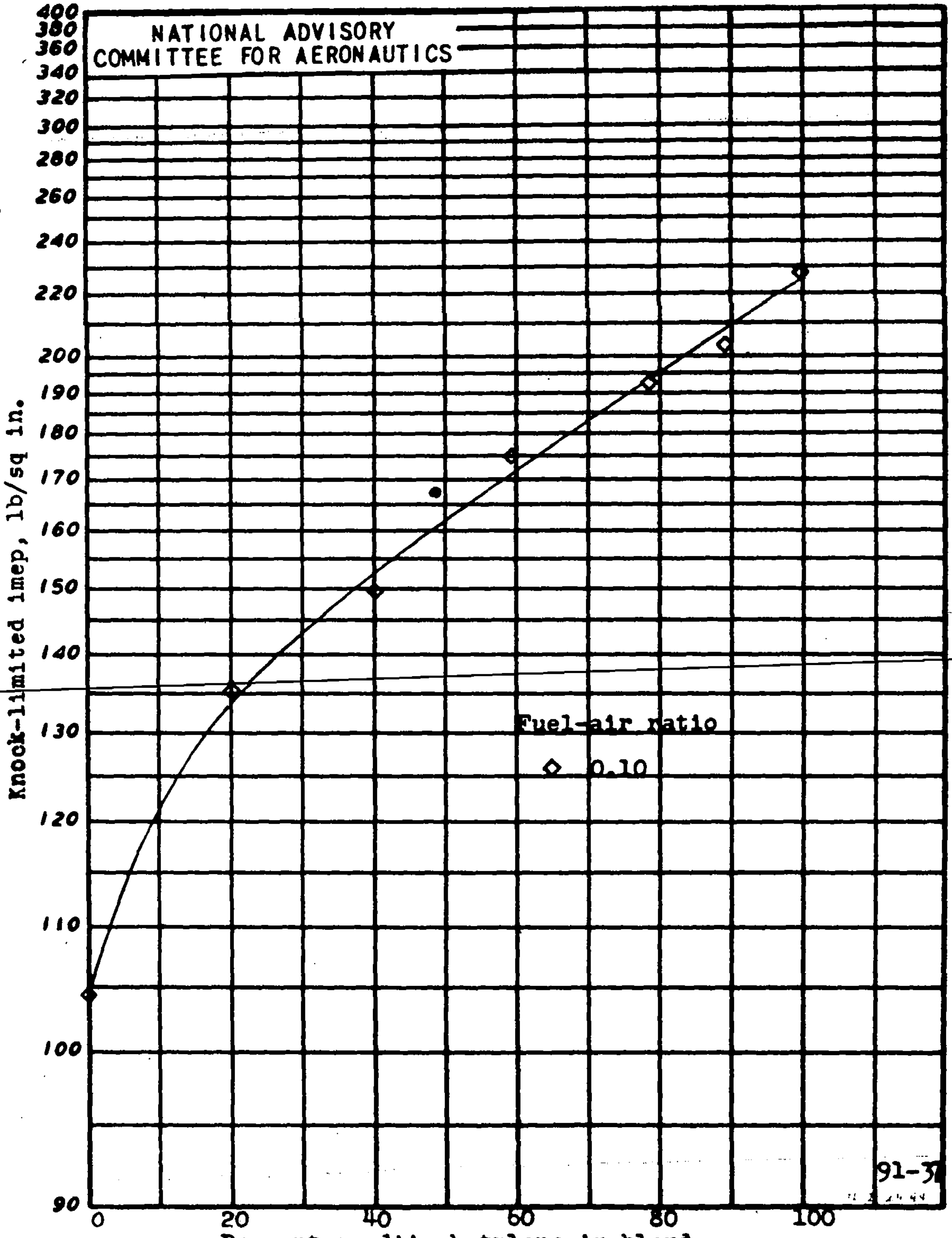
Percentage aviation alkylate plus 6 ml TEL/gal in blend

(b) Relationship of knock limit to fuel composition.

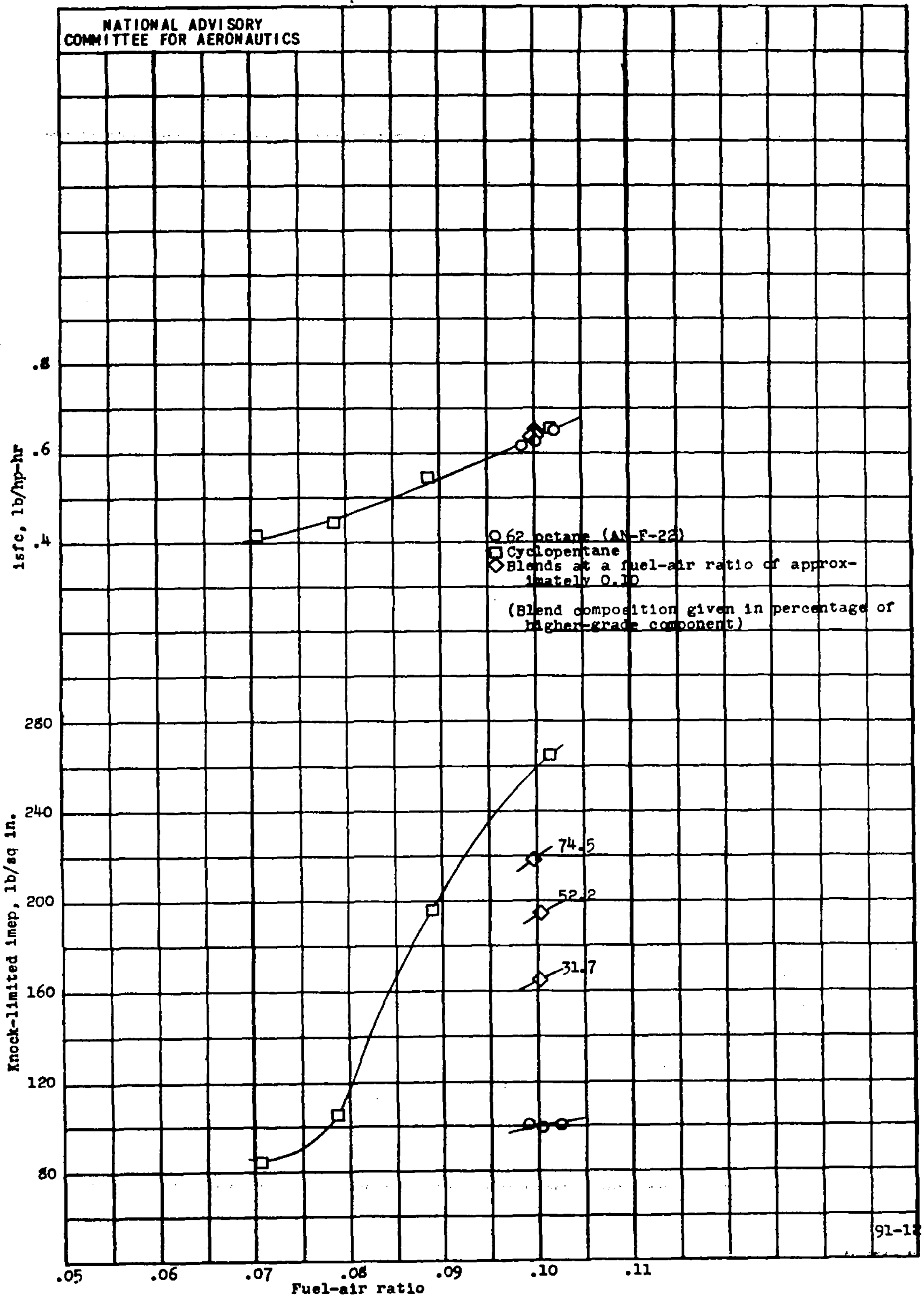
Figure 8. - Concluded.



(a) Mixture-response curves.
Figure 9. - The knock-limited performance of blends of diisobutylene and 62-octane fuel. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

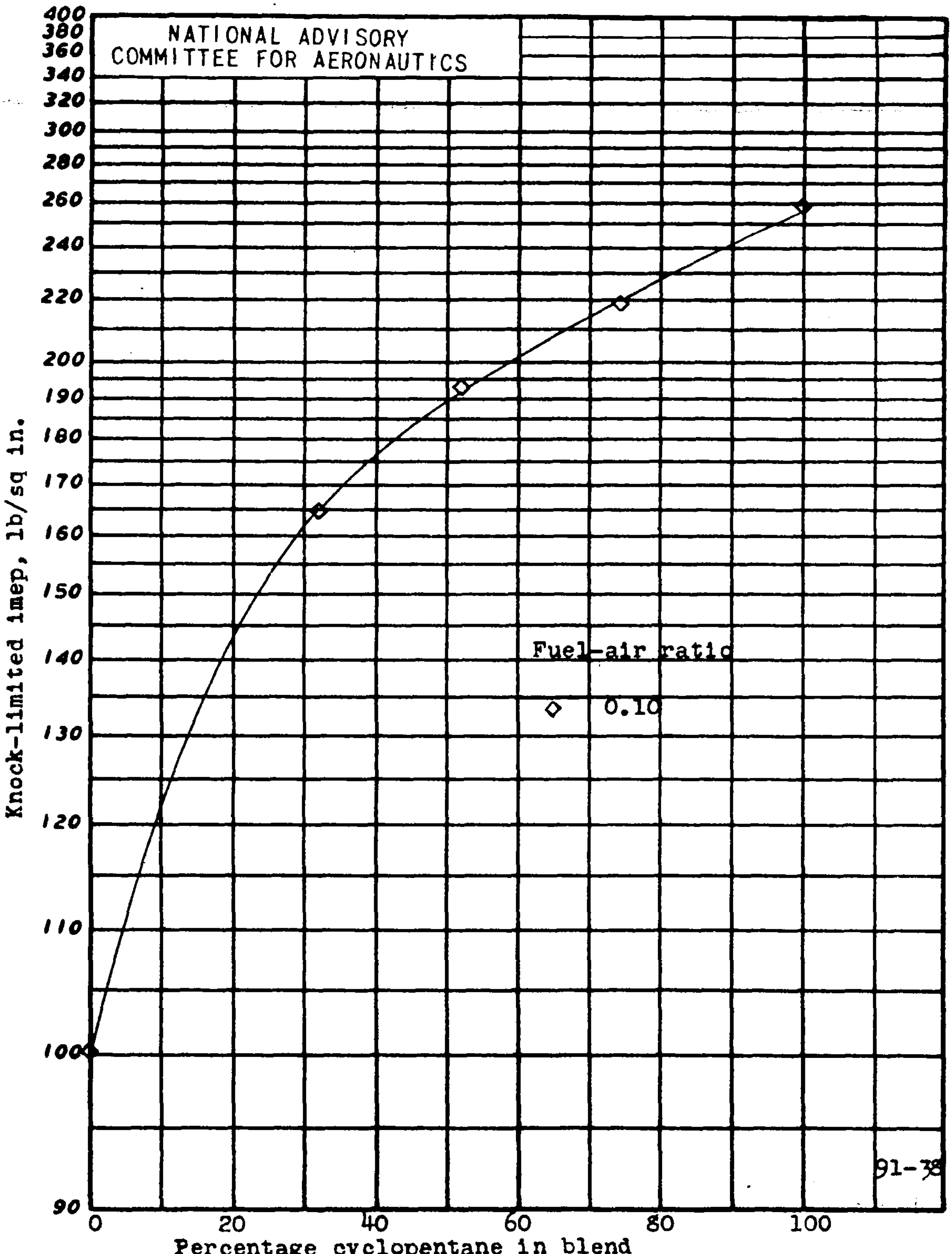


(b) Relationship of knock limit to fuel composition.
Figure 9. - Concluded.

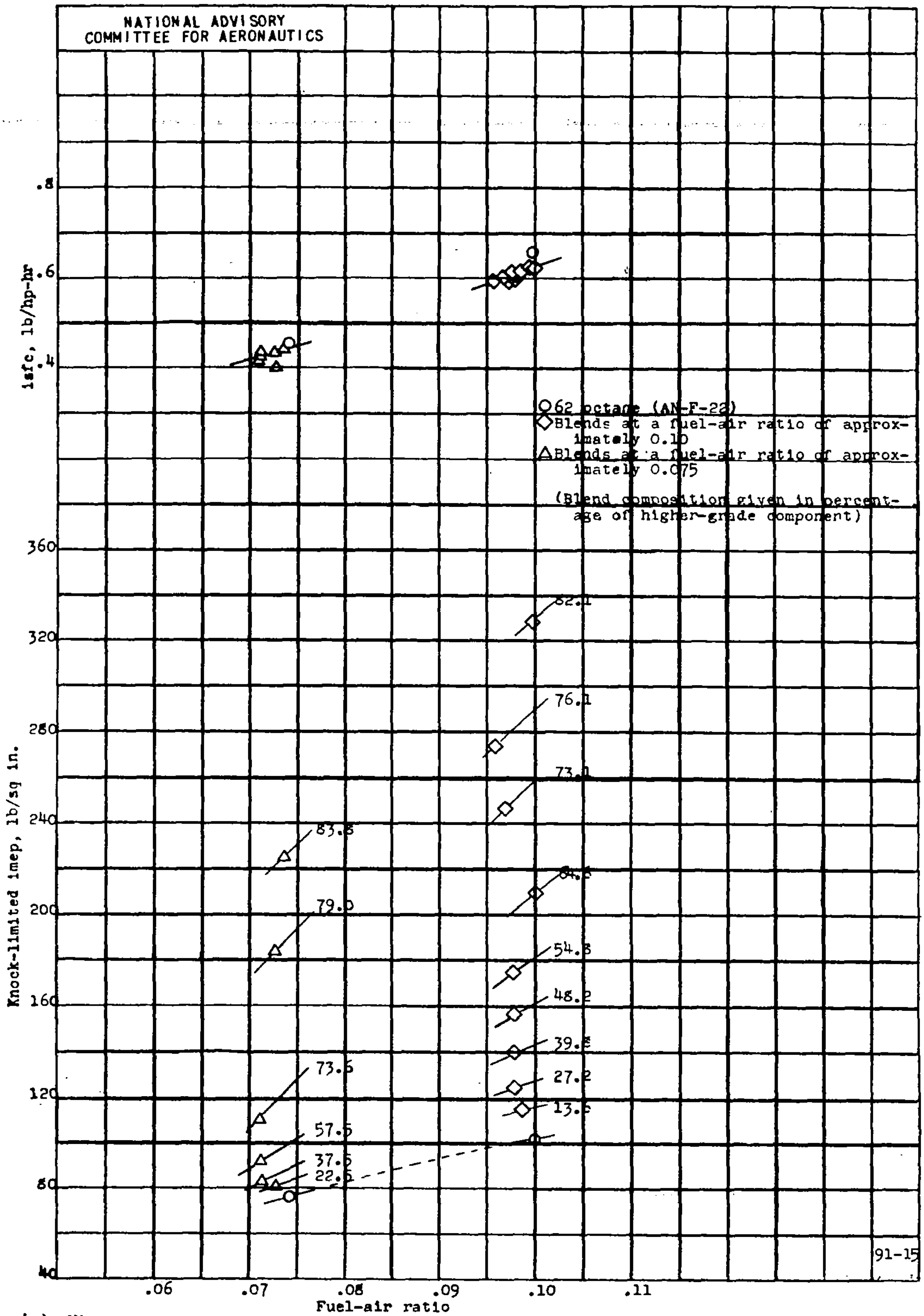


(a) Mixture-response curves.

Figure 10. - The knock-limited performance of blends of cyclopentane and 62-octane fuel. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

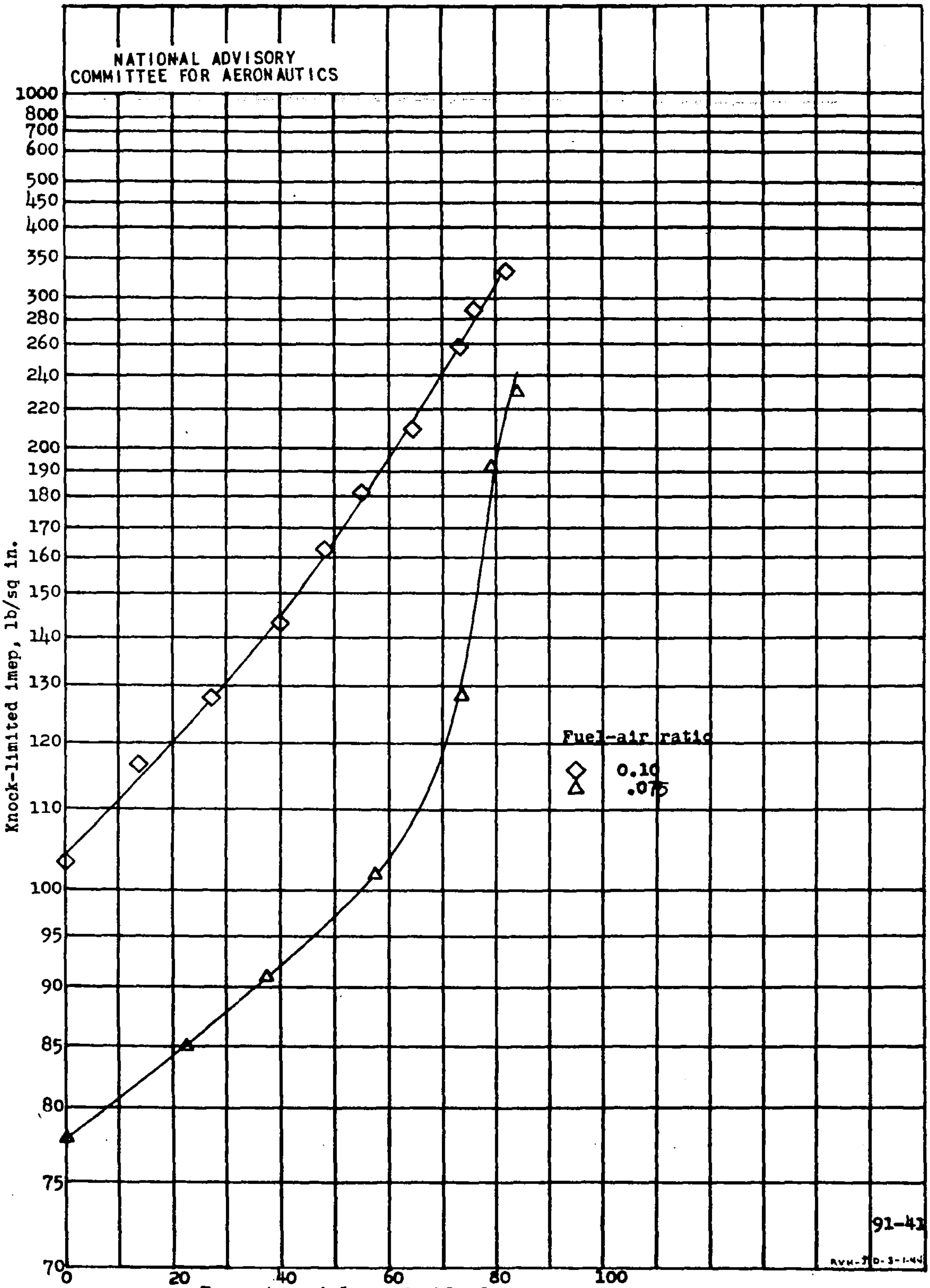


(b) Relationship of knock limit to fuel composition.
Figure 10. - Concluded.

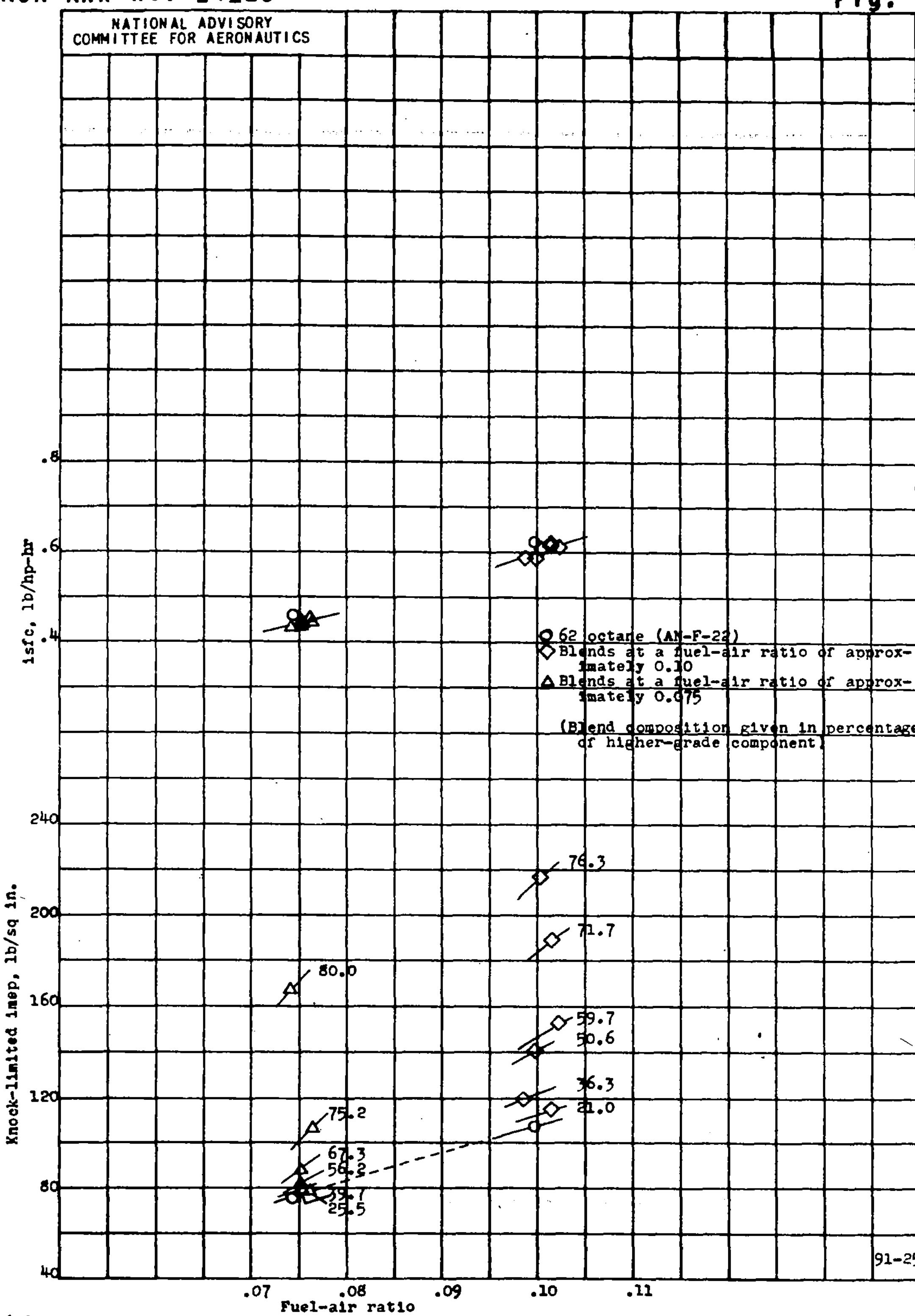


(a) Mixture-response curves.

Figure 11. - The knock-limited performance of blends of toluene and 62-octane fuel. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

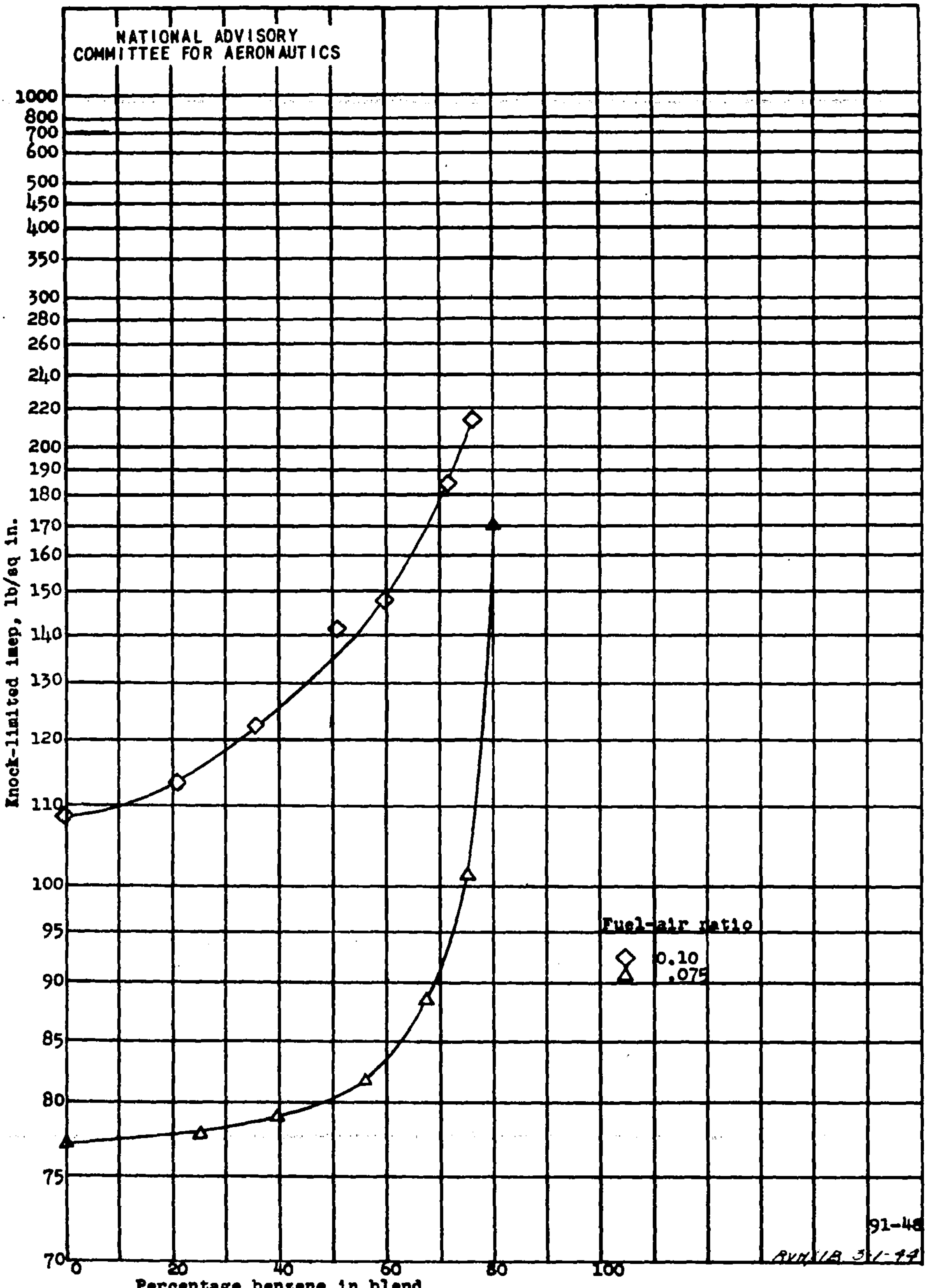


(b) Relationship of knock limit to fuel composition.
Figure 11. - Concluded.

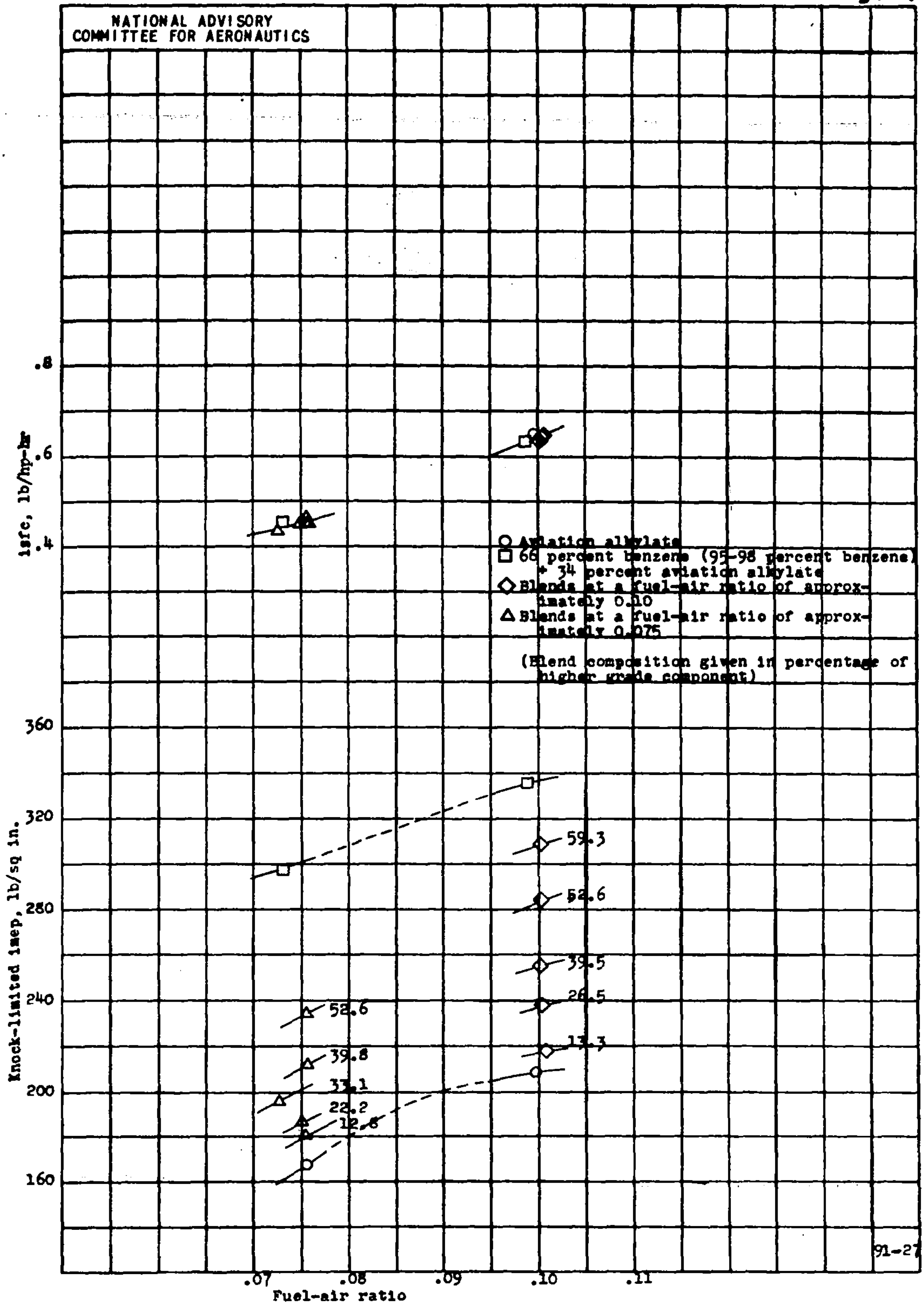


(a) Mixture-response curves.

Figure 12. - The knock-limited performance of blends of benzene (95-98 percent benzene) and 62-octane fuel. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

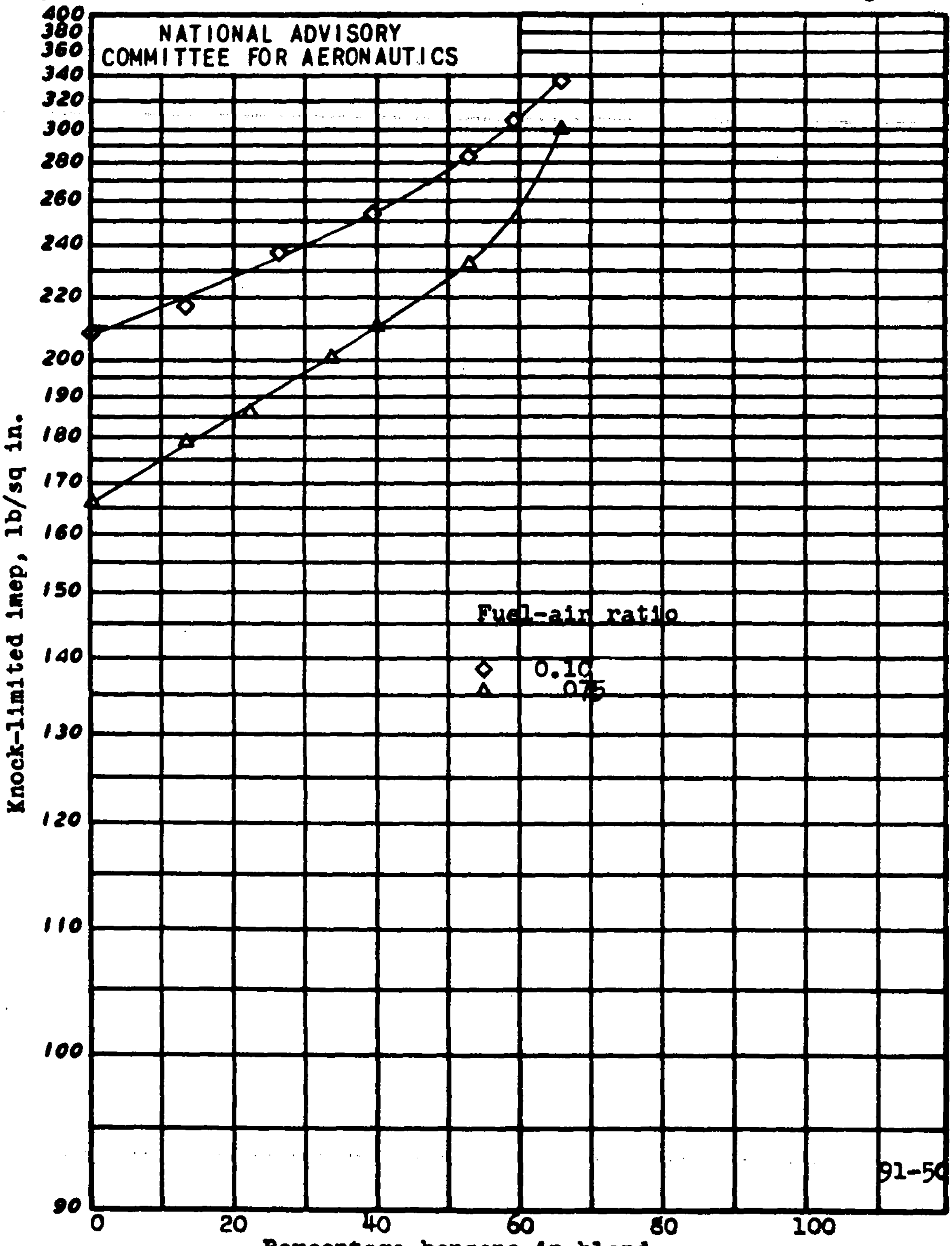


(b) Relationship of knock limit to fuel composition.
Figure 12. - Concluded.



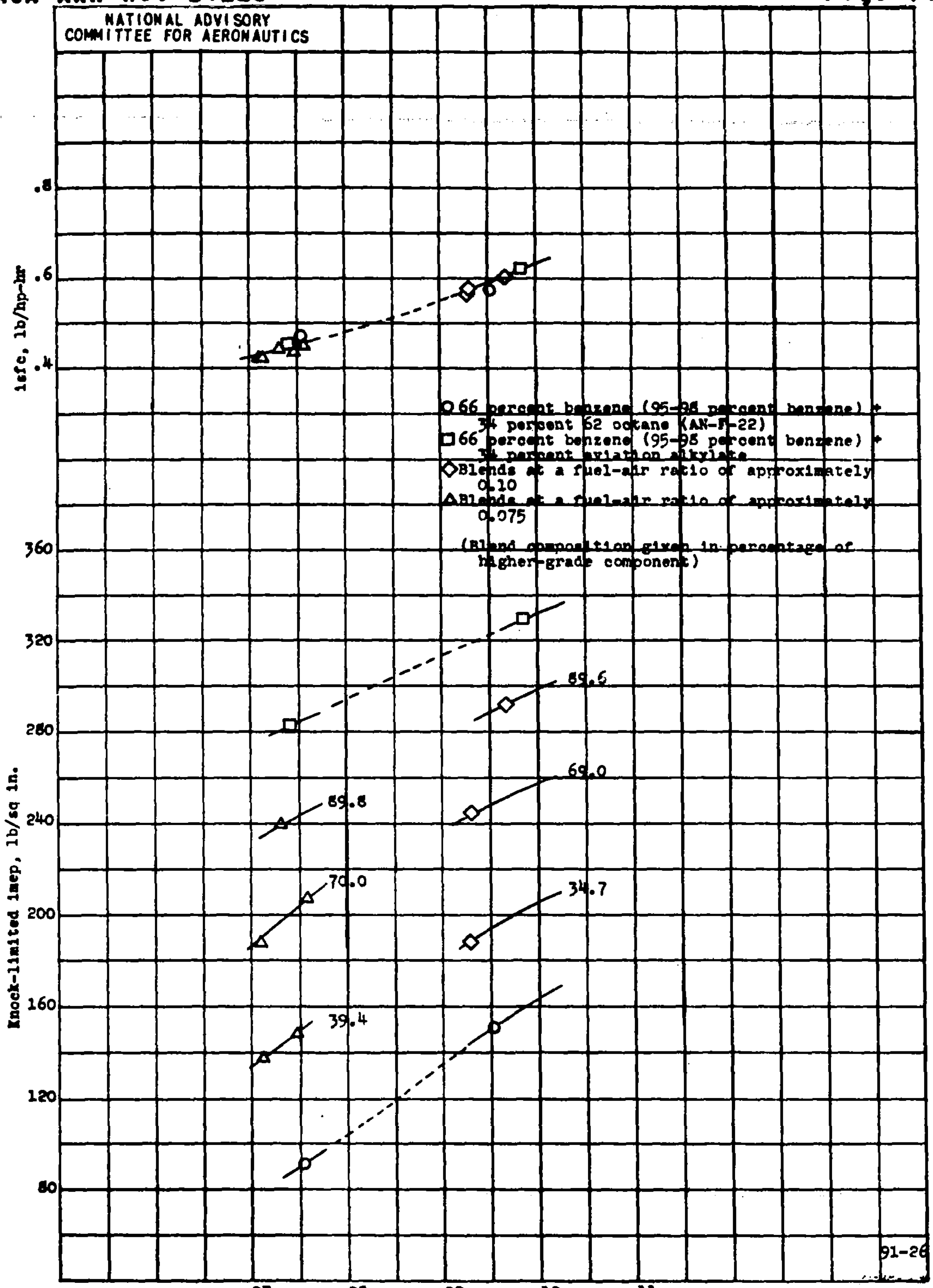
(a) Mixture-response curves.

Figure 13. - The knock-limited performance of blends of benzene and aviation alkylate. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 165° F.



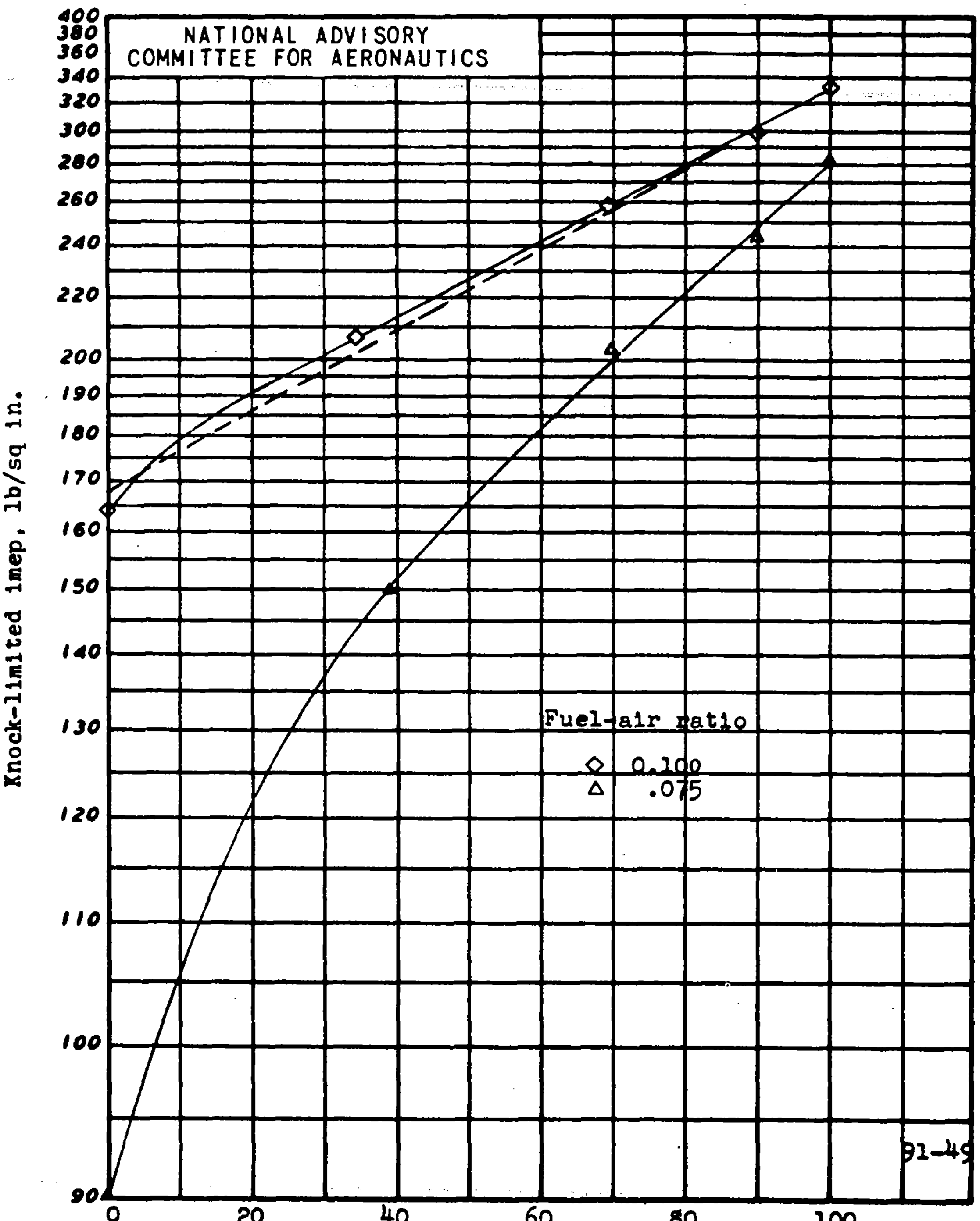
(b) Relationship of knock limit to fuel composition.

Figure 13. - Concluded.



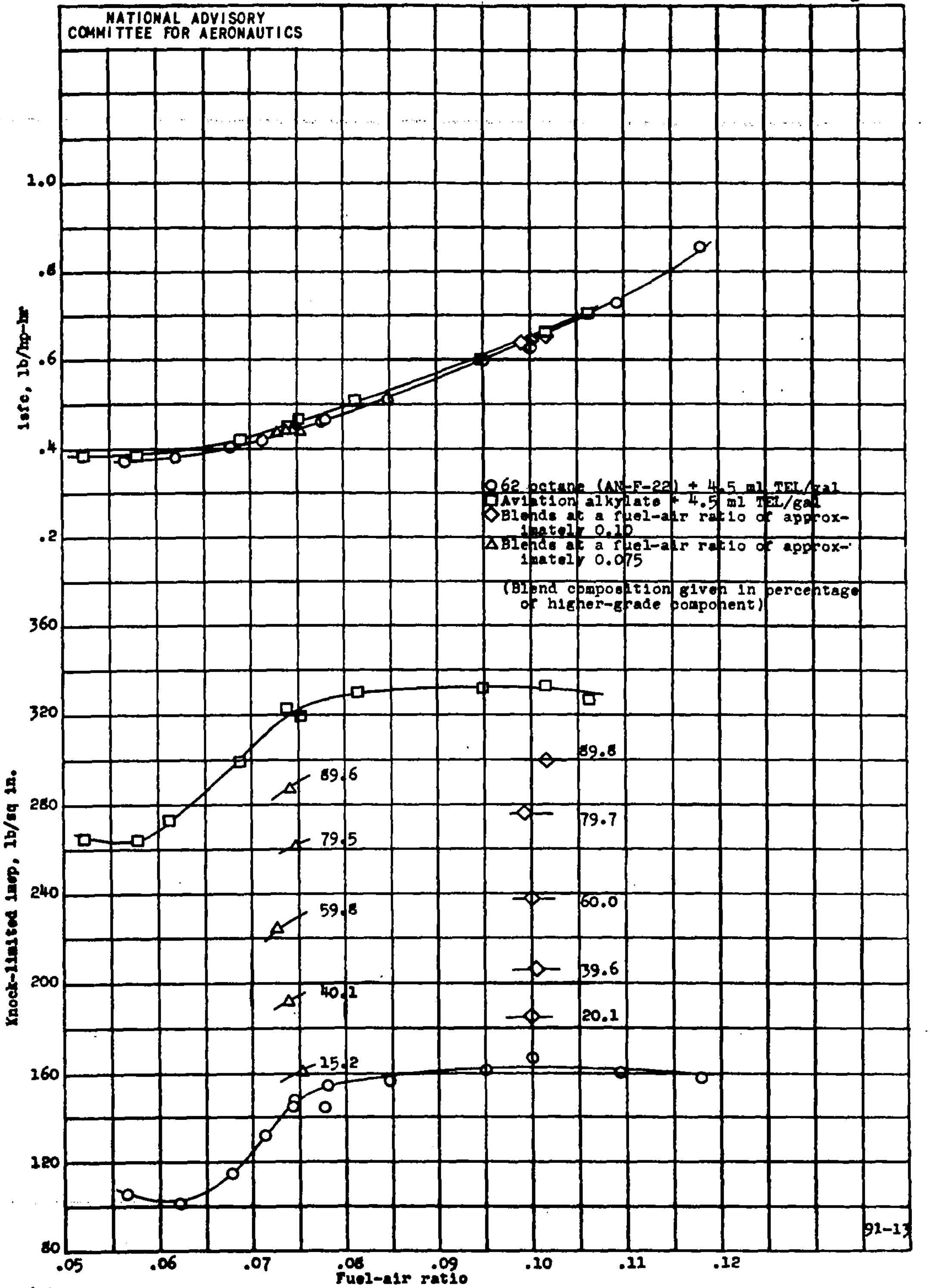
(a) Mixture-response curves.

Figure 14. - The knock-limited performance of blends of 66 percent benzene plus 34 percent aviation alkylate and 66 percent benzene plus 34 percent 62-octane fuel. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.



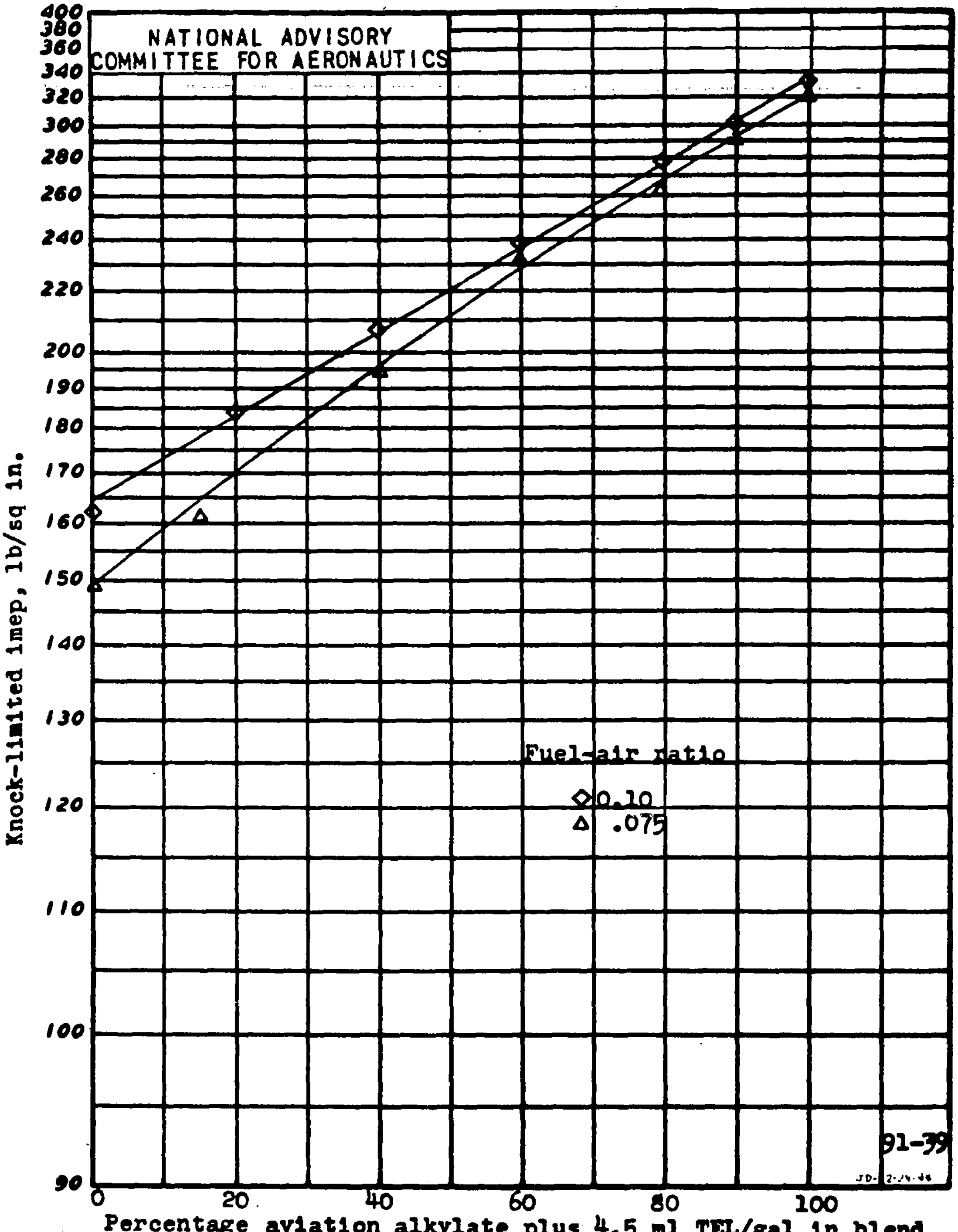
Percentage 66 percent benzene plus 34 percent aviation alkylate in blend

(b) Relationship of knock limit to fuel composition.
Figure 14. - Concluded.

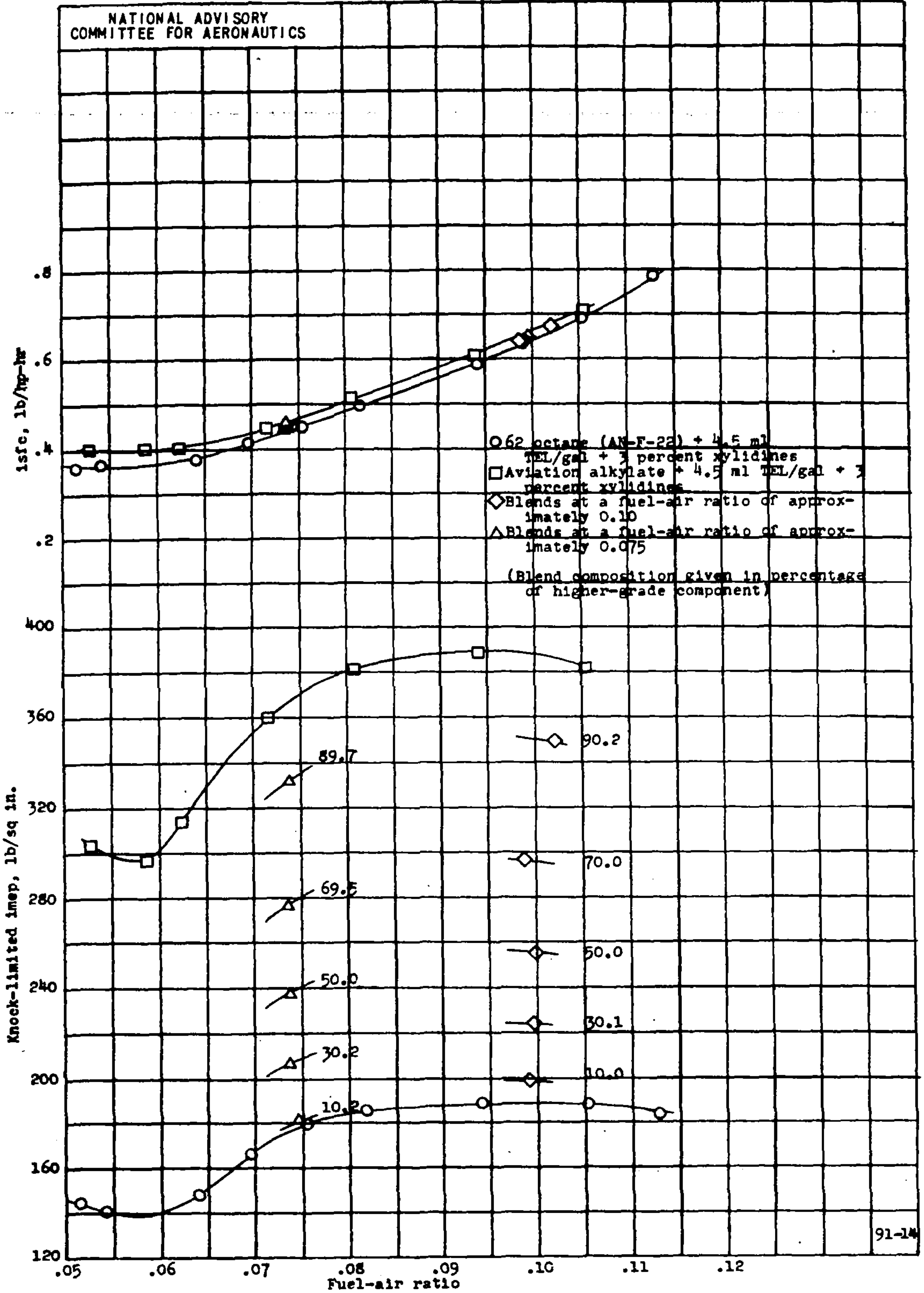


(a) Mixture-response curves.

Figure 15. - The knock-limited performance of blends of aviation alkylate plus 4.5 ml tetraethyl lead per gallon and 62-octane fuel plus 4.5 ml tetraethyl lead per gallon. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

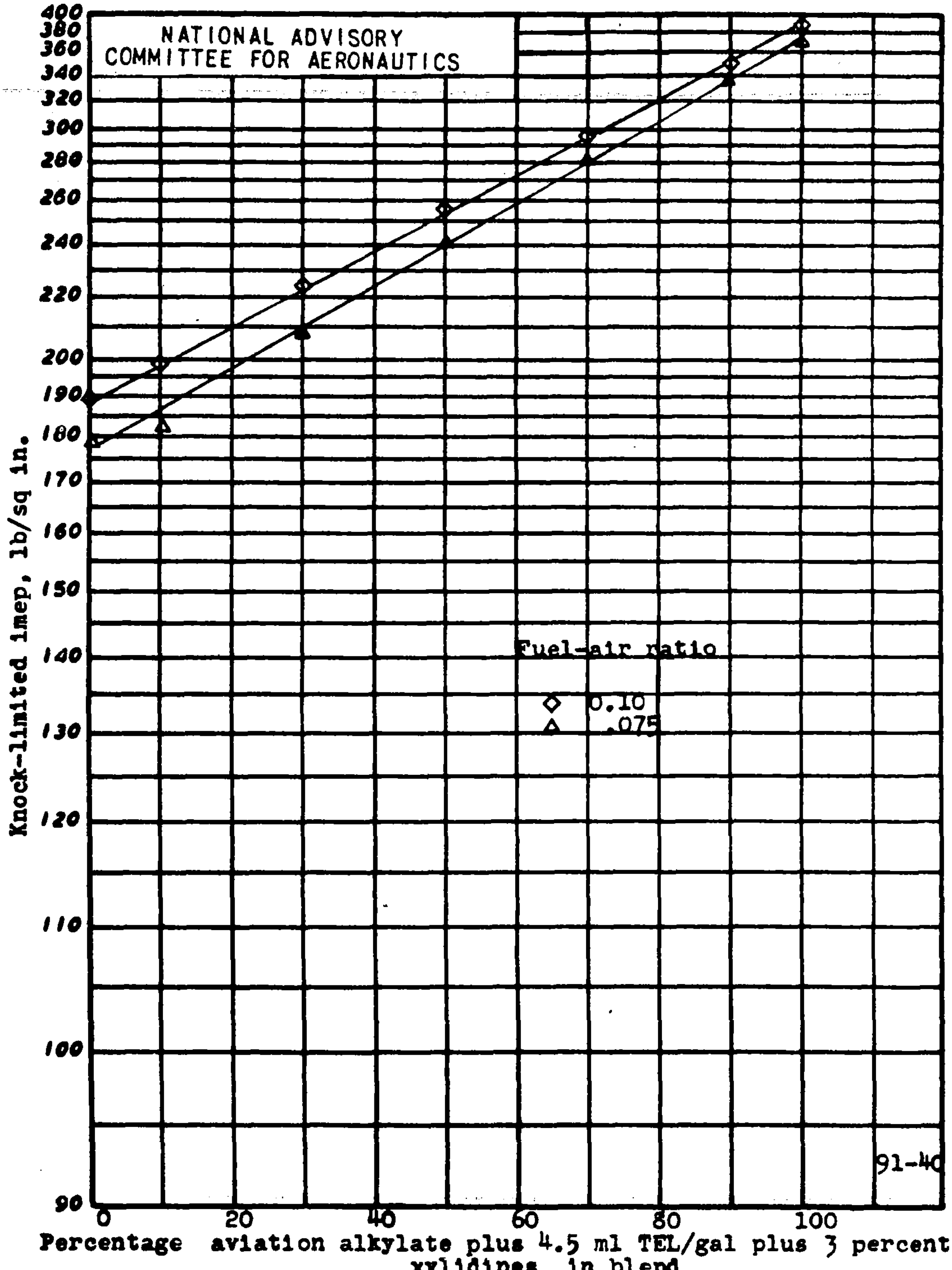


(b) Relationship of knock-limit to fuel composition.
Figure 15. - Concluded.

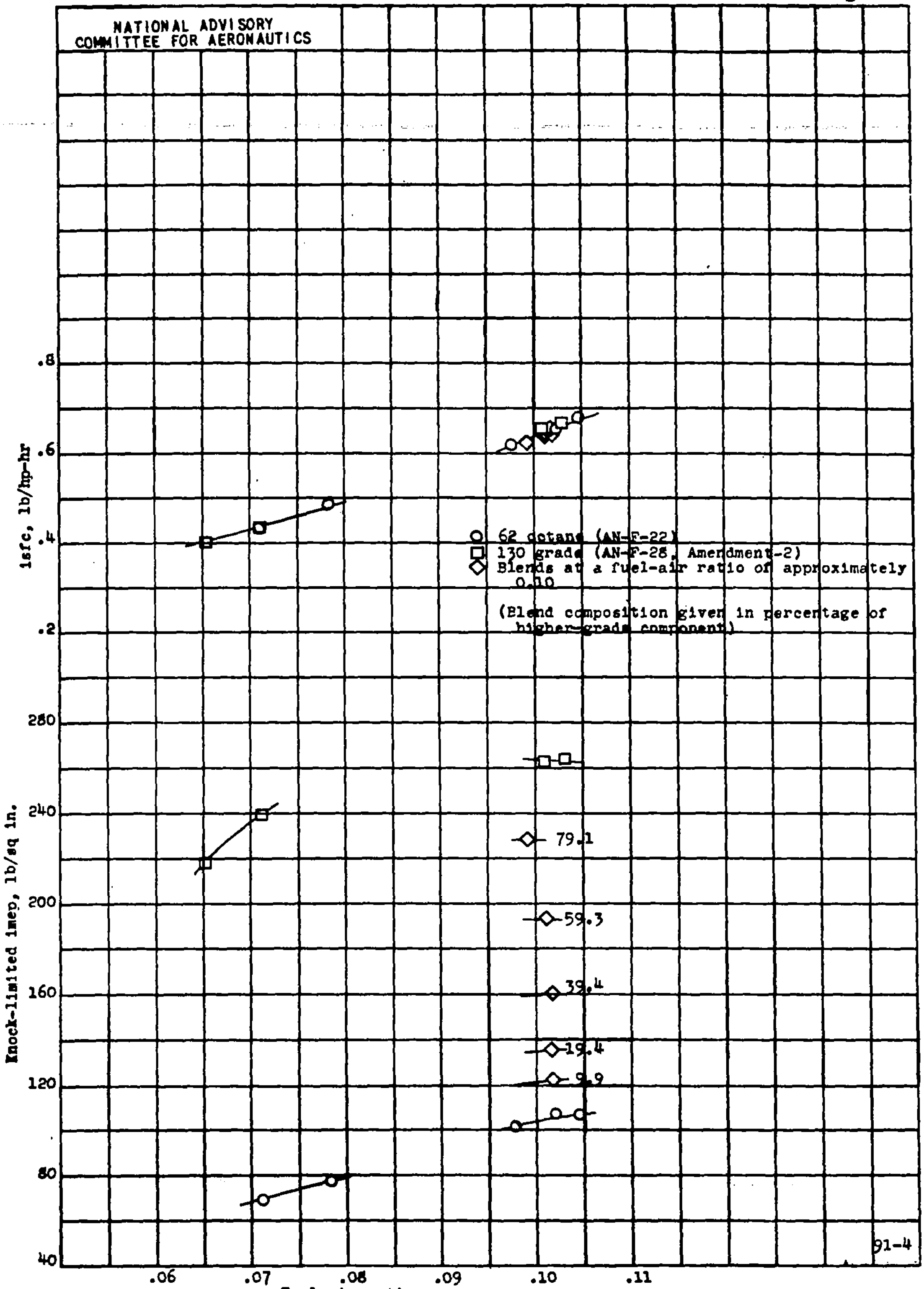


(a) Mixture-response curves.

Figure 16. - The knock-limited performance of blends of aviation alkylate plus 4.5 ml tetraethyl lead per gallon plus 3 percent xylidines and 62-octane fuel plus 4.5 ml tetraethyl lead per gallon plus 3 percent xylidines. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

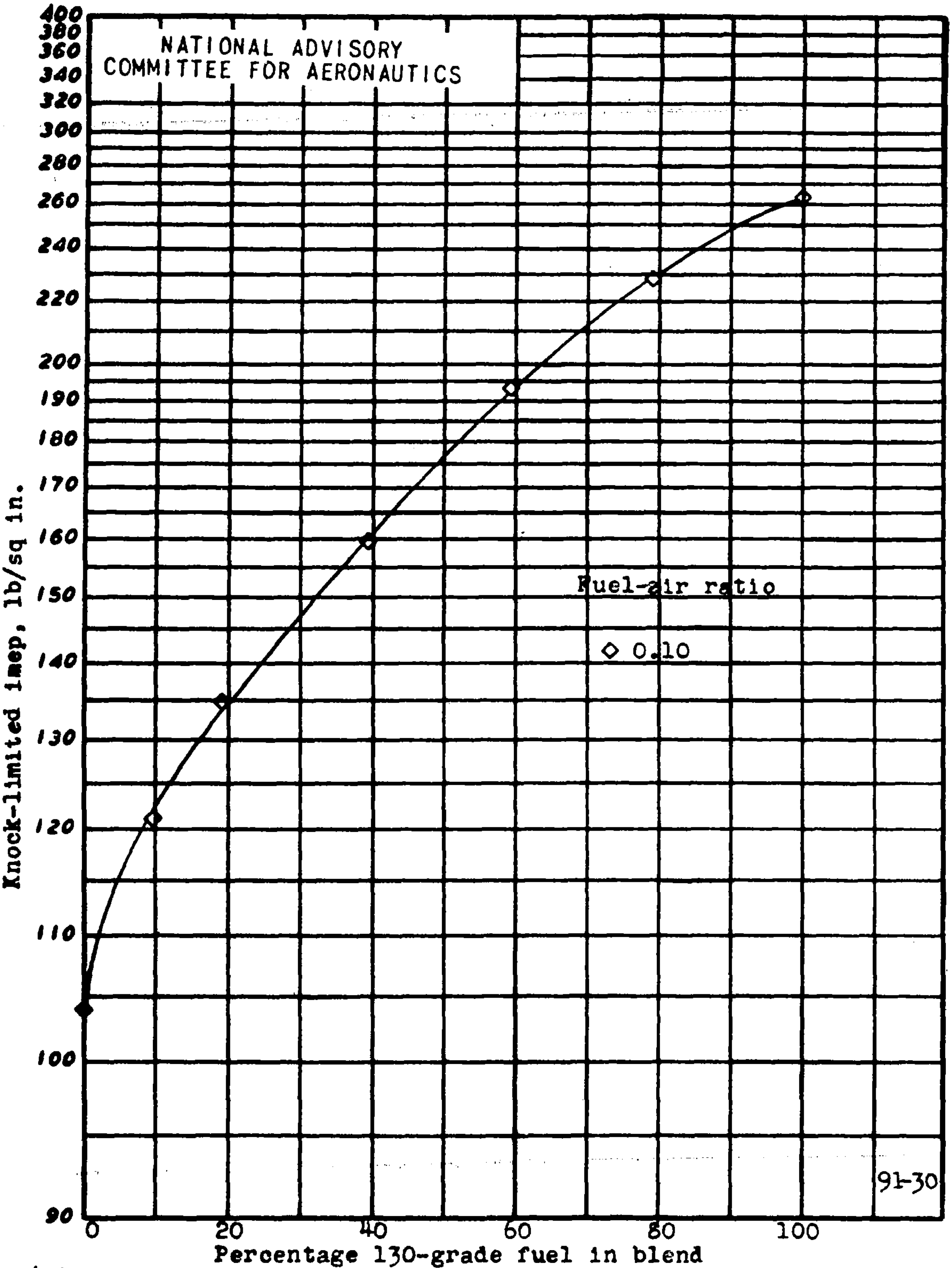


(b) Relationship of knock limit to fuel composition.
Figure 16. - Concluded.

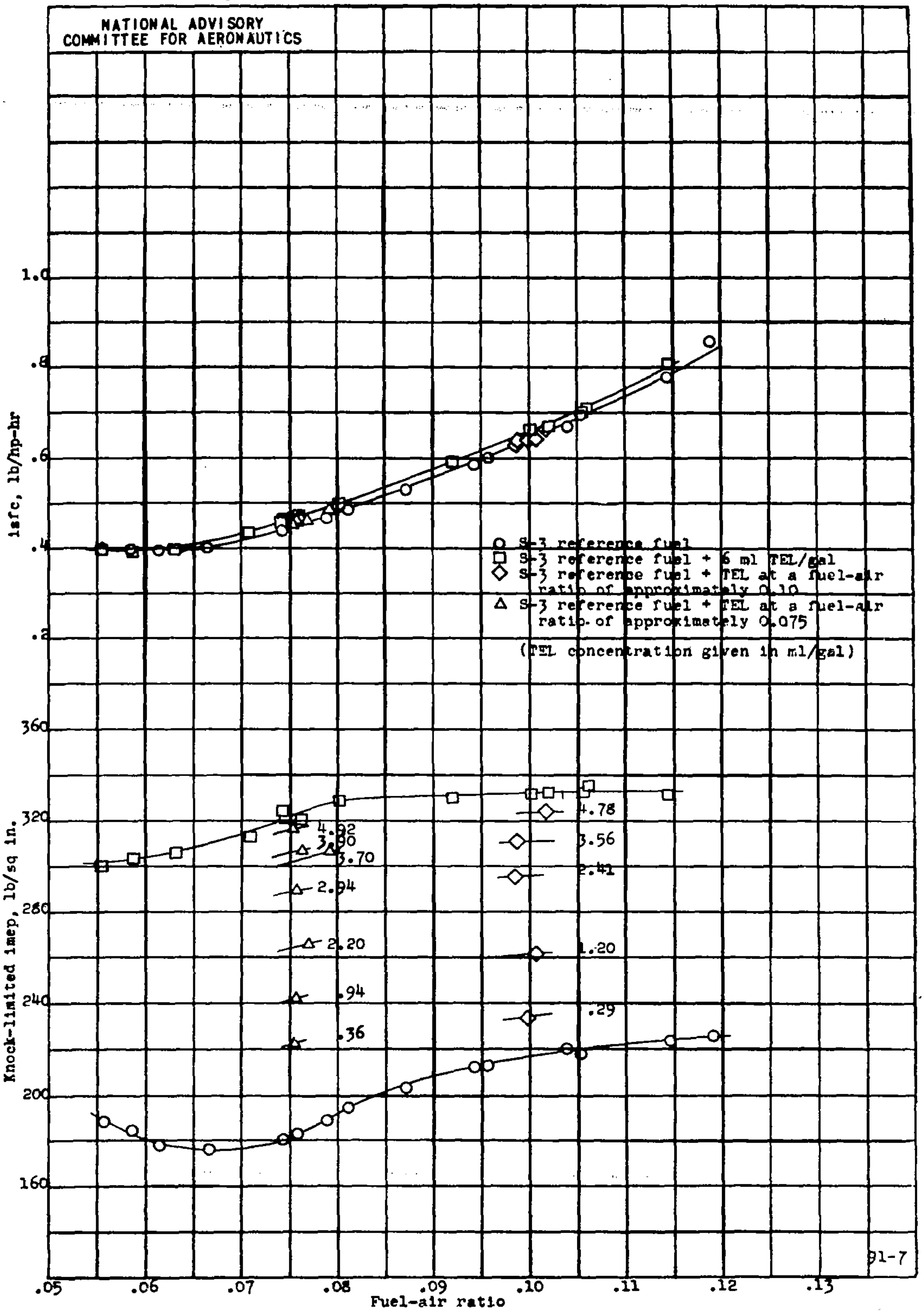


(a) Mixture-response curves.

Figure 17. - The knock-limited performance of blends of 130-grade fuel and 62-octane fuel. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

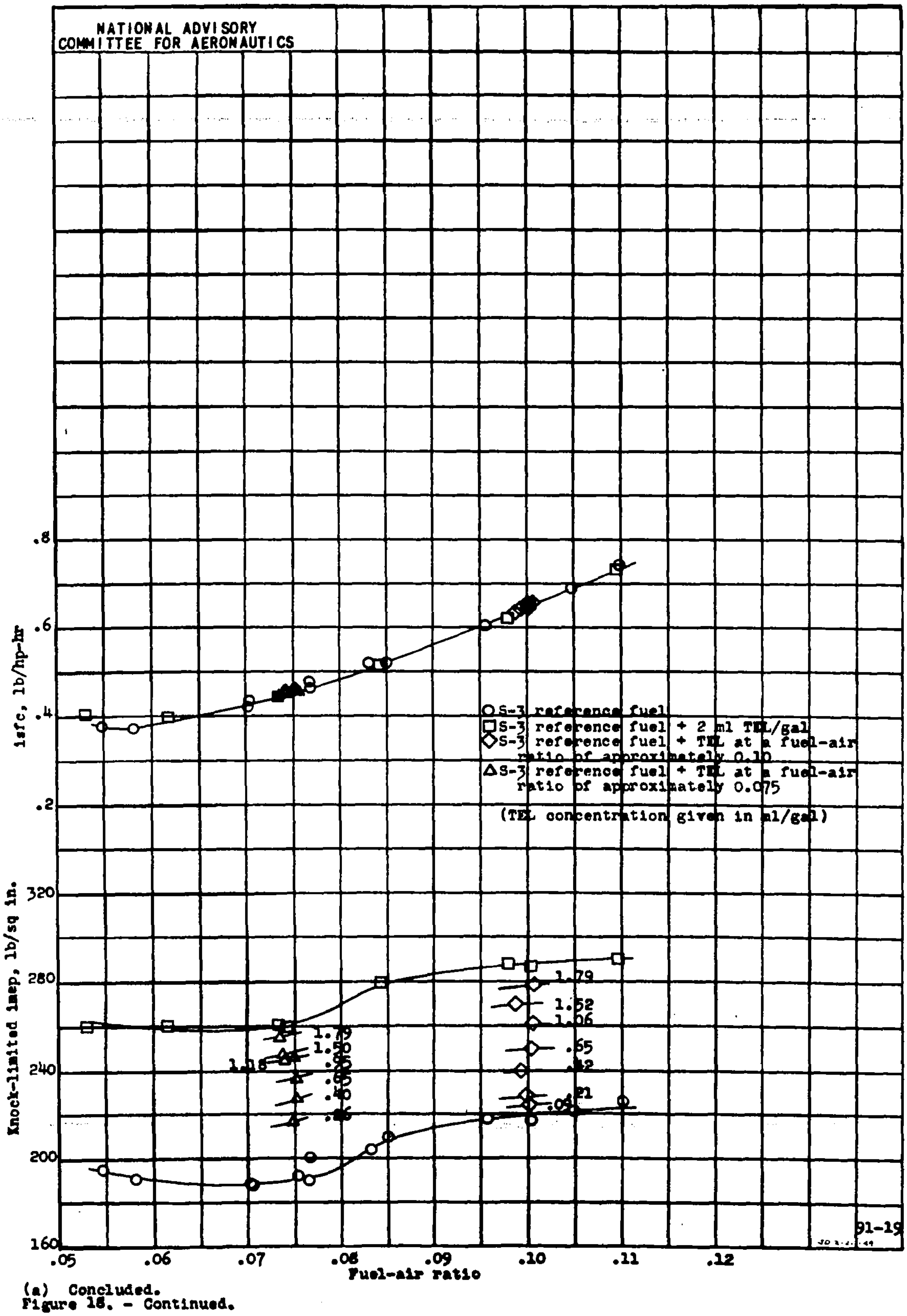


(b) Relationship of knock limit to fuel composition.
Figure 17. - Concluded.

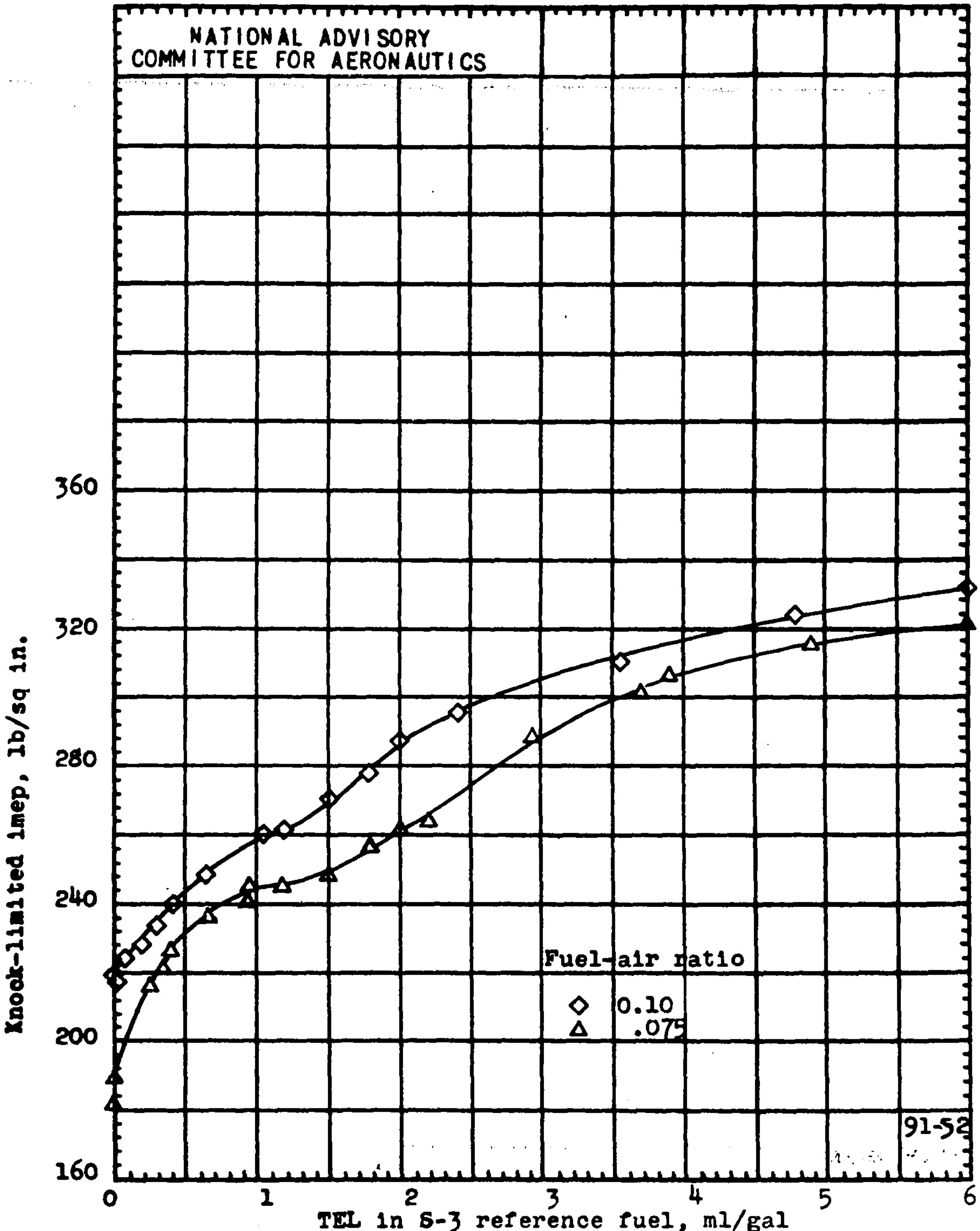


(a) Mixture-response curves.

Figure 18. - The knock-limited performance of S-3 reference fuel plus tetraethyl lead. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.



(a) Concluded.
Figure 18. - Continued.



(b) Lead-response curve.
Figure 18. - Concluded.

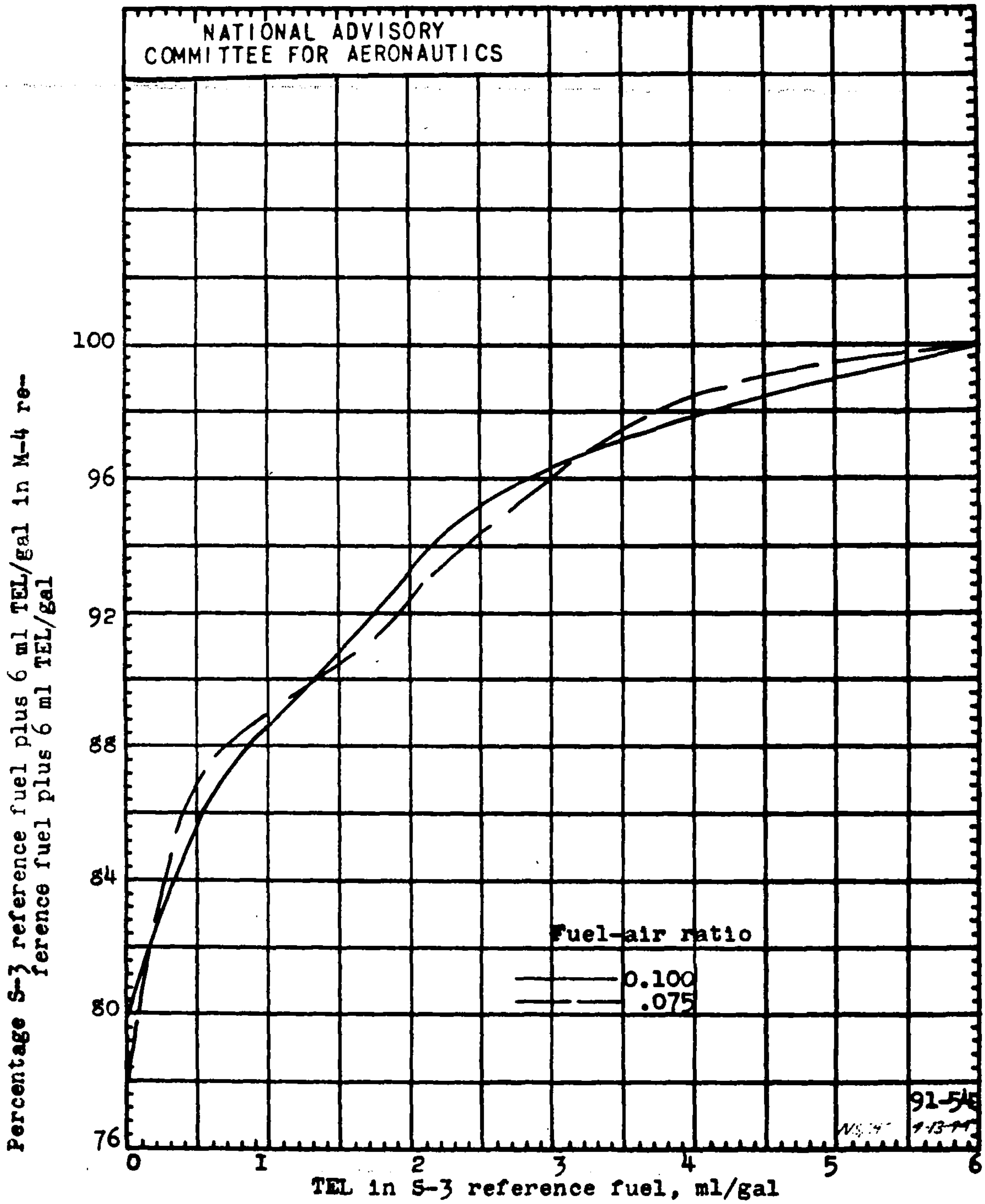


Figure 19. - Conversion of lead rating scale to percentage S-3 reference fuel plus 6 ml TEL/gal in M-4 reference fuel plus 6 ml TEL/gal. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

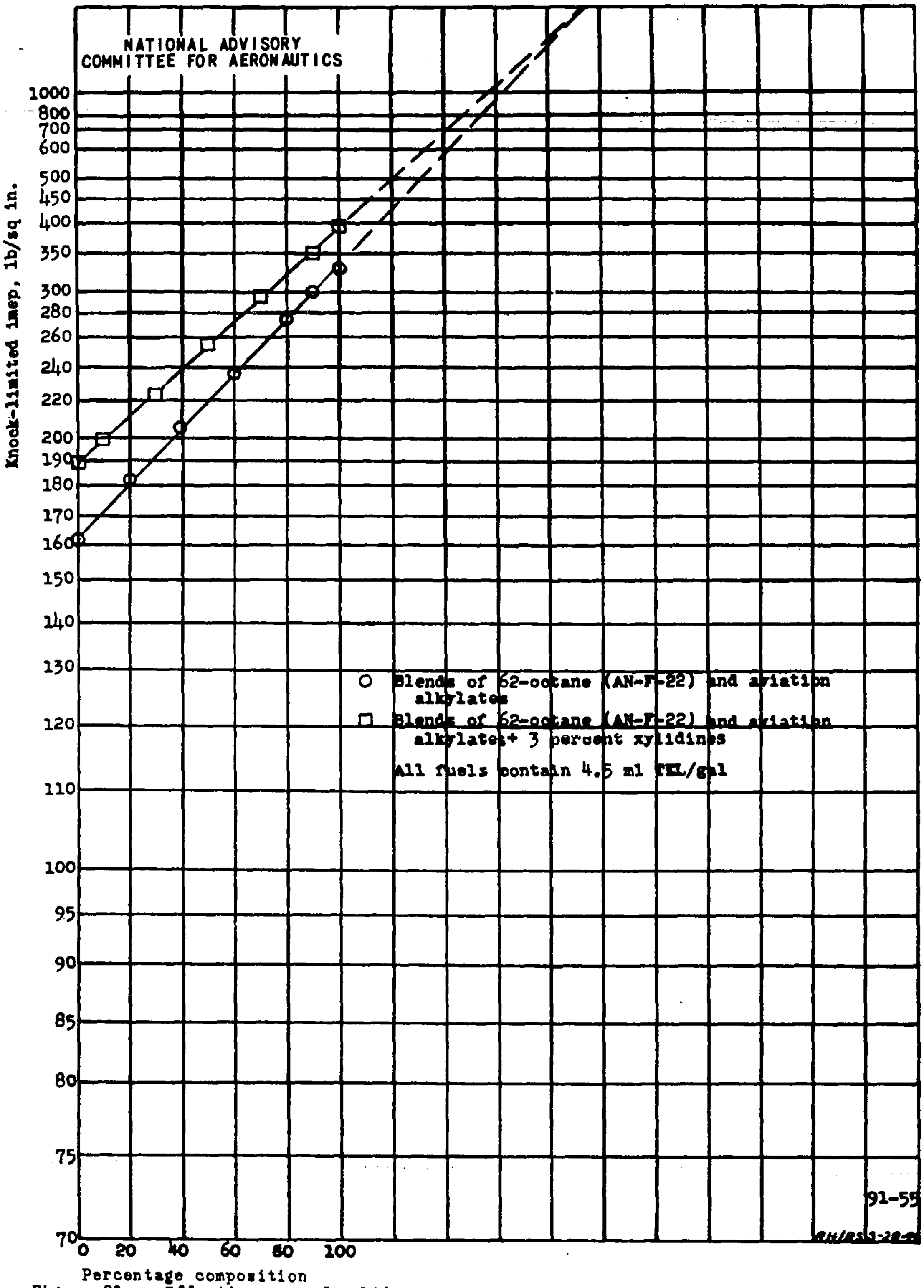


Figure 20. - Effectiveness of xylidines in blends of paraffinic fuels. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F; fuel-air ratio, 0.10.

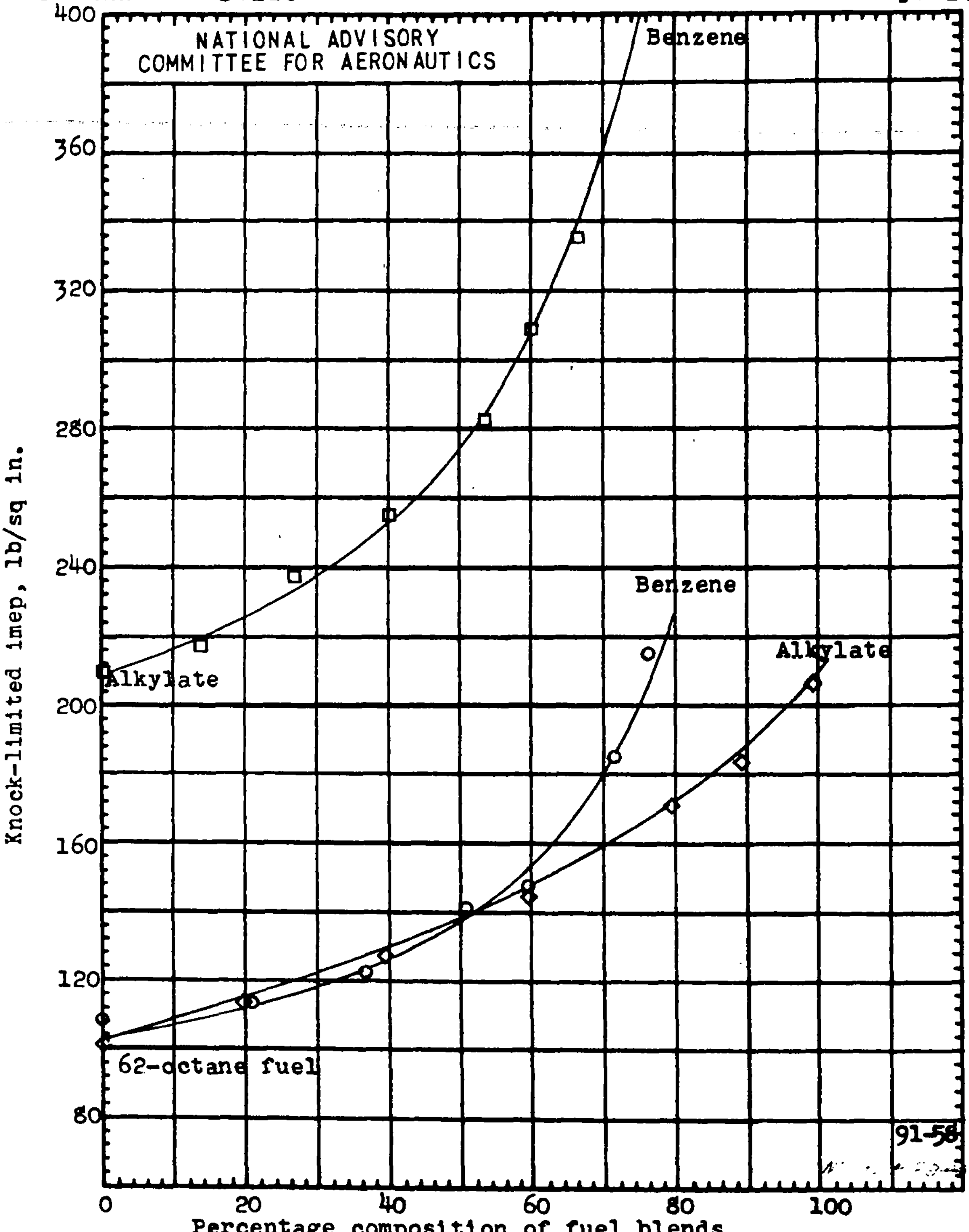


Figure 21. - The knock-limited indicated mean effective pressures of blends of benzene, alkylate, and 62-octane fuels at a fuel-air ratio of 0.10. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

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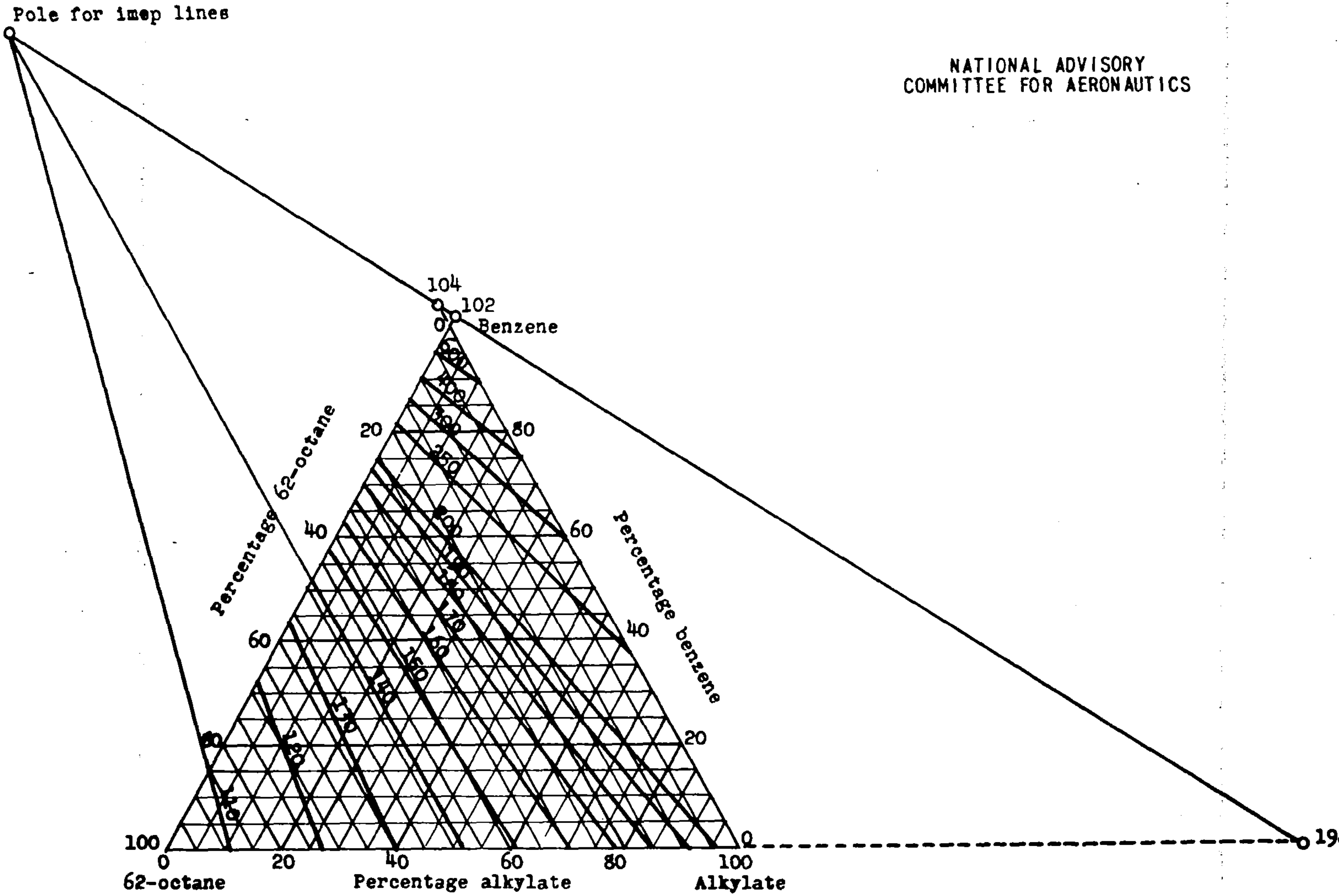

Figure 22. - Trilinear graph for finding the knock-limited indicated mean effective pressures of blends of benzene, alkylate, and 62-octane fuel at a fuel-air ratio of 0.10. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

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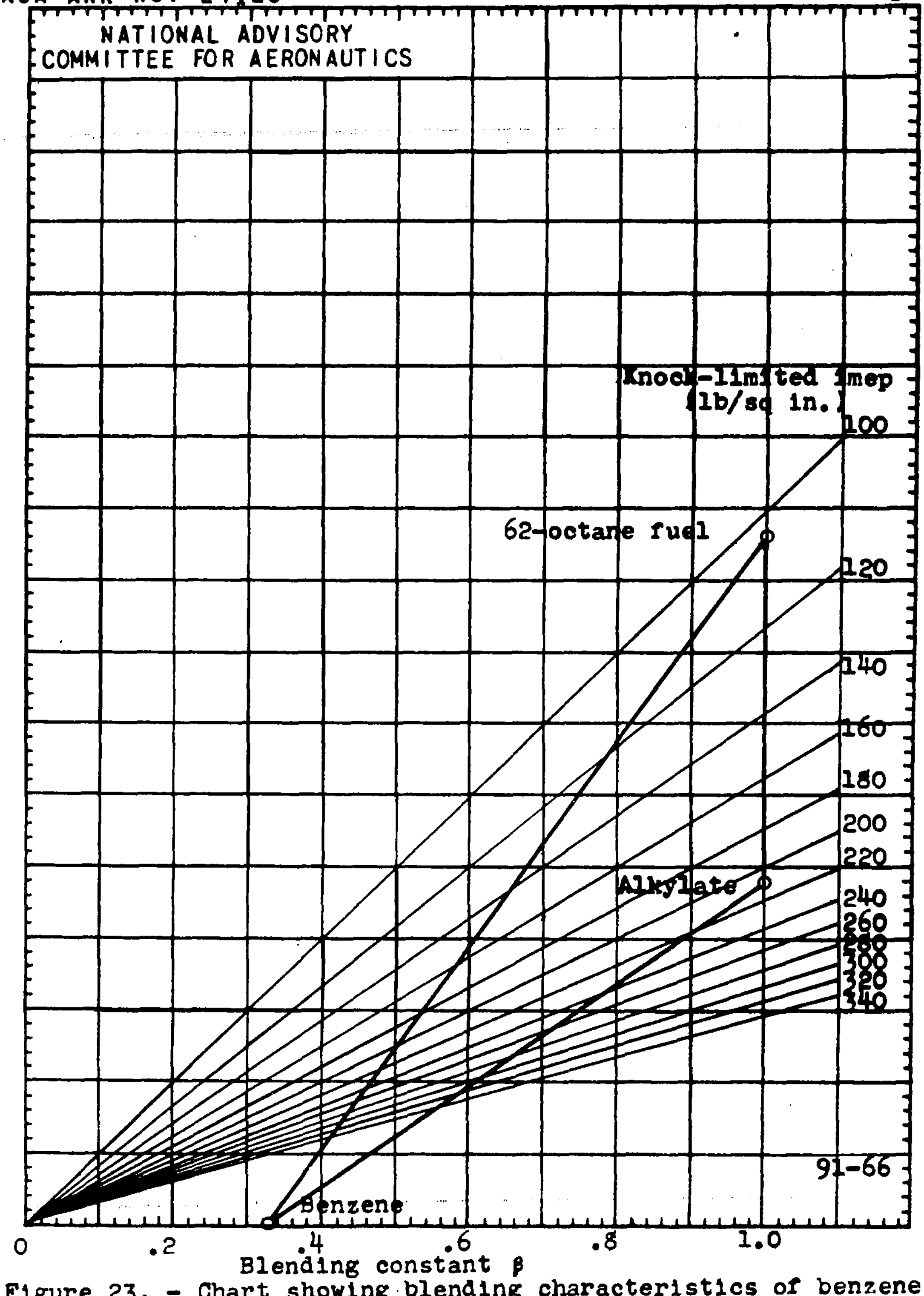

Figure 23. - Chart showing blending characteristics of benzene in alkylate and 62-octane fuels at a fuel-air ratio of 0.10. P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

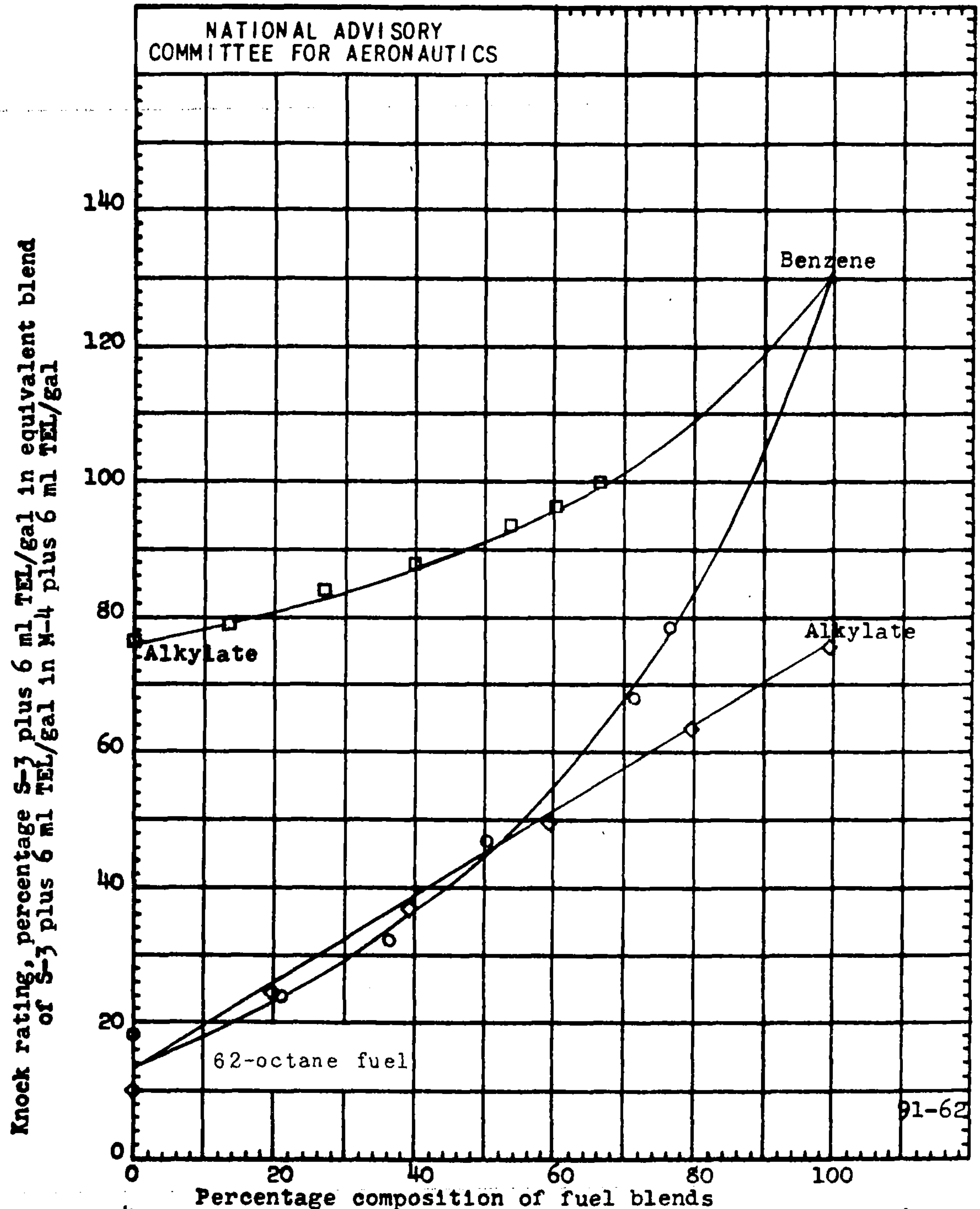

Figure 24. - Knock ratings of blends of benzene, alkylate, and 62-octane fuels expressed in terms of equivalent blends of leaded reference fuels. Ratings at a fuel-air ratio of 0.10; P. & W. R-2800 cylinder; compression ratio, 6.7; spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

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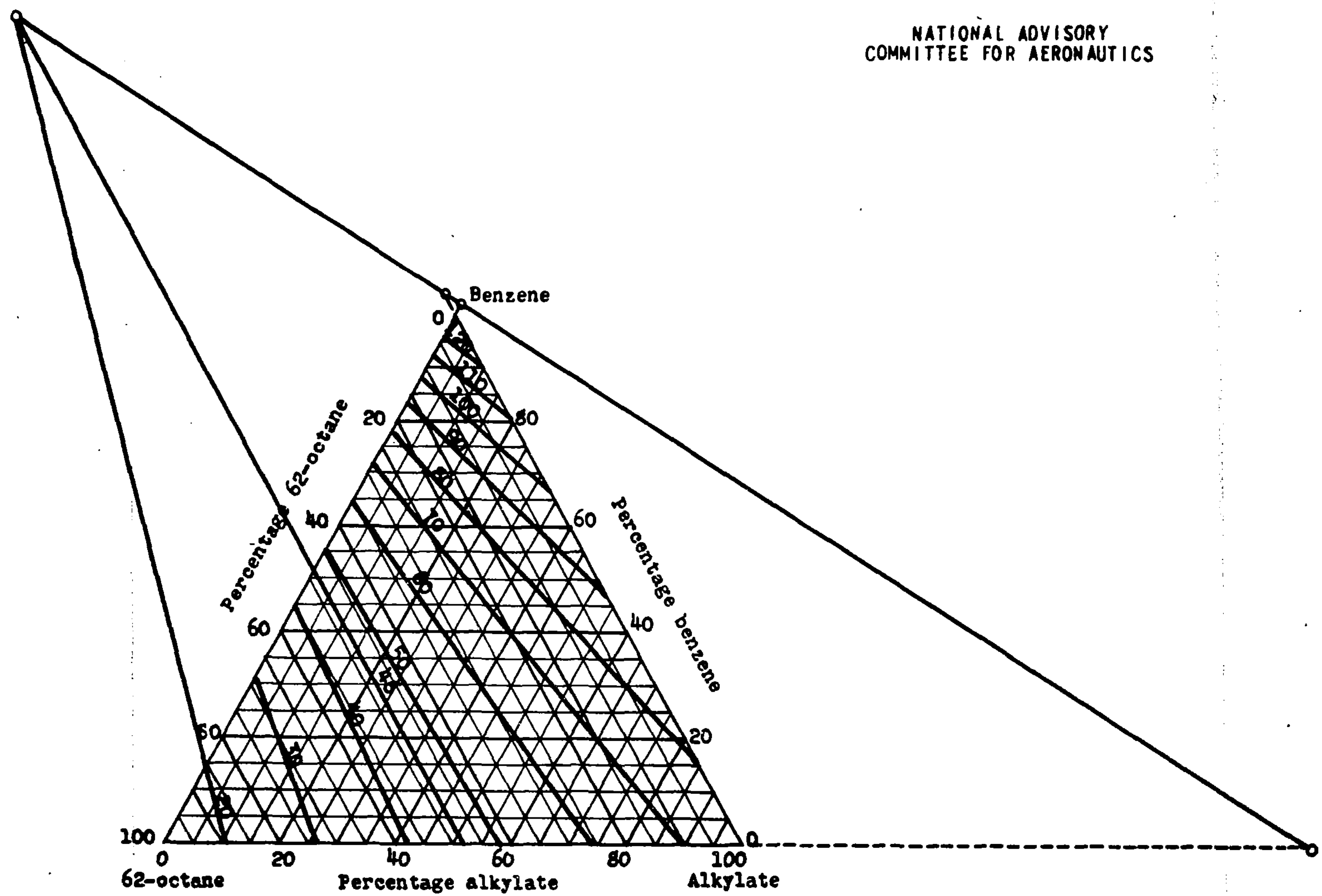

Figure 25. - Trilinear graph for finding the knock ratings of blends of benzene, alkylate, and 62-octane fuel at a fuel-air ratio of 0.10. Ratings expressed as percentage of S-3 plus 6 ml TEL/gal in blends of S-3 plus 6 ml TEL/gal and M-4 plus 6 ml TEL/gal; P. & W. R-2800 cylinder; compression ratio, 6.7 spark advance, 20° B.T.C.; engine speed, 2000 rpm; inlet-mixture temperature, 200° F; rear spark-plug-boss temperature, 400° F; oil-in temperature, 185° F.

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