NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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COMPARISON OF RELATIVE SENSITIVITIES OF THE KNOCK LIMITS OF TWO FUELS TO SIX ENGINE VARIABLES

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SUMMARY

A sensitive fuel (42 percent S reference fuel, 40 percent toluene, and 18 percent M reference fuel by volume + 4 ml TEL/gal; grade 103/145) and a relatively insensitive fuel (100 percent S reference fuel + 4 ml TEL/gal; grade 153/153) were knock-tested in a full-scale air-cooled cylinder. Sensitivity was indicated by different degrees of knock-limited response to changes in engine conditions. Six engine variables were investigated: (1) fuel-air ratio, (2) compression ratio, (3) inlet-air temperature, (4) spark advance, (5) exhaust pressure, and (6) cylinder temperature.

The relative changes in the knock-limited indicated mean effective pressure and charge-air flow of the two fuels were different for the six engine variables and, except for cylinder temperature, varied over the range investigated. These results indicate that, in order to correlate the effects of engine variables on knock-limited performance of fuels, more basic knock factors than knock-limited indicated mean effective pressure and charge-air flow are required. Fuel-air ratios above the stoichiometric showed the greatest relative sensitivity of the knock limits of the two fuels, except for tests at high exhaust pressure. The relative sensitivities shown in fuel-air-ratio and exhaust-pressure tests became more consistent with those for the other engine variables when the fuel-air-ratio data were compared on a percentage excess fuel basis rather than on a fuel-air basis and the exhaust-pressure data were compared on either an exhaust to inlet pressure ratio basis or inlet to exhaust-pressure difference basis rather than on the basis of exhaust pressure.

INTRODUCTION

Tests were conducted at the NACA Cleveland laboratory during April and May 1945 to determine the effect of engine operating variables on the knock-limited performances of a sensitive and a relatively insensitive fuel and to correlate the effects of engine variables on the knock limits of fuels in a full-scale air-cooled cylinder. Data were obtained to show to what extent fuel-air ratio, compression ratio, inlet-air temperature, spark advance, exhaust pressure, and cylinder temperature affected the knock limits of a sensitive fuel compared with a relatively insensitive fuel. Sensitivity of a fuel is indicated by the degree of response of the knock-limited indicated mean effective pressure and the charge-air flow to changes in engine operating conditions.

APPARATUS AND PROCEDURE

The full-scale air-cooled single-cylinder test setup used in this investigation is shown in figures 1 and 2. A special high-compression-ratio piston was used in place of a standard piston. All the tests were run with the fuel injected upstream of the vaporization tank.

Mixture temperature was obtained with an iron-constantan thermocouple in the center of the passage downstream of the vaporization tank. Cylinder temperatures were measured by iron-constantan thermocouples at the rear spark-plug bushing (at a point one-fourth in. below the spark plug and about one-half in. from the combustion chamber), at the exhaust end zone (in the head approximately one-eighth in. from the combustion chamber, one-fourth in. above the barrel, and 30° to the rear of the cylinder from the exhaust side of the head), and at the rear middle barrel.

The difference between the static pressure of the cooling air in front of and behind the cylinder was used as the cooling-air pressure drop. This pressure drop was multiplied by σ, the ratio of the density of air ahead of the cylinder to a standard air density of 0.0765 pound per cubic foot.

All tests were conducted at an engine speed of 2100 rpm. Each engine variable was investigated separately. The range of each variable and the basic value at which it was maintained in the tests of each of the other variables are given in the following table:

Engine variable	Basic value	Range investigated
Fuel-air ratio	0.078	0.058-0.112
Compression ratio	6.9	6.9-10
Inlet-air temperature, °F	200	150-325
Spark advance, both plugs, deg. B.T.C.	20	15-40
Exhaust pressure, in. Hg. absolute	10	10-73
Cylinder temperature at exhaust end zone, °F	500	446-500

SELECTION OF FUELS

The sensitive fuel was obtained by blending 42 percent S reference fuel, 40 percent toluene, and 18 percent M reference fuel by volume plus 4 ml TEL per gallon. For this fuel F-3 and F-4 ratings of 103 and 145 performance number, respectively, were obtained at the NACA Cleveland laboratory.

The insensitive fuel consisted of 100 percent S reference fuel with a concentration of TEL per gallon sufficient to cause the knock-limited performance to equal that of the sensitive fuel at the basic engine conditions. A fuel-air ratio of 0.08 was originally selected as a basic value but was changed to 0.078 when preliminary tests on the full-scale air-cooled cylinder showed that the knock limit of S reference fuel plus 4 ml TEL per gallon matched the knock limit of the sensitive fuel at a fuel-air ratio of 0.078. The F-3 and F-4 ratings (153 performance number) of the insensitive fuel are by definition the same.

RESULTS AND DISCUSSION

From a consideration of the differences in F-3 and F-4 ratings of the two fuels, the sensitive fuel would be expected to show the greatest change of knock-limited performance with varying engine operating conditions. That this result did occur is shown by the knock-limited performances of the two fuels presented in figures 3 to 8.

The engine performance with the sensitive fuel differed from that with the insensitive fuel in that the sensitive fuel imposed a higher cooling load on the cylinder than the insensitive fuel. This higher cooling load, as indicated by the higher cooling-air pressure drops at the basic engine conditions, occurred in spite of the fact that the mixture temperature with the sensitive fuel was about 5° F lower than that with the insensitive fuel. The difference in mixture temperature is attributed to the heats of vaporization of the fuels, whereas the difference in cooling loads is attributed to combustion characteristics.

The temperature of the rear spark-plug bushing varied during the tests, (in all of the tests except the cylinder-temperature test, the exhaust end-zone temperature was held constant at 500° F) thus indicating changes in the temperature distribution of the cylinder head. These changes in cylinder temperature distribution probably had little effect on the knock-test results because varying the cylinder temperature (fig. 8) had little effect on the knock limits of either fuel.

The range of cylinder-temperature tests was limited by the maximum cooling-air pressure drop available and by the poor sealing of the piston rings at exhaust end-zone temperatures higher than 500° F. Changes in the sealing of the piston rings were indicated by erratic increases in the crankcase pressure (from a normal value of 3 in. to more than 7 in. of water) and increases in barrel temperature from about 30° to 50° F. This condition occurred more often with the sensitive fuel than with the insensitive fuel and in most cases the erratic increases in crankcase pressure were accompanied by rough running. This same effect of high cylinder temperature also occurred in the variable exhaust-pressure tests. Short periods of operation under such conditions caused extremely rapid wear of piston rings, which necessitated frequent replacement.

Indicated specific fuel consumptions were approximately the same for both fuels except for a small difference at lean mixtures in the variable fuel-air-ratio tests (fig. 3). The difference in specific fuel consumptions near the stoichiometric fuel-air ratios (0.069 for sensitive fuel and 0.066 for insensitive fuel) is attributed to the chemical properties of the fuels. The decrease in indicated specific fuel consumption with high exhaust pressure (fig. 7) did not appear as an equal reduction in brake specific fuel consumption because the motoring horsepower of the engine increased at the higher exhaust pressures.

The knock-limited indicated mean effective pressures presented in figures 3 to 8 are replotted in figure 9 and the corresponding knock-limited charge-air flows are presented in figure 10. In order that the data can be more easily compared, each curve has been shifted, to compensate for day-to-day variations, so that all pass through a common point at the basic engine conditions. The amounts the curves were shifted are shown in the following table:

Variable	Amount of shift			
	Knock-limited charge-air flow (lb/hr)		Knock-limited imep (lb/sq in.)	
	Sensitive fuel	Insensitive fuel	Sensitive fuel	Insensitive fuel
Fuel-air ratio	0	-12	0	-4
Compression ratio	4	8	-1	3
Inlet-air temperature	14	13	1	3
Spark advance	12	10	5	6
Exhaust pressure	1	11	3	6
Cylinder temperature	7	10	3	6

The maximum shift of any of the curves is 2 percent of the values at the basic engine conditions.

Variations in knock-limited indicated mean effective pressure and charge-air flow show similar trends for both fuels (figs. 9 and 10). If the engine variables affected the knock limit of the sensitive fuel a constant amount relative to the insensitive fuel, a plot of the change of the knock limit of the sensitive fuel against that for the insensitive fuel would result in a straight line. The slope of the line would indicate the relative sensitivity of the two fuels. The fact that the data fall along several curved lines rather than a single straight line shows that the relative sensitivity was different for the six engine variables and varies over the range of the variable (fig. 11). The relative sensitivities at the basic conditions are as follows:

Variable	Relative sensitivity at the basic conditions	
	imep	Charge-air flow
Fuel-air ratio	2.6	2.1
Compression ratio	1.8	1.7
Inlet-air temperature	1.6	1.7
Spark advance	1.8	1.8
Exhaust pressure	1.3	1.3
Cylinder temperature	1.1	1.2

In the case of some variables, the variation of the relative sensitivity over the range investigated was quite large. Fuel-air ratios above the stoichiometric showed the greatest relative sensitivity of the knock limits of the two fuels, except for the tests at high exhaust pressures. The results of the variable exhaust-pressure tests differ considerably from the other test results. Increasing the severity of engine conditions by increasing compression ratio, inlet-air temperature, or spark advance decreased the relative sensitivity from that shown at the basic conditions. The change in knock limit with cylinder temperature was too small to show variation, if any, in the relative sensitivity. The variation of relative sensitivity of the two fuels to engine conditions indicates that, in order to correlate the effects of engine variables on knock-limited performance of fuels, more basic knock factors than knock-limited indicated mean effective pressure or charge-air flow are required.

The comparison of the effects of fuel-air ratio on the knock limits of the two fuels was improved by using percentage excess fuel (based on stoichiometric fuel-air ratio) rather than fuel-air ratio directly. Figure 12 shows that the relative sensitivity of the two fuels was decreased when determined on a percentage excess fuel basis rather than on a fuel-air-ratio basis and therefore was more consistent with the results of tests of the other engine variables except exhaust pressure. The use of a percentage excess fuel basis rather than a fuel-air-ratio basis, which improved the comparison of the fuel-air-ratio test results, indicates that the comparison of other engine variable test results should have been made on a percentage excess fuel basis. The higher cooling load on the engine when using the sensitive fuel at the basic engine conditions compared with the insensitive fuel was due in part to the fact that a fuel-air ratio of 0.078 is 13 percent excess fuel for the sensitive fuel and 18 percent for the insensitive fuel.

This difference in excess fuel at a fuel-air ratio of 0.078 undoubtedly has a large effect on the exhaust-pressure tests through its effect on the temperature of the residual gases. A higher residual gas temperature with the sensitive fuel could account in part for the increase in relative sensitivity at high exhaust pressures.

The relative sensitivity of the knock limits of the fuels to exhaust pressure is shown in figure 13 on both an exhaust to inlet pressure ratio basis and an inlet pressure minus exhaust pressure bases. Both methods show an improvement over using exhaust pressure alone in that the results are much more consistent with those of the other variables tested. Data presented herein are too limited to prove which of the two methods is actually the best to use.

The comparison of knock-test results was improved when the exhaust pressure was related to the inlet pressure, which indicates that in comparing the sensitivities of the knock limits of fuels to engine variables a constant relation of exhaust pressure to inlet pressure should be maintained rather than a constant exhaust pressure. In the fuel-air-ratio tests, for example, the exhaust to inlet pressure ratio varied from 0.19 to 0.15 and 0.18 to 0.16 for the sensitive and insensitive fuels, respectively. Holding a constant exhaust to inlet pressure relation would have tended to lower the relative sensitivity of the knock limit of the two fuels.

SUMMARY OF RESULTS

From knock tests of two fuels of different sensitivity in which six engine variables were investigated on a full-scale air-cooled cylinder it was found that the relative changes in the knock-limited indicated mean effective pressure and the charge-air flow of the two fuels were different for the six engine variables and, except for cylinder temperature, varied over the ranges of the variables. These results indicate that, in order to correlate the effects of engine variables on knock-limited performance of fuels, more basic knock factors than knock-limited indicated mean effective pressure or charge-air flow are required. Fuel-air ratios above the stoichiometric showed the greatest sensitivity of the knock limits of the two fuels, except for tests at high exhaust pressure. The relative sensitivities shown in fuel-air-ratio and exhaust-pressure tests became more consistent with those for the other engine variables when the fuel-air-ratio data were compared on a percentage excess fuel basis and the exhaust-pressure data were compared on either an exhaust to inlet pressure ratio basis or inlet to exhaust pressure difference basis.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 4, 1946.

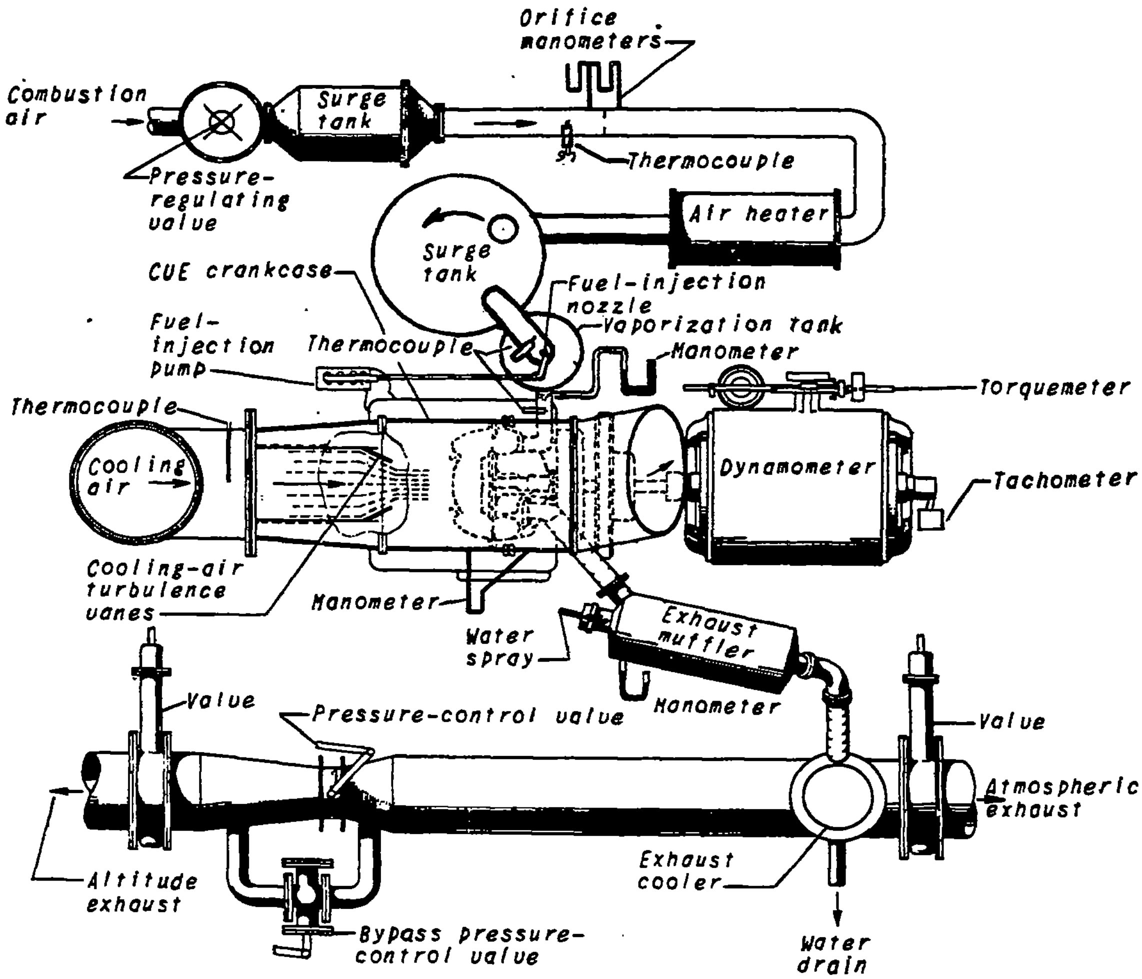

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Figure 1. - Arrangement of apparatus for full-scale air-cooled single-cylinder test setup.

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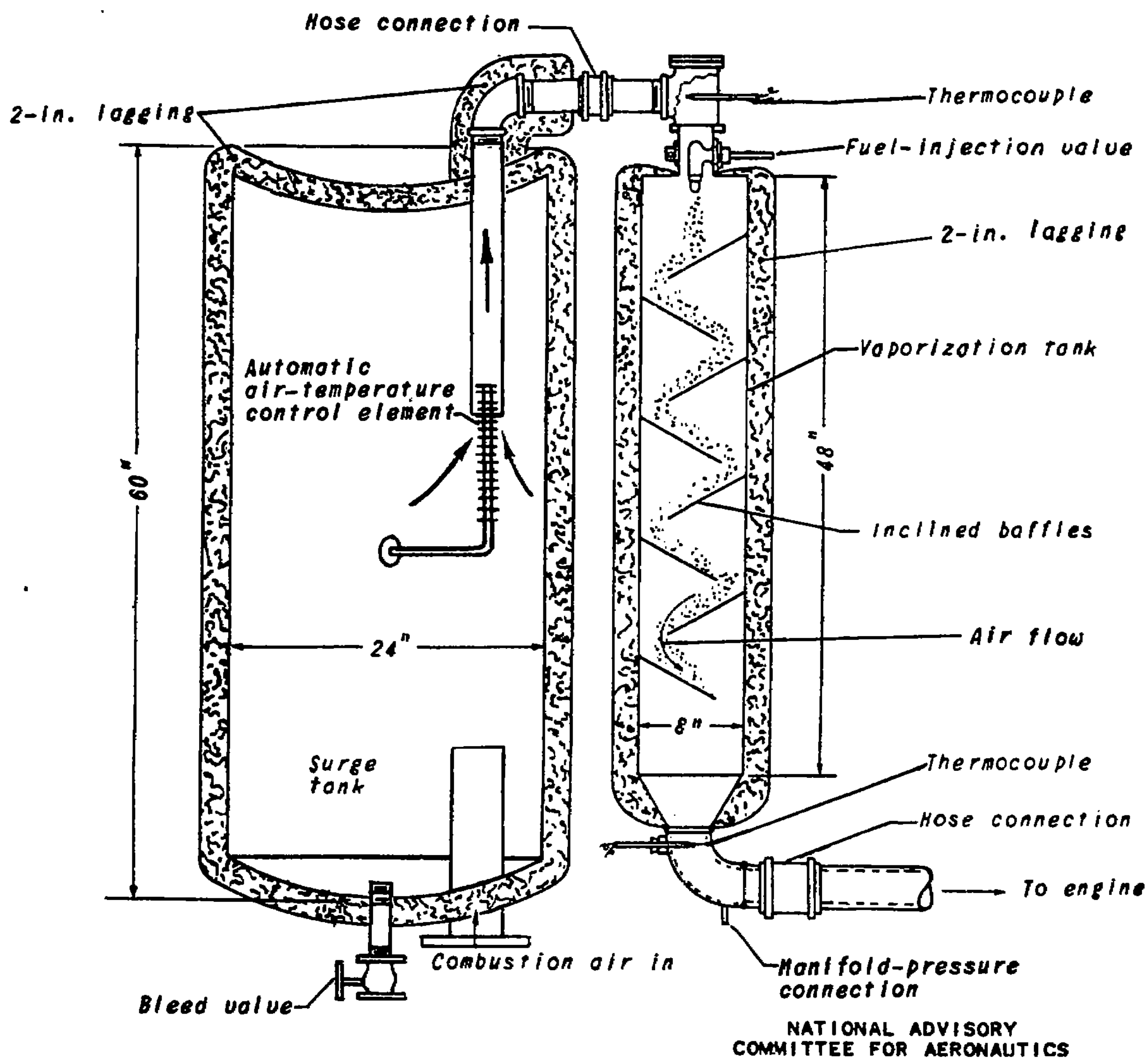


Figure 2. - Surge tank and fuel-vaporization tank for full-scale air-cooled single-cylinder test setup.

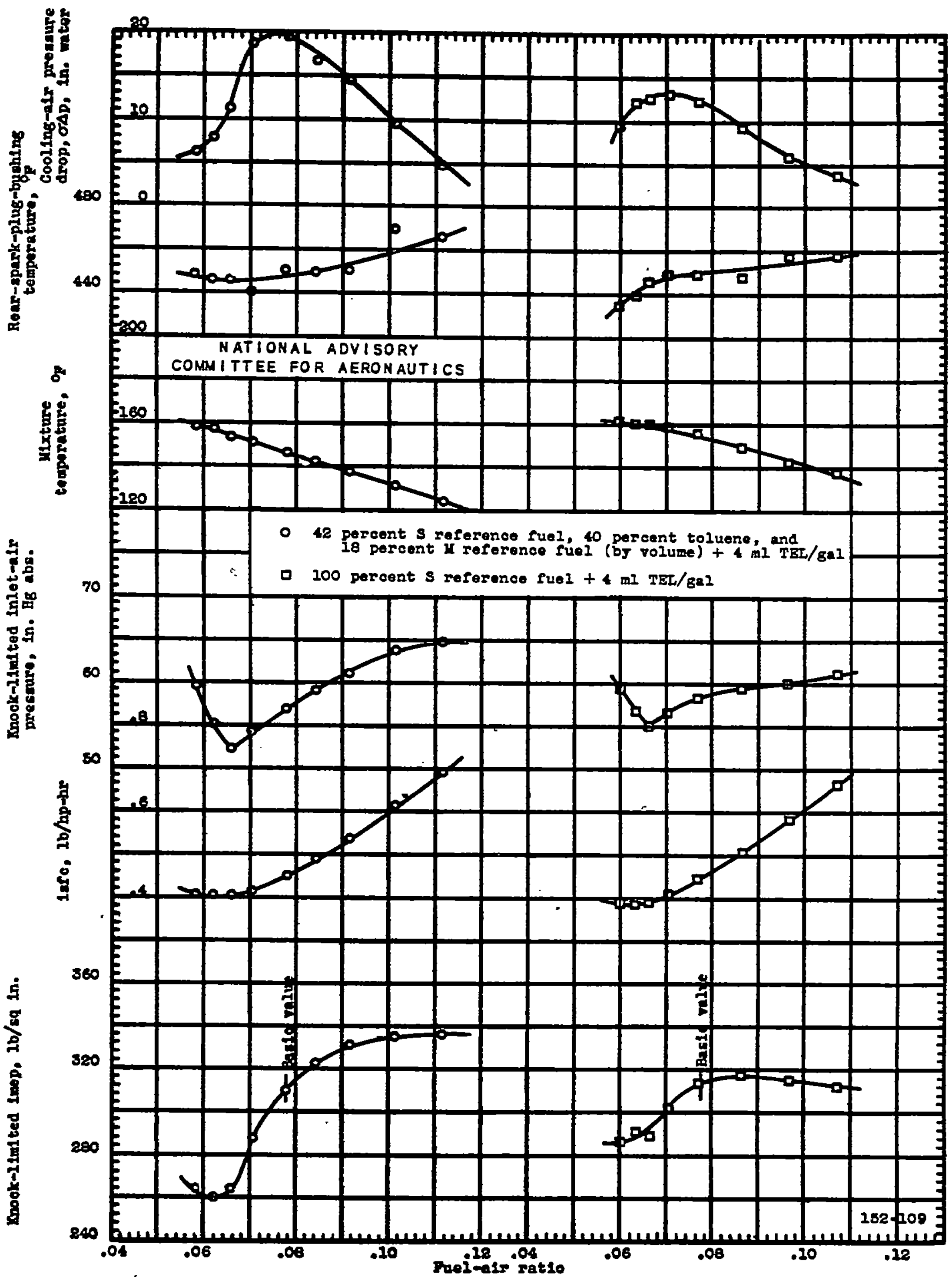


Figure 3. - Effect of fuel-air ratio on knock-limited performance of two fuels. Full-scale air-cooled cylinder; engine speed, 2100 rpm; compression ratio, 6.9; inlet-air temperature, 200 °F; spark advance, both plugs, 20° B.T.C., exhaust pressure, 10 inches mercury absolute; cylinder temperature at exhaust end zone, 500 °F.

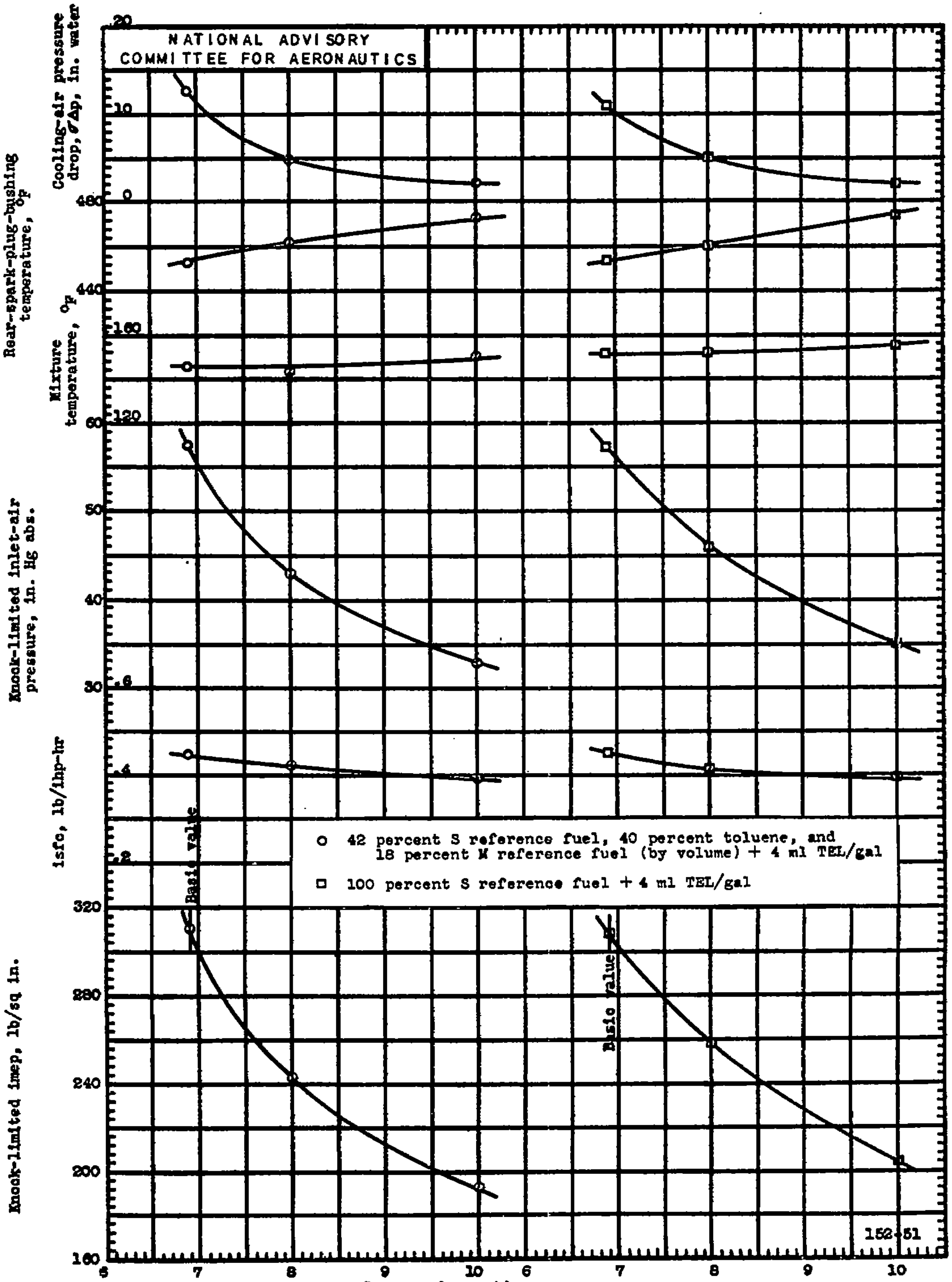


Figure 4. - Effect of compression ratio on knock-limited performance of two fuels. Full-scale air-cooled cylinder; engine speed, 2100 rpm; fuel-air ratio, 0.078; inlet-air temperature, 200 °F; spark advance, both plugs, 20° B.T.C.; exhaust pressure, 10 inches mercury absolute; cylinder temperature at exhaust end zone, 500 °F.

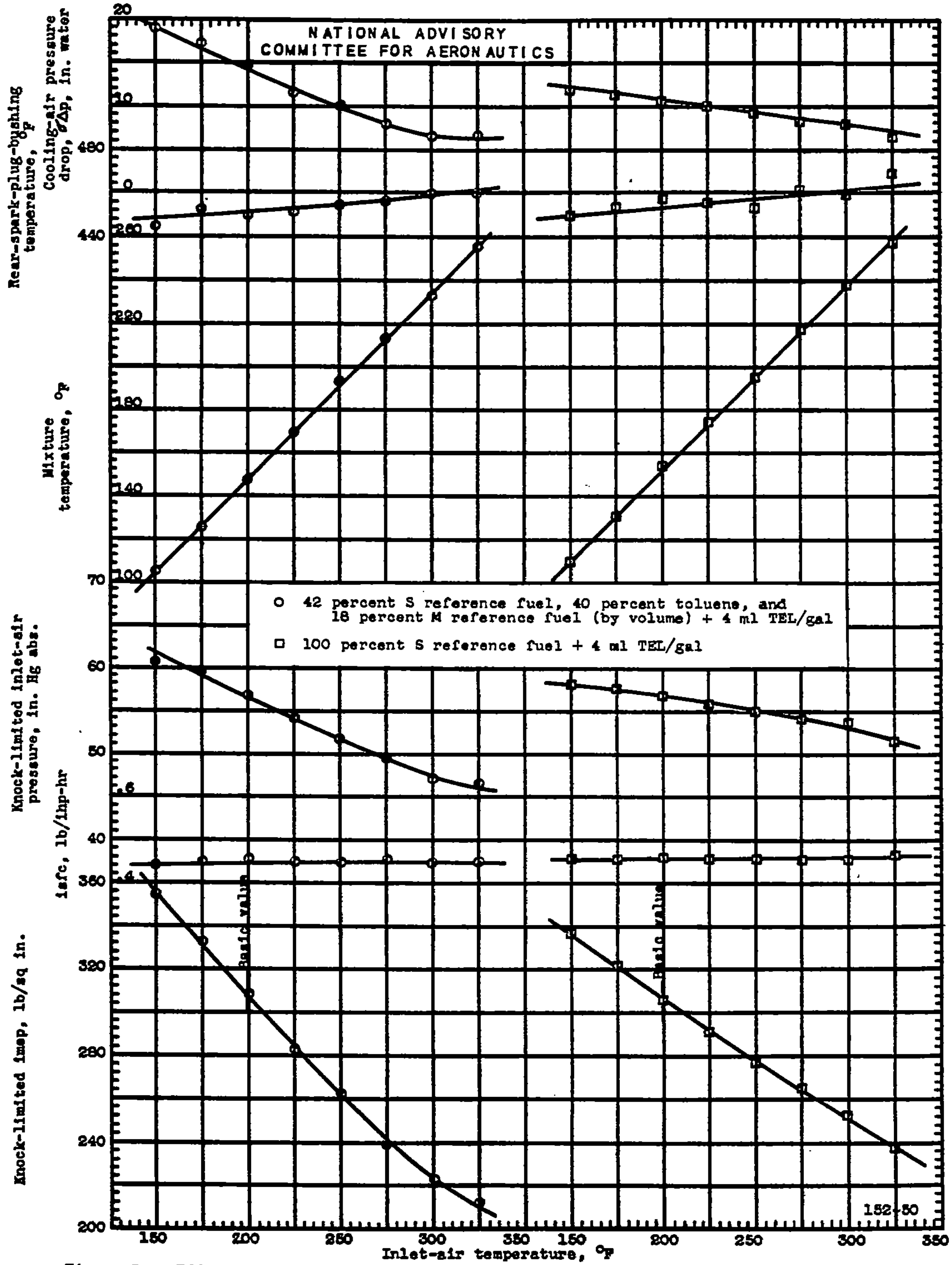


Figure 5. - Effect of inlet-air temperature on knock-limited performance of two fuels. Full-scale air-cooled cylinder; engine speed, 2100 rpm; fuel-air ratio, 0.078; compression ratio, 6.9; spark advance, both plugs, 20° B.T.C.; exhaust pressure, 10 inches mercury absolute; cylinder temperature at exhaust end zone, 500° F.

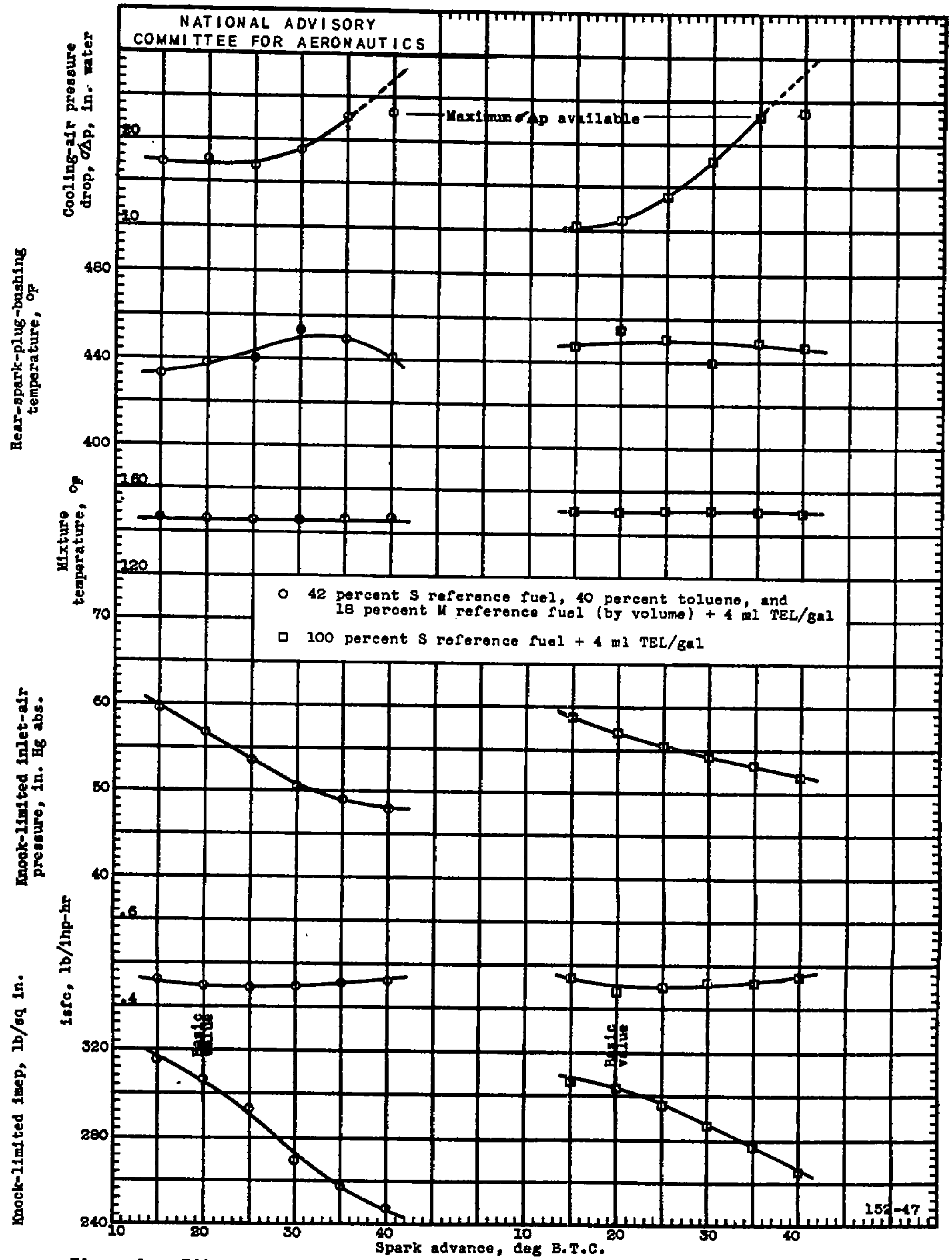


Figure 6. - Effect of spark advance on knock-limited performance of two fuels. Full-scale air-cooled cylinder; engine speed, 2100 rpm; fuel-air ratio, 0.078; compression ratio, 6.9; inlet-air temperature, 200° F; exhaust pressure, 10 inches mercury absolute; cylinder temperature at exhaust end zone, 500° F.

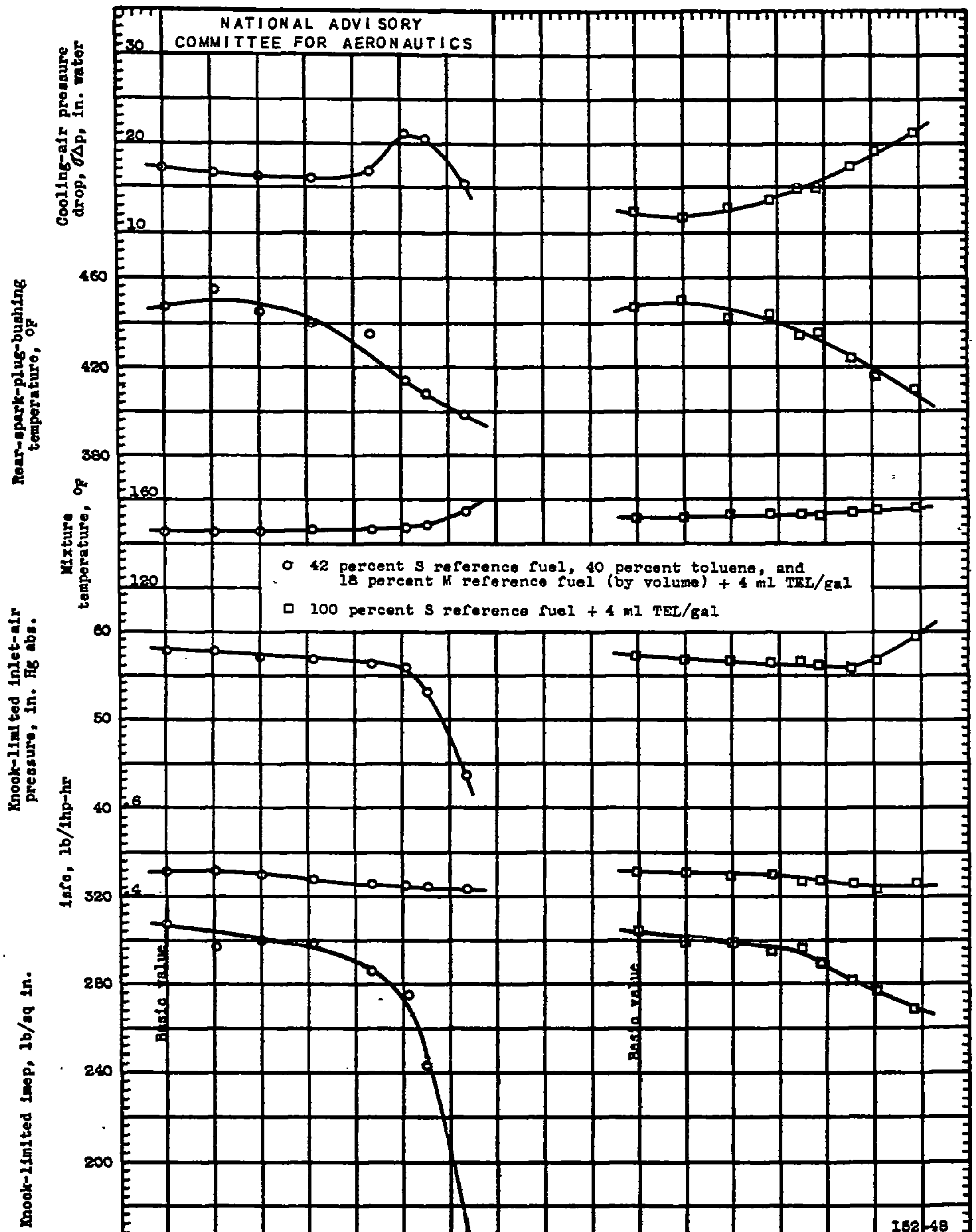


Figure 7. - Effect of exhaust pressure on knock-limited performance of two fuels. Full-scale air-cooled cylinder; engine speed, 2100 rpm; fuel-air ratio, 0.078; compression ratio, 6.9; inlet-air temperature, 200° F; spark advance, both plugs, 20° B.T.C.; cylinder temperature at exhaust end zone, 500° F.

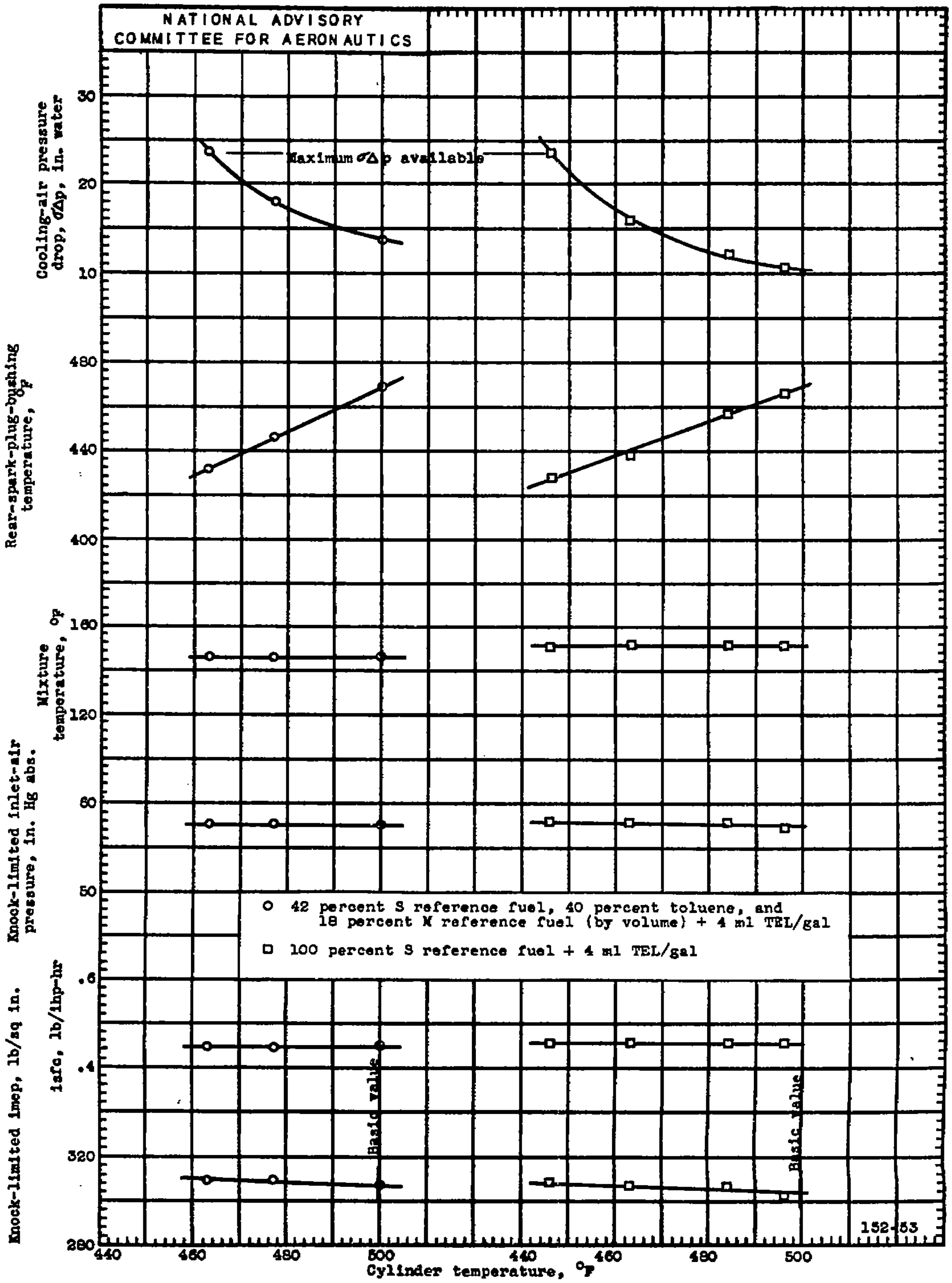


Figure 8. - Effect of cylinder temperature at the exhaust end zone on knock-limited performance of two fuels. Full-scale air-cooled cylinder; engine speed, 2100 rpm; fuel-air ratio, 0.078; compression ratio, 6.9; inlet-air temperature, 200° F; spark advance, both plugs, 20° B.T.C.; exhaust pressure, 10 inches mercury absolute.

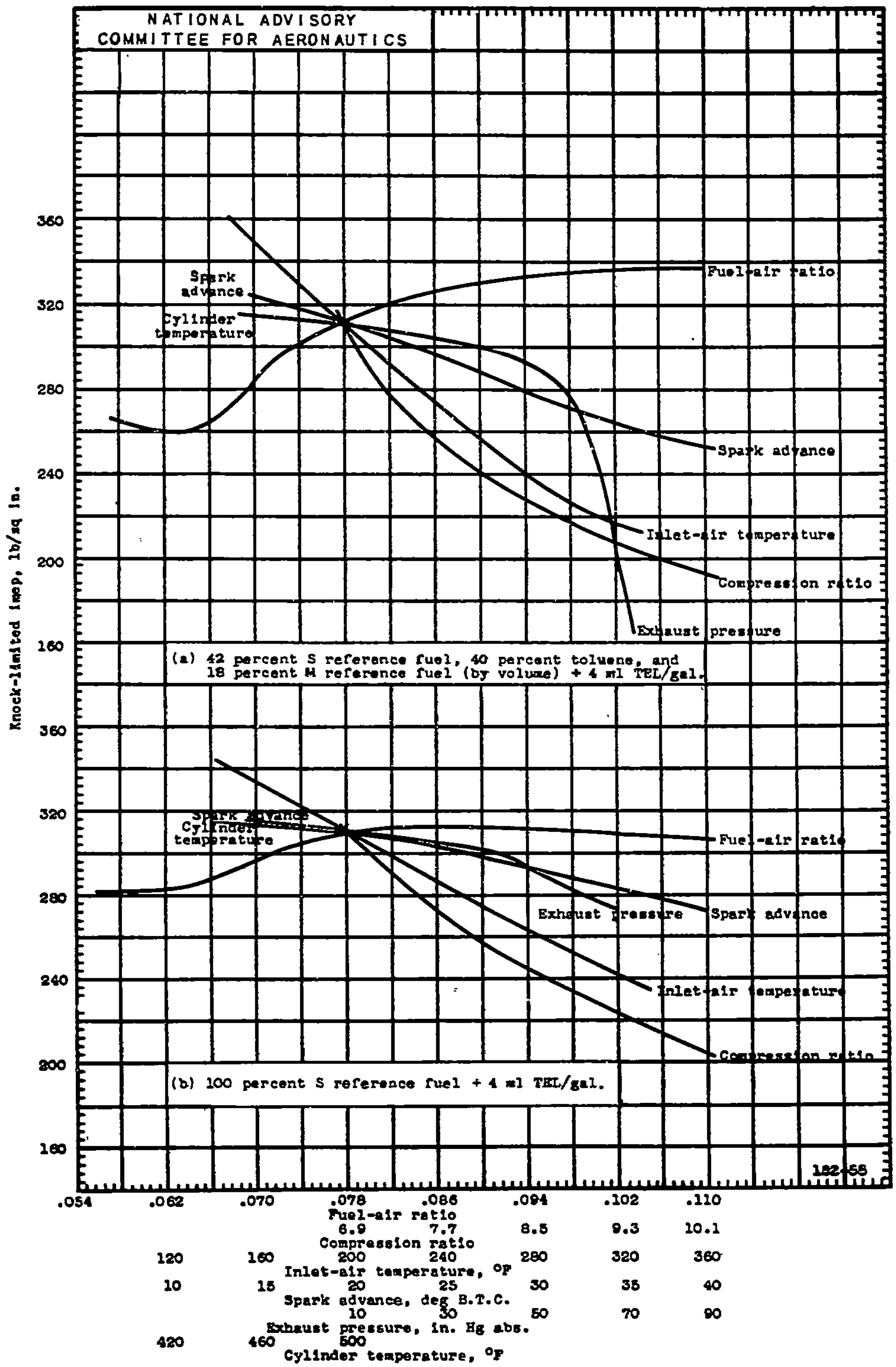


Figure 9. - Comparison of effects of six engine variables on knock-limited indicated mean effective pressure of two fuels. Full-scale air-cooled cylinder; engine speed, 2100 rpm. (Each engine variable was investigated separately; the others were maintained constant at the value shown for the point common to all the curves.)

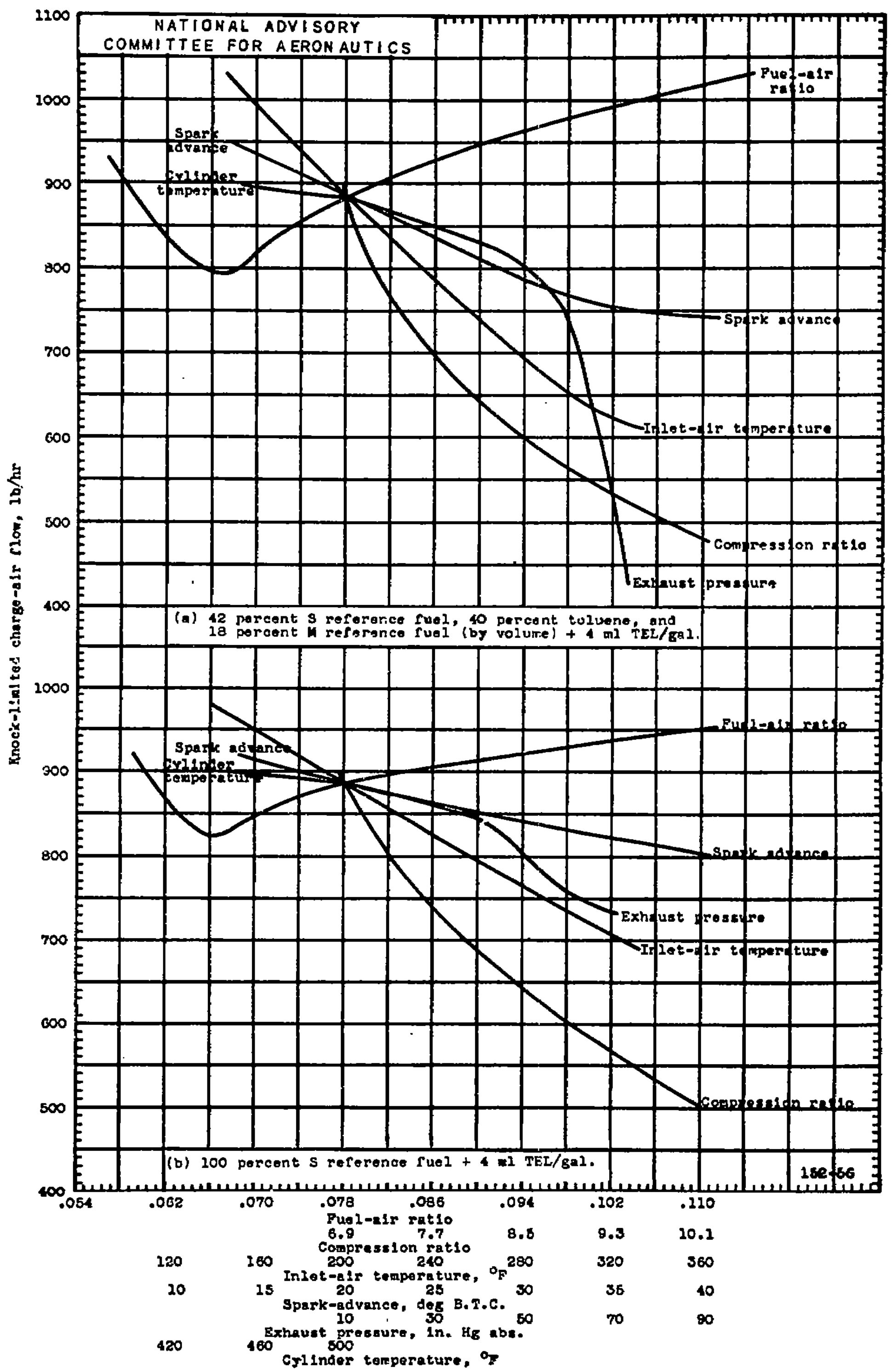


Figure 10. - Comparison of effects of six engine variables on knock-limited charge-air flow of two fuels. Full-scale air-cooled cylinder; engine speed, 2100 rpm. (Each engine variable was investigated separately; the others were maintained constant at the value shown for the point common to all the curves.)

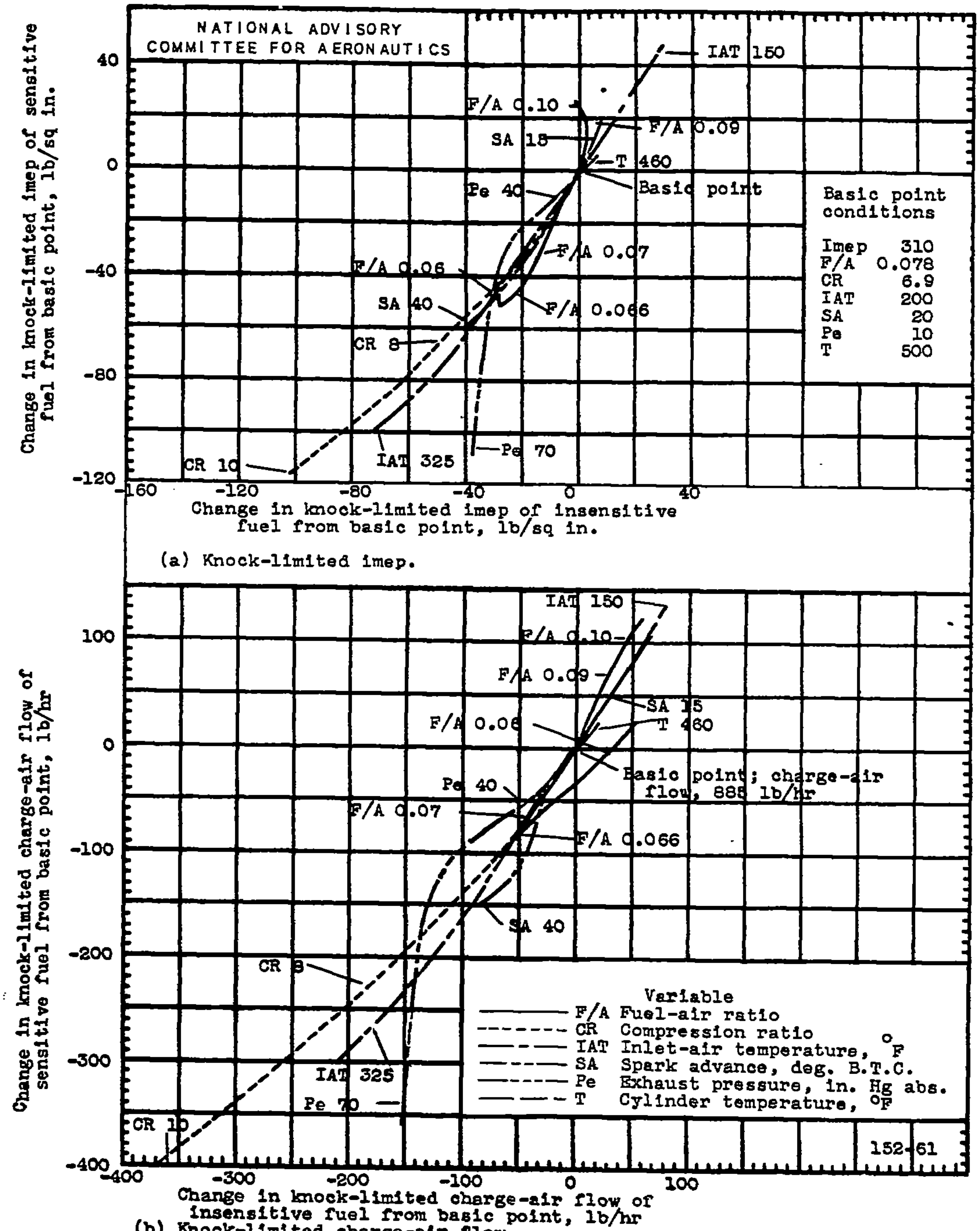
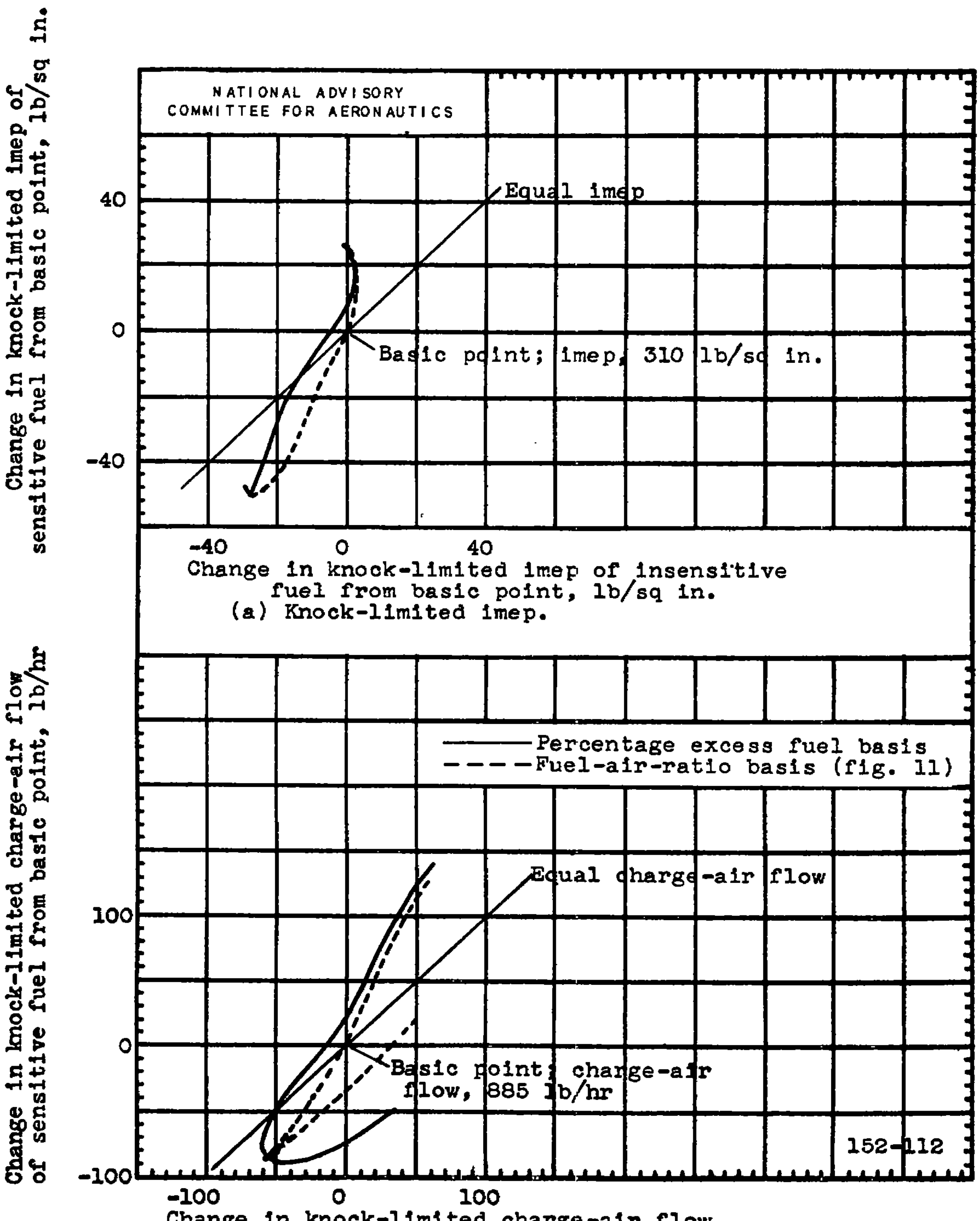


Figure 11. - Comparison of changes in knock-limited performances of sensitive fuel (42 percent S reference fuel, 40 percent toluene, and 18 percent M reference fuel by volume + 4 ml TEL/gal) and insensitive fuel (100 percent S reference fuel + 4 ml TEL/gal) in full-scale air-cooled cylinder.



(a) Knock-limited imep.

(b) Knock-limited charge-air flow.

Figure 12. - Effect of comparing fuel-air-ratio knock-test data on percentage excess fuel basis rather than fuel-air-ratio basis.

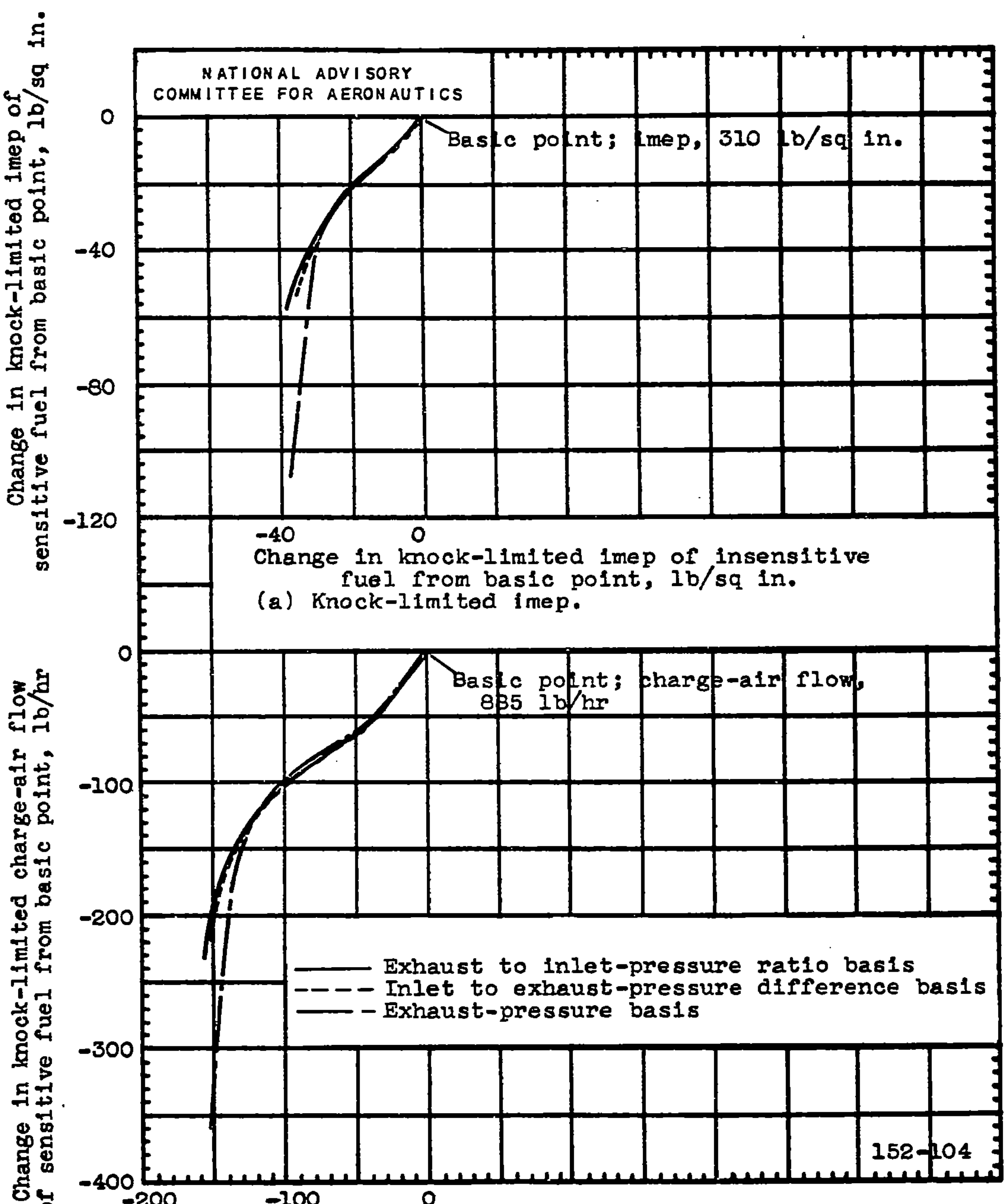


Figure 13. - Effect of comparing exhaust-pressure knock-test data on exhaust pressure to inlet-pressure ratio and inlet to exhaust-pressure difference basis rather than exhaust-pressure basis.