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EFFECT OF INTERNAL COOLANTS ON THE KNOCK-LIMITED PERFORMANCE OF A LIQUID-COOLED MULTICYLINDER AIRCRAFT ENGINE WITH A COMPRESSION RATIO OF 6.0

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MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

EFFECT OF INTERNAL COOLANTS ON THE KNOCK-LIMITED PERFORMANCE OF A LIQUID-COOLED MULTICYLINDER AIRCRAFT ENGINE WITH A COMPRESSION RATIO OF 6.0

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SUMMARY

An investigation was conducted to determine the effect of internal coolants on the knock-limited performance of a liquid-cooled multicylinder aircraft engine with a displacement of 1710 cubic inches and a compression ratio of 6.0. Knock-limited performance tests were conducted at an engine speed of 3000 rpm, fuel-air ratios from 0.075 to 0.085, carburetor-air temperatures of 120° and 60° F, and with water and water-ethanol as internal coolants. Each internal coolant was injected in turn through the fuel-spray nozzle and through intake-manifold spray jets. All tests were conducted with 28-R fuel.

The following results were obtained:

1. The maximum knock-limited brake horsepower attained was 2310 at a fuel-air ratio of 0.079 and a carburetor-air temperature of 60° F with 663 pounds per hour of water-ethanol introduced with the fuel through the fuel-spray nozzle.

2. In general, at low internal-coolant flows or at the high carburetor-air temperature, water was more effective than water-ethanol in raising the knock-limited brake horsepower. As the internal-coolant flow was increased or the carburetor-air temperature decreased, water-ethanol became more effective than water.

3. Fuel-nozzle injection of a given internal coolant at a given carburetor-air temperature was generally more effective in raising the knock-limited brake horsepower than injection through intake-manifold spray jets.

4. Except at some of the lower internal-coolant flows a higher manifold pressure was required to obtain a given knock-limited brake horsepower by means of internal-coolant injection than by means of lowering the carburetor-air temperature.

INTRODUCTION

At the request of the Air Technical Service Command, Army Air Forces, tests are being conducted at the NACA laboratory in Cleveland to evaluate several methods of increasing the power output of a liquid-cooled multicylinder aircraft engine. The effect of water injection through 12 spray jets in the intake manifolds on the knock-limited performance was determined by tests reported in reference 1.

This report presents the results of tests conducted from July to December 1944 to determine the effects of internal coolants on the knock-limited performance of test engine with a compression ratio of 6.0. The data were obtained from eight series of knock tests using two internal coolants injected by each of two methods at carburetor-air temperatures of 120° and 60° F. Tap water and a mixture consisting of 50 percent water and 50 percent ethanol by volume were used as internal coolants. Each internal coolant was injected with the fuel through the fuel spray nozzle and also through 12 spray jets mounted in the intake manifolds.

APPARATUS

Engine. - The tests were conducted on three V-type 12-cylinder liquid-cooled aircraft engines of 1710-cubic-inch displacement fitted with pistons giving a compression ratio of 6.0. In order to decrease the possibilities of piston failure, the diametral clearances between the pistons and the cylinder walls were increased 0.008 inch over the standard diametral clearances. Each cylinder had two spark plugs, one between the two exhaust valves and one between the two intake valves. The engines are equipped with single-speed, single-stage superchargers with impeller diameters of $9\frac{1}{2}$ inches and gear ratios of 9.6:1.

Engine installation. - The engine-dynamometer installation was the same as that used for the tests of reference 1. The external coolant was a mixture of 70 percent water and 30 percent ethylene glycol by volume. The laboratory refrigerated-air system supplied dry combustion air by first cooling atmospheric air and then heating it to the desired temperature. The engine was fitted with special water-jacketed exhaust stacks having inside diameters of $1\frac{7}{16}$ inches.

This size represents a reduction in diameter of 1/4 inch below the diameter of the exhaust-valve-port outlets and a reduction in area of 27.4 percent. The exhaust gases were carried away through a 12-inch-diameter gallery within which exhaust-gas cooling was accomplished by multiple sprays of water. Pressure in the gallery was held slightly below atmospheric by an exhauster fan.

Internal-coolant injection equipment. - Two internal-coolant injection systems were used. In one system the internal coolant was introduced continuously with the fuel through the fuel spray nozzle, which sprayed the liquid into the supercharger inducer. Internal coolant was supplied to the fuel spray nozzle by a line from a tank where the internal coolant was kept under pressure by compressed air. Internal-coolant flow rates were measured by a calibrated rotameter in the line from the tank to the fuel nozzle.

In the second system, internal coolant was continuously injected through 12 spray jets inserted into the intake manifolds through holes drilled in the top of the manifolds about 1 inch back from the faces of the manifold mounting flanges. The spray jets were 5/32-inch-diameter stainless-steel tubing about $2\frac{1}{2}$ inches long with six holes, 0.025 inch in diameter, arranged in two rows of three holes each to spray internal coolant directly into each intake port. The spray jets and their installation are shown in figures 1 and 2 of reference 1. Internal coolant was supplied to the spray jets by individual lines from a tank where it was kept under pressure by compressed air. Internal-coolant flow rates were measured by calibrated rotameters in the individual lines.

Special equipment and instrumentation. - Vibration-type pickup units were used for knock detection. Knock indication was by means of an amplifier-oscilloscope combination in which a commutator was used to reduce background interference.

Fuel-air mixture control was facilitated by the use of an air-bleed valve connected across the air diaphragm in the metering section of the carburetor.

Carburetor-inlet static pressure was measured by a mercury manometer connected to a static-pressure tap. This tap was located on the combustion-air stack $4\frac{5}{16}$ inches upstream from the carburetor face at a point where the cross-sectional area of the stack was 12.5 square inches. Carburetor static-pressure drop was measured by a mercury manometer connected to the pressure taps on the carburetor.

Carburetor-air temperatures were measured by eight iron-constantan thermocouples connected in parallel and arranged to survey the air stream immediately ahead of the carburetor. Mixture-temperature data reported herein were obtained with an unshielded thermocouple inserted to the center of the central manifold approximately $9\frac{1}{4}$ inches downstream from the flange of the supercharger outlet; therefore, when internal coolant was injected through spray jets in the intake manifolds, mixture-temperature measurements were made upstream from the points of injection. Another unshielded thermocouple inserted through the right rear-manifold primer hole was used for checking mixture temperatures. Readings from this thermocouple, which are not presented in this report, were approximately 10° F higher than those from the central-manifold thermocouple.

TEST CONDITIONS AND PROCEDURE

The two internal coolants used were tap water and a mixture, by volume, consisting of 50 percent water and 50 percent ethanol (ethyl alcohol denatured with 5 percent methyl alcohol). Knock tests were conducted at fuel-air ratios from 0.075 to 0.085 with as great a range of internal-coolant flow as was possible under limitations imposed by auxiliary equipment at each of the following combinations of conditions:

Series	Carburetor-air temperature (°F)	Internal coolant	Means of internal-coolant injection
1	120	Water-ethanol	Fuel nozzle
2	60	---do--------	Do.
3	120	---do--------	Intake-manifold spray jets
4	60	---do--------	Do.
5	120	Water	Fuel nozzle
6	60	---do--------	Do.
7	120	---do--------	Intake-manifold spray jets
8	60	---do--------	Do.

For the tests of series 6, the first tests conducted in this program, knock points were obtained at five values of constant manifold pressure. In this series internal-coolant flow was gradually increased to suppress knock as the manifold pressure was raised to the desired value. When the desired manifold pressure was obtained, internal-coolant flow was decreased until knock was observed.

In the subsequent tests (every series except 6) knock curves were obtained at each of several constant internal-coolant flows by maintaining the desired internal-coolant flow while the manifold pressure was increased until knock was observed. This method was used because it was found to offer simpler control features than the first method.

In all tests the fuel-air ratio was held within the desired range by manipulation of the air-bleed valve connected across the carburetor-air diaphragm. The data were taken at a medium knock intensity; that is, when the oscilloscope indicated that three to five cylinders were knocking.

The following engine conditions were maintained during all tests:

Engine speed, rpm	3000 ±5
External coolant-out temperature, °F	250 ±5
Oil-in temperature, °F	170 ±5
Spark advance, deg B.T.C.	
Exhaust	34
Intake	28

All tests were conducted with 28-R fuel.

RESULTS AND DISCUSSION

Effect of fuel-air ratio and internal-coolant flow on knock-limited performance. - Figures 1 to 4 present knock-limited engine performance data for the eight series of tests showing directly the effect of fuel-air ratio and internal-coolant flow on the knock-limited performance. The knock curves obtained consist of a number of knock points sufficient only to determine the correct values of the dependent engine variables at a fuel-air ratio of 0.08. The data therefore do not permit drawing knock curves of the proper curvature.

Knock points were obtained without internal coolants each day that tests were conducted. Figure 1 shows the variation in results obtained without internal coolants at carburetor-air temperatures of 120° and 60° F. Only the average curves for results without internal coolant are shown in the other figures. During the period in which tests were conducted the knock-limited horsepowers obtainable without internal coolants gradually increased. The reason for this increase is not known.

The maximum brake horsepower attained in these tests was 2310 at a fuel-air ratio of 0.079 and a carburetor-air temperature of 60° F with 663 pounds per hour of water-ethanol introduced with the fuel through the fuel spray nozzle (series 2, fig. 1(b)).

Comparison of internal coolants and methods of injection. - The knock-limited performance data of figures 1 to 4 are cross-plotted in figure 5 as functions of internal-coolant flow at a fuel-air ratio of 0.08 and are tabulated in table I to facilitate comparisons of the effects of the two internal coolants, methods of injection, and carburetor-air temperatures. Figure 5 shows that neither internal coolant was at all conditions more effective than the other in raising the knock-limited brake horsepower.

The following table shows the conditions at which each internal coolant was more effective than the other:

Carburetor-air temperature (°F)	Means of injection	Internal-coolant flow range (lb/hr)	Superior internal coolant
120	Fuel nozzle	0-530	Water
		530-max[a]	Water-ethanol
120	Spray jets	0-710	Water
		710-max[a]	Water-ethanol
60	Fuel nozzle	Entire range	Do.
60	Spray jets	0-410	Water
		410-max[a]	Water-ethanol

[a]Max indicates the maximum internal-coolant flow used in each case.

Introduction of the internal coolant through the fuel nozzle generally increased the knock-limited brake horsepower more than its introduction through the intake-manifold spray jets. With the same conditions of internal-coolant injection, lowering the carburetor-air temperature from 120° to 60° F raised the knock-limited brake horsepower in all cases.

On all curves of mixture temperature against internal-coolant flow (fig. 5) there is a point beyond which an increase in internal-coolant flow does not serve to lower the measured mixture temperature. This leveling of the curves is due to the fact that, as internal-coolant flow is increased, an increasing amount of internal coolant is carried past the mixture-temperature thermocouple before vaporizing.

Comparison of methods of lowering mixture temperature. - Figure 6 compares the effects on knock-limited brake horsepower and manifold pressure of lowering the mixture temperature by internal coolants and by lowering the carburetor-air temperature. Curves for internal-coolant injection have been cross-plotted at a fuel-air ratio of 0.08 from figures 1 to 4 and curves for variable carburetor-air temperature from unpublished data have been added for comparison. The vertical parts of the curves for fuel-nozzle injection in figure 6 result from the fact that, when the internal-coolant flows reached certain values, increases in internal-coolant flow failed to lower the measured mixture temperatures. Except at the low mixture temperatures, the knock-limited brake-horsepower curves for fuel-nozzle injection in figure 6 follow closely the curves for variable carburetor-air temperature. This agreement indicates that the effect of water or water-ethanol on knock-limited brake horsepower is primarily one of cooling the mixture.

Figure 7, cross-plotted from figure 6, shows the relation between knock-limited brake horsepower and manifold pressure with and without internal coolants. The engine was maintained at the knock limit over the power range in one case by varying the carburetor-air temperature without internal coolants and, in the other cases, by varying the internal-coolant flow rates with constant carburetor-air temperature. Figure 7 shows that except at some of the lower internal-coolant flows a higher manifold pressure is required to obtain a given knock-limited brake horsepower by means of internal-coolant injection than by means of lowering the carburetor-air temperature.

Horsepower correction for power required to supply high carburetor-inlet pressures. - Carburetor-inlet static pressures greater than sea-level pressure were required and were supplied by the laboratory refrigerated-air system for all tests in which the manifold pressure was higher than approximately 70 inches of mercury absolute. The data for knock-limited brake horsepower shown in figures 1 to 7 have not been corrected for the power required to supply carburetor-inlet static pressures greater than sea level.

Calculations, presented in the appendix, have been made to determine the approximate power required to supply carburetor-inlet static pressures higher than sea level used in each series of tests. The calculated powers have been subtracted from the knock-limited brake-horsepower data of figure 5 and the resulting corrected curves are presented in figure 8 together with the uncorrected curves traced from figure 5. From the curves of figure 8 it is evident that the correction changes only slightly the comparisons of the effects of the two internal coolants, methods of injection, and carburetor-air temperatures.

SUMMARY OF RESULTS

The following results were obtained from tests to determine the effect of internal coolants on the knock-limited performance of a V-type 12-cylinder liquid-cooled aircraft engine with a 1710-cubic-inch displacement and a compression ratio of 6.0:

1. The maximum knock-limited brake horsepower attained was 2310 at a fuel-air ratio of 0.079 and a carburetor-air temperature of 60° F with 663 pounds per hour of water-ethanol introduced with the fuel through the fuel-spray nozzle.

2. In general, at low internal-coolant flows or at the high carburetor-air temperature, water was more effective than water-ethanol in raising the knock-limited brake horsepower. As the internal-coolant flow was increased or the carburetor-air temperature decreased, water-ethanol became more effective than water.

3. Fuel-nozzle injection of a given internal coolant at a given carburetor-air temperature was generally more effective in raising the knock-limited brake horsepower than injection through intake-manifold spray jets.

4. Except at some of the lower internal-coolant flows a higher manifold pressure was required to obtain a given knock-limited brake horsepower by means of internal-coolant injection than by means of lowering the carburetor-air temperature.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, June 30, 1945.

APPENDIX - CALCULATION OF POWER REQUIRED TO SUPPLY CARBURETOR-INLET STATIC PRESSURES GREATER THAN SEA LEVEL

Carburetor-inlet static pressures greater than sea level were necessary for all tests in which the manifold pressure was greater than approximately 70 inches of mercury absolute. Figure 9 shows the relation between manifold pressure and the required carburetor-inlet static pressure at wide-open throttle for each series of tests. The power required to produce these carburetor-inlet pressures was supplied by the laboratory refrigerated-air system. Much of the knock limited brake-horsepower data of figures 1 to 7 are therefore higher than they would have been had the engine been charged with the power required to supply high carburetor-inlet pressures.

Calculations have been made to determine the approximate knock-limited brake horsepowers that would have been obtained if the engine had been equipped to supply its own high carburetor-inlet pressures.

It was assumed that:

(a) The increased carburetor-inlet pressures were obtained from an auxiliary-stage supercharger and the air leaving this supercharger was cooled by an intercooler so that the temperatures at the carburetor inlet were held constant at 120° and 60° F.

(b) The maximum intercooler effectiveness was 0.6.

(c) The temperatures of the intercooler cooling air and the air at the entrance to the auxiliary-stage supercharger were both constant at 95° and 35° F in order to obtain carburetor-inlet temperatures of 120° and 60° F, respectively. Intercooler drag was neglected.

(d) Intercooler cooling-air flow was varied by means of flaps in order to maintain constant carburetor-inlet temperatures with variable temperature rise through the auxiliary-stage supercharger.

(e) The charge-air pressure drop across the intercooler was in all cases 1 inch of mercury.

(f) The adiabatic efficiency of the auxiliary-stage supercharger was 68 percent.

(g) The mechanical efficiency of the auxiliary-stage supercharger drive was 95 percent.

The following equation was then used to determine auxiliary-stage supercharger horsepowers:

$$hp = \frac{W \frac{\gamma}{\gamma - 1} RT_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}{550\ \eta_{ad}\ \eta_m}$$

where

W charge-air flow, lb/sec

γ specific-heat ratio for air, 1.39

R gas constant, 53.5 ft-lb/(lb)(°F)

T_1 auxiliary-stage supercharger entrance temperature, °R

p_2 auxiliary-stage supercharger outlet pressure, in. Hg absolute

[p_2 = carburetor-inlet static pressure required, in. Hg absolute (from fig. 9) + intercooler pressure drop (1 in. Hg)]

p_1 atmospheric pressure, 29.92 in. Hg absolute

η_{ad} adiabatic efficiency, 68 percent

η_m mechanical efficiency of drive, 95 percent

The horsepowers obtained from this equation were subtracted from the knock-limited brake-horsepower data of figure 5 and the resulting corrected knock-limited brake-horsepower curves are shown in figure 8 together with the uncorrected curves traced from figure 5.

REFERENCE

1. Harries, Myron L., Nelson, R. Lee, and Berguson, Howard E.: Effect of Water Injection on Knock-Limited Performance of a V-Type 12-Cylinder Liquid-Cooled Engine. NACA Memo. rep., Sept. 9, 1944.

TABLE I - SUMMARY OF KNOCK-LIMITED PERFORMANCE

WITH AND WITHOUT INTERNAL COOLANTS

[V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R; fuel-air ratio, 0.08]

Internal coolant	Means of internal-coolant injection	Internal-coolant flow (lb/hr)	Brake horse-power	Increase over bhp without internal coolant (percent)	Manifold pressure (in. Hg absolute)	Increase over manifold pressure without internal coolant (percent)
Carburetor-air temperature, 120° F						
Water-ethanol	Fuel nozzle	0	1175	----------	52.7	----------
		200	1450	23.4	61.2	16.1
		400	1770	50.6	72.5	37.6
		600	1970	67.6	79.8	51.4
	Intake-manifold spray jets	0	1175	----------	52.7	----------
		200	1290	9.8	56.6	7.4
		400	1480	26.0	63.4	20.3
		600	1755	49.4	73.9	40.2
Water	Fuel nozzle	0	1175	----------	52.7	----------
		200	1650	40.4	67.5	28.1
		400	1810	54.0	73.5	39.5
		600	1925	63.8	78.2	48.4
	Intake-manifold spray jets	0	1175	----------	52.7	----------
		200	1465	24.7	63.0	19.6
		400	1645	40.0	70.1	33.0
		600	1795	52.8	76.5	45.2
Carburetor-air temperature, 60° F						
Water-ethanol	Fuel nozzle	0	1520	----------	63.1	----------
		200	1805	18.7	71.2	12.8
		400	2030	33.5	79.1	25.4
		600	2230	46.9	86.8	37.6
	Intake-manifold spray jets	0	1520	----------	63.1	----------
		200	1670	9.9	67.4	6.8
		400	1840	21.0	73.8	17.0
		600	2020	32.9	80.2	27.1
Water	Fuel nozzle	0	1520	----------	63.1	----------
		200	1780	17.1	70.8	12.0
		400	1950	28.3	75.6	19.8
		600	2010	32.2	79.2	25.5
	Intake-manifold spray jets	0	1520	----------	63.1	----------
		200	1740	14.5	70.5	11.7
		400	1840	21.0	74.4	17.9
		600	1940	27.6	78.5	24.4

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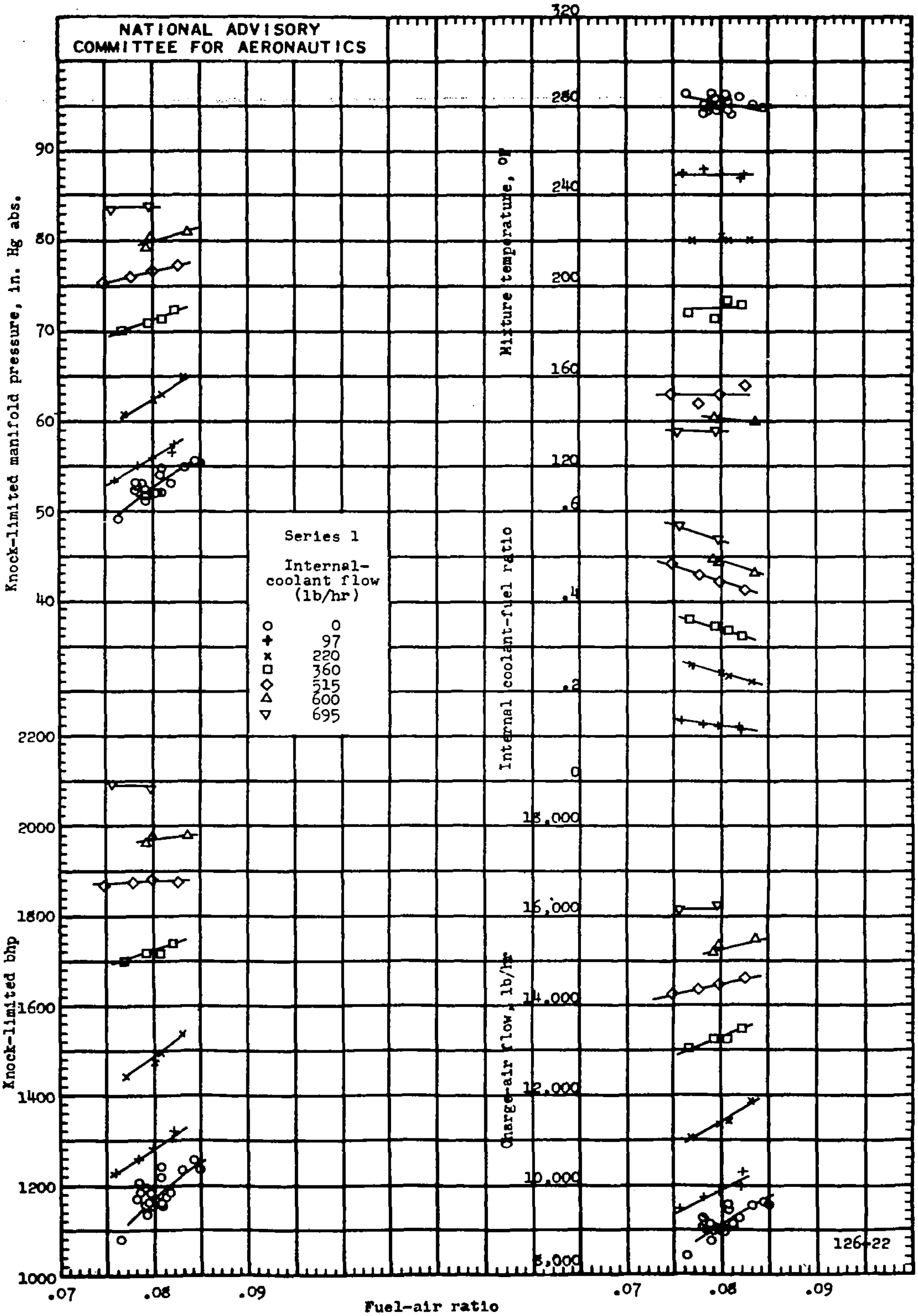
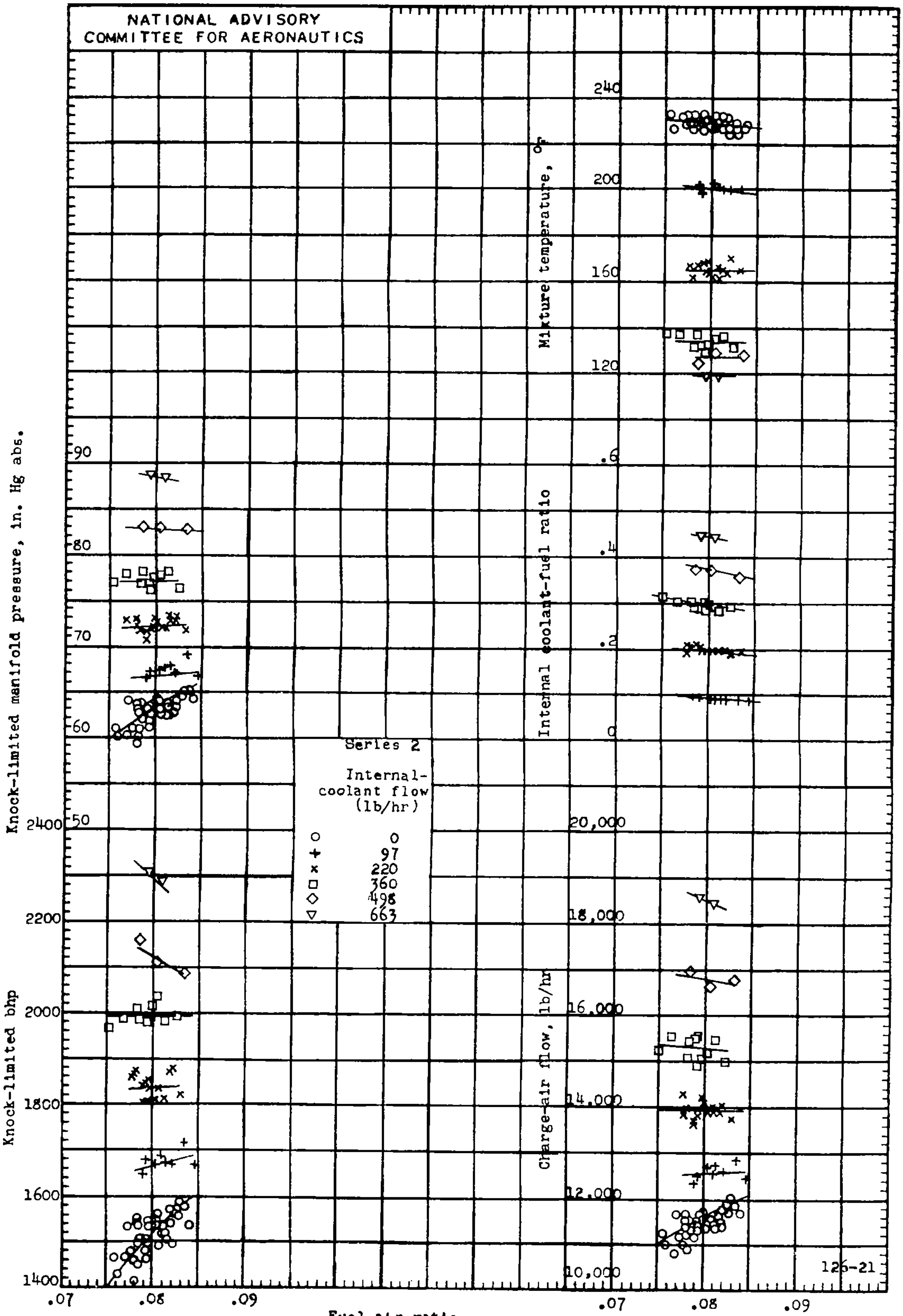
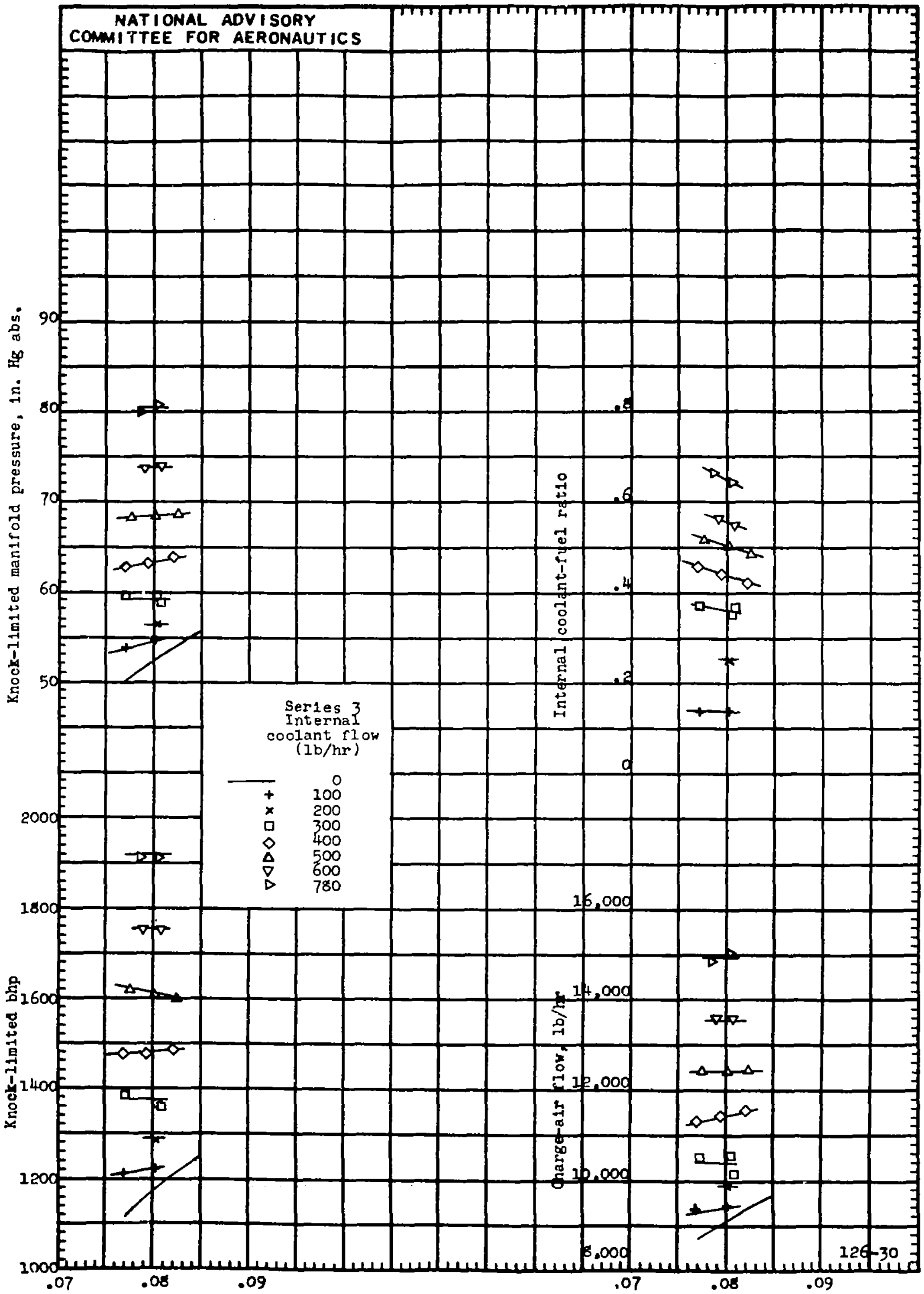


(a) Carburetor-air temperature, 120° F.

Figure 1. - Knock-limited data with a 50-50 mixture by volume of water-ethanol introduced with fuel through fuel nozzle. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R.

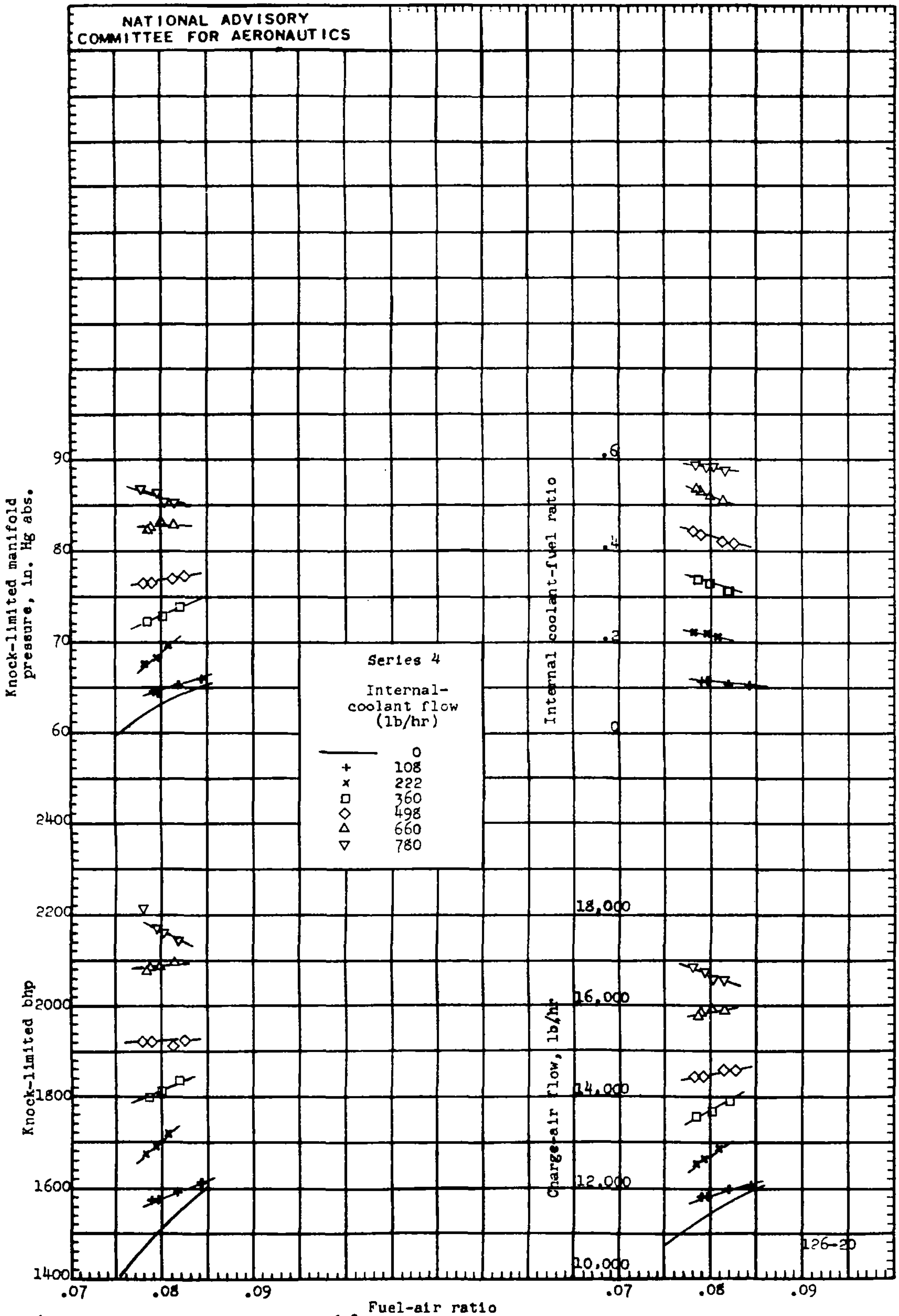


(b) Carburetor-air temperature, 60° F.
Figure 1. - Concluded.

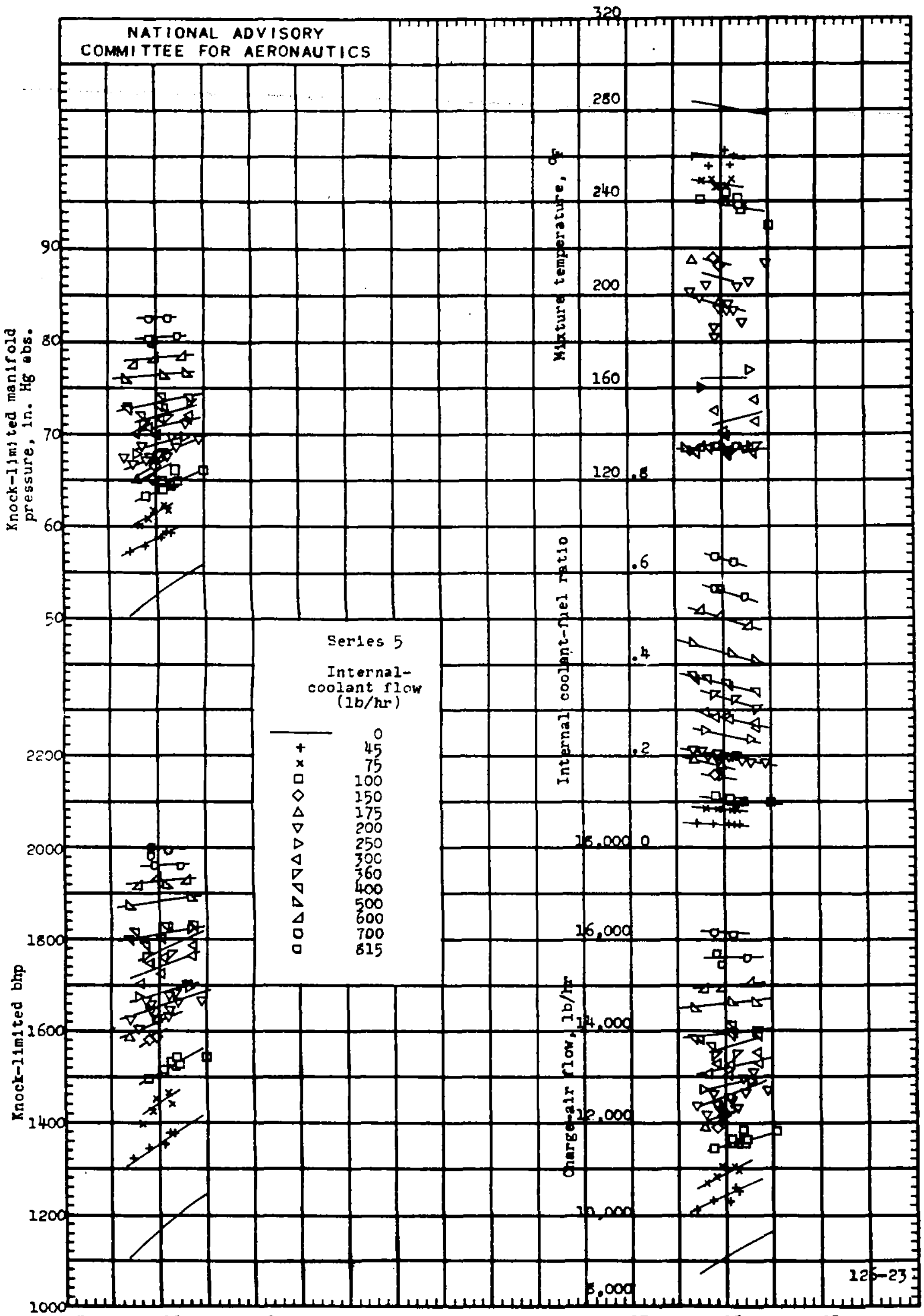


(a) Carburetor-air temperature, 120° F.

Figure 2. - Knock-limited data with a 50-50 mixture by volume of water-ethanol introduced through spray jets in intake manifolds. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R.

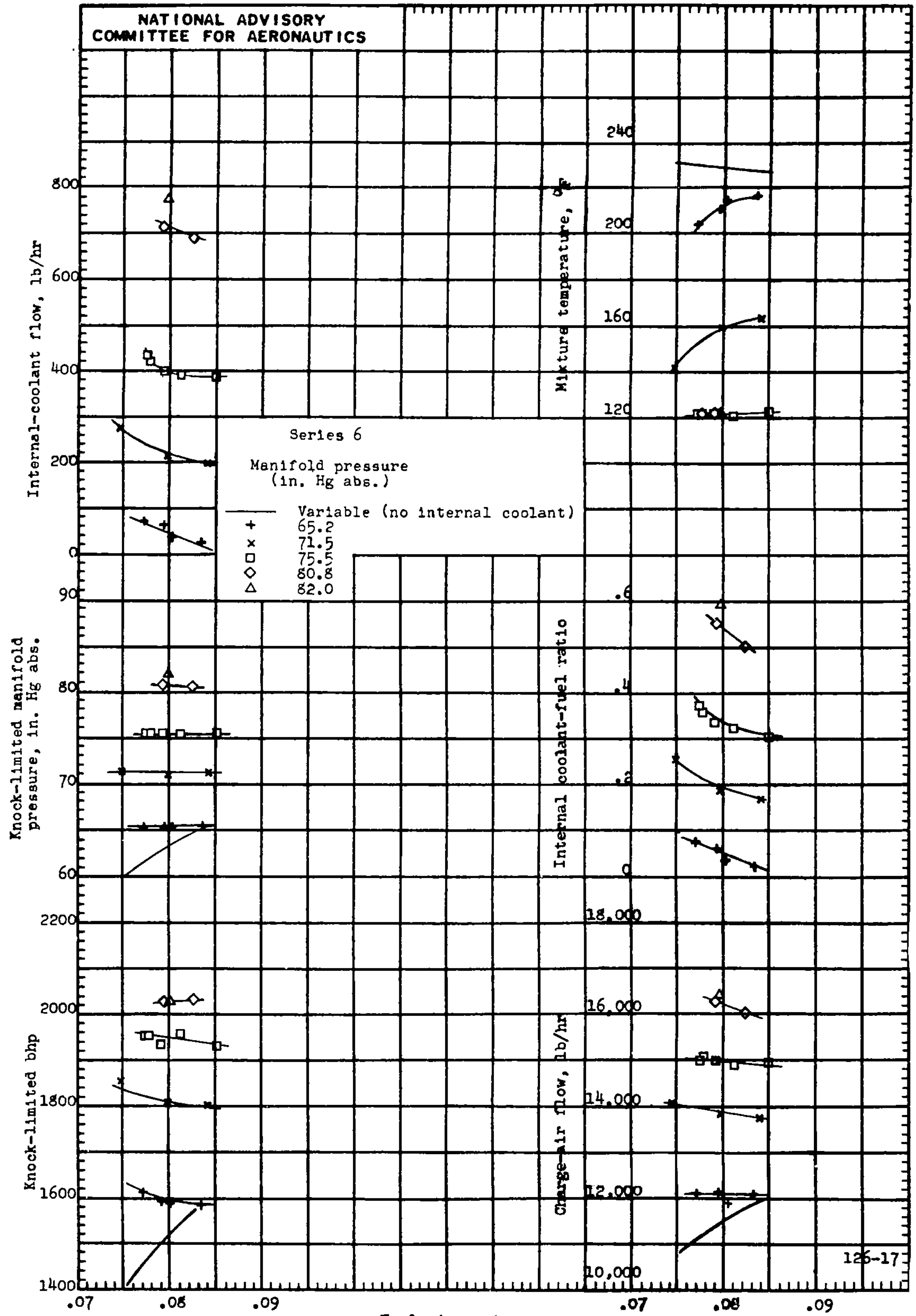


(b) Carburetor-air temperature, 60° F.
Figure 2. - Concluded.

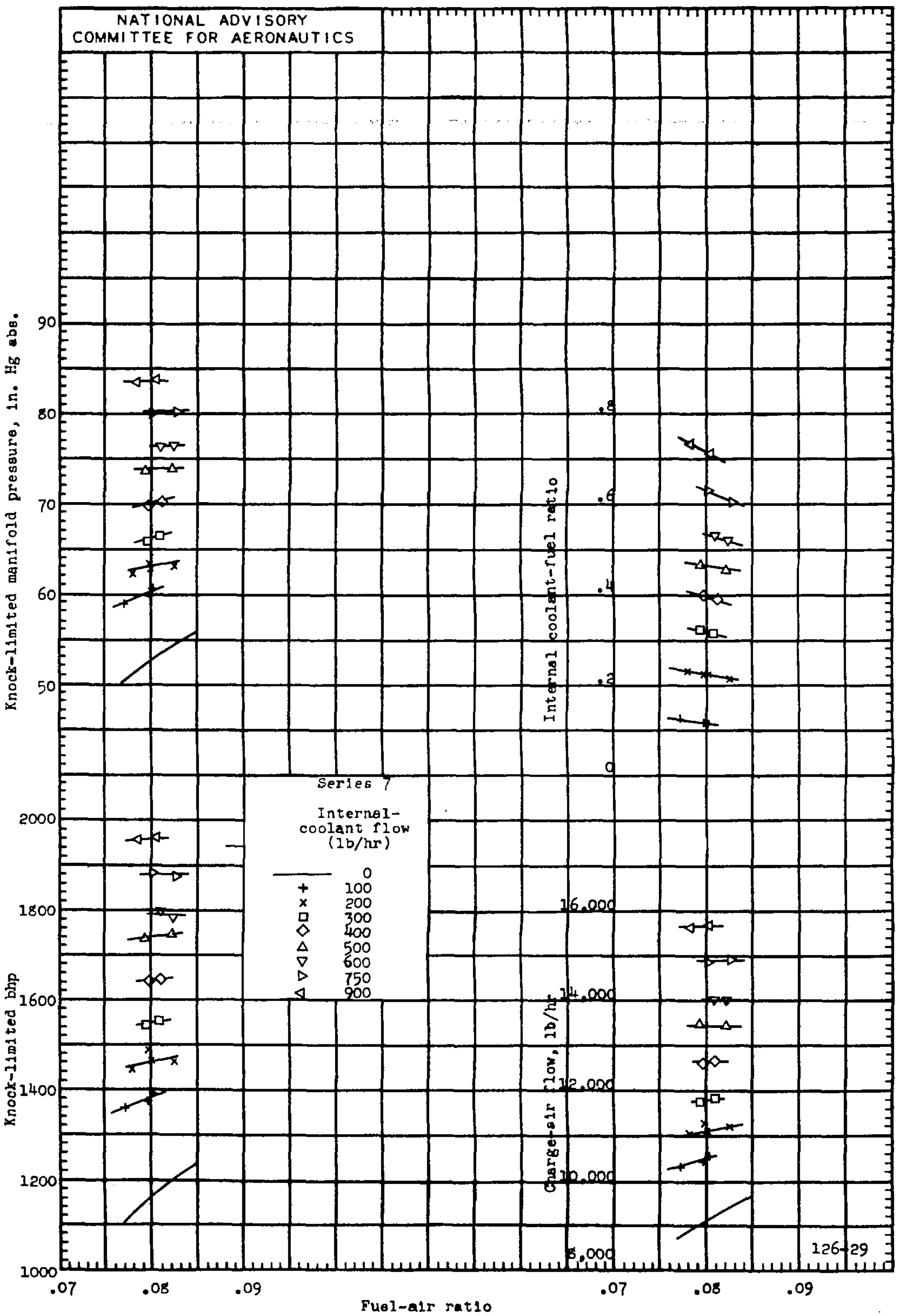


(a) Carburetor-air temperature, 120°F.

Figure 3. - Knock-limited data with water introduced with fuel through fuel nozzle. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R.

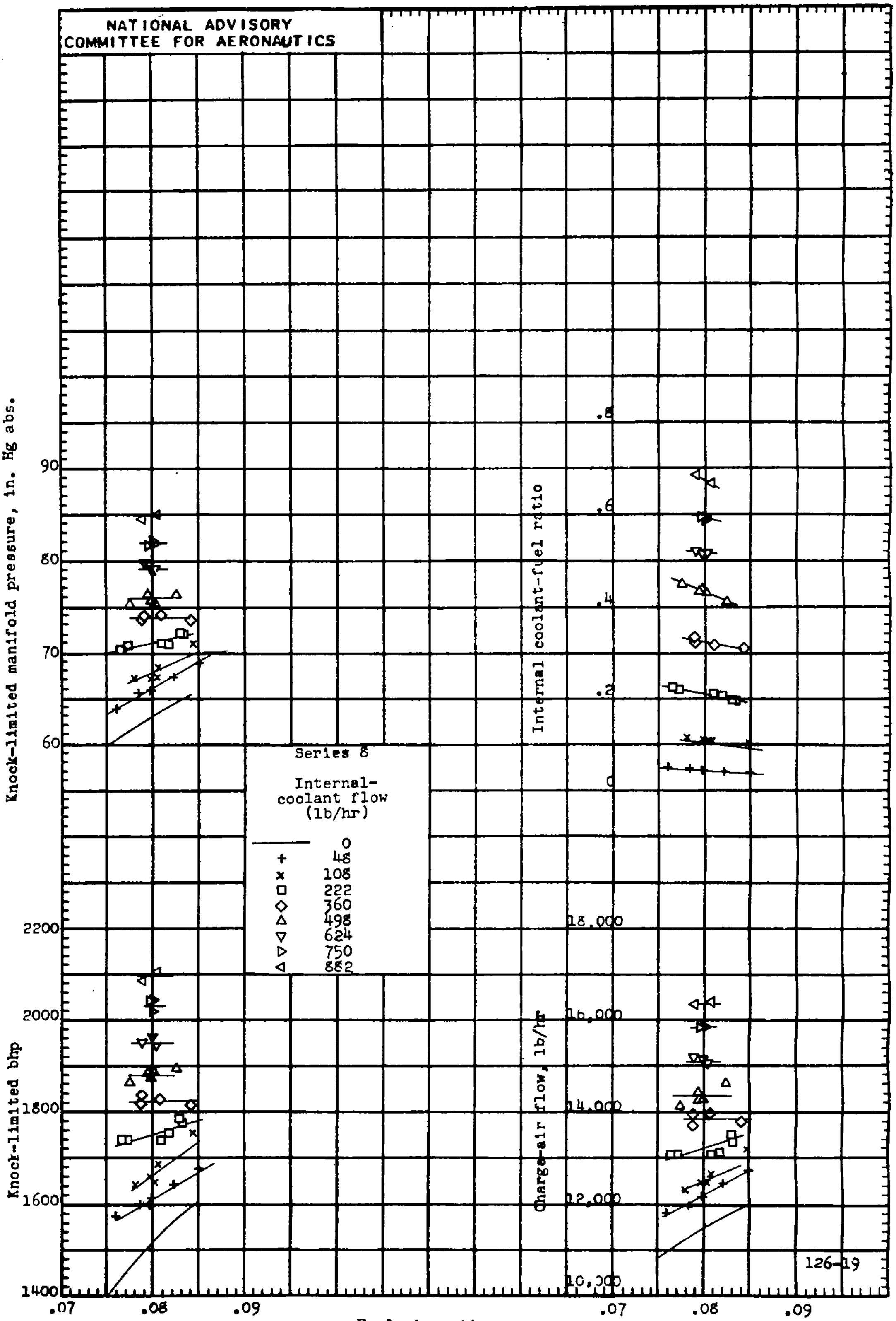


(b) Carburetor-air temperature, 60° F.
Figure 3. - Concluded.

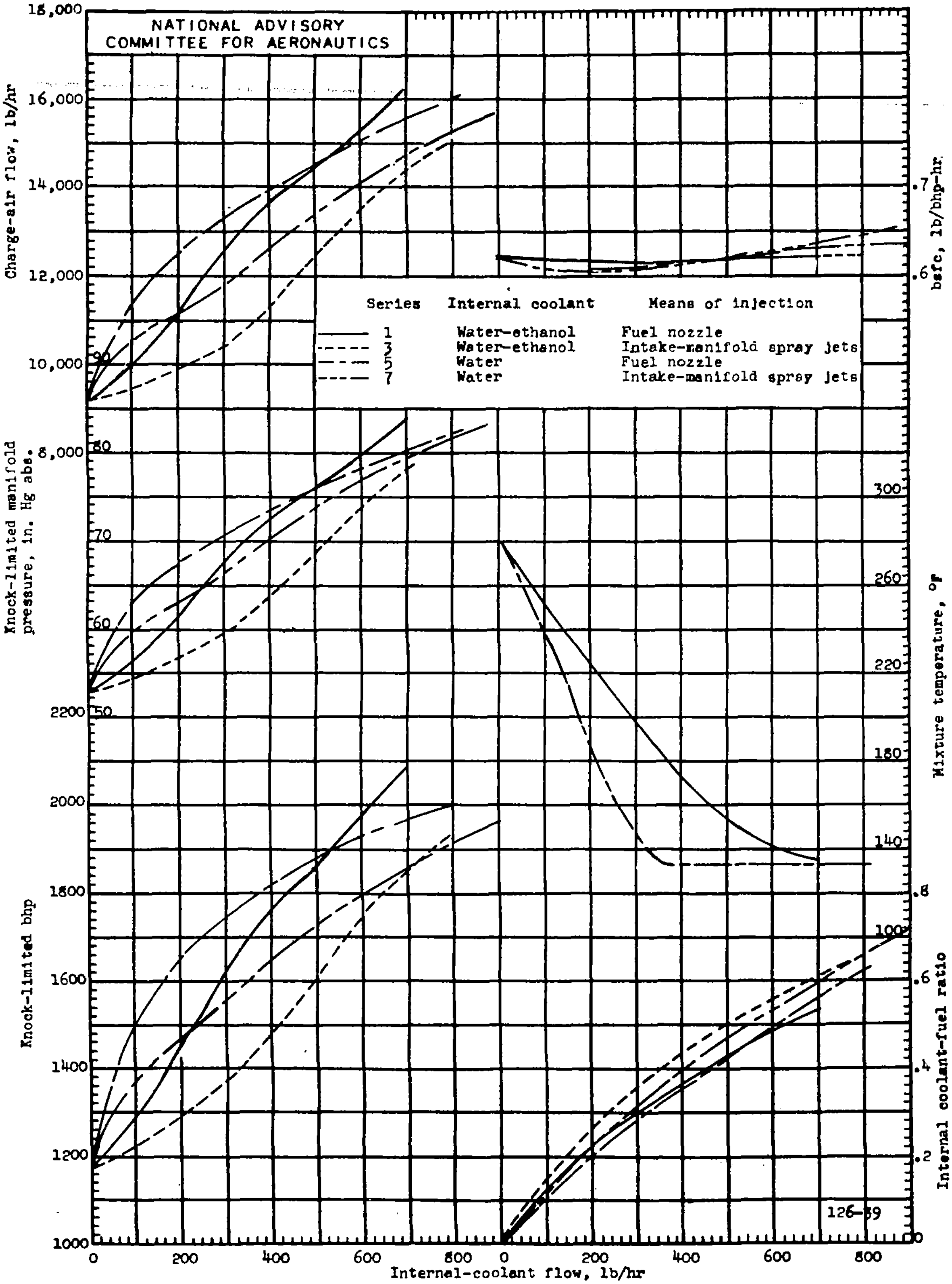


(a) Carburetor-air temperature, 120° F.

Figure 4. - Knock-limited data with water introduced through spray jets in intake manifolds. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R.

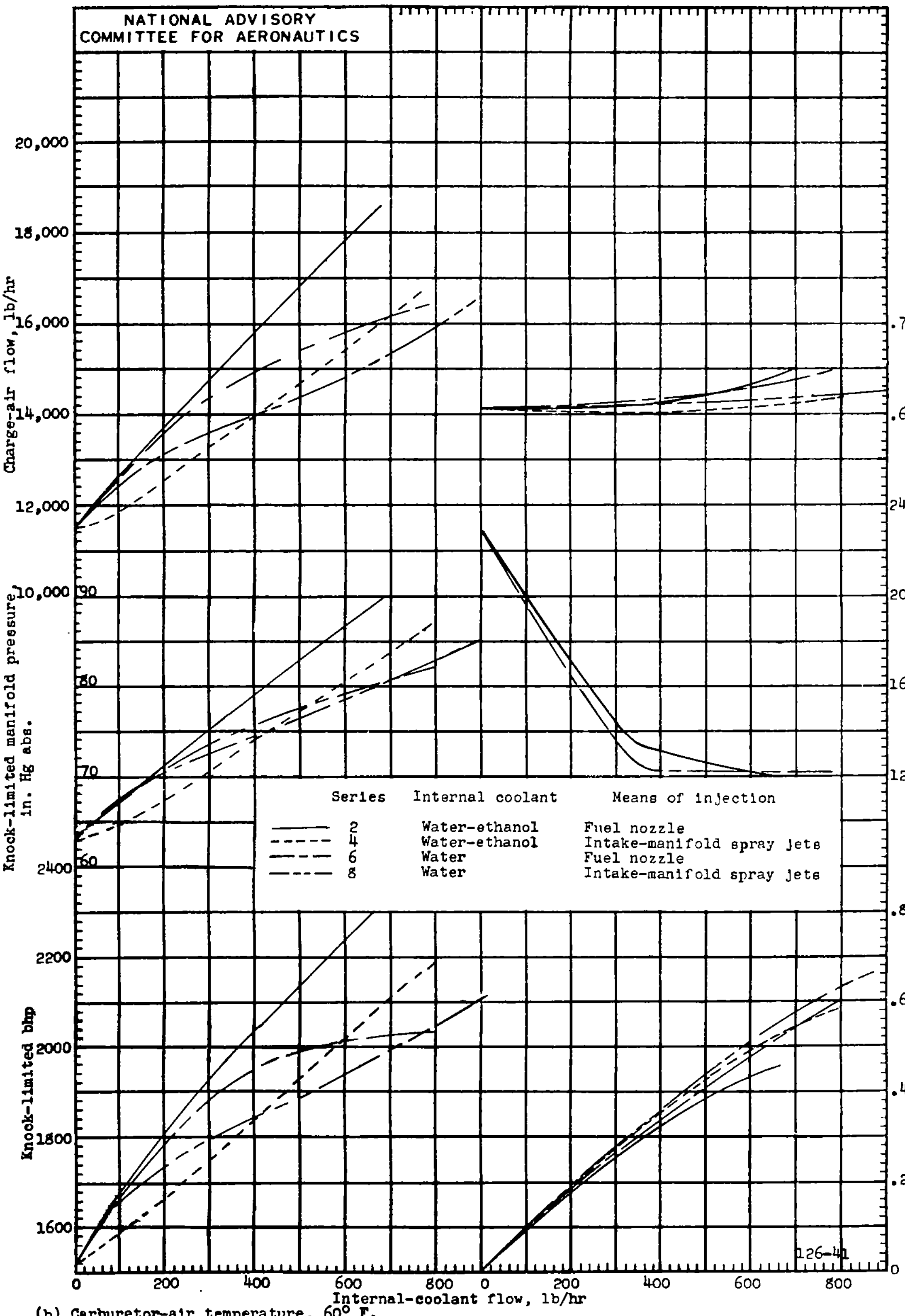


(b) Carburetor-air temperature, 60° F.
Figure 4. - Concluded.



(a) Carburetor-air temperature, 120° F.

Figure 5. - Effect of internal-coolant flow on knock-limited performance. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R. Cross plot at a fuel-air ratio of 0.08.



(b) Carburetor-air temperature, 60° F.
Figure 5. - Concluded.

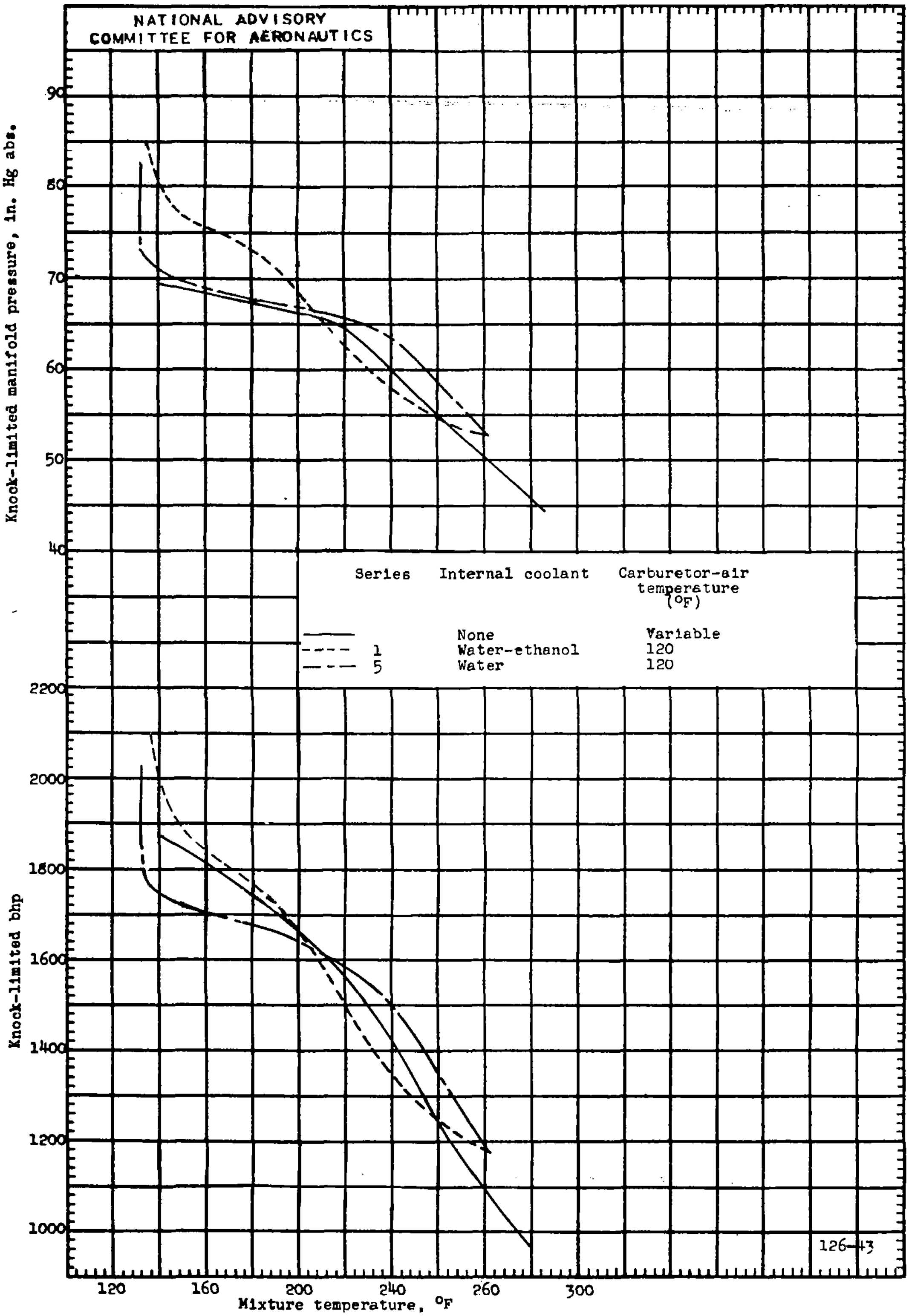


Figure 6. - Effect of mixture temperature on knock-limited performance with and without internal coolants. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R; fuel-nozzle internal-coolant injection. Cross plot at a fuel-air ratio of 0.08.

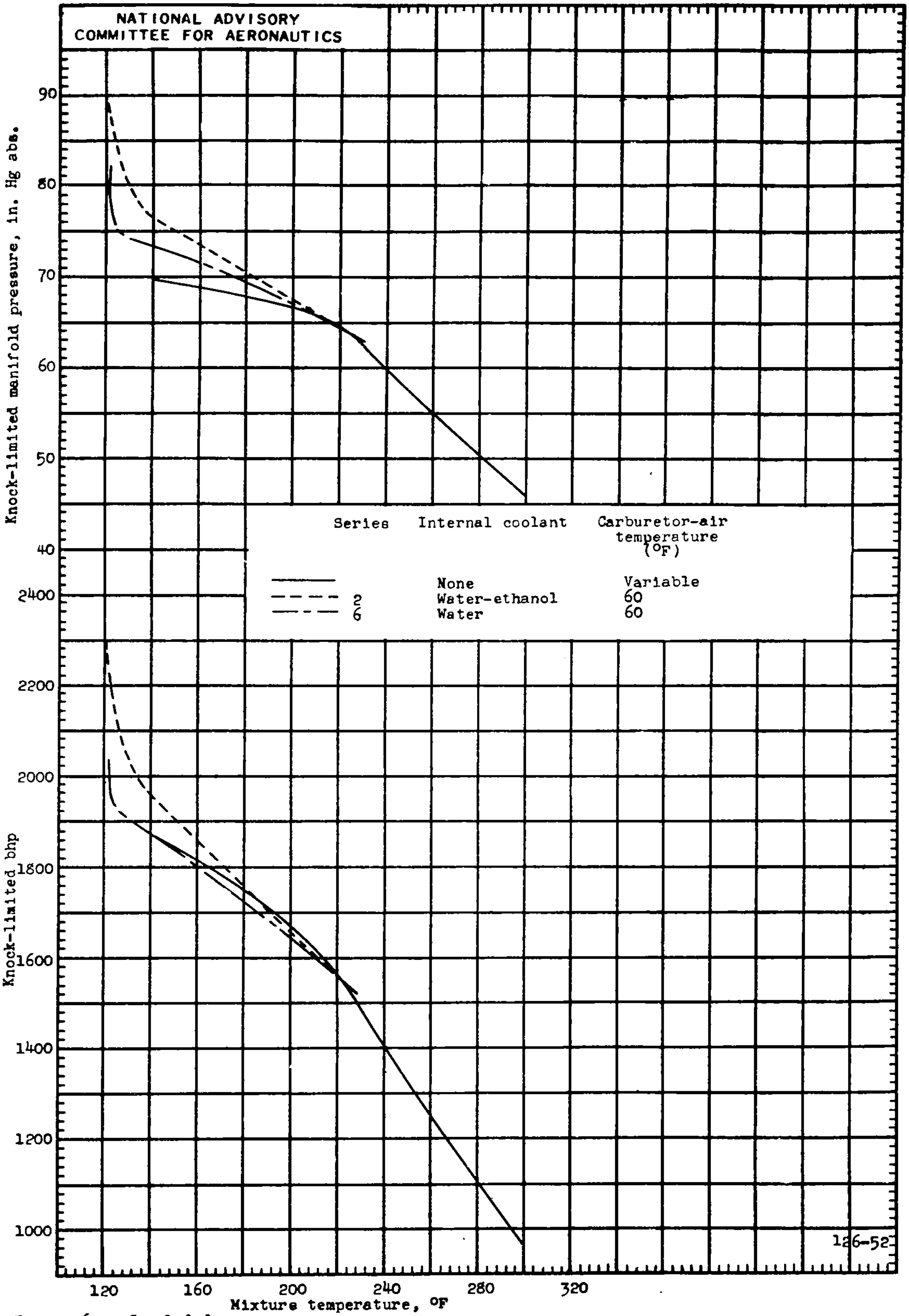


Figure 6. - Concluded.

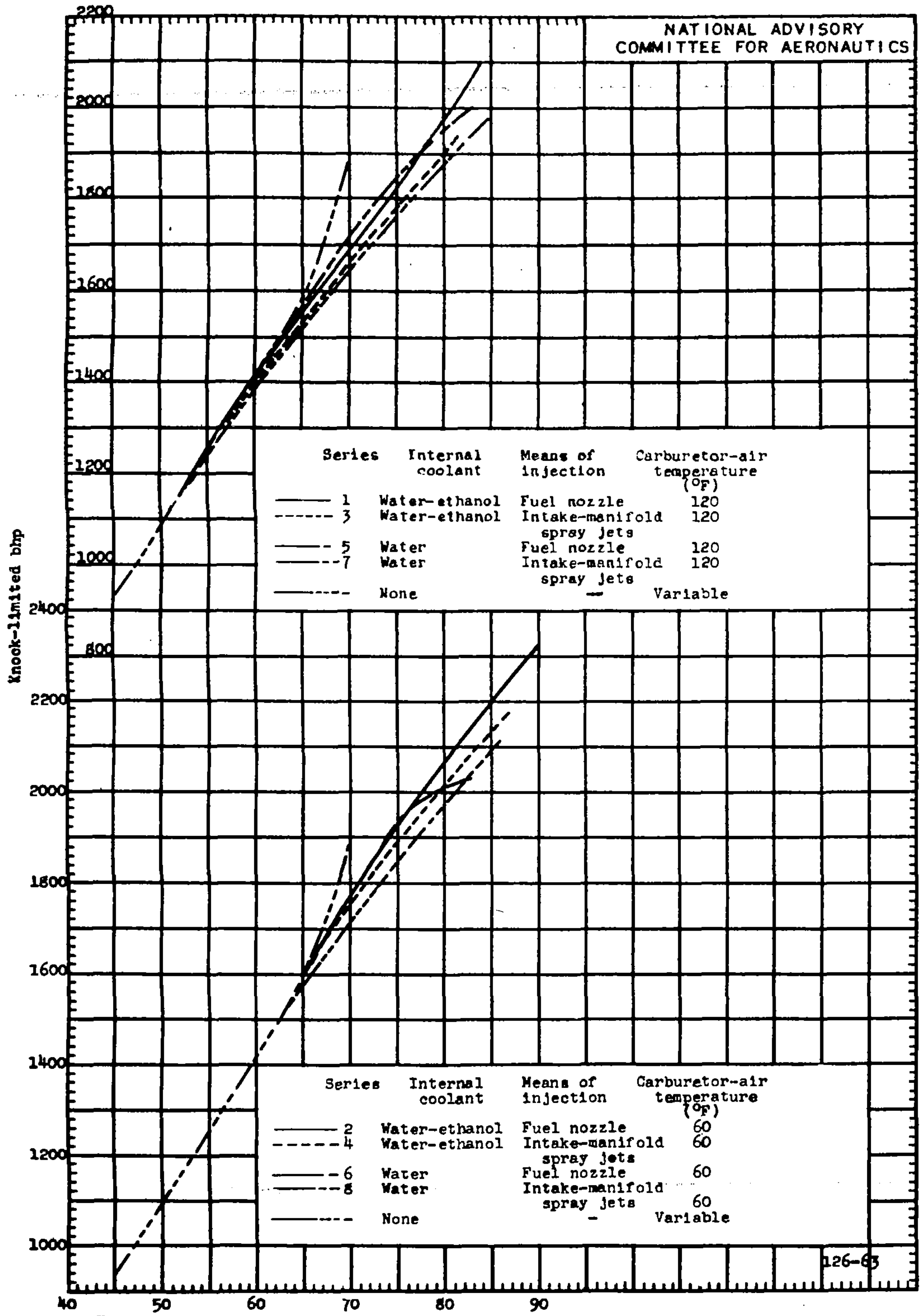
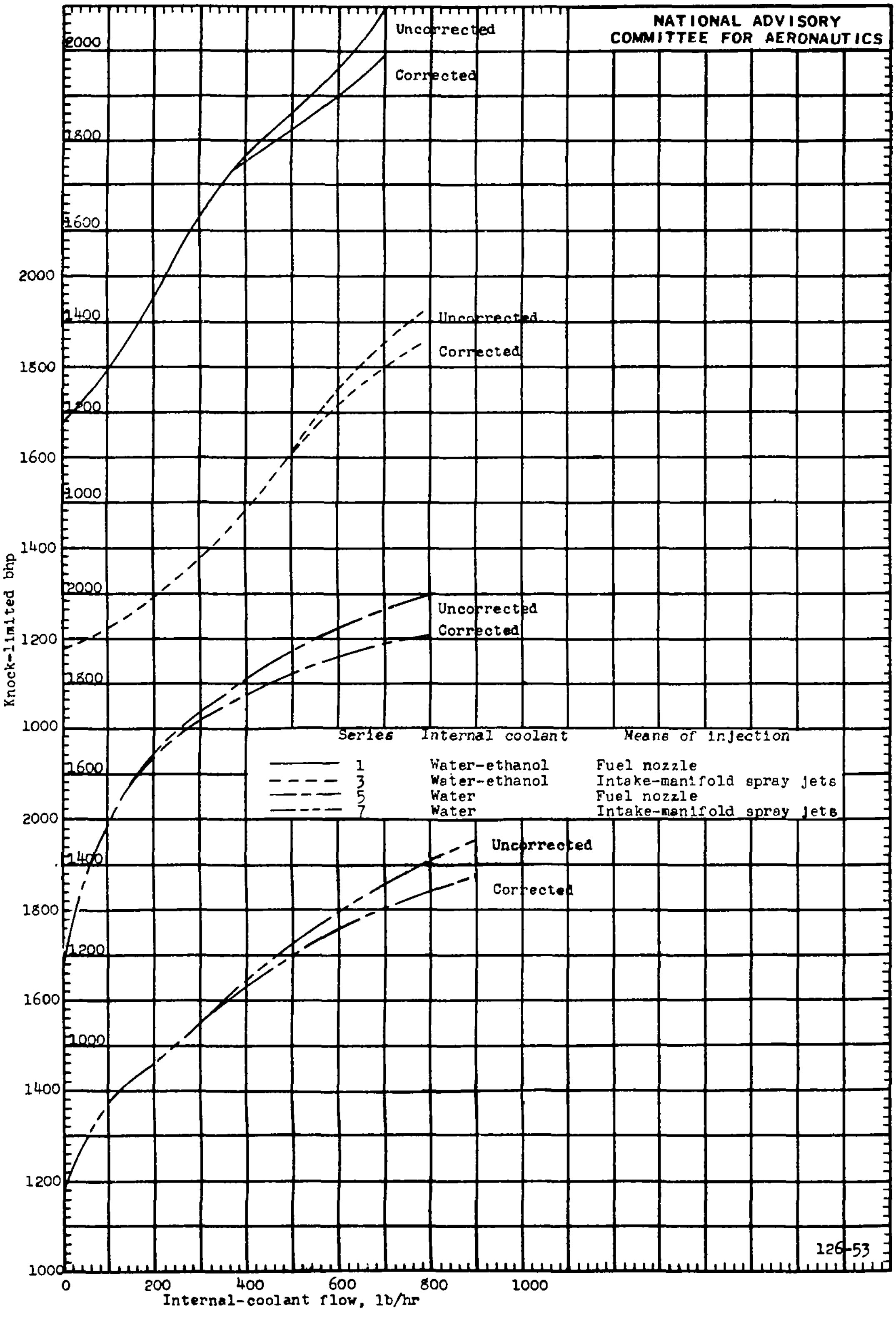
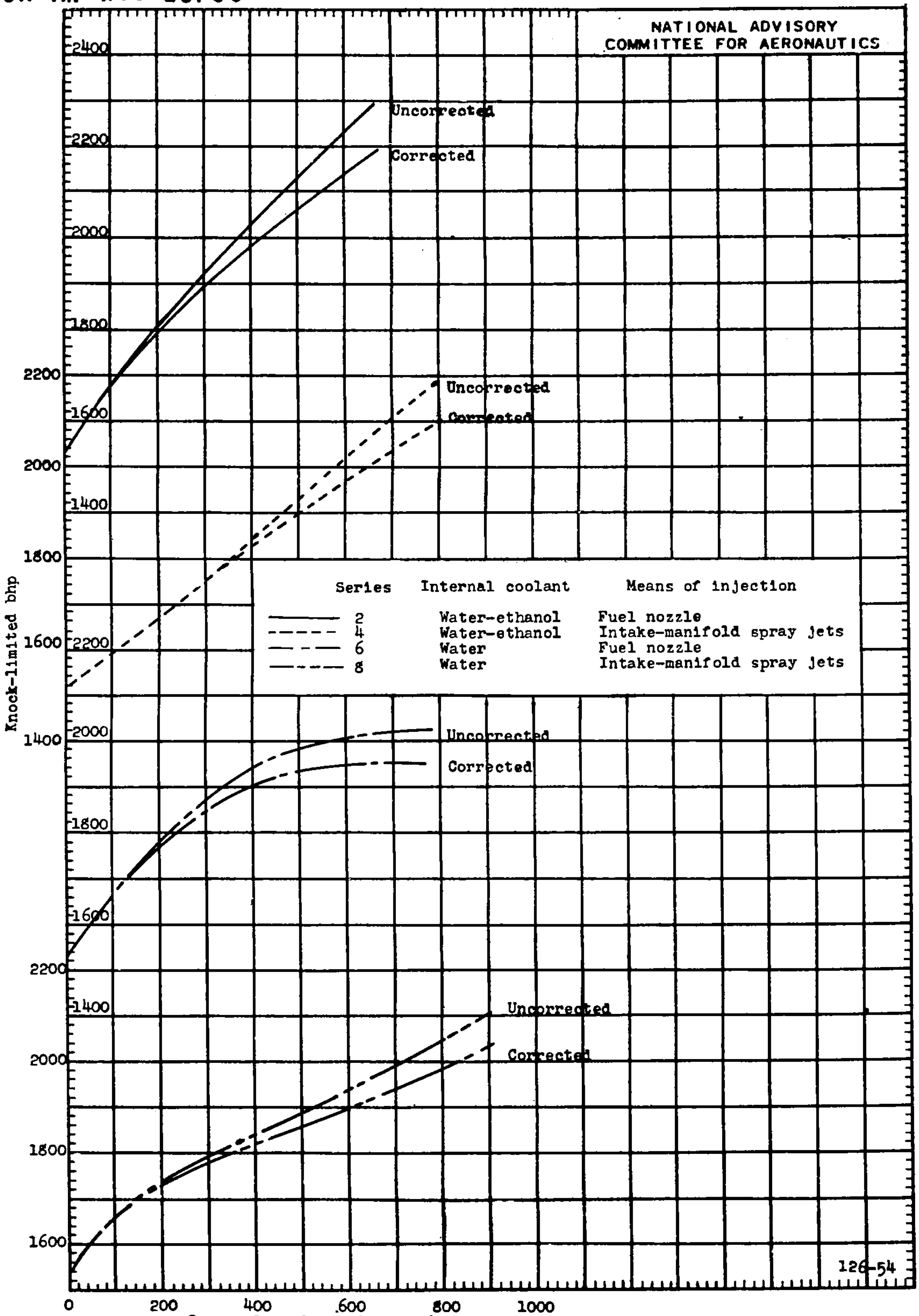


Figure 7. - Relation between knock-limited brake horsepower and manifold pressure with constant knock-intensity maintained by variation of internal-coolant flow or by variation of carburetor-air temperature. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R. Cross plot at a fuel-air ratio of 0.08.



(a) Carburetor-air temperature, 120° F.

Figure 8. - Variation of corrected and uncorrected knock-limited brake horsepower with internal-coolant flow. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R. Cross plot at a fuel-air ratio of 0.08.



(b) Carburetor-air temperature, 60° F.
Figure 8. - Concluded.

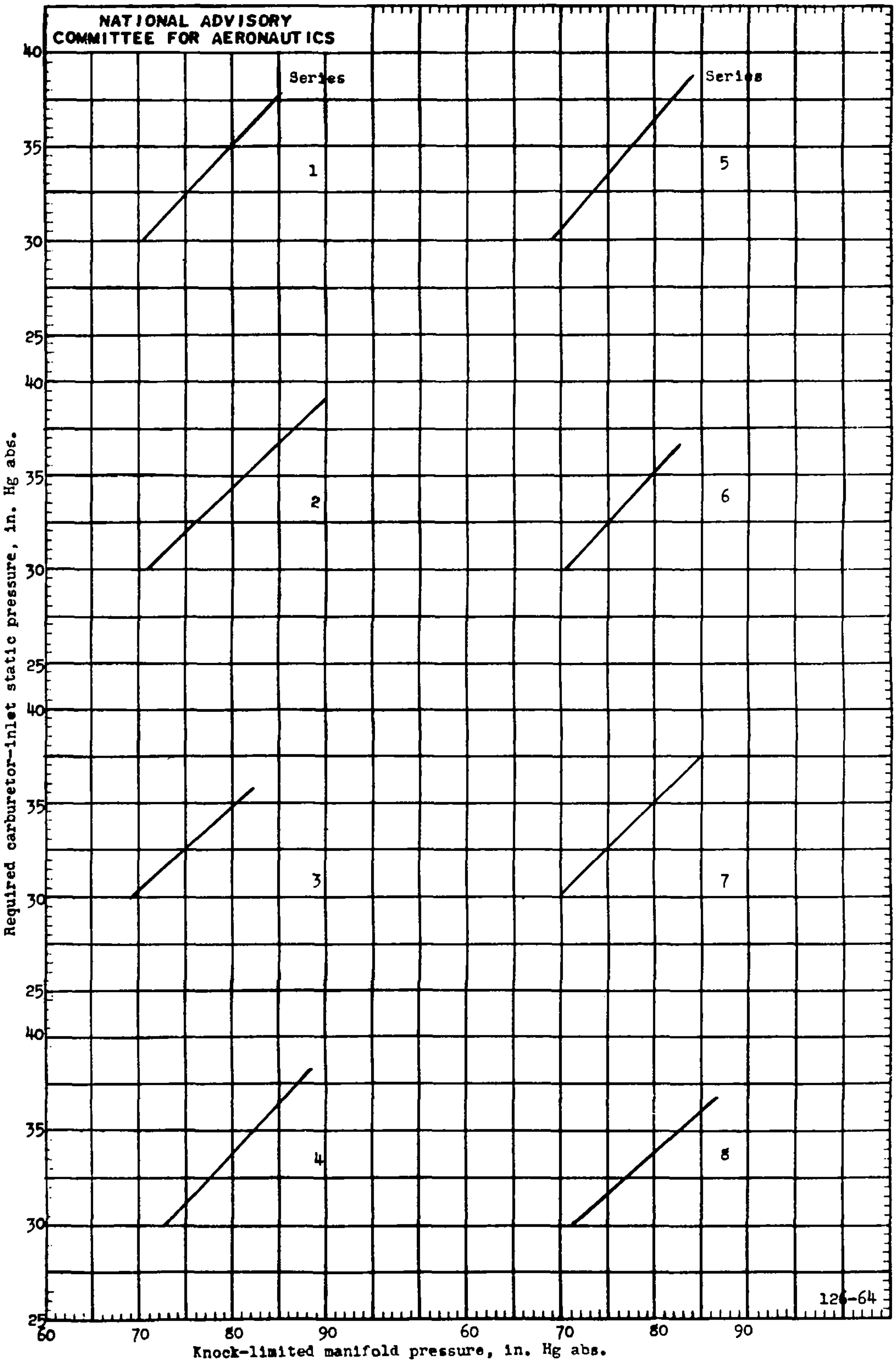


Figure 9. - Required carburetor-inlet static pressure at wide-open throttle as a function of knock-limited manifold pressure. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; compression ratio, 6.0; fuel, 28-R.